CAD/CAM

Selected articles on Advanced Manufacturing Technologies

Reprint #3

FOREWORD

As a result of advances in computer technology, the cost of information is steadily decreasing while permitting an ever increasing computing capacity. This is fostering the development of widespread changes in design and manufacturing techniques at an unprecedented rate that have given birth, towards the end of the 1970s, to new techniques referred to as Computer Aided Design and Computer Aided Manufacturing, or CAD/CAM, at an unprecedented rate. This presents both a challenge and an opportunity for manufacturing companies to maintain or advance their relative positions as suppliers of manufactured goods of virtually all kinds.

In terms of long-term growth and job creation, the manufacturing industries constitute one of the most important sectors in the Canadian economy. In this context, the rapidly emerging use of CAD/CAM technology is of special significance.

It is becoming increasingly evident that the design of an up-to-date plant is just as important as the design of the product. Future developments will lead increasingly to the marriage of both Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) into highly integrated design and production systems.

In the next decade, productivity will be especially important to Canadian manufacturers. Tariff protection will be lowered, competition from external sources will undoubtedly increase. At the same time a new worldwide wave of industrial automation, based on a rapidly increasing use of computers in design and manufacturing, is occurring.

Since 1977, interest and activity in CAD/CAM by Canadian companies has increased substantially. Indeed, the first reprint of 15 articles made available by the Department of Industry, Trade and Commerce to encourage a wider interest by Canadian industry was so well received that it was followed by a second reprint of 28 articles in 1981. This reprint of more recent information will be equally useful to those wishing to gain an appreciation and introduction to this important technology.

Copies of this publication and a companion Directory of Companies providing CAD/CAM products and services are available from:
Regional Industrial Expansion
Office of Industrial Innovation
Technology Assessment Directorate
235 Queen Street
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AVANT-PROPOS

Grâce aux progrès réalisés dans le domaine de l'informatique, le coût de l'information ne cesse de diminuer, alors que la capacité de traitement informatique ne fait que croître. De ce fait, on assiste à un nombre grandissant de changements dans les techniques de conception et de fabrication, lesquels s'effectuent à un rythme sans précédent qui a donné naissance, vers la fin des années 70, à la conception et à la fabrication assistées par ordinateur. Une telle évolution constitue un défi pour les entreprises de fabrication et leur donne en même temps la possibilité de conserver ou d'améliorer leur position à titre de fournisseurs de presque tous les produits manufacturés.

Du point de vue de la croissance à long terme et de la création d'emplois, les industries de la fabrication comptent parmi les plus importants secteurs de l'économie. Dans cette optique, l'utilisation accélérée de la technologie CFAO revêt une importance toute particulière.

Il devient de plus en plus évident que l'élaboration d'une usine moderne est tout aussi importante que la conception d'un produit. Les progrès futurs conduiront de plus en plus à l'union de la conception assistée par ordinateur (CAO) et de la fabrication assistée par ordinateur (FAO) pour donner lieu à des systèmes de conception et de production hautement intégrés.

Au cours de la prochaine décennie, les fabricants canadiens devront accorder une attention toute particulière à la productivité. La protection tarifaire diminuera et la concurrence étrangère ne fera que s'accentuer. Parallèlement se déferle une nouvelle vague d'automatisation industrielle, fondée sur l'utilisation de plus en plus croissante des ordinateurs dans la conception et la fabrication.

Depuis 1977, l'intérêt des sociétés canadiennes à l'égard de la CFAO et leurs activités dans ce domaine n'ont cessé de croître. La preuve en est dans l'accueil réservé à la première parution de 15 articles publiés par le ministère de l'Industrie et du Commerce en 1977 en vue de susciter l'intérêt de l'industrie canadienne sur le sujet. Celui-ci fut tel qu'on a pris la décision d'y donner suite et de publier, en 1981, 28 autres articles. La présente édition qui renferme des données encore plus récentes devrait se révéler tout aussi utile à ceux désireux de s'initier à cette importante technologie ou de pouvoir mieux l'appréhender.

Vous pouvez obtenir des exemplaires du présent ouvrage qui s'accompagne d'un répertoire de sociétés utilisant la conception et la fabrication assistées par ordinateur en vous adressant au :
Bureau de l'innovation industrielle
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CAD/CAM: helping Canada to compete

It's a key factor in industrial productivity and the CAD/CAM Technology Advancement Council recommends a CAD/CAM Technology Centre to encourage its wider use.

THE USE OF computer aided design and computer aided manufacturing (CAD/CAM) has been identified by industry leaders and governments in the industrialized countries as a new, rapidly emerging, and key technology, having particular impact on manufacturing industry productivity and competitiveness. Especially in Germany and Japan, and to a lesser degree, in the United Kingdom and the U.S.A., governments and industry are working together in the national interest on the development and rapid application of this technology.

In Canada, the Department of Industry, Trade and Commerce established a CAD/CAM Technology Advancement Council in 1978, with members from industry, universities, and government. Objectives of the council include increasing the awareness in industry, and elsewhere, of the importance of this technology, and dissemination of information to encourage and assist CAD/CAM development and application in Canadian industry.

A recent report by the council points out that it is important to recognize that the general and widespread revolution in information processing involves at least two main thrusts: firstly, the relatively straightforward processing of large volumes of information, as in service industry and office applications of word processing and communications equipment; secondly, a new wave of factory automation involving computer aided design and computer aided manufacturing. The latter technology, the subject of the council's report, is of particular importance to the discrete parts manufacturing industry which comprises a very large portion of the manufacturing industry.

The CAD/CAM thrust in the manufacturing sector requires large amounts of user-oriented, mechanical, process and systems engineering. With the advent of CAD/CAM, it will become increasingly evident in the 1980s that the design of the factory will be just as important as the design of the product. Development will lead increasingly to the marriage of both CAD and CAM into integrated design and production systems.

What is CAD/CAM technology?

When the use of computers first began in Canadian industry in the mid 1950s, the emphasis was on engineering computation. In the intervening 25 years, the capabilities of electronic computing power have evolved from initial emphasis on computation ability to the inclusion of logical ability, memory and the current great emphasis on graphic display and output.

CAD uses all these abilities. Of particular note, the advent of graphic displays has enabled the automation of the draftsman's task as well as the engineer's. Because of this enlargement in scope, the name of the activity has been appropriately changed from engineering computation to Computer Aided Design, widely abbreviated as CAD.

Computers have also been employed in manufacturing for many years. However, their use is now taking on a new involvement in the more direct control of production equipment and is assuming a more total systems nature.

In most manufacturing companies, initial use of computers was not on the factory floor, but indirectly in support of production planning and inventory control. At the same time, the concept of numerical control (NC) had been revolutionizing the machine tool industry. Today, NC users employ computers not only for parts programming, but also for local control of machine tools. Increasingly, this is being done with groups of machine tools supervised by a single computer. This principle is being applied not only to metal cutting and removal, but to other manufacturing processes as well. Interconnected computer systems can make the totally automated factory a reality from initial design/conception through to final manufacture, test and shipment.

All of the subsystems for fully automated production are available in some form now. These include computer graphics, computer generated parts lists, centralized data bases, computer controlled stacker cranes, computer controlled material handling for delivery of components, direct computer control of machine tools, automatic inspection and test equipment. Their further development and interconnection into a total manufacturing system is only a matter of time. This will have a dramatic effect on the design and layout not only of modern manufacturing plants, but warehouses as well.

CAD/CAM should not be thought of as being only synonymous with the numerical control of machine tools. It really refers to the entire manufacturing process as summarized in Table I and illustrated in Figure 1. Many significant mechanical, process and systems engineering tasks are included and accomplished in such systems.

Studies have shown that in many shops, the average workpiece spends only 5% of its time in the machine, with moving and waiting between operations accounting for most of its production lifetime. Furthermore, studies on cut-

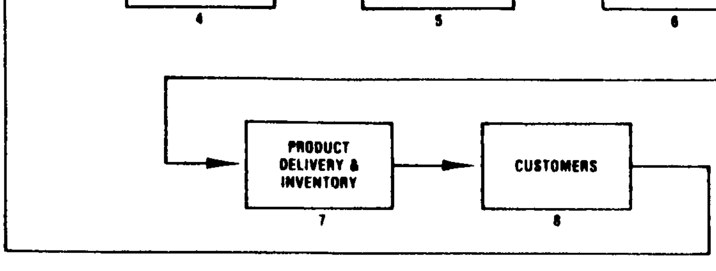


Figure 1. Flow tasks for manufacturing.

ting machines show that of this 5% in the machine, only 30% of the production time is actually employed in the fundamental task, which is metal removal. In the general machinery industry, these inefficiencies drive up the cost of work in process inventory, a figure of 22% of annual sales being generally reported.

The economic justifications for CAD/CAM include:

- Increased utilization and more efficient use of machine tools and other capital equipment.
- Faster delivery time to the customer.
- Reduced work-in-progress inventory.
- A more disciplined approach to both design and manufacture.
- Greater design creativity through use of computer graphics.
- Cost reduction through design optimization.
- Improved use of materials through family of parts classification and coding.
- Reduced scrap material by minimizing fabrication errors.
- Improved quality control through NC machining accuracy, repeatability and automated testing.
- Improved coordination and information transfer between engineering, production control, manufacturing and accounting.
- General productivity improvement of the available work force.
- Automation of one-off parts and short production runs.

Advances in computer technology

It should be clearly understood that the computer is applied in CAD/CAM systems as an available tool. CAD/CAM technology is of a systems, mechanical and manufacturing engineering nature, and needs to be developed "in-house" by the user. It would be a mistake, therefore, to consider "CAD/CAM" as a product developed and supplied solely, or even primarily, by the electronics industry. Figure 2 illustrates some of the many technologies involved.

It is the continued improvement in the performance/cost ratio of available computers that makes applications like CAD/CAM possible. The improved economics and performance of computers are the result of increasing density of logic and memory devices, embodied today in the term "microelectronics" and typified by the ubiquitous and pervasive microprocessor.

Comparatively low cost computing power and data storage devices, coupled with an expanding awareness of computers, has made possible a continual supply of new applications. There are many ways of plotting this trend, much of which can be related to advances in microelectronics technology, very large scale integration (VLSI) and the microcomputer in particular. For example, the number of components per circuit has doubled every year since 1959, resulting in a thousandfold increase every 10 years. This trend in miniaturization is expected to continue.

Computer Aided Design	—Production design and analysis including graphic design, functional analysis, stress strain analysis, heat and material balances, simulation and modelling, data reduction and analysis and cost estimating of the proposed product or system to determine fitness of purpose and economically optimized production.
Customer Order Handling	—Record keeping, tracking and reporting on the status of individual customer orders, particularly when part of an integrated on-line system.
Production, Material & Inventory Control	—Scheduling and information handling pertaining to material requirements planning, inventory control, facilities planning and order scheduling, particularly when related to an integrated on-line system.
Automated Production	—Numerical and computer control of machine tools, lathes, milling, boring machines, pattern and fabric cutting, welding, brazing, plating, flow soldering, casting, flame cutting, spray painting and automated assembly (all of these exist and are under further development).
Automated Material Handling	—Integrated materials handling using computer operated conveyors, robotic units, etc.
Automated Testing	—Automated inspection of machined parts, testing of electronic components, circuits and products, automated material inspection and grading using sensor based computer systems, pattern recognition.
Automated Packaging	—Computer implemented coordination of material and information in packaging, bottling, labelling and weighing systems.
Automated Warehousing	—Computer implemented order picking and material handling for both work in progress inventory and finished goods inventory. Automated label reading, routing of packages, parcels, baggage in shipping, sorting and distribution centres.

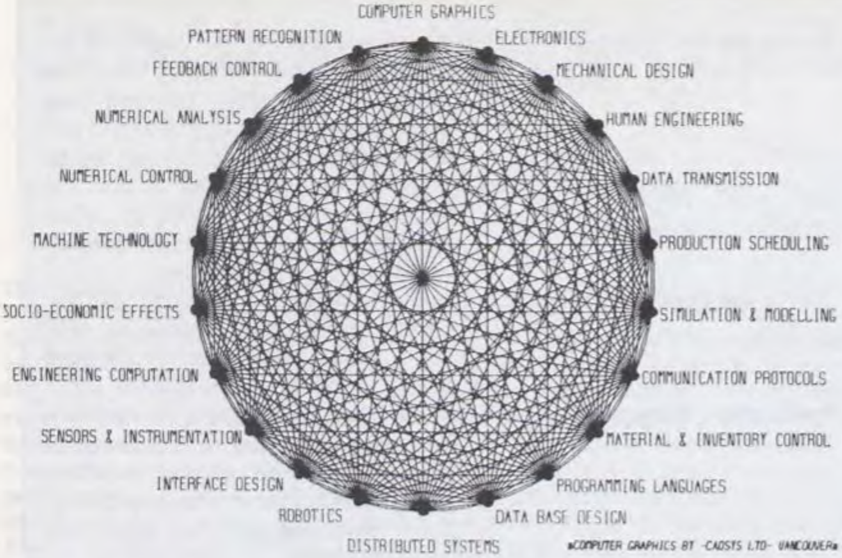
CAD/CAM technology will yield its greatest economic and productivity gains when all or most of the above application areas are married or joined together to form an integrated system. Hence there is a strong development trend in this direction.

Table I. Summary of CAD/CAM application areas.

At the user level, improvements in the computer price/performance ratio have improved annually by a factor of about 32% for memory, 23% for logic and 11% for communications. Such improvements of 10 to 1 or better every ten years mean that a calculation costing $1000 in the early days of computing would cost only $10 in 1972 and a mere dollar in 1982!

Why a CAD/CAM Centre is needed

Canadians must realize that CAD/CAM technology is an essential tool in building Canada's economy. It is



COMPUTER GRAPHICS BY -CADSYS LTD- VANCOUVER

Figure 2. CAD/CAM technologies and their interrelationships.

critical that a national policy be adopted to disseminate information and encourage the development of CAD/CAM technology in support of industry.

It is essential that a domestic infrastructure be established that is fully cognizant of the application as well as the means of economically deploying CAD/CAM technology. Industry cannot rely solely on importation of this advanced technology, as this by itself would not be adequate to ensure a Canadian competitive position.

There is a need for a major information dissemination and contracting centre in Canada for the cooperative development of user oriented CAD/CAM technology. This is particularly important for smaller businesses which cannot individually support the infrastructure, manpower and high cost of developing software and technology for CAD/CAM applications. Manufacturing firms of virtually all sizes would benefit from coordinated efforts managed by the centre to arrange development of applications of special interest to Canadian industry.

Canadian R&D essential

Research and development in CAD/CAM technology must be actively encouraged and supported in Canada. This effort must be coordinated and distributed in order to develop the best possible structure for transferring advanced technology to industry. Importation of this advanced technology, due to the dynamic nature of its development as demonstrated by U.S., Japanese, German, U.K., and Scandinavian companies, will not in itself be adequate to ensure a Canadian competitive position. Other nations have an established lead in various areas as the result of coordinated effort, both public and private, in research, development and application of CAD/CAM. The development period for CAD/CAM systems can be long, due to the amount of detailed knowledge required, but the interval between development and implementation and subsequent economic advantage can be very short. Consequently, the time delays inherent in a reliance on the use of imported technology can negate the apparent advantage of this approach.

The cost of developing CAD/CAM systems is high, and the skills required are sophisticated. For successful timely implementation, it is essential that, where possible, costs be shared through joint projects and through government assistance. Skills can be developed and employed effectively through a concentration of effort in a few ongoing teams. These development teams would be in technical institutes or universities where long term continuity of effort must be arranged and which might serve any industry desiring their assistance.

In order to keep the R&D work oriented to industrial needs, it is desirable that industry have a direct channel for input in selecting projects for funding and in monitoring the progress of approved projects. This is best done through a centre devoted to this objective, separate from the institutes and other centres undertaking in-house research and development.

A Canadian centre would demonstrate the application of existing technology and would provide technological leadership through the dissemination of reports, and the organization of seminars and CAD/CAM courses. The centre would also be active in funding original work particularly suited to Canadian conditions by the placement of shared cost development projects at other centres and companies. It would enable participating companies to share software and technology and ensure that Canadian industry remains competitive by applying the latest CAD/CAM developments.

Centres serving as focal points for CAD/CAM development already exist in Europe and the U.S.A., and parallel centres are active in certain other industrial sectors. For example, in the electric utility field, R&D is coordinated and funded with government assistance by the Canadian Electrical Association. A Canadian Centre for CAD/CAM Technology would play a similar role in its field in Canada.

CAD or CAM?

In the allocation of funds and the planning of R&D programs, there is a need to make decisions as to the relative emphasis or allocation of effort on CAD or CAM or CAD/CAM integration. Although CAD and CAM do draw together in integrated systems, they are for the most part two separate fields. They will continue to be regarded by many users as separate activities, requiring different experience and different skills.

CAD projects are of a "soft" engineering nature and are more closely related to the historically predominant activities of most engineering departments or university research. Most CAD projects can be undertaken by individuals without the formation of large teams, although discipline, planning and teamwork are required if larger sets of mutually compatible programs are to result.

Some aspects of CAD development work are homogeneous, such as computer graphics, data base design or numerical analysis. However, many parts are not. Separate teams and centres will tend to develop in such areas as: integrated circuits and VLSI; printed circuit board design and layout; building design in the construction industry; design and stress analysis of mechanical parts, etc; and industrial robots.

It will seem tempting and "easy" to rely on imported CAD programs, particularly software developed in the U.S.A. On the other hand, the user never really understands a software package as well as its developer. A near total dependence on the source can develop for changes, extensions, in-depth understanding of the program use and applicability to special conditions. A widespread use of imported CAD systems, or CAD services imported through remote computing facilities, could result in a near total loss of technological sovereignty for the Canadian manufacturing industry.

The CAM field is probably a more homogeneous field across industry sectors than is the CAD field, particularly in metal cutting. For this reason, it would seem in some ways to be the easier area on which to focus attention. The CAM area is directly related to the potential reductions in manufacturing costs, which for most manufacturing companies are greater than design costs. Furthermore, in the makeup of Canadian industry, while many companies are engaged in manufacturing who do little or no design, there are few who design but do not manufacture. These factors would favor early development or emphasis on CAM over CAD.

On the other hand, CAM projects involve "hard" as well as "soft" engineering. There is a greater need in CAM projects for the formulation of teams and teamwork in development. Capital equipment is required in addition to "normal" R&D expenditures and the work is not as closely related to traditional engineering work or university research as usually undertaken in Canada.

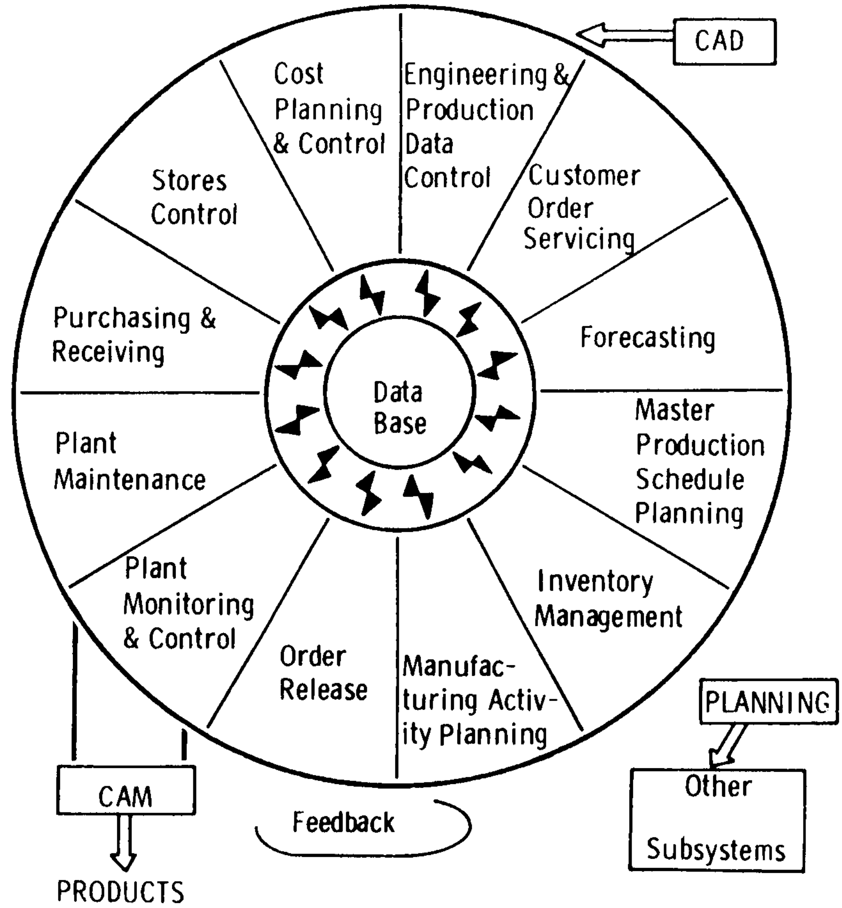


Figure 3. CAD and CAM become integrated through the central data base.

CAD and CAM drawing closer

In more and more applications, the design and manufacturing applications of computer technology are tending to meld together. This integration is due in part to a greater acceptance of CAD and CAM technologies, but more because the two disciplines can be joined through a central data base, as illustrated in Fig. 3. As CAD/CAM technology develops, especially in mature manufacturing activities, the distinction between the two functions will diminish and eventually become one.

To date, only the largest manufacturing firms have had the in-house systems engineering capability to fully exploit CAD/CAM technology. CAD/CAM systems, particularly those of an integrated systems nature, tend mostly to be employed by only the world's largest corporations; General Motors, Ford, Boeing, Lockheed, McDonnell-Douglas, IBM, Caterpillar. This is currently the primary area of CAD/CAM systems application. A study by the Canadian Institute of Metalworking (CIM) to identify the attitudes and awareness of Canadian numerical control users to CAD/CAM technology also clearly shows that awareness, knowledge, development and application of CAD/CAM systems tends to be filtering down, over time, from large to medium to smaller sized companies.

There is a need for a focus for the development of user oriented CAD/CAM technology on a cooperative basis in Canada. This is particularly important for smaller enterprises which cannot adequately support the infrastructure, manpower and high cost attached to the development of the technology but the organization would be of value to manufacturing firms of virtually all sizes, as it would orchestrate the development of applications of CAD/CAM technology of special interest to Canadian industry.

As the single most important conclusion of its report, the CAD/CAM Council has recommended the establishment of a major centre in Canada for the development of user oriented CAD/CAM technology on a cooperative basis.

In order to ensure maximum service to industry, and to make optimum use of existing organizations, the role of the centre would be primarily devoted to:

- Disseminating information to stimulate awareness and improve the knowledge base on CAD/CAM technology in Canada, especially in industry; and
- Contracting-out to appropriate development centres and private companies of user-oriented and defined development projects of common interest to Canadian manufacturing companies.

The centre would require funding for its permanent staff, facilities and to finance projects. The base support would be provided by government, with additional funding generated through contract funds paid by project supporters, and from membership in the Centre on a company, institutional and individual basis.

CAD/CAM and productivity

Productivity will be especially important to Canadian manufacturers in the 1980s. During this decade, tariff protection will be lowered, competition from external sources will undoubtedly increase, and inflation will continue at a strong pace. At the same time a new worldwide wave of industrial automation, based on a rapidly increasing use of computers in design and manufacturing, is occurring.

As a result of the latest round of trade negotiations, Canadian industry will face increasing competition from imported products. On the other hand, our industry will have better access to foreign markets. However, to compete successfully in this new trading environment, Canadian industry will have to achieve levels of performance, in terms of productivity and technical excellence, equivalent or superior to industry in other countries.

A wider understanding and adoption of computer aided design and computer aided manufacturing would appear to be essential to reach these goals. ■

Adapted from a report by the CAD/CAM Technology Advancement Council, "Strategy for Survival—The Canadian CAD/CAM Option."

THE COMPUTER AND MANUFACTURING

Quick reflexes and an integrated system are the keys to survival

THE COMPUTER is bringing manufacturing into the Information Age. This new tool, long a familiar one in business and management operations, is moving into the factory, and its advent is changing manufacturing as certainly as the steam engine changed it 100 years ago.

The basic metalworking processes are not likely to change fundamentally, but their organization and control definitely will.

In one respect, manufacturing could be said to be coming full circle. The first manufacturing was a cottage industry: the designer was also the manufacturer, conceiving and fabricating products one at a time. Eventually, the concept of the interchangeability of parts was developed, production was separated into specialized functions, and identical parts were produced thousands at a time.

Today, production is much more batch-oriented, and, although the designer and manufacturer may not become one again, the functions are being drawn close in the movement toward an integrated manufacturing system.

It is perhaps ironic that, at a time when the market demands a high degree of product diversification, the necessity for increasing productivity and reducing costs is driving manufacturing toward integration into a coherent system, a continuous process in which parts do not spend as much as 95% of production time being moved around or waiting to be worked on.

The computer is the key to each of these twin requirements. It is the only tool that can provide the quick reflexes, the flexibility and speed, to meet a diversified market. And it is the only tool that enables the detailed analysis and the accessibilty of accurate data necessary for the integration of the manufacturing system.

It may well be that, in the future, the computer may be essential to a company's survival. C.H. Link, former senior vice president and general manager of CAM-I Inc, puts it this way: "The computer 'have-nots' will be left behind and will become increasingly out of step in the Information Age. Many of today's businesses will fade away to be replaced by more-productive combinations."

Arthur R. Thomson, professor of manufacturing engineering, Cleveland State Univ, describes such more-productive combinations as "superquality, superproductivity plants. The goal, as I would see it, is to design and operate a plant that would produce 100% satisfactory parts with good productivity. People may say that such a goal is crazy, but we can develop turbines that are 98% efficient, and the struggle to reach 100% is bringing us fairly close to it. I think that we in manufacturing have settled for a lot less than we could really get."

A sophisticated, competitive world is requiring that manufacturing begin to settle for more, to become itself sophisticated. To meet competition, for example, a company will have to meet the somewhat conflicting demands for greater product diversification, higher quality, improved productivity, and lower prices.

The company that seeks to meet these demands will need a sophisticated tool, one that will allow it to respond quickly to customer needs while getting the most out of its manufacturing resources.

The computer is that tool.

Becoming a "superquality, superproductivity" plant requires the integration of an extremely complex system. This can be accomplished only when all elements of manufacturing—design, fabrication and assembly, quality assurance, management, materials handling—are computer integrated, both individually and collectively.

Charles F. Carter, technical director of Cincinnati Milacron and president of SME, separates manufacturing into three phases: product design, planning for manufacturing, and the manufacturing itself. "The computer," he points out, "is revolutionizing all three phases."

In product design, for example, interactive computer-aided-design (CAD) systems allow the drawing and analysis tasks to be performed in a fraction of the time previously required and with greater accuracy. And programs for prototype testing and evaluation further speed the design process.

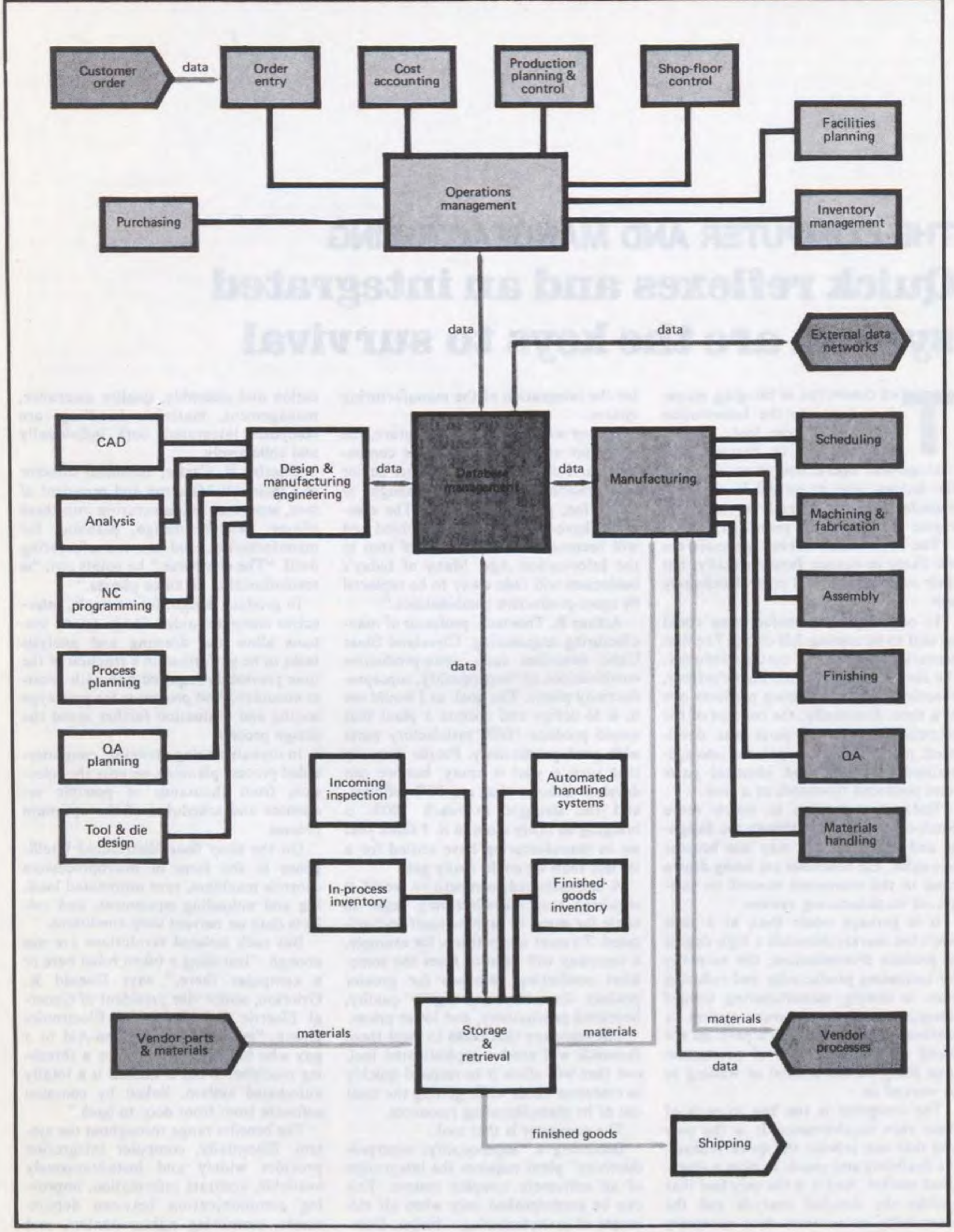
In manufacturing planning, computer-aided process planning permits the selection, from thousands of possible sequences and schedules, of the optimum process.

On the shop floor, distributed intelligence in the form of microprocessors controls machines, runs automated loading and unloading equipment, and collects data on current shop conditions.

But such isolated revolutions are not enough. "Installing a token robot here or a computer there," says Donald K. Grierson, senior vice president of General Electric Co's Industrial Electronics Group, "is like giving a Band-Aid to a guy who has been run over by a threshing machine. What is needed is a totally automated system, linked by common software from front door to back."

The benefits range throughout the system. Essentially, computer integration provides widely and instantaneously available, accurate information, improving communication between departments, permitting tighter control, and

Computer-integrated manufacturing



generally enhancing the overall quality and efficiency of the entire system.

Improved communication can mean, for example, designs that are more producible: "The NC programmer and the tool designer," says Jack Ulmer, chief of Design Technology, Research & Engineering for Boeing Military Airplane Co (BMAC), "have a chance to influence the designer, and vice versa."

Engineering changes, thus, can be reduced, and those that are required can be handled more efficiently. Not only does the computer permit them to be specified more quickly, but it also alerts subsequent users of the data to the fact that a change has been made.

Furthermore, the use of design data in NC programming means better NC tapes and, therefore, less rework and scrap.

Better data, better control

The instantaneous updating of production-control data permits better planning and more-effective scheduling. Expensive equipment, therefore, is used more productively, and parts move more efficiently through production, reducing work-in-process costs.

Product quality, too, can be improved. Not only are more-accurate designs produced, for example, but the use of design data by the quality-assurance department helps eliminate errors due to misunderstandings.

People are enabled to do their jobs better. By eliminating tedious calculations and paperwork—not to mention time wasted searching for information—the computer not only allows workers to be more productive but also frees them to do what only human beings can do: think creatively.

Boeing's Ulmer points out, too, that his company's experiment with an integrated team approach "heightens [workers'] sense of involvement and interdependence that has been lost in our more complex production environment."

Computer integration may also lure new people into manufacturing. Kingston-Warren Corp, for example, discovered that its computer-graphics system gave it an edge in a designer-scarce job market. "People are attracted to us because they want to work in a modern, technologically sophisticated environment," says Dr Victor Azzi, vice president and director of engineering.

Documenting the specific benefits of computer-integrated manufacturing is frequently hard to do: new installations in one area of the operation may produce effects in another far downstream. But some companies have identified just where improvements can be seen.

GE's Computer Aided Engineering & Manufacturing Council, surveying more than 300 organizations in 160 GE businesses, has determined the distribution of primary benefits of new CAD/CAM applications: 56% to productivity, 25% to quality, 17% to cycle time, and 2% to meeting contract requirements.

BMAC, says Ulmer, calculates a $2.8-million return on its investment in an experimental CAD/CAM program. Savings have been realized through such improvements as a reduction in engineering changes as a result of better drawing quality, a reduction in scrap and rework through improved control of NC tapes, elimination of duplicated effort, an improved reaction to changes, the integration of the handling of CAD/tool-design/NC data, and the cross-utilization of personnel.

Sikorsky Aircraft, according to Dr Kenneth M. Rose, manager of Air Vehicle Design & Development, figures that a designer at a terminal is, on the average, three times more productive than on a drawing board and, in some cases, as much as eight times more productive. Considering planned CAD-system acquisitions, the company expects to save 500,000 hr in design work during the period 1981-85.

In manufacturing engineering, Rose reports, CAD/CAM decreases tool-design, NC-programming, and planning times while speeding the response rate, which will eventually permit in-house staff to perform work that is currently being contracted out.

For smaller firms, too

And it's not just for the giants and the aerospace firms. For Setco Industries Inc, a 150-employee producer of machine-tool components, the speed of its computer-aided-engineering system has meant the difference between winning contracts and losing out. "In the five years that we've had the system," declares W.A. Ferguson, president and CEO, "we've doubled our sales. Estimating job costs by hand," he explains, "would take two or three days. On one particular job, a customer asked for a quote, and we were able to process the data in a matter of hours. We had the order before our competitor even had a chance to quote it."

The transition to computer-integrated manufacturing is, to say the least, not simple. "Basically, manufacturing is trying to move from a seat-of-the-pants and play-it-by-ear approach," says Milacron's Carter, "to a completely structured, computer-run system. Obviously, you can't just plug in a CAD terminal and let it go to work. You have to build up a database that will give the computer the information necessary to work with the particulars of your product lines."

Building up this database requires a real understanding of how the manufacturing process works, an understanding that is frequently lacking in the seat-of-the-pants operation and necessitates an in-depth analysis of the entire system.

Ironically, here the computer is both cause and aid: while creating the need for in-depth analysis of a multiplicity of complex operations, the computer is the only tool with which such analysis can logically be performed. And, too, such analysis in itself is beneficial, revealing the way the manufacturing process actually works and, therefore, can be organized and controlled.

Integration also "will force manufacturing to change the way in which it works," says Carter. "We no longer will have the freedom to customize data to fit our own jobs. Data must remain uniform throughout the operation. Each person who uses the data or adds to it will have to understand the needs of all others who use it. In short, we will have to get our various acts together."

Still a long way to go

Fully integrated manufacturing is not yet here. "Individual computer-aided functions provide greater speed and efficiency for individual tasks," Carter points out, "but we have a long way to go in assimilating the technology and applying it to every phase of our operations, which is the only way to derive the full benefit of the new technology."

The investment—in commitment as well as money, labor, and time—is enormous, but so are the potential benefits. And there may soon be no alternative.

Painful though the transition may be, any company that intends to survive in this increasingly sophisticated, highly competitive world will have to enter the Information Age. "I honestly believe," says William F. McAnirlin Jr, CAD/CAM-systems manager at Kingston-Warren, "that manufacturing companies not involved with computer systems have only two choices: get on board or get out of business."

The sections that follow are intended to help you stay in business. They cover the state of the art in currently and soon-to-be available hardware and software and their linkage into information networks; the changing role of the manufacturing engineer and education's response to the demands of this new world of manufacturing; management's responsibility in meeting the challenge of computer integration; government's and academia's participation in technology development; and what this all means to you and your company.

Welcome aboard!

THE COMPUTER AND JOHN DEERE

The right tool for the right job is the rule for computers at Deere

MANUFACTURING at Deere & Co depends on the computer. It is the tool that is considered absolutely necessary to ensure a competitive edge.

Several years ago, this world-renowned producer of farm and related equipment recognized that, of all the developments promising increased productivity and an improved competitive posture, the use of computer-based systems in design and manufacturing appears to offer the greatest prospect.

Today, fully committed to computer-integrated manufacturing, or CIM, Deere exemplifies the successful application of the computer to a complex and diverse manufacturing enterprise. For Deere, it's just a way of doing business.

This is not to say that it's a simple thing. The proper integration of computer-based systems is a monumental task, primarily because it involves the mastery of a new, rapidly changing technology that is often perceived as exotic and mysterious.

But Deere's efforts have been based on one fundamental, almost simplistic concept: the computer is simply a tool, not an end in itself.

"It is merely a tool to do all the things we have always wanted to do and to do them better—nothing more, nothing less," says James F. Lardner, vice president for manufacturing development and a chief motivator of the drive toward computer-integrated manufacturing at Deere. "Those who keep talking about the profundity of the computer in very intellectual terms are misunderstanding the challenge facing us. The real intellectual challenge is to use the computer as a tool to extend our capabilities beyond anything we have ever dreamed of.

"The danger is that we may act like the sorcerer's apprentice: the temptation is to learn only half the spell!"

What Lardner means is that the user must master the computer, not vice versa. Such mastery requires commitment and education, and these are the essential elements of Deere's implementation of CIM. Its management, led by people like Lardner, has made sure that the spell is complete.

Behind Lardner's apparent dismissal of the complexity of the task is a very thorough analysis and clearly defined understanding of the computer's multifaceted role in the manufacturing scheme. That analysis led to the decision to plan from the top down but to implement from the bottom up.

The planning started with the realization, some six or seven years ago, that the many scattered but isolated computer applications within this decentralized company had more far-reaching implications than had generally been recognized and that there was a great potential for changing the entire structure of design and manufacturing. Fortuitously, the realization occurred during a period when Deere managers had access to the largest capital-spending budget in the company's history.

In the mid-70s, most people at Deere who were interested in the potential of the computer in support of design and manufacturing activities considered the applications strictly as extensions of existing capabilities. For example, computer-graphics systems were originally regarded as nothing more than the computerization of conventional drafting techniques.

But inherent in the drafting activity is the creation of a series of instructions for the many tasks required to produce the product, including inspection and verification to ensure that the design intent has been met. Traditionally, this has resulted in the proliferation of many derivative drawing sets each aimed at a particular activity and claiming a single authority.

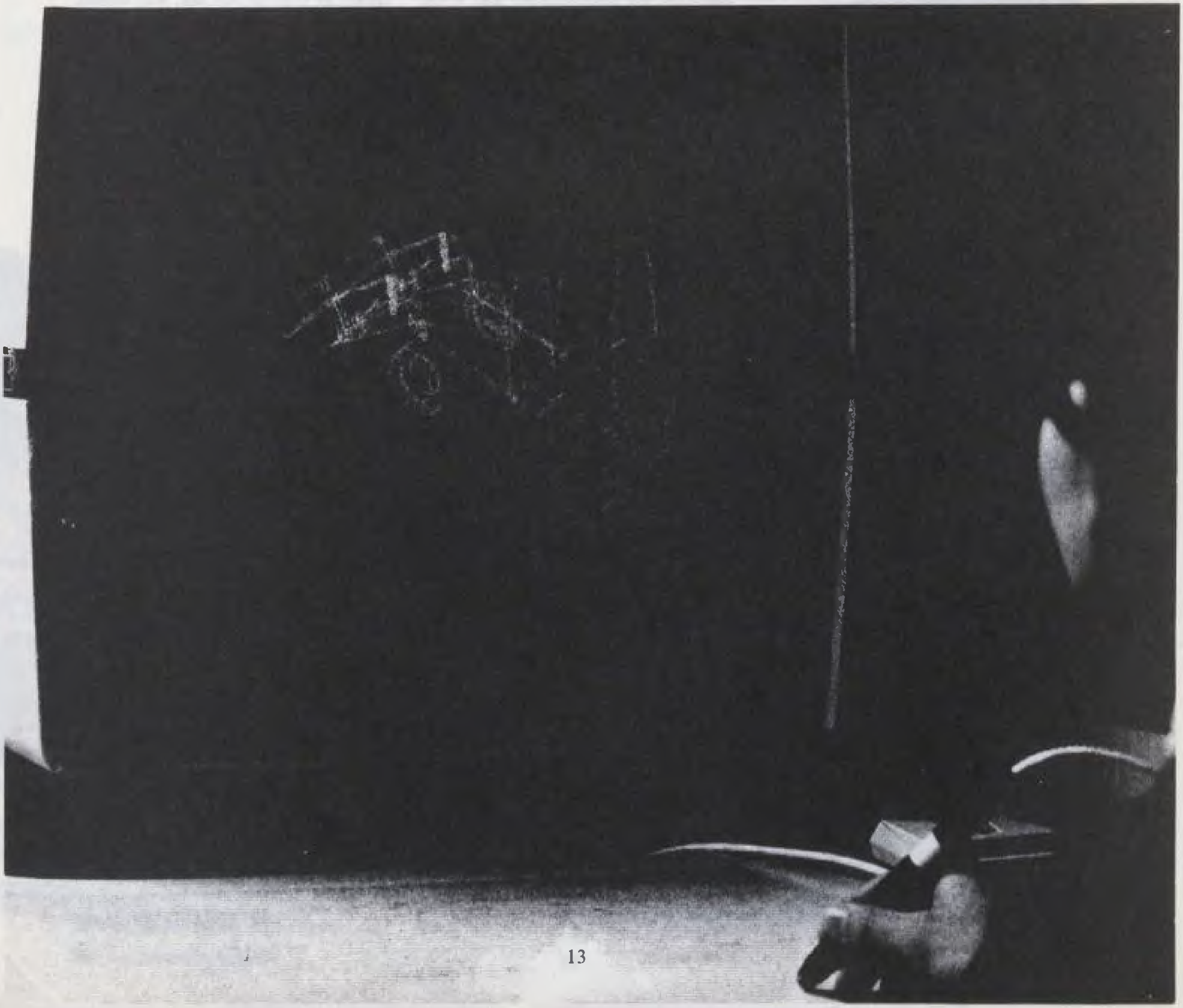
In reality, they turn out to be one individual's interpretation of the original and often end up like a book that has gone through several bad translations from its original language. Add to that the necessity of recording the many changes that occur in the natural course of manufacturing, and maintaining the database becomes a major problem.

Managing the data flow from what Lardner describes as "this cascade of derivative drawings" is probably one of the most complex aspects of any manufacturing operation.

It soon became clear that, regardless of the individualized approaches, many of the CAD/CAM applications at Deere were attempting to address some part of a common problem: the need for more accurate and timely information and control. "But, while we all seemed to be going in the same direction, we were surely going to end up like the Tower of Babel," notes Lardner.

And so a conscious decision was reached that the changing nature of the design and manufacturing functions, brought about by the introduction of computers, should be approached on a coordinated basis. There should be a set of goals, instead of a hit-or-miss process that depended almost entirely on the initiative of those who happened to become interested in a particular aspect of the CAD/CAM spectrum and who would then develop some small segment either in ignorance of or with indifference to activities elsewhere in the operation.

The idea was to develop a coordinated



'It is merely a tool to do all the things we have always wanted to do and to do them better – nothing more, nothing less.'

James F. Lardner

plan without imposing restrictions. Arthur D. Little Inc was brought in as a consultant to help review the various computer-related developments within Deere, ranging from design through engineering and manufacturing to field testing of prototypes and finished products. As many as 200 Deere employees, at all levels, were actively engaged in this review.

The joint effort produced a general recommendation for an overall plan based on two concepts. First, each system should be classified and developed according to one of two categories: (1) systems that would form part of a corporatewide CAD/CAM system set and would therefore be developed in accordance with uniform corporate standards for software, hardware, and database structures; and (2) "stand-alone" local systems that are self-contained and whose data is not likely to be required for activities in other location within the operation.

Second, four fundamental computer-system building blocks should be created for computer-integrated manufacturing: (1) geometric modeling through the use of computer-graphics systems, to get the data set out of the designer's mind into a form that everyone can use; (2) group technology, to help identify manufacturing problems and opportunities; (3) computer-aided process planning, to help establish optimum manufacturing routings and processing steps; and (4) a system of computer-aided inspection and reporting, to close the loop between design intent and product performance.

Concurrent with the ADL study, Deere managers mounted an educational effort that culminated in an in-house conference titled "CAD/CAM, the Competitive Edge" and intended to reinforce the development of a common underlying philosophy. The introduction to the conference program stated the philosophy quite clearly: the success of CAD/CAM systems depends on a uniform corporate understanding of CAD/CAM technologies and of the use of such technologies to achieve "the competitive edge." The conference was carefully orchestrated to present a cohesive picture of where CAD/CAM technology was and where it was heading.

A formidable group of experts representing vendors, educators, and users was assembled to discuss the basic elements of CAD/CAM and to provide insight into the experiences of other major US and foreign manufacturing companies in introducing and exploiting CAD/CAM systems. Existing Deere programs were also reviewed, and a hands-on system display demonstrated key elements, the building blocks, of CAD/CAM integration: group technology, geometric modeling, computer-aided process planning, NC graphics, and computer-aided inspection and reporting (CAIR, developed at Deere).

Representatives of General Electric were asked to address the problems of implementing a coordinated program in a decentralized company. Boeing was asked to participate because of its pioneering experience in such systems.

"We knew that not all their experiences were good," says Lardner. "They had struggled through many early hardships resulting from a lack of adequate computer languages, software, and well-developed concepts of database structures, and they therefore could point out some pitfalls."

Prof Walter Eversheim, executive director of the Laboratory for Machine Tools & Production Engineering at the Technical Univ of Aachen, was invited because his lab was very experienced in the classification and coding techniques of group technology and automated process planning. Prof Toshio Sata, of the faculty of engineering at the Univ of Tokyo, was there to shed some light on how the Japanese were approaching the integration of CAD/CAM.

General Motors had just been through the downsizing of its cars and was known to be moving very rapidly in the area of computer graphics and computer-aided engineering (CAE). "And GM was doing it under the stress of very tight schedules and very strong economic pressure," notes Lardner. The GM input was considered important.

Perhaps the greatest influence, however, at least according to Lardner, was a presentation by Dr Joseph Harrington Jr, who first coined the term *computer-integrated manufacturing* in his prophetic book of that title and who is a recognized expert in the field. "Harrington really has one of the better grasps of manufacturing and what CAD/CAM can do if we're only smart enough to make it happen," says Lardner.

The nature of manufacturing

Harrington claims that, to grasp the importance of computer-based systems to manufacturing, it is essential to understand two fundamentals about the nature of manufacturing itself, and he defines these clearly and simply. First, manufacturing, which begins with product design and ends with support and maintenance in the field, is a monolithic, indivisible function. It can be incredibly complex in its fine detail, but all of its components are so intricately connected that no part can be successfully considered in isolation.

The second fundamental defined by Harrington is that, diverse as the various parts of manufacturing may seem, there is a common thread running through all manufacturing activities: what we call manufacturing is, in the ultimate analysis, a series of data-processing operations. All manufacturing involves creating, sorting, transmitting, analyzing, and modifying data.

Therefore, everything done in manufacturing, whether in the physical act of material transformation or in planning and management, is part of a continuum of data processing. This data-processing activity provides the base to which all parts of manufacturing may be related, and it satisfies the intuitive belief in the monolithic character and singleness of the entity that the term *computer-integrated manufacturing* seeks to describe.

This view of manufacturing is not a theoretical abstraction, Lardner explains, but a reflection of manufacturing reality. "If this is the real nature of manufacturing," says Lardner, "two conclusions can be reached. One is that any technology that will make manufacturing more efficient must address all phases of manufacturing. The second is that the technology most likely to make manufacturing more efficient is the one that can make major improvements in the effectiveness of the data-processing task." Lardner firmly believes that US industry must turn more and more to computer technology to resolve the data-management problems, and that is precisely the impetus behind Deere's commitment to CIM.

The ADL study also included three very significant specific recommendations: (1) establish an engineering-systems group that could champion the computer needs of the engineering community; (2) evaluate available computer-graphics systems and select one to become the standard for the corporation; and (3) embark on the development of a common-engineering-database system.

Engineers at Deere have always had access to the corporate mainframe computer system through time sharing. But those systems are developed and administered by the Corporate Computer Systems Div, whose orientation has been toward commercial application of computers; business applications, such as accounting and payroll systems, have long been fostered at Deere.

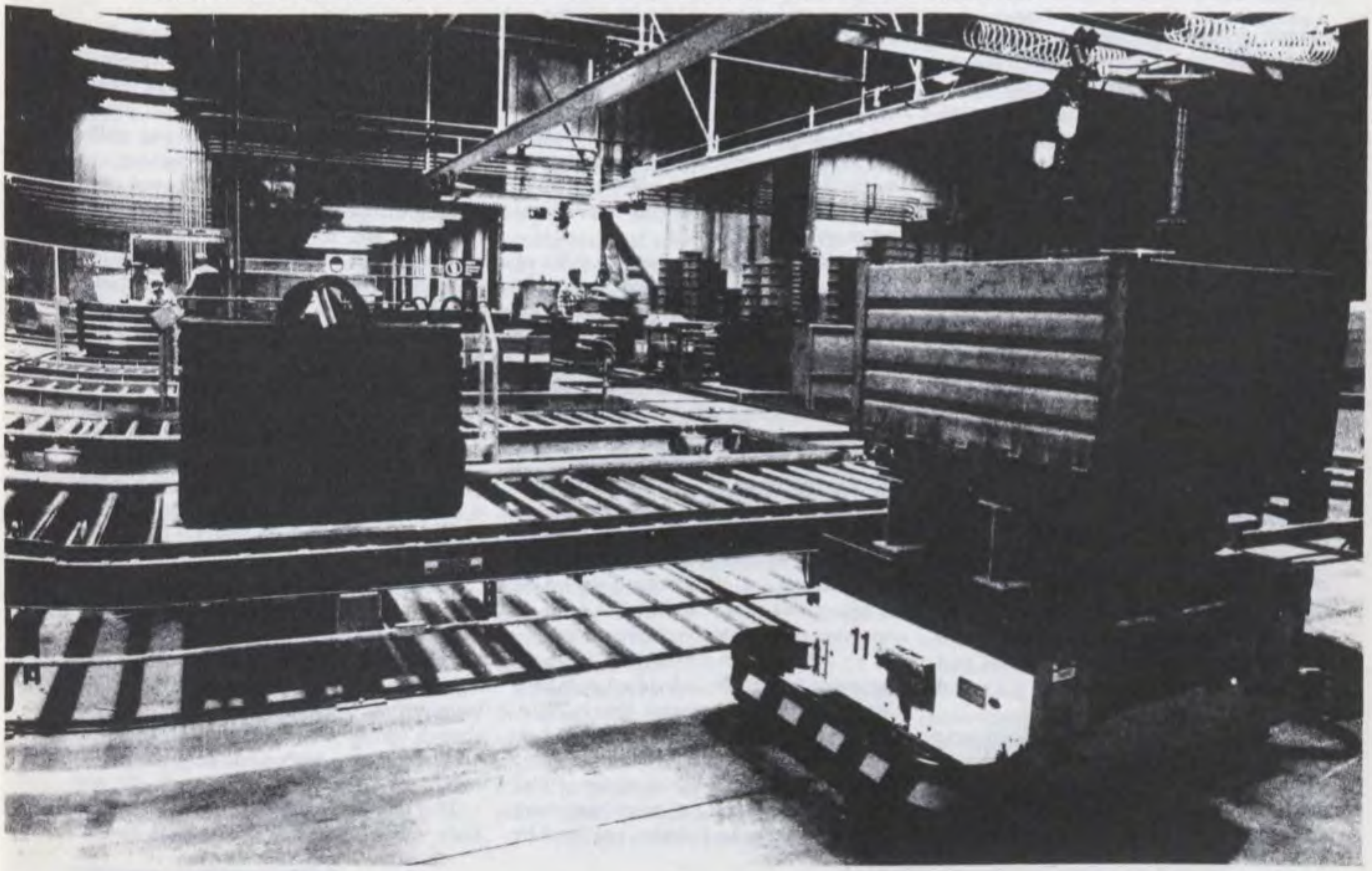
Traditionally, such business-oriented data-processing organizations have little appreciation of the immediacy of most engineering- and manufacturing-related needs or of the real-time nature of manufacturing. Systems development for manufacturing applications is difficult under those circumstances.

"The business group would typically put a request for development of an engineering system in a common queue of computer-system-development tasks, and your turn might come up three years later," comments Don Manor, project manager in the relatively new Engineering Systems Dept. "By that time, you're probably involved in a whole new product-design/manufacturing phase, and you no longer need the system originally requested." As a result, a host of minicomputer-based systems had sprung up to address little parts of the CAD/CAM function, according to Manor.

Interestingly enough, the Engineering Systems Dept was constituted as one of five departments within the Corporate Computer Systems Div; the others are Computer Operations, Systems Planning & Administration, Database Management, and Commercial Systems. At Deere, the basic engineering functions—such as manufacturing engineering, product engineering, and research—first converge at the senior-vice-presidential level, and placing the systems group under any of those separate functions would make it suspect of bias.

"Putting us with the systems people theoretically eliminates that bias," notes Manor. "It puts us in the camp of what was once considered the enemy, the business-data-processing group." He reports that the engineering-systems people have developed an excellent rapport with the commercial-systems group. Now, however, Engineering Systems tends to be looked on as one of the computer-

Robocarrier carts automatically deliver materials from high-rise AS/RS to all areas of Hydraulics Div



Binoculars help supervisor survey FMS system and physically identify cart locations noted by computer

systems groups, and there are emerging signs of conflict between the new systems types and the operating personnel.

The survey of computer-graphics system has resulted in the installation of 12 Computervision Corp computer-graphics systems with a total of 63 terminals. Five of the systems are located at various facilities in Waterloo, Iowa; three are at the Dubuque, Iowa, works; and the remaining four are located in the Quad City area, including the Moline, Ill, corporate headquarters.

The systems are shared mostly by product engineering and manufacturing engineering. Primary use is currently allocated to product design, including conceptual work as well as design layout and engineering drafting; plant engineering and layout, including architectural design; and tool design, including inspection gages. Other uses are NC programming, which is just getting started; development of electrical schematics, including both product requirements and control requirements for machine tools and systems; foundry drafting; and a limited amount of electronics design.

The development of the corporate engineering-database system is one of the major projects tackled by the Engineering Systems Dept. "All the separate computer-aided functions have paid off in the past," says Roscoe Pershing, manager of the department, "but we think that the greater payoff will come from the integration of all those systems through access to a common database." The idea is to create any geometry or associated data just once and then make it available to anyone with a terminal and proper authorization.

Although most people tend to think of such a database as a single entity, Pershing points out that, in reality, it is an integrated set of databases that appear to be one.

"All the relevant data exists somewhere today," he explains. "Some of it is in a notebook, some on paper or on drawings, some may be tucked in a drawer, and some of it is on a variety of computer systems. We have to manage that mixed bag of data sources in some way. What we are simply saying is that the management of that data would be far better and more efficient if it were all computer-compatible and integrated."

The master plan for such a database system calls for the individual database files to reside in a central library, adequately indexed and cross-referenced so that any user can access or temporarily transfer a particular file or group of files to a remote location for interaction with the data-processing function required by a local activity. The database-management system also attends to security considerations and permits timely updating of all data in the various files.

That's the plan, but there are still some formidable hurdles to overcome.

"The biggest hurdle is that we are dealing with a wide variety of sources for hardware and software and there is no common way of interfacing all these disparate systems," says Pershing. "How you actually get interface 1 to match interface 2 is, in my mind, one of the biggest barriers, to CIM, and it is not being adequately addressed."

But then, database development is a long-range plan being implemented in a series of modules. The master plan is really only a philosophical guideline, not a hard plan, and the modular approach should allow sufficient interaction with the users to ensure success.

Some of the underlying conflict between the computer-systems people and the operating personnel centers mainly on the degree of integration of computer-based systems and how much interaction and data transfer there should be. It is a conflict over control and, to some degree, a conflict over turf.

The real fear, however, is that everybody will want to know everybody else's

business and, in the process, local initiative will be strangled: personnel, for example, wants to get a peek at what people are doing, the payroll department wants to get time and attendance figures, purchasing wants to tie MRP to production control, and soon a little stand-alone system gets hauled into the big corporate system.

Lardner believes that such an approach is wrong. "You should never take a system further away than you absolutely have to from the people that use it, even if it means putting an extra computer right there at their disposal." There should always be local control. As long as each department meets the master schedule, there is little reason to pass all the details of individual activities all the way up the information chain.

A big master-schedule system that spells out the results expected from each activity is good; trying to schedule all the activities down to the operator's level from one overall production-control system is absolutely wrong and self-defeating, according to Lardner. "Keeping the little stand-alone systems out of the grasp of the big systems is going to be increasingly difficult because, whether you like it or not, there's a Big Brother lurking inside everyone of us," he warns.

The operating people are keenly aware of this phenomenon and are on the constant lookout to prevent their stand-alone systems being co-opted or larger corporate systems' being foisted on them. "We don't always agree with all the concepts promulgated at headquarters," says Troy W. McAffee, manager of manufacturing engineering at the John Deere Component Works in Waterloo, Iowa.

Although he is an enthusiastic supporter of computer-based systems, he takes a cautious view of the overall-systems approach. "You have to be careful when you deal with systems people because they usually understand only systems, not the applications. And what you often get is a system that the user doesn't understand or even know how to operate and maintain."

McAffee agrees with the basic building blocks under development but doubts that they are all fully applicable in his operation. For example, he considers computer-aided process planning (CAPP) a controversial issue. "We're willing to be shown, but we want something that is cost-effective. I claim that you cannot really do generative process planning. Our situation is such that the families of parts you end up with are very small and you might as well stick to manual process planning."

He believes that process planning is one activity requiring heavy intervention by those with manufacturing-engineering experience and knowledge of available capacities.

"The point is, when it comes to computers, it's a matter of choosing the right tool for the right job. If that happens to be a personal computer, then that's what we use." In fact, he believes, the use of simple personal computers is an excellent way of educating people who may be afraid of larger, more complex systems. "It's a way to become familiar with computers. Progress to larger systems is then much easier," says McAffee. He considers many of the problems of engineers and the day-to-day activities of individual departments to be best handled with a small computer.

McAffee also suspects that the development of a big centralized engineering-database system may be overkill. "If we really need such a database, then the Pareto principle should apply with respect to both the number of parts included and the amount of information stored about each part.

[Vilfredo Pareta, an Italian sociologist and economist observed the phenomenon of "the vital few and the trivial many" as applied to the distribution of wealth. J.M. Juran identified its applicability to many fields, including manufacturing.]

"If you take those two scaling factors into account," says McAffee, "you have suddenly shrunk the information, and you no longer need such a large integrated system." What he is concerned about is that an iron-clad system will be handed down for his people to operate under without being able to change it as experience warrants.

An award-winning plant

Most recent publicity about Deere's accomplishments in the application of computers has focused on the relatively new Tractor Works in Waterloo, the first recipient of the annual LEAD award for "leadership in the application and development of computer-integrated manufacturing."

The award was granted by the Computer & Automated Systems Assn of the Society of Manufacturing Engineers (CASA/SME) last November.

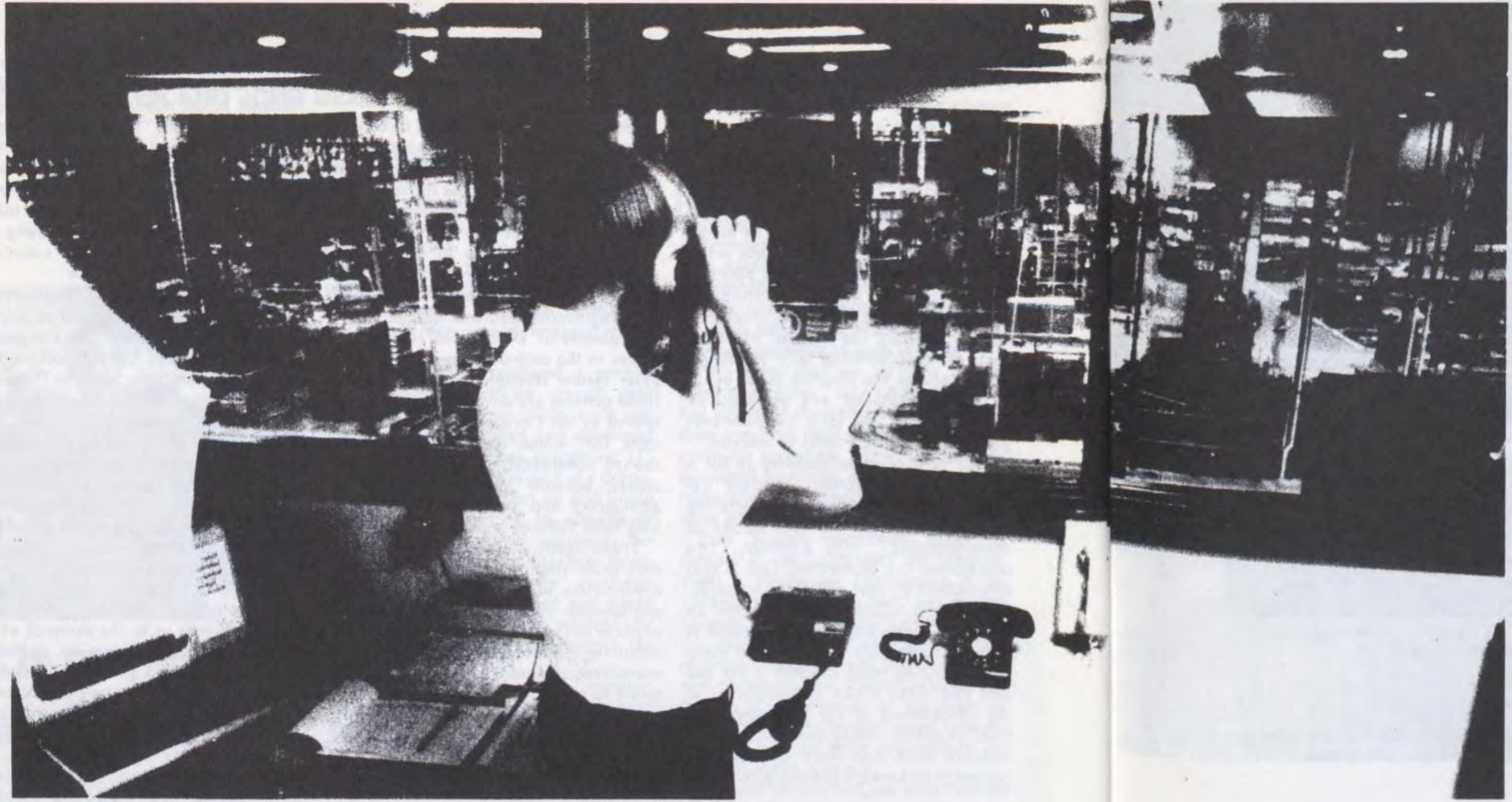
Basically an assembly plant, the Tractor Works is a prime example of computer-aided materials handling—ensuring that the correct parts and components arrive at the right place on the assembly line at the right time. Computers provide complete control over the complex flow of materials within and among four buildings of the 48 acres under roof.

Seven automated storage and retrieval systems (AS/RS) and two automated transportation systems serve the mostly conventional tractor-assembly operations. Shop operations, storage, and transportation functions are controlled by nine separate minicomputers working under the coordinated supervision of a host computer handling overall production and inventory control.

But a broader picture of computer applications more illustrative of some of the emerging conflicts between the systems approach and the more pragmatic solutions often preferred by operating personnel is gained at the Component Works. Despite the conflicts, the managers of the Component Works fundamentally support many of the larger corporate systems. "We are full subscribers to the group-technology system, and, to my knowledge, we are probably the largest user of GT in the country or, for that matter, in the world," points out McAffee.

A unique opportunity to apply group technology on a large scale came when the new Tractor Works was formed, removing about 1½-million sq ft of manufacturing space from the Component Works and making it a prime target for rearrangement and capital improvement. "Who in the world ever had the opportunity to take a 4½-million-sq-ft factory and completely reorganize it?" exclaims McAffee with unbridled enthusiasm.

The first completed project of that



Binoculars help supervisor survey FMS system and physically identify cart locations noted by computer rearrangement has been the creation of a new Hydraulics Div, with some 500 machines in approximately 533,400 sq ft of floor space designed, arranged, and operated through the application of a corporatewide GT system.

The John Deere Group Technology System (JD/GTS) has evolved under the watchful eye of Adel Zakaria, manager of manufacturing-engineering systems, who considers the system both a manufacturing philosophy and a powerful analytical tool. JD/GTS is an extension of the MICLASS system to include a great deal of process-related information. (MICLASS was originally developed by TNO, The Netherlands, and is now maintained, augmented, and marketed by Organization for Industrial Research, Waltham, Mass.)

Capturing the logic

The classification and coding scheme, involving a 37-digit code, was developed, in part, from responses of Deere process planners and manufacturing engineers to a questionnaire that elicited existing practice for typical work. Analysis of the responses captured the "logic" behind established practice, and a code was developed to reflect that logic.

There are four major areas at the Hydraulics Div facility: cast-iron machining, steel machining, assembly, and material storage. All of these are supported by smaller areas devoted to such critical functions as quality control, inspection, maintenance, and related plant-operation functions.

Using the many analysis features of the JD/GTS—some 25 different software programs can group parts according to type, manufactuing processes, historical demand, cost, etc—the Hydraulics Div was further subdivided into departments, each solely responsible for machining and assembling specific families of components.

Simply stated, this means that a part enters a department in an unfinished state and leaves that department only as a finished component ready for either final assembly or shipment. This concept eliminates costly materials handling, or cross-flows, between departments.

The analysis logic used involves the following steps.

- Form part families by part code.
- Combine families to form machine cells by part code and machine code.
- Modify routing of parts within cells for optimum efficiency.
- Combine cells to form departments by machine code.

The actual method of forming part families involves analysis of part codes, production flow, starting machine, production requirements, unique processes, and chip-cutting vs non-chip-cutting activities.

Apple II personal computer is the right tool for the tool-grinding department, where it is used to control inventory. As a result, inventory has been cut in half

Operator at head of FMS line (photo right) receives instructions for mounting parts on pallets of automated carts (foreground) after they pass through wash station

The idea is to start out with a theoretical cell arrangement and then adjust it to practical reality by weighing cell arrangement against machine utilization within each cell. The cells, which are not necessarily in one physical location, are then combined to form departments.

The materials storage, inventory control, and materials-handling operations are all computerized and tightly integrated with a high-rise storage facility and an automated Robocarrier transport system supplied by Eaton-Kenway. The MRP-operated high-rise AS/RS towers 70 ft above ground level and provides space for 5500 material loads.

Fourteen driverless battery-operated Robocarriers, guided automatically by in-floor signal cable to predetermined pick-up or delivery stations, transport loads of up to 4000 lb between the AS/RS and all departments. A self-contained battery-monitoring feature of the Robocarriers automatically dispatches them to an automatic recharge station.

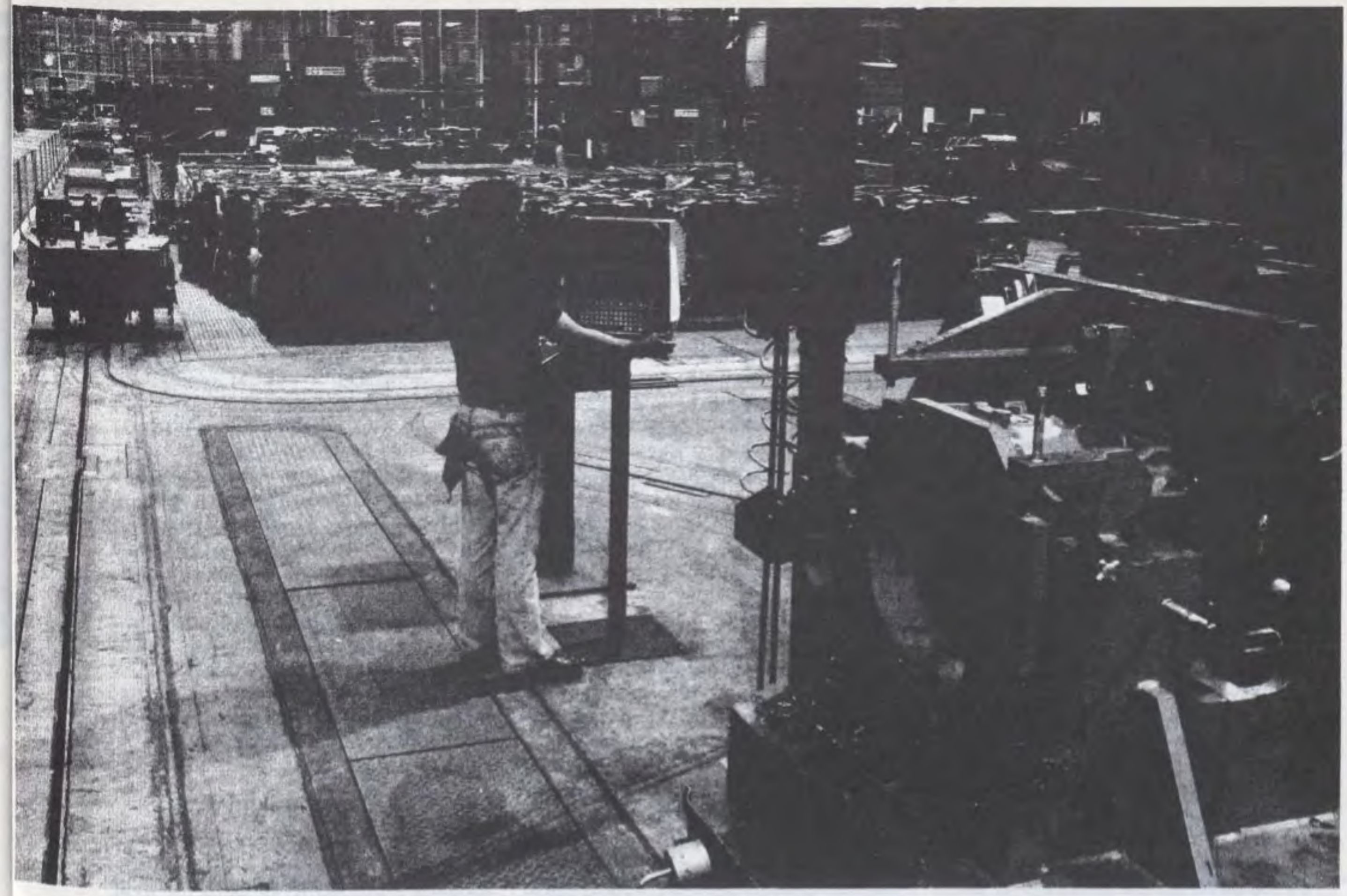
Recently, Zakaria added an "application" module to the JD/GTS to provide corporate managers as well as system users with a simple method of tracking the pattern of projects on which the system was used as an analytical tool. The aim is to obtain some insight into the resulting savings or improvements, and the program is strictly voluntary, says Zakaria, not an attempt to play Big Brother.

After completing a project, the user is asked to input, through an interactive program, certain data describing briefly what the project was all about, the results, the saving achieved, who requested the project, and who did the work. The JD/GTS is available at any of the hundreds of multipurpose CRT terminals located throughout Deere facilities and used to access major systems.

The projects are classified according to 12 categories: part elimination or avoidance; material substitution; reference for design, process routing, tooling, or inspection; cost estimating; tooling elimination; machine-tool procurement; plant layout; materials handling; decisions regarding outside manufacturing; new technology; and other.

"This data is stored in an application database that we can access with the interactive program in the GT package," explains Zakaria. "For example, we can generate a distribution showing the number of projects by unit, application area, user, or any multiple combinations. We can also plot the pattern of use over time, and we can isolate applications of a given type. And, of course, we can generate reports reflecting this information."

The data generated by this application module is used to monitor results, trace patterns of use, share innovative ideas among users in different units of Deere,



and consult with selected users when it appears that the user was not aware of the full capabilities of the GT package.

"To date, we have had very good experience with the module," comments Zakaria. In fact, he reports that group technology is now so well accepted that users are beginning to question the need to prove its benefits. "And, incidentally," Zakaria points out, "we know that the majority—well over 50%—of the applications never even get reported."

At the other end of the computer-applications scale at the Component Works is a stand-alone personal-computer-based inventory-control system recently installed for the tool-grinding department. The basic objective was to improve scheduling of regrinding operations to reduce work in process (WIP) and, in turn, tool inventory overall. An Apple II personal computer, programmed by tool-grinding personnel with no prior computer experience, is doing the job.

Although the same number of tools are finished (about 13,000 per week), the overall inventory has been reduced from 32,000 to 16,000; the number of workers has been cut from 94 to 79. As of June '81, there was a 999.9% return on investment on the original $4635 expenditure. Obviously, the Apple has been the right tool for the right job.

Using a somewhat larger and more sophisticated stand-alone system, a Digital Equipment PDP 11/23, the area maintenance-shop operation at the Components Works has successfully combined the operations of three formerly separate shops into a much leaner, more efficient, and more responsive department. Although combining the operations eliminated many duplications and overlapping responsibilities, as well as reducing requirements for valuable floor space, it did promise to complicate the difficult and frustrating task of job tracking.

The DEC minicomputer was installed to aid planners and supervisors in prioritizing, tracking, and estimating jobs that come into the department. All work coming into the machine shop is received by a planner, who checks the job for necessary instructions and ensures that all required information is available. Typically, repair jobs are made from samples, and no specifications or drawings are available.

The planner establishes the routing for the job and enters the information into the computer system, thereby opening a maintenance work order (MWO). A hardcopy version of the MWO is generated on an associated printer. One copy of this MWO is given to the initiator of the work to help check on progress of the job. A second copy travels with the work until the order is closed out.

The operator assigned to a job is required to "log on" the computer. The remote job-entry terminal provides prompting messages to ensure that all necessary information, such as clock number and machine ID, is properly entered. From then on, the computer keeps track of the job until it is finished and each operator has logged off.

"The computer gives us the ability to retrieve job information by selecting any one of many criteria," says Robert L. Osborn, manager of mechanical services. Information can be retrieved on the basis of machine number, department charged, tool number, or maintenance area. In addition, the performance of the department, by work station or operator, can be reviewed. The planner assigns a work difficulty—easy, medium, or hard—to each job at the planning stage. The computer continually compares the actual hours charged with the time estimate assigned to each difficulty category and updates those times. Consequently, the computer provides a real and valid backlog report, and any anomalies can be readily addressed.

The software for this shop-management system was written by Digital Equipment Corp (DEC) from functional specifications developed by a Deere project team composed mainly of the users. "We simply computerized what we had been trying to do by long-hand," remarks Russell L. Mattox, manager of process and tool engineering at the Component Works. The result is a neat, comfortable system that operators, supervisors, and planners understand because they had a hand in putting it together. "If we imposed a production-control system from up top and then took it away, the operators and supervisors would cheer. But, if we tried to take this system out, I predict, we would have a riot on our hands," says Mattox.

On a totally different scale, the Component Works has a fully automated 12-machine FMS (flexible manufacturing system) to manufacture eight parts of a clutch-housing and transmission-case family. Supplied by Kearney & Trecker, the system has nine Modu-Line CNC machining centers, three two-axis Head Indexers, with 23 heads, and a towline materials-handling system with 45 pallets and 46 fixtures.

A DEC computer manages the entire FMS through a distributed-logic architecture operating at several levels. Part programs are downloaded to the CNC machines for non-real-time DNC operation, eliminating the need for a constant stream of data between the system computer and the machine computer. An intermediate level of control takes care of materials handling and is responsible for coordinating the movement of material through the manufacturing system.

Parts are mounted on cart-transported pallets according to instructions transmitted from the supervisory computer to a CRT terminal at the loading station. Before parts are loaded, each car/fixture unit passes through an automatic wash station to remove chips and other debris left by the manufacturing cycle.

The computer also dispatches tooling according to the expected tool life for each tool. As the cycle time logged for any particular tool reaches 90% of the intended tool life, the computer notifies the toolroom to prepare a new preset tool and deliver it to the appropriate FMS station. At 100% tool life, a beacon at the machine summons a roving setup person, who changes the tooling.

The supervisory computer can be used to generate a variety of pertinent reports, including tool-life data and production data, as well as such maintenance-related information as the accumulated length of track trave.ed by an individual cart or the total cycle time of any machine per shift.

All areas of manufacturing engineering have had an opportunity to use the corporate GMS (geometric-modeling system) via the Computervision computer-graphics system. One typical application is the design of pattern plates for the foundry operation. The Component Works includes one of the largest captive gray-iron foundries in the US.

Pattern-plate drawings are generated with library elements of standard plates and part geometry of patterns also stored in the system. An appropriate number of patterns is arranged on the pattern plate to obtain the best yield. The entire design/drafting procedure is performed on the computer-graphics screen. The operator then adds the gating system, puddle cavity, and sprue pin and calls up an automatic dimensioning routine to finish the drawing.

Operator assigned to repair job 'logs on' minicomputer system that helps track jobs and updates time estimates. Terminal provides prompting messages to prevent errors

In some instances, the use of computers at the Components Works is almost imperceptible. A recently automated gear line is a good example. The line was established using GT to develop three different process lines. The actual installation is a turnkey job supplied by Liebherr GmbH. "After analyzing this operation, we decided it was not appropriate for actual computer-based process control," says Mattox. "But we did incorporate automated parts handling."

In fact, the line uses Allen-Bradley programmable controllers which are, after all, special-purpose industrial minicomputers, to control the flow of blanks to the various machining stations and to ensure that the buffer-storage area for each automated machine is adequately stocked. An automatic inspection station checks for running errors at the end of each line, and an annunciator panel, prompted by conditions reported by the PCs, summons an operator when a machine misses a cycle.

The right tool for the right job

The computer applications at Deere cover the entire spectrum, but, in each instance, it is a matter of using the right tool for the right job. What about the conflict between the systems approach and the stand-alone applications? "It seems to me that there are two distinct levels of computer applications," says McAffee. "At the operating level, we need autonomy and we need to keep the systems simple to allow people to use their own creativity. At another level, we need planning systems, such as master scheduling and GT. Those are appropriately run and managed in a host environment. These are two separate issues, and a lot of people haven't made that distinction yet." What he doesn't want is CIM for the sake of integration. What he wants is the computer as a tool.

How will the conflict be resolved? There's a feeling at the Component Works that pragmatism will win out in the end. "Suddenly, manufacturing engineers are beginning to get access to computers and are beginning to understand what computers can do," says Mattox. "They're bound to figure out how to apply them as effective manufacturing tools. That's a manufacturing engineer's job."

And, chimes in McAffee, "I really think that the manufacturing engineer owns the future. Any organization that neglects the health, well-being, and care of the manufacturing engineer is going to fall by the wayside because the future of any organization depends on manufacturing costs."

At Deere, the computer is the tool to help control these costs.

CAD/CAM—a challenge and opportunity for Canadian industry*

Advances in computer technology foster widespread changes in design and manufacturing techniques

by J. Scrimgeour

Without making any attempt to be melodramatic it would appear that developments in computer aided design and computer aided manufacturing are taking place at a rate around the world that will strain the ability of companies and nations to maintain their positions in the world economy. This is both a challenge and an opportunity.

It is appropriate therefore in this light to examine some trends in Canada's performance in manufacturing industry productivity and in world trade participation. It is appropriate also to examine some previous changes in technology and productivity, for example in agriculture and process computer control, and to see what effects or parallels may apply or provide guidance to what is happening today through the use of computers in design and manufacturing—which some would describe as the CAD/CAM revolution.

It is appropriate that we should have some definition, or at least an envelope of concepts, of what is meant by the term CAD/CAM. Last but not least, it is useful to identify some of the issues involved, and responses that will be required, of Canadian industry, educational institutions and government in adapting to this new technological environment.

There is no doubt that CAD/CAM represents both a threat and a challenge to industry. It is the nature of the response to this challenge that will determine whether it represents an opportunity which will be used widely and to best advantage.

Manufacturing vital

In terms of long term growth and job creation, the manufacturing industries are one of the most important sectors of the total Canadian economy; yet manufacturing industry employment, as a percentage of the total labour force, has been on a declining trend. Productivity will be especially important to the Canadian manufacturing industries in the 1980's if traditional markets are to be retained and new ones gained in the face of lowered tariff protection and increasing external competition. In this context, the rapidly emerging use of Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) technology is of special importance.

With the advent of CAD/CAM, it will become increasingly evident in the 1980's that the design of the factory is just as important as the design of the product. Developments will lead increasingly to the marriage of both Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) into highly integrated design and production systems.

Productivity will be particularly important to Canadian manufacturers in the 1980's. During this decade, tariff protection will be lowered, competition from external sources will undoubtedly increase, and inflation will continue at a strong pace. At the same time, a new world wide wave of industrial automation, based on a rapidly increasing use of computers in design and manufacturing, is occurring.

As a result of the latest round of trade negotiations, Canadian industry will face increasing competition from imported products. At the same time, however, our industry will have better access to foreign markets. To compete successfully in this new trading environment, Canadian industry will have to achieve levels of performance, in terms of productivity and technical excellence, equivalent or superior to industry in other countries, whereas Figures 1, 2 and 3 indicate Canada's current declining trend in export performance, manufacturing industry employment and productivity improvement in manufacturing relative to other nations.[1]

Technology brings rapid change

It is useful to remind ourselves that change is always with us, and that some very major adaptions have been made successfully, but not without effort, in the past.

One of the largest changes, which Canadians have responded to in the past 50 years, has been the change in farm labour and population as a percentage of total population. This has happened largely due to technology and the use of machinery. At one time nearly 100 per cent of the population was directly involved in agriculture and food production. In 1941 it was over 30 per cent. Today it is less than five per cent.

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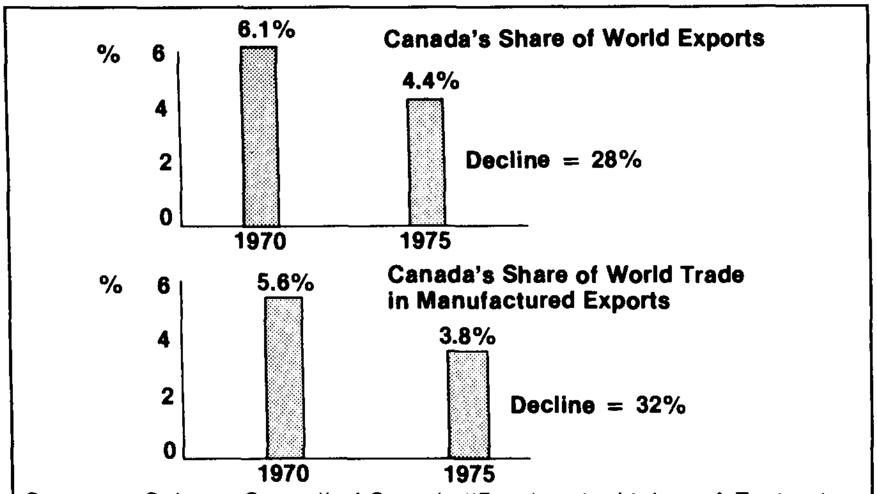
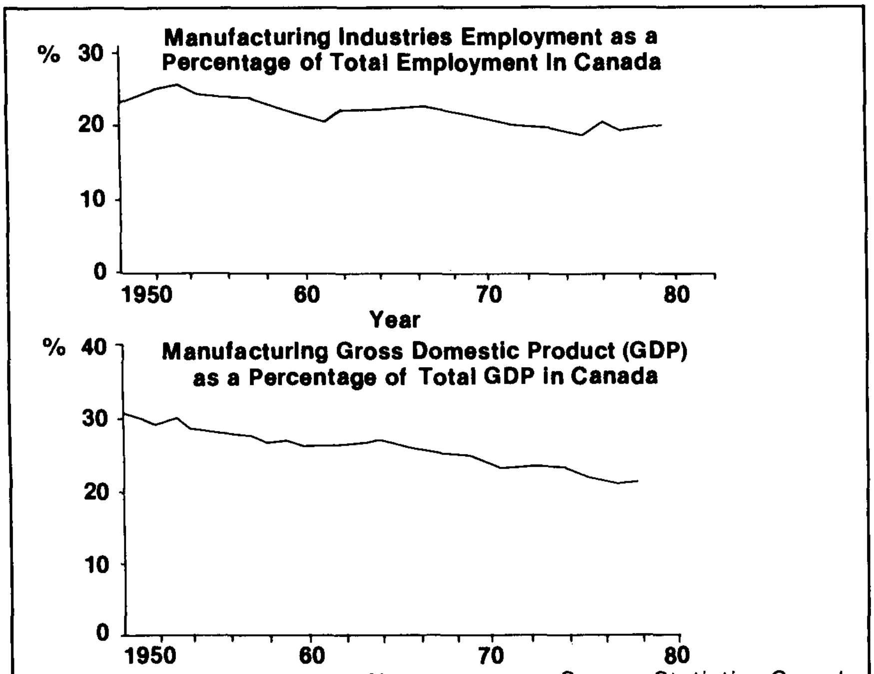


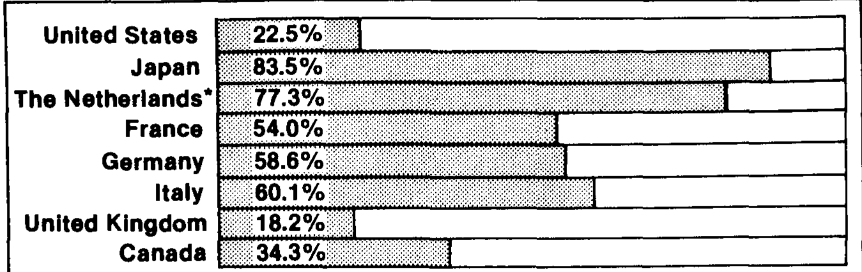
Source — Science Council of Canada "Forging the Links— A Technology Policy for Canada" 1979

Figure 1: Trends in export performance.



Source: Statistics Canada

Figure 2: Manufacturing industries employment and output.



Source—U.S. Department of Labour May 1978

Figure 3: Productivity increase in manufacturing, 1968-1977.

However, we don't have 95 per cent unemployment, because people now do other things—and most prefer it that way. In a mere 40 years this has produced a huge social and demographic change from a rural to an urban population society, from an agricultural to a non-agricultural economy.

A more recent example of technological change, bearing a closer relationship to computer technology, is the application of computers in control sytems, which began about 1960, and which has since become widespread in the process industries such as pulp and paper, mineral production and petroleum refining. This is a particularly useful example because it bears many technical similarities to the current emerging use of computers in the discrete parts manufacturing industries which is generally referred to as CAD/CAM. Both the similarities and some differences are shown in tabular form in Figure 4.[2]

It will be to the advantage of many Canadian companies undertaking CAD/CAM developments and applications that much pioneering work has already been done, at considerable time and expense, in the process industry and capital intensive industry applications where it could be first afforded. Executive operating systems for handling real time, sensor based data, interrupts and distributed computing are a by-product or legacy that is available today from this earlier work, along with some of the lessons learned regarding system and project organization. Hopefully they will not be ignored or forgotten in too many instances.

Improvements growing

It is useful to consider why this change in design and production technology is happening. As one might expect, there are a number of factors. Basically it is because it is economically justifiable, and technically possible. Without going into detail, a vast number of developments in microelectronics and computer technology have reduced the size of computers, increased their reliability, and above all reduced their cost to the point where a myriad of new applications are possible—provided that one has the applications knowledge in hand to do it. A calculation costing $1,000 to perform in 1952 cost $10 in 1972 and will cost 10 cents in 1992.

While microelectronics and computer industry developments make the computation part of CAD/CAM systems possible, it is the applications knowledge, people, economic justification and availability of funds for development and investment that will determine the diffusion rate for adoption of this technology. Technological change does not take place overnight. While the concept of an invention may take place in an instant, the adoption of a new technology on a widespread basis is a diffusion process that takes time—time largely determined by the magnitude of the economic justification.

The economic justification and know-how for CAD/CAM does not come as a packaged product from the microelectronics or computer industry. It resides in the manufacturing industries which are not only the users, but also the application developers. The mechanical engineering community has a large role to play in this. Reports from Germany, for example, indicate that CAD/CAM projects are organized with the mechanical engineering or manufacturing engineering personnel as leaders, and the electronics or computer oriented personnel in a secondary role.[3,4] That could be a good formula for success, assuming that the mechanical or manufacturing engineering personnel are equal to the task, and particularly that they have the necessary orientation to think in terms of systems development.

Trained or experienced personnel are already in short supply. There is a need for education and training in computer programming and applications analysis in virtually all industry sectors and disciplines. The situation today has been described succintly with the remark: "People who know how to program don't know how to solve problems. People who know how to solve problems don't know how to program."

What is CAD/CAM?

Besides being a useful abbreviation, it is helpful to have some sort of definition, or envelope of concepts, for what is meant by the term CAD/CAM. The term, with some slight variations, has come to be very widely used in the past five or six years.

One may examine first the sequence of manuacturing industry tasks as shown in Figure 5, starting with the customer and proceeding to product design, manufacturing process planning, manufacturing, quality assurance, inventory, shipment and final delivery. If one then identifies the ways in which computer systems are being used to assist in each of these design and manufacturing tasks, a series of application areas results, as shown in Table I, which can be regarded as a composite definition for the term "CAD/CAM".

Attribute	Process Control	CAD/CAM
Computer implemented	Yes	Yes
Real time sytem	Yes	Yes
Embedded System	Yes	Yes
Sensor based inputs	Main source for most information in system (Pressure, temperature flow etc, etc.).	Minor portion of information in system. Mostly events,timing,etc.
Input of human origin	Minor portion of information in system. (set points, etc.)	Major source of information.(Design configurations, production status, order status, information).
Expanding data base	No	Yes
Process control	Major purpose is feedback or feed forward control in classic sense. Major process units included within these loops, process gains & dynamics important.	Orientation is more towards the mere handling, timing, release etc. of large volumes of information.
Output interfaces	Set point stations, valves, etc.	Plotters, machine tools, wiring machines, flame cutters, robotic units, automatic test equipment.
Predominant user industries	Chemical, petroleum, steel, pulp and paper.	Discrete parts manufacturing, (transportation equipment, machinery, etc.)
Socio-economic impact	Modest	Much larger
Main period of pioneering	1960-1975	1975-1990

Figure 4: Some similarities and differences between CAD/CAM and process control.

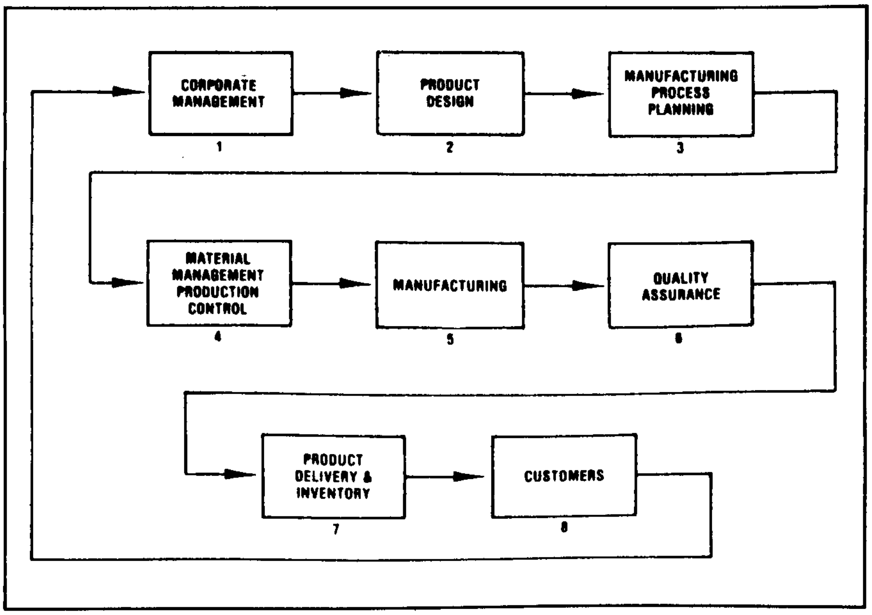


Figure 5: Flow tasks for manufacturing.

TABLE 1

Summary of CAD/CAM application areas

Computer Aided Design	—Production design and analysis including graphic design, functional analysis, stress strain analysis, heat and material balances, simulation and modelling, data reduction and analysis and cost estimating of the proposed product or system to determine fitness of purpose and economically optimized production.
Customer Order Handling	—Record keeping, tracking and reporting on the status of individual customer orders, particularly when part of an integrated on-line system.
Production, Material & Inventory Control	—Scheduling and information handling pertaining to material requirements planning, inventory control, facilities planning and order scheduling, particularly when related to an integrated on-line system.
Automated Production	—Numerical and computer control of machine tools, lathes, milling, boring machines, pattern and fabric cutting, welding, brazing, plating, flow soldering, casting, flame cutting, spray painting and automated assembly (all of these exist and are under further development).
Automated Material Handling	—Integrated materials handling using computer operated conveyors, robotic units, etc.
Automated Testing	—Automated inspection of machined parts, testing of electronic components, circuits and products, automated material inspection and grading using sensor based computer systems, pattern recognition.
Automated Packaging	—Computer implemented coordination of material and information in packaging, bottling, labelling and weighing systems.
Automated Warehousing	—Computer implemented order picking and material handling for both work in progress inventory and finished goods inventory. Automated label reading, routing of packages, parcels, baggage in shipping, sorting and distribution centers.

Note: CAD/CAM technology will yield its greatest economic and productivity gains when all or most of the above application areas are married or joined together to form an integrated system. Hence there is a strong development trend in this direction.

TABLE 2

Technologies involved in CAD/CAM

- Computer Graphics
- Mechanical Design
- Electronics
- Simulation & Modelling
- Engineering Computation
- Numerical Analyses
- Data Base Design
- Interface Design
- Distributed Systems
- Programming Languages
- Communication Protocols
- Human Engineering
- Data Transmission
- Production Scheduling
- Material & Inventory Control
- Robotics
- Machine Tool Technology
- Numerical Control
- Sensors & Instrumentation
- Feedback Control
- Pattern Recognition
- Socio-Economic Effects

As indicated in Table I, the systems integration concept is important. There is a strong drive in this direction, particularly by larger companies which are the leaders in developing and applying the technology.

Another approach which can be useful is to identify some of the technologies which are involved as elements in CAD/CAM, as shown in Table 2. Education, understanding and development in these technologies, as applied to design and manufacturing, will determine the growth rate for CAD/CAM systems in numbers and in their technical capability.

Education and training is therefore of paramount importance. There are many facets to this. One point to be recognized is that if CAD/CAM was being developed and applied slowly on a worldwide basis over a period of 30 to 40 years or more before use became prevalent, then it would be sufficient to focus the educational needs on the schools, colleges and universities which will train and educate the next generation of Canadians for their working life span.

The role of these conventional education channels is important, but not sufficient under the circumstances. If the change to the widespread use of computer aided design and computer aided manufacturing takes place as quickly as would appear likely, then education and training of the existing work force is of equal or even greater importance. The mechanism preferred by industry for this is by means of in-plant training courses. The first requirement in this process, to multiply and fan-out capability, will be to assemble the best available source material and train the instructors who will then train their co-workers.

It may be important, especially in the long run, not to take too narrow a view of the training and education requirements related to CAD/CAM, particularly if the secondary effects of its adoption are to be as broadly beneficial as possible. Education in the arts and cultural pursuits, in addition to education in technology, may become increasingly important if increased leisure is to be enjoyed, and as an alternative to the work ethic.

CAD/CAM flourishing elsewhere

A brief overview of CAD/CAM development in other countries, and the degree of involvement by governments, may provide a useful perspective.

Germany: Government funding of approximately $179 million was provided for CAD/CAM and automatic process control from 1971-1979 as part of the $1,366 million Second and Third Data Processing Plans.[3] CAD/CAM development is conducted through an extensive system of centres and institutes employing thousands of scientists and engineers with strong emphasis on the mechanical engineering aspects.

Japan: CAD/CAM and robotics have high priority. Individual companies such as Mitsubishi and the automotive industry manufacturers have extensive working systems. The Methodology for Unmanned Manufacture (MUM) project, with $100 million government funding to develop an un-manned factory, has been modified to develop a Flexible Manufacturing System (FMS) as an intermediate step, incorporating machine tools and industrial robots.[5] Funding now reported is $60 million over seven years.[6]

United States: CAD/CAM activity is increasing rapidly as companies strive to meet the productivity challenge of Germany and Japan. The Society of Manufacturing Engineers is one organization playing a leading role, for example, through their Autofact conferences and special interest groups.

Government projects, largely contracted out, include: the $100 million United States Air Force, Integrated Computer Aided Manufacturing (ICAM) project for aerospace companies; the National Aeronautics and Space Administration CAD oriented Integrated Planning for Aerospace Design (IPAD) program; the United States Navy Computer Aided Shipbuilding Design and Construction (CASDAC) program and others.[7,8]

Following a bill enacted by Congress in October 1980, the Detroit Cooperative Generic Technology Center Inc. has been selected by the U.S. Department of Commerce to create and operate a research facility in the area of computer integrated manufacturing, supported by a grant of $1 million plus a $5 million grant for facilities and equipment.

United Kingdom: Funding for CAD/CAM comes from three principal sources —the Science Research Council, Department of Education and Science, and the Department of Industry. The National Engineering Laboratory near Glasgow undertakes development and provides advice in NC machine tool technology and tape preparation.

The Computer Aided Design Centre, a Department of Industry Research Establishment in Cambridge, reached a staff of 150 and an annual expenditure of $5 million in 1980.

A January 1980 report by a Cabinet Office Advisory Council for Computer Aided Design and Manufacturing recommended:

- Greater coordination and focus for CAD/CAM research and development.
- An expenditure of £1.5-2.0 million over the next three years in measures to increase awareness and disseminate CAD/CAM information (in addition to the Microelectronics Awareness Program—MAP).
- A merger of the NEL at East Kilbride and the Computer Aided Design Centre (CADC) at Cambridge into a single institute, and a physical move to "one or more sites nearer the main manufacturing centres of the United Kingdom" in order to facilitate access by industrial companies.

France: The French government is making a major effort under the Ministry of Industry to create awareness in general in industry of computer systems and to encourage small and medium sized firms to use CAD. A recent bulletin of the Institut National de Recherche en Informatique et en Automatique contains an extensive paper on CAD/CAM and reports on the CAM research and development activities of 19 other laboratories and institutes in France.[9]

Italy: As of 1974, Italy ranked fourth in the world in production of numerically controlled machines (behind Japan, USA and West Germany), and second in NC machine tool installations (second and almost equal to West Germany). Italy does not appear to be a leader in CAD/CAM developments but the number of industrial robot installations reported is considerable.

The following figures for industrial robot installations (1979 estimates) may serve as a useful overall *indicator* of CAD/CAM technology diffusion and application.[10]

Japan	10,000
USA	3,000
West Germany	850
Sweden	600
Italy	500
Poland	360
France	200
Norway	200
Britain	185
Finland	130
USSR	25

The Canadian figure is estimated to be in the order of 100.

Another useful indicator of CAD/CAM activity may be provided by a count of the technical papers published on the technology. Of those selected in 1979-80 from the internationally recognized "Computer and Control Abstracts" for inclusion in the monthly newsletter *CAD/CAM and Canada*, the publications by country of origin are:

	%
USA	40
UK	23
Germany	14
Japan	6
France	3
Canada	3
USSR	2
Switzerland	1
Other	8
	100

In using these data, it should be recognized that some preference for papers of most value or interest to Canadian readers is exercised in the selection process.

Industrial robots widespread

It is clearly evident that development of CAD/CAM systems and equipment is widespread throughout all industrial sectors, and increasing rapidly. This is especially evident in the case of industrial robots, because they are relatively new, they are readily identifiable, and because they can be quickly programmed to perform repetitive manipulation tasks that were difficult, prohibitively expensive or even impossible to perform in the practical sense with any form of previously available mechanical apparatus.

As indicated already, the number of robots installed or produced by an industrial country is regarded by some as an indicator of the state of the art in manufacturing technology. It should be stressed that at best this is only an indicator. It could be as useful, as another indicator, to count CAD application programs, lines of code, or data bases, except that these are harder to define, identify and quantize.

Another indicator is to count computers. During the early introduction of computers it was a common practice to maintain and publish survey data on numbers of computer installations of all types and sizes. For medium to large systems this census data is still partly maintained. For small computers it is becoming impossible. Such statistics can be useful, particularly when a new technology is at the frontier and the use of industrial robots is in this position today.

To maintain perspective, however, we may remind ourselves that printing presses, when first introduced, probably raised fears similar to some concerns regarding robots today. The number of printing presses installed in the year 1500 was 73 in Italy, 51 in Germany, 39 in France, 24 in Spain, 15 in the low Countries and eight in Switzerland. Although the number in use today is vastly greater, the associated fears have long since disappeared. The situation for typewriters is somewhat similar.

Major suppliers of industrial robots and their customers have now achieved hundreds of highly productive, relatively trouble free industrial robot installations. Many applications are now considered straightforward such as spot welding of automobile bodies, die casting, investment casting, machine tool loading and unloading, injection moulding of plastic parts, forging and spray painting.

Quick payback possible

Provided that the application engineering is done carefully, the increased production, more consistent operation, improved operator safety, reduced scrap and savings in labour will frequently pay for a $30-$80,000 robot in one to three years, depending on the application.

It is important to give neither too much nor too little attention to the industrial robot "revolution" and its impact. Most robots today perform only a routine sequence of mechanical motions, often characterized by the "pick-and-place" nature of the function performed. Lacking any form of sensor input, if something goes wrong they will continue to perform dumbly until shut-off. This will change as sensor inputs are added, most notably force feed back signals from the hand or gripper and vision capabilities using TV cameras and pattern recognition techniques.

Market forecasts for numbers of robots to be produced and installed are highly dependent on the assumption of these developments, which will not necessarily take place without effort. Difficulties in achieving successful pattern recognition and other forms of robot "intelligence" may be greater than realized by some forecasts or popular reviews.

Nevertheless, we are in a world wide race for improvement of industrial productivity. Japan, in particular, which already has 10,000 robot installations, has established a robot leasing program through the Japan Industrial Robot Association (JIRA), Ministry of International Trade and Industry (MITI) and 10 insurance companies.

World literature reviewed

The abstracts on CAD/CAM technology selected from the world literature and reproduced monthly in the newsletter of the CAD/CAM Technology Advancement Council provide a vantage point to view the fundamental technology change which is taking place on a world scale, which is revolutionizing design engineering and manufacturing and which will penetrate every industrial sector.

The 20 abstracts reproduced by permission each month from the INSPEC publication *Computer and Control Abstracts* provide a good representation of the world literature. The following review represents those selected in the June 1979–December 1980 time frame, and has been organized in a subject sequence which could be used to prepare a reference text or series of chapter monographs for education and training on CAD/CAM systems and technology.

Introductory and review references[11-31] include two collected sets of reprints[11-12] available from the Department of Industry, Trade and Commerce, Ottawa. Published information on the economic justification of CAD/CAM is not widespread,[32-34] partly due to the difficulty of documentation and commercial secrecy in detail but is known to exist elsewhere, for example in the papers of the SME Autofact conferences, Numerical Control Society and CAM-I.

Computer graphics, along with the use of industrial robots, represent one of the fastest growing segments of CAD/CAM in commercial terms and capability, as well as the use of microprocessors in terminals and production equipment.[35-59] Two rapidly emerging CAD analytical techniques are the use of geometric modeling for the generation of NC machine tool cutter paths,[60] and finite element analysis[61-64] for stress, vibration and heat transfer analysis. Pattern router algorithms[65] may represent another useful CAD analytical technique with particular application to printed circuit board connection layout.

Production material and inventory control[67-74] has been a common manufacturing industry computer application for the past 20 years, but which may be considerably extended due to the information demands of integrated CAD/CAM systems, and the greater availability of shop floor and feedback data.[75] Similarly data base systems have received a long history of development, but are likely to receive new impetus due to their key and central nature in integrated CAD/CAM systems.[76-86]

Metal cutting machine tools, including direct numerical control (DNC) and computer numerical control (CNC), are the most widely used form of numerically controlled production equipment.[87-108] This is being extended however into many other forms of production equipment including arc welding, spot welding, resistance welding, sheet metal punching and shearing, grinding, polishing, injection moulding and packaging.[109-129]

Automated testing and inspection for improved production and quality control form an important part of CAD/CAM systems if maximum benefits are to be obtained. Applications include mask testing for integrated circuits, line width testing on printed circuit boards, weld quality inspection, checking of dimensions, surface roughness, weighing and the on-line monitoring of other production equipment.[130-147]

Industrial robots,[148-177] along with turnkey CAD graphic systems, represent one of the two most rapidly emerging CAD/CAM technologies. Their widespread use for parts handling, machine tool loading, spot welding, arc welding, die and investment casting, spray painting and even sheep shearing, as an experimental application, will change the nature of many factory and production systems.

The integrated CAD/CAM factory of the future must necessarily be designed as a distributed or hierarchical system. Hence, developments in message handling, bus and data highway design, distributed and hierarchical sytems[178-205] are an important yet complex aspect of system planning.

Computer programming languages are also an important consideration[206-209] and some special languages have emerged or are under development such as Grapple for CAD, ADA for real-time embedded systems, VAL for industrial robots in addition to the many languages for NC machine tool programming such as APT and ATLAS for automatic testing.

Project management[210-222] and systems design[223-252] bear special consideration. Education, training, the location and most efficient use of scarce people will be important to project managers. Proper design of flexible manufacturing systems will be important to the profitability of the firm. The social implications of CAD/CAM are being recognized and discussed[253-262] as part of the adaptation process to this new technology.

Application papers are becoming more and more prevalent as the technology advances from concept to installation in a wide variety of industries including automotive,[263-272] machinery and equipment manufacturing,[273-284] and the aerospace industry.[7,8,14,30,285,286]

The electrical and electronics industry is noted for many applications[287-310] because its personnel tend to be close to and familiar with CAD/CAM systems potential at an early date, and also because some industry products, such as the LSI chip, would be impossible to design by any other method.

Conversely, food and beverage industry applications are not widespread as yet, although examples do exist.[311] Chemical and plastics industry applications are more widespread,[312-318] particularly for injection moulding and the production of plastics parts.

CAD/CAM in the architecture, building and construction industry tends to focus on the CAD or design end.[319-330] Conversely, as one would expect, automated warehousing and distribution systems[331-346] deal primarily with mechanical movement. It should be noted that automated warehousing techniques are being applied in integrated CAD/CAM systems to the movement of parts and work in progress between work stations, and not just to the storage and handling of finished goods—reductions in work in progress inventory, interest carrying charges and shorter delivery time to the customer being the objective and economic justification.

Miscellaneous applications[347-363] as in the textile, printing, glass and shipbuilding industries give evidence that every type of industrial activity is a potential user of the technology.

Major national programs and studies exist, such as those in Germany,[3,4,364,365] Japan,[7,8,366-368] the USA,[7,8,369-371] the United Kingdom[6,372-376] and elsewhere.[377-381]

Competition increases

Productivity will be especially important to Canadian manufacturers in the 1980's. During this decade, tariff protection will be lowered, access to foreign markets will increase, but competition will also increase for both domestic and foreign markets.

At the same time, a new world wide wave of industrial automation is occurring in manufacturing, based on a rapidly increasing use of computers and industrial robots. As an indication of the rate and breadth of this technological change, approximately one thousand published articles on CAD/CAM are now appearing each year in the open literature.

Within this wave of change, two of the most rapidly advancing fronts are the use of graphic systems for computer aided design and industrial robots for parts and tool handling, in addition to the more established use of numerically controlled machine tools and production machinery. It is the response to CAD/CAM, and not CAD/CAM itself, which will determine for companies and countries whether CAD/CAM represents a net challenge or opportunity to them.

References

Due to space limitations, the 381 references accompanying this paper have not been included. For a complete listing, please refer to the Proceedings of the 95th EIC Congress, *available from the Engineering Institute of Canada, Ste. 700, 2050 Mansfield St., Montreal, Quebec, H3A 1Z2. Telephone (514) 842-8121; price: $15—members, $20—nonmembers.* •

Autofact III — a big success

by J.H.C. Scrimgeour

AUTOFACT is a major CAD/CAM, Robotics and Automation Conference sponsored annually by the Computer and Automated Systems Association of the Society of Manufacturing Engineers (SME). Autofact III, held November 9-12, 1981 in Detroit, was billed as the major event in 1981 for Computer Integrated Manufacturing and the Automated Factory. With over 16 000 manufacturing engineers, executives and industrialists attending, including 2000 persons registered for the Technical Sessions, it would appear to have been just that. This is an explosive increase, for example, from the approximately 250 persons attending the SME CAD/CAM conference in 1975, and the 9000 persons registered for Autofact II in 1979.

IT is impossible to give a single impression or a fully accurate and concise summary of the entire conference which included technical sessions running concurrently from 8:30 in the morning to 9:30 at night; conference proceedings of more than 500 pages plus other papers distributed separately and a nearly equal amount of manufacturers' product literature obtained by most attendees from approximately 125 exhibitors. In addition, the impression of such an event depends on the individual's background and especially whether or not it is the first Autofact conference attended.

For most attendees it is a 14-hr/day crush course on CAD/CAM technology. For first time attendees it is almost overwhelming. There is clear evidence everywhere that a dramatic change — some call it a revolution — in manufacturing is taking place. How does one apply it fast enough to keep up, and how can one be sure to be doing the right thing, are the two questions uppermost in the minds of most visitors. In order to help in this regard the conference is organized with a good mix of overview papers held in plenary sessions, plus technical and application papers held in subsequent parallel sessions.

In an opening session a senior U.S. government official pointed out that this kind of technological change does not result from government or top-down planning but results instead from bottom-up action and involvement. A conclusion is that one could not possibly stop this trend, even if that were desirable, but rather it is essential that it be well managed. Many speakers spoke of the declining productivity trend and degradation of product quality in the U.S. manufacturing industry and attributed this to the fall-off in R&D over a twenty-five year time period.

It is also attributed to over-attention to financial matters and a lack of long-term planning in most company boardrooms. A return to fundamentals, technology, and the use of computers in design and manufacturing in particular are seen as major opportunities to improve productivity and competitive capability. As stated in a recent National Science Foundation report, "CAD/CAM has more potential to radically increase productivity than any other development since electricity".

At the same time conference speakers were both experienced and realistic. As one speaker said, CAD/CAM is not a panacea, but it will increase your odds for success. And another speaker pointed out, "CAD/CAM is not a piece of computer hardware, nor is it a software program, nor is it a department name. Rather, it is a philosophy of using the computer, plus people, plus procedures, plus programs in an integrated fashion."

Another leading speaker, who later accepted the SME's award on behalf of his company for having implemented the leading CAD/CAM system of the year, identified the following impediments to achieving the full potential and benefits of this technology:

- — It is not yet an integrated structure.
- — The user must bear the burden of identifying applications and developing the structure.
- — The economics of CAD/CAM are mostly based on future cost avoidance, whereas industry accounting is more keyed to shorter-term concerns.

A viewpoint of labour was expressed by an official from the United Automobile Workers who cited the current loss of 203 000 jobs in that industry from 977 000 workers in 1978 to 774 000 workers in 1980 and projected a further reduction to 544 000 workers by 1985. This is a seven-year decline from 977 000 workers to 544 000 workers, attributed to a declining market, i.e. the declining market share of the U.S. automobile industry, the change in product mix toward smaller cars and to increased productivity. From his remarks it appears to be generally recognized that productivity improvements are needed to regain competitive position. Hence, technology is not expected to be opposed in principle by labour. Rather, an emphasis on the retraining of workers for higher job skills can be expected in union contract negotiations.

COMPUTER GRAPHICS IN COLOR

Before commenting on individual technical papers it is useful to give a few additional conference overview comments. There was great emphasis in the exhibits on the use of computer graphics for design, and especially the use of color. Three companies, ComputerVision, McAuto, and Intergraph were reported to be introducing new low cost turnkey graphic systems priced below

$100 000; therefore, the line between low cost, limited capability, turnkey systems and the higher cost systems is blurring.

Usage of CAD is reported to be moving from the larger to the smaller companies. Since 70 000 companies in the U.S.A. employ four draftsmen or more each, there is currently believed to be only 7% market pentration for CAD systems. Figures quoted from the new September 1981 Merrill Lynch report on the CAD/CAM graphics market report a 1980 market of $565 million, a 44% increase in 1981 to $815 million, and a 30% increase in 1982 to $1060 million.

Just as one can argue that money is not essential for happiness it can be equally argued that color is not necessary for most computer graphics applications. However, in both cases, used judiciousy, it can certainly help and in the case of color we can expect to see a lot of it. Of the three display technologies, storage tube, raster refresh and stroke refresh there is a strong industry trend to raster refresh because of its easy update capabilities and because it is good for color.

In addition to the turnkey CAD graphic system suppliers, there was considerable evidence of larger main frame computer suppliers offering CAD graphics capability and extended engineering analysis packages such as the PATRAN geometric modeller from DEC, Circuit Board Design System from IBM, MEDUSA mechanical engineering design through Prime Computer Inc., and ICEM from Control Data and others.

There was also considerable emphasis on industrial robots in the exhibits, including three by suppliers from Japan.

Among the exhibits of 13 robot manufacturers, the General Electric exhibit (for the first time) was of interest to many. This included a demonstration of two Allegro robots traversing on a single, horizontal rail and working together in bench level assembly operations.

In 1975 it was forecast at the CAD/CAM conference that the future integration of CAD and CAM would allow parts designed on the graphics screen to be immediately produced in metal on the shop floor without the use of intervening drawings or computer tapes. This has since become a widespread capability in many advanced companies. In the ComputerVision display it was demonstrated on the exhibit floor with the use of a ComputerVision three-dimensional color graphic system, a Pratt and Whitney Horizon V horizontal milling machine, a Unimate PUMA 600 robot for handling the part, and a Bendix Cordax 1810 coordinate measuring machine for automatic inspection of the finished part.

At Autofact II held in 1979 in Detroit two companies, Unimation, Inc. and Cincinnati Milacron, presented papers on robot systems for continuous path arc-welding. Although spot welding is one of the most common of all robot applications, particularly in the automobile industry, the complexities of arc-welding have required further development before it could be accomplished or become common place. At Autofact III, robot arc-welding was demonstrated by General Electric on the exhibit floor.

PLENARY SESSION AND TECHNICAL PAPER PRESENTATIONS

If the exhibits tended to emphasize computer graphics and industrial robots, the speakers' presentations tended to emphasize careful corporate planning, the integration of CAD/CAM which was the Conference theme (see also "Computer-Integrated Manufacturing" in this issue), data management considerations, the importance of people and enormous challenge to be faced in education and training.

The use of computer graphics to present three-dimensional views or drawings will also become very widespread. While the use of 3D drawings has never been common in industry in the past due to the drafting cost, it must be recognized that many drawings are actually flat representations or orthogonal views of three-dimensional objects. The use of 3D views in drawings will become very common because:

1. The shape of complex objects is more quickly recognized.
2. The inter-relationship of parts is easier to visualize.
3. The mating of parts and dimensionality is readily checked.
4. Fewer errors and misunderstandings will occur.

As a specially invited evening speaker, Dr. E. Merchant presented a paper on "The Importance and Role of Computer Integrated Manufacturing." Widely recognized as a world authority on CAD/CAM, Dr. Merchant presented some interesting facts and figures concerning the most advanced applications by companies in The Federal Republic of Germany and Japan.

For example, the Messerschmidt plant producing the Tornado fighter aircraft has a flexible manufacturing system with 27 machines and an automatic workflow system using wire guided carts for movement of work pieces and fixtures plus an overhead conveyor for tooling. The FMS system, which has been operating for two years, has produced the following results:

1. The machine tools are actually cutting metal for 75 to 80% of the time as compared to as little as 5% in ordinary plants.
2. The lead time for the Tornado fighter has been reduced to only 18 months as compared to 30 months if stand-alone NC machine tools were employed.
3. 44% fewer NC machine tools and shop floor personnel are required.
4. 39% less shop floor space is required.
5. Last, but not least, the capital investment is 9% less than if the work was done by conventional NC equipment.

Dr. Merchant is one of the few persons who have visited the Project for Unmanned Manufacturing Technology in Japan. He reported that as of the Summer of 1980, 15 of the 200 NC machine tools were operating unmanned during night shift. Similarily, the Fujitsu-Fanuc plant manufacturing robots uses flexible manufacturing system technology similar to that of the Messerschmidt plant.

During the day shift 19 workers on the floor and 63 workers in assembly operations manage 29 cells of the flexible manufacturing system. At night the 29 cells are managed by one worker only in a control room. Calling on both industry and educational institutions to meet the challenges imposed by this technology, the speaker advised that industry can continue to be lackadaisical in its approach only at the utmost peril to itself and the country. A cooperative approach, both individually and through existing institutions, is seen as the only solution.

Persons attending the technical paper presentations generally realize that they cannot copy someone else's solution for implementation in their company or organization, but they are looking for guidelines and suggestions from experienced speakers on how they should proceed, what they should do and what they should avoid. In that context the following points extracted from presentations will be of value.

— Today the technology for productivity improvement is here. The question is how do we use it? This should be done in the framework of a strategic plan for the company covering a time period of 5 to 10 years and defining where the company wishes to be at the end of that time frame.

— CAD/CAM should not be viewed as just a matter of technology, but should be viewed as corporate strategy.

— Integration, from design conception right through to production on the shop floor is of great importance.

— Data management considerations are of paramount importance in achieving CAD/CAM integration. Successful integration is not just a matter of equipment inter-connection or the establishment of proper communication protocols for message handling. The important concept is the universal availability and control of data.

— One of the substantial benefits obtained is from having all functions such as engineering, drafting, scheduling, tooling and production working from the same data.

— Remember that while the integrity of data is a computer or system department's responsibility, the validity of data is a user's responsibility. That is, a computer department may ensure that data, once entered, may correctly read out but the user must be fully aware of the data flows through departments and its modification in order to know whether it is fit for his purpose.

— It is in drawing changes and assembly drawings where one really makes money from CAD because all the data is already in.

— Unless you are building a brand new plant, and most companies are not, automation will evolve gradually from islands of automation which will gradually become linked according to a master plan.

— System planners should search for island projects such as numerical control, robotics and the use of programmable controllers, but plan for future linking.

— Most CAD/CAM systems will be hierarchical distributed systems. Fully centralized data processing requires too much management. Fully decentralized data processing is too hard to control. Distributed systems offer easier expansion, reduced host computer and line dependency and higher end user availability.

— The data handling requirements also demand a hierarchical distributed system.

— In one paper, IBM described how at its East Fishkill, N.Y., plant for manufacture of semiconductor silicon wafers, it was found necessary to change from a four-level hierarchical system to a five-level system in order to meet the data handling requirements, particularly at the shop floor production and quality control monitoring level. The system tracks 50.8 mm and 203.2 mm multilayer ceramic wafers in a number of manufacturing lines through some 100 to 125 physical process steps as they are automatically transported on an air float conveyer system.

— There are a number of new problems created by CAD/CAM, such as the difficulty of system integration, difficulties with data accessibility to the user, data quality, and user control.

— Another problem is the cost of system change as the company grows and requirements change. Getting into a system you cannot change could be a real problem for some companies.

— In evaluating CAD systems for purchase be sure to configure the test systems to your requirements and run benchmark tests on the system with your work which are witnessed personally. In addition, look closely at the vendor's language documentation and compare with others.

— In a distributed system avoid having multiple copies of the same data. Otherwise this generates an update problem in knowing where all the copies are located and ensuring that all copies are updated at the same time. It can be better for each user application to fetch the data when needed from a single master file.

— A speaker on robot applications offered the following guidelines for staying out of trouble: Don't be afraid of the technology — it is 20 years old. Keep it simple — do the simple jobs first. Don't choose a particular robot model as the solution before you understand the problem. Purchasing the most technically sophisticated model may result in overkill. Don't rush to get the robot first and plan the application later. Delivery time for robot hands and grippers can be longer than for the robot itself. Involve people at all levels including the union. Integrate your technology.

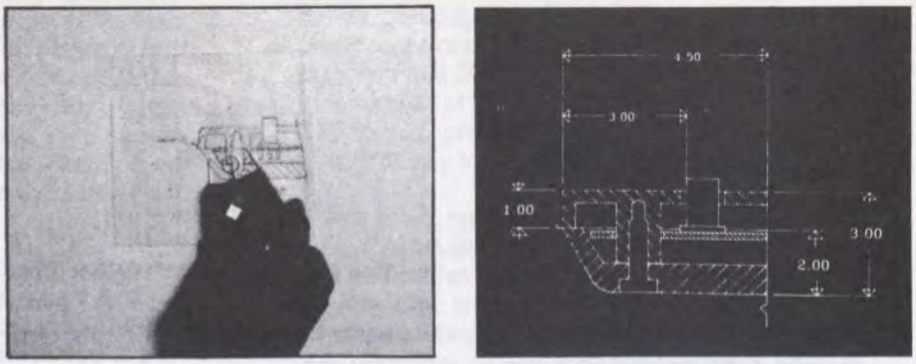
— Remember the user interaction in planning any system. Not only must the system be accurate, easy to use and familiar to them but it must be better for the user than the current system.

CONCLUSION

While a whole new wave of automation in design and manufacturing is in motion most fundamentals are already known to experienced system planners. The 1980 report "Strategy for Survival" prepared by the CAD/CAM Technology Advancement Council represents a valid plan and is on the right track. The big challenge is to implement the recommendations that have been made, to follow the plan and achieve the objectives. This starts with awareness and strategic planning as cited above, plus emphasis on awareness and the training of people.

John Henry Carron Scrimgeour, P.Eng., Consultant, Technology Branch, Dept. of Industry, Trade and Commerce, Ottawa, Ontario.

Further information concerning CAD/CAM technology can be obtained by writing Council Secretariat, CAD/CAM Technology Advancement Council, Technology Branch (61), Dept. of Industry, Trade and Commerce, 235 Queen Street, Ottawa, Ont. K1A 0H5.



Rough input sketch of a mechanical component is digitized with a hand-held cursor on a Summagraphics Corp. system. This enters an idealized form of the sketch into the computer, which "cleans up" the drawing and displays it on a CRT screen for checking. When the operator is satisfied with the drawing, the data is directed to a plotter to produce a finished document.

AUTOMATED DRAFTING: THE FIRST STEP TO CAD/CAM

For companies that want to take advantage of CAD/CAM but cannot afford the full complement of computers and peripherals, automated drafting provides a reasonable first step. The equipment is inexpensive and is designed specifically to speed one of the most costly and time-consuming of engineering activities: the generation of drawings.

JOHN K. KROUSE
Staff Editor

COMPUTER-ASSISTED drafting increases productivity dramatically, so its use has skyrocketed. But many potential users cannot afford the $400,000 price of a full CAD/CAM system. And some companies simply do not need the geometric modeling, structural analysis, and numerical control capabilities of a complete system.

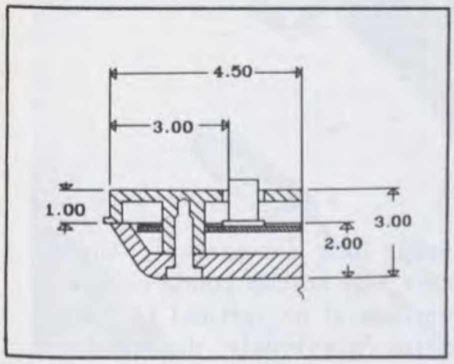
These companies often find automated drafting systems a more reasonable way to get started in CAD/CAM. The systems are intended exclusively for the generation of drawings and are typically priced from $30,000 to $100,000, depending on equipment and software. These systems are primarily turnkey operations purchased ready-to-use from commercial vendors. But some users build their own customized systems from equipment and software purchased individually.

Invisible computers

Like their full-blown counterparts, automated drafting systems require no knowledge of computers or programming. The user simply communicates with the system interactively with pictures instead of with tabulated numerical data. In this sense, the computer in an automated drafting system is totally transparent to the user.

Both CAD/CAM and automated drafting systems contain the same basic equipment: typically a minicomputer, CRT terminal, digitizer, and plotter. The primary difference is the complexity of the software in the computer. Software for most automated drafting is for 2D applications and has little computational capability. But modular software packages typically may be added to the basic system to increase capabilities. This permits a gradual expansion from simple automated drafting to more sophisticated CAD/CAM functions.

The cost of an automated drafting system generally is repaid in less than two years. This rapid return on investment results from two to six-fold increases in productivity for typi-



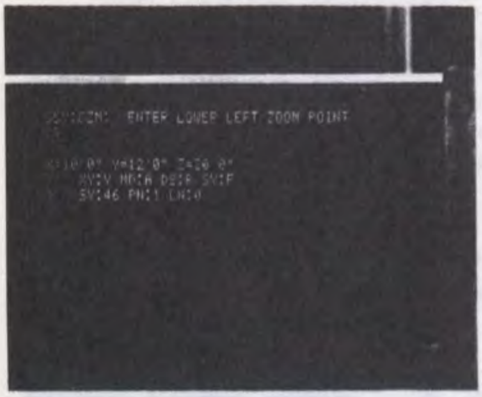
cal drafting applications. And higher increases—up to twenty times—are possible in some instances. Typically, a 2-by-3-foot drawing that takes three days to produce manually may be completed in less than a day with automated drafting. Moreover, the drawing is stored in computer memory and can easily be changed and replotted in a few hours to accommodate engineering modifications.

Computer-assisted drafting increases productivity by coupling the creativity of the designer with the computer's high speed and huge memory. This frees the user from performing the time-consuming, repetitive tasks such as drawing the same shape many times, making the same change to several drawings, or painstakingly measuring and dimensioning a part. And the drawing is produced in minutes with the push of a button. As a result, the man- machine team can produce a drawing more quickly and more accurately than would otherwise be possible.

Points and lines

The points and lines that comprise a drawing are entered into the automated drafting system through any of a number of input devices. One of the most common devices is the touch-sensitive electronic tablet. A stylus is maneuvered somewhat like a pencil on the

Operators input drawing data on a bank of Calcomp automated drafting workstations. Multiple workstations such as these share common computers, digitizers, and plotters to reduce system cost. Terminals are added as drafting requirements increase.



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[illegible] ENTER LOWER LEFT ZOOM POINT

[illegible]
SV:46 PN:1 [illegible]
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Plasma display on a Sigma Design West system asks the operator to specify the drawing area to be enlarged on a CRT screen for detailed work. This question-and-answer approach permits an interactive dialog between the operator and computer, which guides the user by providing prompts and error messages.

tablet surface while a set of cross-hairs moves correspondingly on the CRT screen. The operator depresses the stylus to specify points, which are then joined with line segments according to user commands. The stylus also may be used to dynamically "drag" symbols or text around the screen.

Electronic tablets are usually small sketch-pad arrangements no more than a few square feet in area. Large drawings may be produced by scaling down the construction on the screen. Conversely, the operator may zoom in on portions of the drawing to construct intricate details.

Some automated drafting systems use electromechanical devices to construct the drawing. A joystick or set of two thumb-wheels may move the cross-hairs in the *x* and *y* directions. Another electromechanical arrangement uses a trackball that spins freely in all directions, with cross-hair movement controlled by ball rotation. Other systems use a set of four pushbuttons that move the cross-hairs up, down, right, and left. A fifth button sometimes is included to return the cross-hairs to an initial position or to control their speed.

In addition to these methods, most automated drafting systems have a large digitizing table that resembles the traditional drafting board. Rough sketches are placed on this table and traced with a cursor, the position of which is sensed and digitally recorded in computer memory. In the digitizing process, the cursor is placed over a point on the drawing and a key pressed to enter the position. In this manner, the user specifies all the points as well as connectivity commands for the lines that make up a drawing. This enters an idealized form of the sketch into the computer, which "cleans up" the drawing by straightening lines, smoothing curves and arcs, and orienting lines at proper angles to one another. After the input sketch is digitized, the completed drawing is viewed on the CRT and edited if necessary to remove any errors.

Some cursors are free-moving types consisting of a hand-held puck connected to the system with a cable. Other cursors are constrained in a moving gantry framework. These gantries sometimes have cursor-lock modes for digitizing points in restricted directions. Using the angle lock, for example, the user may specify points either horizontal or vertical to the point previously digitized. Other angular locks place the cursor on the same angle as an existing line or one specified at the keyboard. Or a grid lock restrains the cursor to an invisible grid of any size.

Even with these automated features, manually digitizing a large complex drawing can be laborious because of the difficulty in maintaining the required hand-eye coordination over long periods of time. In fact, the mechanical precision of the digitizer may exceed the manipulative capabilities of the operator. For this reason, some systems have automatic digitizers such as line followers and scanners for manual entry of drawn finished documents into the computer. These automatic digitizers and the required software are expensive, but this expense is offset by increased efficiency, when many completed documents must be digitized.

Line followers are semiautomatic photosensing devices that digitize individual curves with some operator supervision. The user positions the device on each curve and selects the appropriate branch to be tracked when the machine reaches a line intersection. Line followers typically outperform manual digitizers on simple outline drawings. But the efficiency of line followers is drastically reduced on cluttered documents that require extensive human assistance.

Scanners are totally automatic digitizers that scan the entire drawing in criss-cross

Plotter in a Data Technology system produces a drawing while the operator completes further work at the interactive terminal. The constrained-gantry digitizer behind the terminal has several lock modes for entering points on parallel lines and other restricted directions. The intelligent plotter has a built-in microprocessor-based system that removes some of the control burden from the host computer. The pushbutton hand-station placed on the plotter is for entering reference points, scaling factors, and other plotting data.

fashion with a camera and light-beam assembly. The operator must only set up the digitizer initially, and no interaction required during operation. Threshold settings permit the system to screen out smudges, and unwanted background tones or poorly defined details. Scanners also can be equipped with color-separation sensors that allow graphical data to be digitized selectively.

As the drawing is being digitized, it may be segregated into as many as 250 subfiles or drawing layers. Designing in separate layers is similar to drawing on separate transparencies and using them to form a composite. In mechanical design, layering can be used to study moving parts or to check interferences between components. And in printed-circuit production, various layers may represent conductors, components, or drill patterns.

Keyboard commands

Most automated drafting systems have an alphanumeric keyboard for entering data and instructions. For example, coordinate data may be entered to specify points and lines on the CRT screen. The keyboard may also be used to specify line weights and types such as solid, dashed, hidden, and dotted.

The user may also type in drawing text with the keyboard. Usually several fonts are available with the characters displayed in any size or angle. And the text may be centered or justified on the right or left. Some systems even position the text on an irregular curve.

Commands to perform these functions may be entered character by character on the keyboard. But the need for a large number of keystrokes can make the process tedious and error-prone for long command sequences. As a result, many automated drafting systems have a function menu on which frequently used commands can be issued merely by pressing a single key.

Menu keys may either be part of the main keyboard or a separate array of pushbuttons. Systems with only a few menu items may have large electromechanical buttons mounted on a table-top housing. However, systems with hundreds of menu items use a more compact array of squares on a pressure-sensitive panel or other surface. Or menu items may be selected with the cursor on an array adjacent to the main work area of a digitizer table.

Most automated drafting menus can be changed merely by loading an appropriate operating program into the system. Overlay sheets on the menu array then identify key functions. In this manner, the same system may be used to produce drawings for mechanical structures as well as integrated circuits and other applications.

Most automated drafting systems permit the user to enter customized menu items. These

For more information

Information on specific computer-aided drafting systems may be obtained from the following vendors by circling the appropriate numbers on the Reader Service Card:

800 AM Bruning
1834 Walden Office Square
Schaumburg, Ill. 60196

801 Broomall Industries Inc.
700 Abbott Drive
Broomall, Pa. 19008

802 Calcomp Inc.
2411 W. La Palma Avenue
Anaheim, Calif. 92801

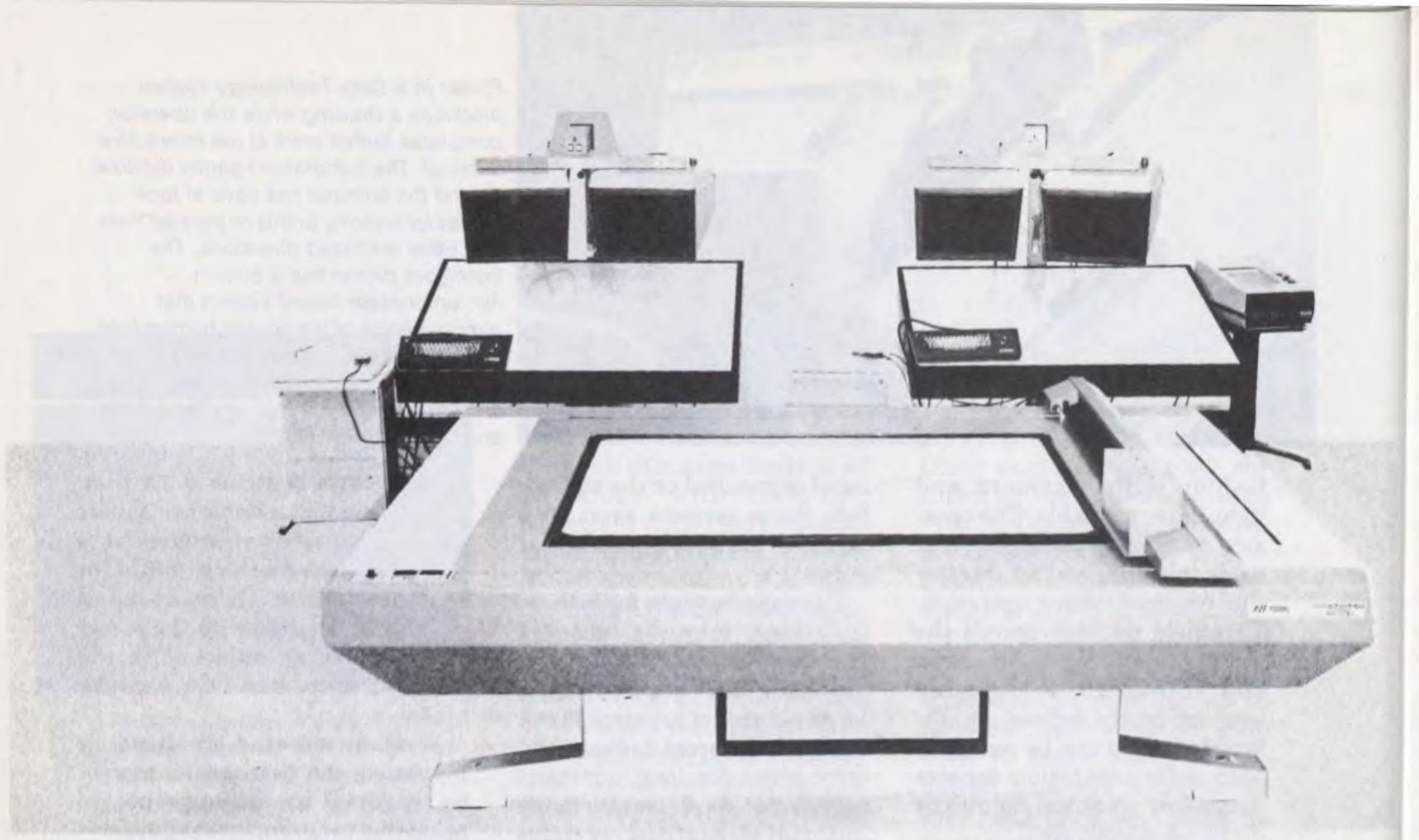
803 Compeda, Inc.
2180 Sand Hill Road
Menlo Park, Calif. 94025

804 Data Technology Inc.
530 Atlantic Avenue
Boston, Mass. 02210

805 Sigma Design West Ltd.
7306 S. Alton Way
Englewood, Colo. 80112

806 Summagraphics Corp.
35 Brentwood Avenue
Fairfield, Conn. 06430

807 Nicolet CAD Corp.
2450 Whitman Road
Concord, Calif. 94518



The flatbed laser scanner in the foreground automatically digitizes drawings for storage and later use in an automated drafting system built by Broomall Industries Inc. The digitized drawing may be edited at either of the dual workstations, where drawings also can be digitized manually.

are specialized symbols or groups of symbols called macros. Some systems permit the user to define hundreds of macros, which may be as simple as a few lines or as complex as a complete drawing. The user calls up the appropriate symbol, which is then scaled and positioned on the drawing.

To speed the construction of drawings, most automated drafting menus contain a set of basic elements that the system constructs automatically from minimal user input. For example, a rectangle can be defined by its diagonal, a circle by its center and radius, a semicircle by its diameter, and an arc by radius and angle. Additionally, line-to-line filleting is available, as is automatic cross-hatching within any boundary specified. Moreover, the user can generate arcs by defining three points. Or a cubic spline may be fit through a series of user-specified points.

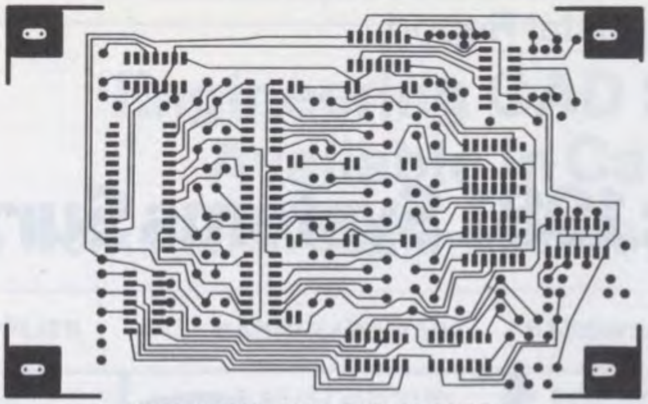
Menu commands also automate much of the dimensioning in some systems. The user can have the system compute and display linear distances between points. The horizontal or vertical distance between the two points may also be determined. The user can also have the system insert radii and diameters into previously digitized circles and arcs. And angular dimensioning features allow the user to label the angle which is between two lines, or the angle through which a previously defined arc travels.

The calculated distances can be scaled and can be provided at various accuracies. And the user also has the option of suppressing the calculated dimension, replacing it with typed text from the keyboard. Menu commands also allow the user to select leader lines and arrowheads for calculated as well as user-specified dimensions.

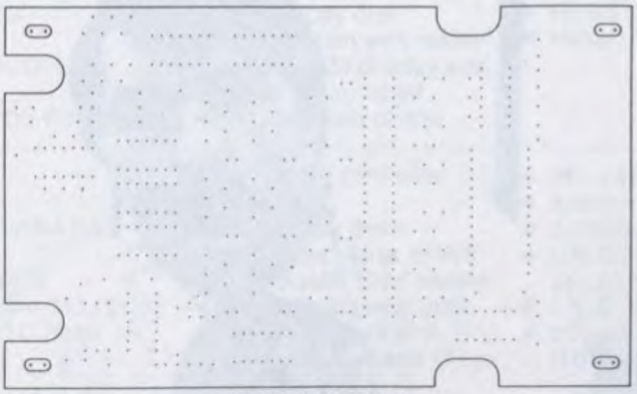
Some software packages provide a number of ways to change the drawing once it is entered into the computer. A line editor deletes lines or shows the line length and angle. A point editor moves points, makes lines parallel, or makes a line intersect another line, circle, or arc. A symbol editor also may be provided to copy, scale, delete, rotate, and move symbols and text. Finally, an eraser is provided to delete all contents within a given area of the drawing.

Plotters

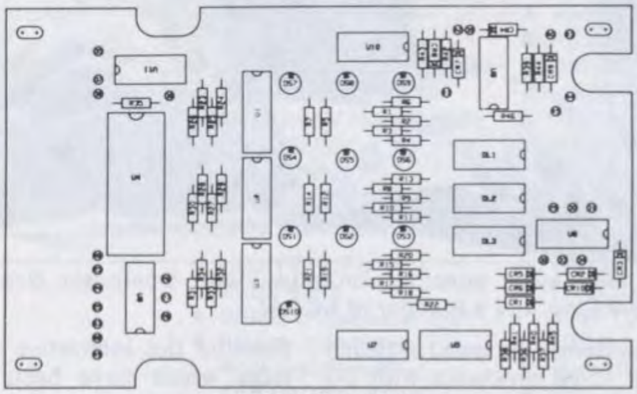
When an operator is satisfied with the accuracy and thoroughness of a document, the data may be directed to a plotter to produce a finished drawing. Drawing data are automatically recorded in computer memory for future reference and archiving. Future modifications and changes are easily made from this permanent record. And additional originals



COMPONENT SIDE, P. C. ARTWORK



DRILL DRAWING



ASSEMBLY VIEW

Layering allows different types of information to be segregated into individual subfiles for separate display and plotting. Circuit artwork, drilling locations, and component assembly are layered in printed-circuit-board design with a Summagraphics system as shown here. The technique is useful in mechanical design for checking mechanism motion or part interference. In mapping applications, different layers indicate soil types, utility lines, property lines, population densities, and other information.

are easily plotted at any time.

Specialized plotters are available to meet specific requirements in the CAD/CAM system. For example, photoplotters are high-precision devices used mainly for the production of printed-circuit artwork masters. And computer-output microfilm plotters are available for placing the CAD/CAM system output graphics directly on microfilm for convenient storage. However, most CAD/CAM systems use pen plotters, sometimes in combination with electrostatic types.

Pen plotters use ink pens to draw graphics on paper, vellum, or other drawing media. Bed-type pen plotters are known for their high accuracy and are used most often in CAD/CAM systems. These types use standard drawing paper rigidly attached to a bed structure. The bed may be a stationary flat bed, a rotating cylinder, or a moving belt. In drum plotters, special paper with holes on the sides is moved back and forth by sprockets on a tractor drum. Drum plotters are less expensive than bed types, but some have overall lower accuracy. For this reason, they are used for less demanding drawing applications.

Electrostatic plotters produce an image on paper as lines of raster dots. Electrostatic point charges are deposited on dielectrically coated paper. The point charges become visible dots when a liquid hydrocarbon toner is applied to the paper. The principal advantage of electrostatics is their high speed, which may be up to 100 times faster than pen plotters. The main limitation of electrostatics is low accuracy. In addition, special conductive paper must be used. And electrostatic plotters tend to be more expensive than pen types. Furthermore, additional software must be included in the system for converting the standard vector output from the computer into raster format for use by the electrostatic plotter.

In spite of these limitations, electrostatic plotters are being used increasingly in CAD/CAM systems. Usually, they are used for their high speed to produce quick preliminary drawings. After the design is completed and refined, a pen plotter can be used to produce accurate, high-quality documentation.

CAD in Canada: 1981 Systems Survey

By Richard MacKay

The use of computer-assisted design (CAD) and drafting has doubled in Canada since 1979. Installations of CAD systems have increased from approximately 100 in January 1979 to slightly more than 200 at the end of September 1981. This growth has resulted from the acceptance of CAD as an increase to drafting productivity and as a supplement to the shortage of skilled design/draftsmen and from the increased availability of CAD systems, software programs and services.

In January 1979, fewer than 10 companies were active in Canada supplying and supporting CAD systems compared with approximately 25 companies today.

This survey is intended to provide a brief comparative description of the CAD systems currently available in Canada and to identify the source of sales and technical support for these systems. The survey is divided into three categories: single workstation, stand-alone systems; multi-workstation, multi-tasking systems; and CAD systems software and services. The survey reflects the trend emerging in the computer graphics industry toward:

- Intelligent microprocessor-based workstations;
- Distributed or networked graphics processing;
- Increased integration of the design, analysis and drafting functions;
- Increased specialization through unique application software.

In the single workstation, stand-alone system, the trend is toward a 16-bit microprocessor with ¼-IMB of memory, a 10-25 MB Winchester disk drive, cartridge tape or floppy disk and a 1024 X 1280 monochromatic raster workstation with menu tablet. An electrostatic plotter is receiving greater acceptance than a pen plotter because of plot time and ease of operation.

Richard MacKay is principal consultant with Computer Graphics Consultants Inc. and a founder of NCGA*

For multi-workstation, multi-tasking systems, the trend is clearly toward a 32-bit processor with 1-2 MB of memory, dual disk drives (60-300 MB), nine-track tape (75 IPS) and a 1024 X 1280 monochromatic raster workstation with menu tablet. These systems usually support an electrostatic plotter and a medium-quality pen plotter. An increased number of systems support a color 1024 X 1280 raster workstation for specialized applications or editing.

The major hardware advancement area is for lower cost color raster workstations and color plotting devices. With most vendors pursuing similar hardware configurations and a 3D graphic design capability, the principal difference in systems during the next three to five years will be the availability of specialized application software.

This survey is intended to describe the interactive CAD systems which have been popularly incorporated into proprietary commercial systems for engineering applications and which are available commercially in Canada. The comparative descriptions included are based on information supplied by the manufacturers or distributors responding to the survey.

Much of the information provided is descriptive rather than objective and for this reason the reader is urged to obtain or derive objective measures of software performance, flexibility and reliability to better evaluate the systems surveyed.

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*The National Computer Graphics Association provides an informal exchange for CAD users, vendors and operators. Potential computer design/drafting users wishing further information should write: NCGA, Suite 1611, 191 Sherbourne St., Toronto, Ont. M5A 3X1.

Engineering CAD Systems Available In Canada

Single Workstation Stand-Alone Systems

SUPPLIER	BASIC HARDWARE	HARDWARE OPTIONS	BASIC SOFTWARE
AM BRUNING EASY DRAF-2 **AM BRUNING** 165 Milner Scarborough, Ont. M1S 4G7 416-298-2700, Ed Hall	• HP 9845T with 318K mem. • Dual floppy disk • Workstation with raster (560 x 455) display and 8½- x 11-in. tablet • HP 7580 pen plotter	• Color raster 560 x 455 display • HP 9872 plotter • Houston plotter	• 2D design/drafting
CALCOMP IGS 400 **CALCOMP CANADA LTD.** 401 Champagne Downsview, Ont. M3J 2C6 416-635-9010, Peter Vasarhelyi	• CC 16/40 CPU with 256KB • 50MB disk drive • Dual floppy disk drives • CALCOMP 1051 plotter • Workstation with Dual 15-in. raster (416 x 300) displays and 11- x 11-in. tablet	• 36- x 48-in. digitizer • Add/on upgrade kit • 200MB disk drives • CALCOMP 960/970 pen plotters • CALCOMP ES plotters • 20-in. raster display (1024 x 712)	• 2D design/drafting
COMPUTERVISION DESIGNER M **COMPUTERVISION CANADA INC.** 180 Atwell Dr., Ste. 202 Rexdale, Ont. M9W 6A9 416-675-9399, Todd Rhems	• CGP-80 CPU with 312K mem. • 80MB Winchester disk • 9-track tape 25 IPS • Designer V mono (1024 x 1024) raster workstation • P 1000 pen plotter	• Versatec ES plotter • PT punch/reader • Communication module • Color raster • Line printer • (1024 x 1024) color raster station	• CADDS 3 3D design/drafting
MCAUTO ADS-100	• DGS140 CPU with 256K mem. • 25MB Winchester disk • Floppy disk drive workstation with TEKTRONIC 4014 display • CALCOMP 960 pen plotter	• VERSATEC ES plotter • TRILOG printer plotter ADS-100C (1024 x 1024) color raster workstation • ADS-100M (1024 x 1024) mono raster workstation • PT punch/reader Communications module TEKTRONIC hard copy unit	• UNIGRAPHICS 3D design/drafting
NICOLET CAD SYSTEM 60 **NICOLET CAD** 120 Aerowood Cooksville, Ont. 416-625-8302, Harley Cooper	• NICOLET 32 bit slice processor with LSI 11/02 PROCESSOR 374K mem. • DUAL FLOPPY DISKS • Workstation with raster 780 x 512 display • NZ 3620 pen plotter	• 36- x 48-in. digitizer • Output station tape unit • Photo plotter • ZETA plotters • Line printer • PT punch/reader	• 2D design/drafting
OMNITECH SYMBOL **OMNITECH GRAPHICS SYSTEMS** 880 Wellington St. Ottawa, Ont. K1R 6K7 613-232-1747, Brian Beniger	• CA CPU with 256K mem. • 32MB disk drive • Workstation with TEKTRONIC 4014 • HP 2580A pen plotter	• 96MB disk drive • 9-track tape 45 IPS • Up to 4 floppy disk drives • CALCOMP 1039, 960 pen plotter • ZETA pen plotters • 36-x 48-in. digitizer	• 2D design/drafting

PRIMARY APPLICATIONS	BASIC SYSTEM PRICE	OFFICES	REMARKS
• Mechanical • Architectural • Electrical schematics	• $114K Cdn.	**Technical support:** Hewlett Packard service locations **Sales:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Hal.	• Hardware maintenance is provided by Hewlett Packard • New product
• Architectural • Electrical schematics • Space planning	• $220 K Cdn.	**Technical support:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Que. **Sales:** Van., Tor., Ott., Mtl.	• System can be expanded with upgrade kit to support 4 workstations. • New product
• Electrical • Mechanical • Manufacturing	• $120 K U.S.	**Technical Support:** Tor., Van., Mtl., Peterborough **Sales:** Tor., Mtl., Cal.	• Application software packages are available for a wide range of design requirements. • New product
• Mechanical • Manufacturing • Space Planning	• $130 K U.S.	**Technical support:** Boston, Florham Park, Minnesota, Seattle **Sales:** Boston, Detroit, Minnesota, Seattle	• Sales & support office planned for Toronto in 1st quarter 1982 • New product
• PCB design • Electrical schematics	• $107 K U.S.	**Technical support:** Mississauga **Sales:** Mississauga	• A SYSTEM 81 is available with an LSI 11/23 & increased memory & capability to support additional stations • New product
• Civil • Electrical • Architectural	• $113 K Cdn.	**Technical support:** Ott., Mtl., Cal., Van., Tor. — TDC Graphics **Sales:** Ott., Mtl., Cal., Van., Tor. — TDC Graphics	• System distributed in SW Ont. by TDC Graphics • 25 systems installed in Canada

SUPPLIER	BASIC HARDWARE	HARDWARE OPTIONS	BASIC SOFTWARE
PHOENIX AUTOMATION SPD 101 **PHOENIX AUTOMATION INC.** 100 Argyle Ave. Ottawa, Ont. K2P 1B6 613-233-7777, Malcolm Cocks	• CA CPU with 128K mem. • Dual floppy disks • Workstation with TEKTRONIC 4014 • HP 7580A pen plotter	• 32MB disk drive • CALCOMP 960 pen plotter • GENESCO G1000 raster (1024 x 1024) station • TEKTRONIC hard copy unit • 36- x 48-in. digitizer	• DRAFT 2D design/drafting
RACAL REDAC CADET **RACAL REDAC INC.** 6271 Dorman Rd. Mississauga, Ont. L4V 1H1 416-676-1525, Rob Lorenz	• RR 16-bit CPU with 64K mem. • 9-track tape 45 IPS • Workstation (512 x 512) mono raster with 15- x 15-in. tablet • HP printer/plotter	• HP 7580 pen plotter • TEK 4662 plotter • TEK 4663 plotter	• CADET PCB layout
SYSTEMHOUSE CAEDS/CADD **SYSTEMHOUSE LTD.** 99 Bank St. Ottawa, Ont. K1P 6B9 613-236-9734, Frank Watts	• HP 1000 CPU with 250K mem. • 20MB disk drive • HP 2648A raster (360 x 720) station • HP 7580A plotter	• 50 120-MB disk drives • 9-track tape • HP 512 x 1024 raster station • CALCOMP 960 pen plotter • HP 2671G printer	• 2D design/drafting

Multi-Station Systems

APPLICON IMAGE	• PDP 11 CPU and APPLICON GRAPHICS 32 processor with .5M mem. • 200MB disk drive • 9-track tape 75 IPS • T26 workstation with color raster (620 x 620) and 12 x 12-in. tablet • CALCOMP 960 plotter	• VAX 11/780, 11/750 CPU's • CALCOMP, XYNETIC plotters • APPLICON COLOR plotters • VERSATEC ES plotters • A/N terminal • Line printer • TV 66 workstation with color raster (620 x 620) and 33 x 44 digitizer	• AGS-900 3D design/drafting
AUTOTROL AD-380 **AUTOTROL LTD.** 6120 2nd St. SE Calgary, Alta. T2H 2L8 403-259-8770, Ken Dedeluk	• UNIVAC V77800 CPU with .5MB mem. • 66MB disk drive • 9-track tape 75 IPS • CC80 19-in. stor/refresh workstation • CALCOMP 960 pen plotter	• VAX 11/780, 750, CPU's • 300, 675MB disk drives • LR raster (512 x 512) station • HR color & monochromatic raster (1024 x 1024) station • Bensen Varian ES plotters • Remote raster review terminal • Remote CC80 workstation • PT punch/reader • 36 x 48-in. digitizer	• GS 1000 General 3D 16 bit design/drafting • GS 32 32-bit design & manufacturing system

PRIMARY APPLICATIONS	BASIC SYSTEM PRICE	OFFICES	REMARKS
• Mechanical • Electrical • Electronic • Structural	• $114 K Cdn.	**Technical support:** Ott. **Sales:** Ott., Mtl., Edm.	• 3 systems installed in Canada
• PCB layout • Electrical schematics	• $76 K U.S.	**Technical support:** Mississauga **Sales:** Mississauga	• Discount offered for additional stations • Stand-alone systems available.
• Architectural • Mechanical • Electrical	• $150 K Cdn.	**Technical support:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Hal. **Sales:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Hal.	• System can be expanded with additional memory to support up to 8 workstations • 2 systems installed in Canada
• Multidiscipline engineering • Electrical • Electronics • Mechanical • Manufacturing	• $250 K U.S. • Add-On workstation price: $77 K U.S.	**Technical support:** Burlington, MA **Sales:** Burlington, MA., Troy, Mich.	• Sales & support office planned for Toronto in 1st quarter 1982 • 3 systems installed in Canada • 4 workstations supported • 12 devices supported
• Multidiscipline engineering • Mechanical • Manufacturing	• $330 K U.S. • Add-on workstation price: $35 K U.S.	**Technical support:** Van., Cal., Tor. **Sales:** Cal., Tor.	• AUTOTROL system has been sold in Canada by CANADIAN DRAFTING SYSTEMS, reincorporated as AUTOTROL LTD. Nov. 1981 • 27 systems installed in Canada • 12 workstations supported • 16 devices supported

SUPPLIER	BASIC HARDWARE	HARDWARE OPTIONS	BASIC SOFTWARE
CALCOMP IGDS-500 **CALCOMP CANADA LTD.** 401 Champagne Downsview, Ont. M3J 2C6 416-635-9010, Peter Vasarhelyi	● CC 16/40 CPU with 320K mem. ● 50MB disk drive ● 9-track tape 75 IPS ● Workstation with dual 15-in. raster (416 x 300) displays and 11- x 11-in. tablet ● CALCOMP 1051 plotter	● 200MB disks ● 36 x 48-in. digitizer ● CALCOMP 960/970 pen plotters ● CALCOMP ES plotters ● CALCOMP 530 printer plotter ● 20-in. raster display (1024 x 712)	● EDS 2D design/drafting
CALMA DDM **CALMA INTERACTIVE GRAPHIC SYSTEMS** Suite 1700, 1 Yonge St. Toronto, Ont. M5E 1E5 416-863-6666, Cliff Gentle	● DG ECLIPSE S230 CPU with 256K memory ● 300MB disk drive ● 9-track tape 75 IPS ● RB 1000 workstation with 19-in. mono (1024 x 1080) raster, 11-in. A/N & 11 x 11-in. tablet ● VERSATEC ES plotter	● 80MB disk drive ● CALCOMP 960 pen plotter ● XYNETIC plotters ● PT punch/reader ● 120 R remote terminal ● Line printer ● A/N terminals ● TRILOG printer plotter ● 36- x 48-in. digitizer ● RC 1000 color (1024 x 1280) raster workstation ● RC 1000 color (512 x 512) raster workstation	● DDM 3D design, drafting and analysis
COMPUTERVISION CADDS 3 **COMPUTERVISION CANADA INC.** 180 Atwell Dr., Suite 202 Rexdale, Ont. M9W 6A9 416-675-9399, Todd Rhems	● CGP-100 CPU with 312K mem. ● 300MB disk drive ● 9-track tape 75 IPS ● Designer V mono (1024 x 1024) raster workstation ● P 1000 pen plotter	● VERSATEC ES plotter ● PT punch/reader ● CALCOMP 960/970 pen plotters ● XYNETIC, Gerber plotters ● CV photoplotter ● Designer V color (64) workstation ● Designer-R remote station ● A/N terminals ● Lineprinters	● CADDS 3 3D design/drafting
COMPUTERVISION CADDS 4 **COMPUTERVISION CANADA INC.** 180 Atwell Dr., Suite 202 Rexdale, Ont. M9W 6A9 416-675-9399, Todd Rhems	● CGP-200 CPU & graphics processor with .5MB memory ● 300MB disk drive ● 9-track tape 75 IPS ● P 1000 pen plotters ● Designer V mono (1024 x 1024) raster workstation	● VERSATEC ES plotter ● PT punch/reader ● CALCOMP 960/970 pen plotters ● XYNETIC, Gerber plotters ● CV photoplotter ● Designer V color (64) workstation ● Designer-R remote station ● A/N terminals ● Lineprinters	● CADDS 4 3D design/drafting & analysis
INTERGRAPH IGDS/DMRS **INTERGRAPH SYSTEMS LTD.** 2020 L 32nd Ave. NE Calgary, Alta. T2P 2M2 403-276-8631, Ken Barrie	● VAX 11/750 CPU with 1M mem. ● 160MB disk drive ● 9-track tape 75 IPS ● Dual 19-in. raster (1024 x 1280) workstation with 36 x 48-in. digitizer ● CALCOMP 960 pen plotter	● VAX 11/780, PDP 11/23 CPU's ● 300, 675MB disks ● VERSATEC ES plotters ● VERSATEC printer plotter ● Remote raster workstations ● Color raster workstations	● 3D design & database management

PRIMARY APPLICATIONS	BASIC SYSTEM PRICE	OFFICES	REMARKS
• Architectural • Electrical schematics • Space planning	• $300 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Tor., Cal., Ott. **Sales:** Tor., Cal.	• Specialized application programs GDS (Microelectronics) & CGI (mapping) available. • 24 systems installed in Canada • 6 workstations supported • 12 devices supported
• Multidiscipline engineering • Mechanical • Electrical • Electronics • Space planning • Engineering analysis	• $300 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Tor., Cal., Ott. **Sales:** Tor., Cal.	• Specialized application programs GDS (microelectronics) and CGI (mapping) available • 24 systems installed in Canada • 6 workstations supported • 12 devices supported
• Multidiscipline engineering • Electrical • Electronics • Mechanical • Manufacturing • Process planning	• $225 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Tor., Van., Mtl., Peterborough **Sales:** Tor., Mtl., Cal.	• Application software packages available for wide range or design, drafting requirements. • 27 systems installed in Canada • 8 workstations supported • 10 devices supported
• Multidiscipline engineering • Electrical • Electronics • Mechanical • Manufacturing • Process planning • Engineering analysis • Mapping	• $325 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Tor., Van., Mtl., Peterborough **Sales:** Tor., Mtl., Cal.	• Application software packages available for wide range of design, drafting and analysis requirements. • New product • 8 workstations supported • 10 devices supported
• Multidiscipline engineering • Resource mapping	• $450 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Vic., Cal., Edm., Reg., Tor., Ott., Mtl. **Sales:** Van., Cal., Edm., Tor., Mtl.	• 42 systems installed in Canada • 12 workstations supported • 16 devices supported

SUPPLIER	BASIC HARDWARE	HARDWARE OPTIONS	BASIC SOFTWARE
MCAUTO DDS-100	• PDP 11/44 CPU with .5M mem. • 67MB disk drive • 9-track tape 75 IPS • Workstation with TEKTRONIC 4014 • CALCOMP 960 pen plotter	• PDP 11/70, VAX 11/780, 11/750 • DG S140, S250, MV 8000 CPU's • VERSATEC ES plotter • PT punch reader • TRILOG printer/plotter • CALCOMP pen plotters • DDS-100C (1024 x 1024) color raster workstation • DDA-100M (1024 x 1024) mono raster workstation • TEKTRONIC hard copy unit	• UNIGRAPHICS 3D design/drafting
PRIME MEDUSA **PRIME COMPUTER OF CANADA** 130 Skyway Ave. Rexdale, Ont. M9W 4Y9, Gordon Tustin	• PRIME 250-2 CPU with 1M mem. • 33MB disk drive • 9-track tape 75 IPS • DW 93 mono (1024 x 1280) raster workstation • 11- x 17-in. tablet	• PRIME 550, 750, 850 CPU's • 300MB disk drives • PW 95 color (1024 x 1280) station • A/N terminals • PT punch/reader • TEKTRONIC 4014 station • Plotter support module • Communications support module	• MEDUSA-2D 2D design drafting • MEDUSA-3D 3D design, drafting & analysis
RACAL REDAC CADENCE **RACAL REDAC INC.** 6271 Dorman Rd. Mississauga, Ont. L4V 1H1 416-676-1525, Rob Lorenz	• PDP 11/34 CPU with 256K mem. • Dual 5.7MB disc drives • TU-11 9-track tape 45 IPS • DESIGNER station with VT 11 refresh screen with 64K and light pen • HP 7580 pen plotter	• CALCOMP 1039, 960 • TEKTRONIC 4663 • VERSATEC ES plotters • VS 11 (512 x 512) color raster • MEGATEK 21-in. (1024 x 1024) (color & mono) • PT punch/reader	• CADENCE MARK 12 2D design/drafting
SYSTEMHOUSE CAEDS/CADD **SYSTEMHOUSE LTD.** 99 Bank St. Ottawa, Ont. K1P 6B9 613-236-9734, Frank Watts	• HP 1000 CPU with 256K mem. • 20MB disk drive • 9-track tape 75 IPS • HP 2648A raster (360 x 720) workstation • HP 7580A pen plotter	• HP 26716 printer plotter • CALCOMP 960 • 50, 120 MB disks • HP high resol. raster (512 x 1024) station	• CAEDS/CADD 2D design/drafting
WILD LEITZ INFORMAP **WILD LEITZ CANADA** 513 McNicoll Ave. Willowdale, Ont. M2H 2C9 416-497-2460, Dieter Zeuner	• PDP 11/44 CPU with .5M mem. • 67MB disk drive • 9-track tape 75 IPS • GWS-11 19-in. stor/refresh • 15-in. A/N workstation with 36- x 48-in. digitizer • CALCOMP 960 pen plotter	• VAX 11/780, PDP 11/70 CPU's • 300MB disk drive • HP 7580 plotter • VERSATEC ES plotters • High resol. raster (1024 x 1280) workstations color, mono • High resol. digitizers • A/N terminals	• INFORMAP 2D survey engineering and mapping

PRIMARY APPLICATIONS	BASIC SYSTEM PRICE	OFFICES	REMARKS
• Mechanical • Manufacturing • Space planning	• $250 K U.S. • Add/on workstation price: $30 K U.S.	**Technical support:** Boston, Florham Park, Minnesota, Seattle **Sales:** Boston, Detroit, Minnesota, Seattle	• Sales & support office planned for Toronto in 1st quarter 1982 • Wide choice of both 16- and 32-bit DEC and DATA GENERAL processors available. • Special application programs include MILL, LATHE, GRIP • 13 systems installed in Canada • 4 workstations supported (PDP 11/44) • 12 devices supported
• Multidiscipline engineering • Manufacturing	• $210 K Cdn. • Add/on workstation price: $64 K Cdn. (plotter not included)	**Technical support:** Van., Cal., Edm., Win., Lon., Tor., Ott., Mtl., Hal. **Sales:** Van., Cal., Edm., Win., Lon., Tor., Ott., Mtl., Hal.	• Wide choice of plotters are quoted as options. • Wide range of specialized engineering application programs available for specific graphic and engineering requirements. • 30 systems installed in Canada • 6 workstations supported • 16 devices supported
• PCB design & layout • Electrical schematics • Logic simulation • Mechanical	• $240 K U.S. • Add/on workstation price $90 K U.S.	**Technical support:** Mississauga **Sales:** Mississauga	• An increased capability system VANTAGE is available and supported on VAX 11/750, 11/780 processors • New product • 6 workstations supported • 10 devices supported • Special application packages MATRIX and CONCEPT are available. Full design rules checking capability.
• Architectural • Mechanical • Electrical	• $190 K Cdn. • Add/on workstation price: $12 K Cdn.	**Technical support:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Hal. **Sales:** Van., Cal., Edm., Win., Tor., Ott., Mtl., Hal.	• Hardware maintenance provided by Hewlett Packard • 24 systems installed in Canada • 8 workstations supported • 16 devices supported
• Survey mapping • Resource mapping • Mun/utility mapping • Cartographic mapping	• $350 K U.S. • Add/on workstation price: $50 K U.S.	**Technical support:** Van., Cal., Tor., Que. **Sales:** Tor., Cal.	• "WILDMAP" system available for photogrammetric applications. • 8 systems installed in Canada • 8 workstations supported • 12 devices supported

CAD systems software or services

The following is a partial list of companies offering software or services for computer drafting and plotting in Canada

Systems/Services	Description	Supplier
GIAM	Entry level 2D drawing and design system	IBM
CADAM	3D design, drafting and manufacturing system	IBM
IGGS	(Interactive Geo-Facilities Graphic Support) An interactive entry, edit and display system for maintaining geo-oriented data bases	IBM Industry Management-Graphics 55 King Street W., P.O. Box 15, Toronto-Dom. Centre Toronto, Ontario M4K 1B1 416-360-2160 — Bob Adams
DRAGON	2D computer aided drafting system for discipline engineering project drawings.	COMPEDA 140 Route 17 North Paramus, N.J. 07652 201-967-5710 — Carl Howk
GDS	Interactive 2D drafting system for mechanical, architecture, construction drawings and electrical schematics	APPLIED RESEARCH CONSULTANTS 765 Cayuga Street, Lewiston, N.Y. 14092 716-754-4380 — Mary Oliverson
CD/2000	Automated design, drafting and numerical-control software	CONTROL DATA 50 Hallcrown Place, Willowdale, Ontario M2J 1P7 416-491-9191 — Haig Saadetian
AD 2000	Computer aided mechanical design and drafting software	PERKIN-ELMER 6486 Viscount Road, Mississauga, Ontario L4V 1H3 416-677-8990 — Albert Pinhas
D-PICT	Device independent graphics plotting software	DATAPLOTTING SERVICES INC. 160 Duncan Mill Road, Don Mills, Ontario M3B 1Z5 416-447-8518 — Wilf Parker
PCB-LAYOUT SERVICES	Printed circuit boards design and layout	CADCAM GRAPHICS 700 Industrial Ave., Ottawa, Ontario K1G 4Y9 613-526-0620 — Woody Caroll
PCB-ARTWORK SERVICES	Computer generated artwork for printed circuit boards, NC drilling tapes and proto-type service	DIGITAL GRAPHICS LTD., 90 Don Park Road, Markham, Ontario L3R 1C4 416-495-9633 — Jim McLochlan
DRAFTING SERVICES	2D drafting of electrical, mechanical and architectural drawings	TDC GRAPHICS 80 Royalcrest Road, Rexdale, Ontario M9V 4C1 416-749-3970 — Chris Adams
DRAFTING SERVICES	3D multi-discipline drafting and computer aided design	CADCO SERVICES INC. Unit 4-1616 Mathison Blvd., Mississauga, Ontario L4W 1R9 416-625-7086 - Bill Woods
DRAFTING SERVICES	2D drafting of survey engineering maps and drawings and architectural layouts	PROCONSUL 435 McNicoll Ave., Willowdale, Ontario M2H 3M7 416-775-7010 - Henry Karbella

What's happening in CAD/CAM

New developments in computer hardware and software offer new opportunities to solve problems and aid productivity. Here are some recent examples

COMPUTERS ARE NOW a part of our daily life. Disembodied, computer-controlled voices sing out the descriptions and prices of the week's groceries as they move across the checkout counters at some supermarkets. Just about every bill that lands in the mailbox is computer-generated.

In industrial applications, to quote Jack Scrimgeour, long-time secretary of the CAD/CAM Technology Advancement Council, the use of computers "is now spreading like wildfire into the area of discrete parts manufacturing, where it has been given a number of new names; computer aided design and computer aided manufacturing, or CAD/CAM for short, computer integrated manufacturing (CIM), or computer aided engineering (CAE).

"These technologies have fundamental importance for the success, even the survival, of the manufacturing industry, an economic sector which provides approximately 20 percent of employment in Canada," Scrimgeour told a recent Toronto seminar on computerized process control.

Computer aided design and drafting (CAD or CADD) has become a mature technology. Some types allow the three dimensional visualization of products before any prototypes are built. Such computers, by decreasing design costs, are a key to international competitiveness.

At the opening of the Canadian Computer Show and Conference last November, John Bates, president of the Canadian Information Processing Society, noted a key trend in the computer field. "We've gone from a world of bulky, room-sized mainframes to one where a computer can be stored easily under an airline seat . . . Microcomputers have come of age."

Superchips cut computer size

How small can a computer be? With the arrival of the superchips—complete computer "brains" squeezed onto miniature chips of silicon only slightly thicker than this page—computers are shrinking even more rapidly than in the past.

Five of the most remarkable of the sueprchips have been put to work in a high performance 32-bit computer, the HP 9000, recently introduced by Hewlett-Packard. These quarter-inch-square chips handle all the main functions of the new computer, which is intended primarily for computer aided engineering applications.

The largest of the HP superchips contains electronic circuits equivalent to 600 000 transistors. Together, Hewlett-Packard's five superchips pack the equivalent of more than two million transistors—more than four times the number of parts in a jumbo jet liner.

The chips are able to hold all of these electronics because of an HP advance in very large-scale integrated circuit technology which squeezes the electronic circuits on the chips down to only one micron, or 40 millionths of an inch, apart. At this circuit density, a pinhead would cover 25 000 of the chip's transistors. With the circuits so close together, information gets transferred from one circuit to another 18 million times every second.

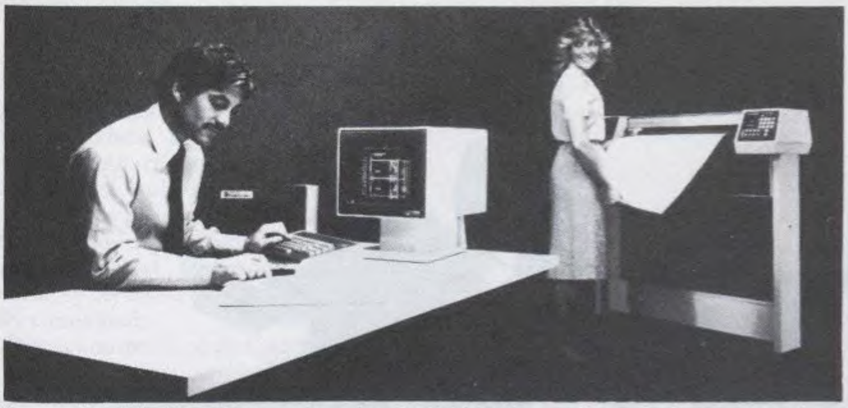
Despite the extreme density of electronic components on each of HP's superchips, an HP 9000 computer requires no air conditioning or special electrical systems.

The power of a 32-bit computer is illustrated by comparing it to 8-bit and 16-bit computers—a bit being the number of digits of information a computer can handle at one time. An 8-bit computer can deal with 256 items at a time, such as the names of all the workers in a company with 256 employees. A 16-bit computer can address 64 000 items of information, such as the names of all the residents of a small city.

A 32-bit computer can address four trillion items of information. That's the same as knowing the names of all four billion people on earth, with room left over to know the names of everyone in the world even if the population should grow to be 1000 times larger.

"Programs are so large, complex and computation-intensive in today's scientific and engineering environment that the traditional approach of dividing the power of an expensive, centralized mainframe among many users often isn't appropriate," said Douglas C. Chance, HP vice president and general manager of HP's Technical Computer Group.

The HP-9000 family of 32-bit computers includes desktop-size workstations priced to let individual engineers have their own personal mainframes.



Computer aided drafting system, the MARS CAD, can be quickly mastered.

"We believe it makes more sense to optimize the productivity of people, not machines. That's the whole idea behind the HP 9000—to enable customers to give each of their key people the full power of a 32-bit computer—complete, undiluted power to enable individuals to get critical work done faster, without interruption, and with greater personal creativity and convenience."

Occupying about as much desk surface area as a daily newspaper page, an HP 9000 integrated workstation can include a monochromatic or color-graphics CRT display, ASCII keyboard, a built-in printer, a built-in 10-megabyte Winchester disc drive, 256-kilobyte flexible disc drive and up to 2.5 megabytes of error-correcting and self-healing main memory.

Since the HP 9000 is available as an integrated workstation, in a box configuration or as a complete multi-user system—and since there are three levels of performance within each configuration—the HP 9000 is expected to make a significant contribution to the technical computing marketplace.

Four station CADD system

What is described as the first truly affordable multi-station Canadian computer aided design and drafting system has been introduced by the Toronto-based Triskelion International Corporation.

Craig Curran, executive vice president of the Canadian-owned company said "This represents a major price breakthrough for Canadian industry. Historically, CADD systems cost in excess of $100 000 per station but with Triskelion's new system the total cost is under $40 000 per station, making CADD available to all segments of the industry."

Incorporating the latest in computer technology and Triskelion's own software, the system supports the standard set of CADD functions for the creation and manipulation of two-dimensional drawings. In addition, more advanced features are provided, such as specification of arbitrarily bounded surfaces and the creation and manipulation of complex symbols. The user can simultaneously view any number of drawing levels as well as magnify drawing detail to any level. The Triskelion system utilizes a drawing file structure which can be easily interfaced to existing inventory control, CAM NC generation or other engineering software packages.

Triskelion CADD systems are currently being used for mechanical drafting, mapping and cartography, as well as space layout for stores and offices.

A turnkey computer aided drafting system, complete with hardware and software, is being offered by Staedtler Mars Ltd. Called the MARS CAD, it can be used in architectural, mechanical and schematic drafting applications. The software package includes a Designer's Reference Manual and the system is claimed to be so easy to use that it can be mastered by any designer in just a few days, without learning computer technology.

At the touch of a few keys, the designer can instantly draw lines and shapes, add dimensions and crosshatching, or rotate any object. All drawing characteristics and properties are user-definable, including scale, grids, guides and increments. Text can be added in any size or at any angle. The designer can zoom in or zoom out of any portion of a drawing, and can maintain up to 63 levels or overlays at a time.

Simple commands allow the designer to rotate, scale, copy or "image" an object. Modifications of objects, groups or entire drawings are easily made.

Anchoring the MARS CAD system is a 16-bit microcomputer with a 64K byte internal memory and dual 8-inch floppy disc drives. A 12-inch, high resolution black and white screen, 71-key detached keyboard with numeric key pad and 11 x 11 inch digitizer pad allow precise graphics input and display. The system is complete with the buyer's choice of plotter, either a Houston Instrument DMP-29 desktop plotter for B-size drawings or a Hewlett-Packard 7580A for D-size output.

Complete MARS CAD systems begin at $24 995.

Easy-to-use new version of Tektronix 2-D drafting package is controlled with a tablet menu of familiar drafting functions and simple keyboard or tablet.

New drafting software package

A new version of the PLOT 50 2-D drafting package, a software system providing automation for all drafting tasks, has just been announced by Tektronix Canada Inc. It now features expanded capabilities for mechanical, electrical, structural and facilities drawings applications.

Tektronix designers have carefully considered human factors in engineering the package to make it easy to use. The package is controlled with a tablet menu of familiar drafting functions and simple keyboard or tablet. The user replies to screen messages and prompts. The package has been designed and field-tested to provide users wanting to automate their manual processes with significant gains in productivity.

The flexibility of the 2-D drafting package accommodates diverse drafting standards and gives users many ways to accomplish similar drafting tasks. It provides 15 ways to input lines, arcs and circles in one feature, 10 annotation methods and six ways to temporarily blank out sections of a drawing for ease in editing. The package permits use of either grids or construction lines to orient drawing features with precision. Symbols can be drawn once to be used repeatedly. Symbols can be merged. They can be displayed in "refresh", rotated, deleted or replaced with another symbol. They are tabulated automatically to assist in takeoffs. With the window function, the user can stretch items or enlarge details to fill the screen.

"This new version of the 2-D drafting package is an example of Tektronix efforts to protect users' investments by providing upward compatibility of products," said Jack Woida, marketing support manager. "We intend to be the price/performance leader in automated drafting. This means updates must provide more performance and system prices must be reduced."

Software link to CMMs

A new software link between turnkey CAD/CAM systems and coordinate measurement machines (CMMs) has been demonstrated using the Bendix Cordax 1820 coordinate measurement machine and Computervision's Designer V CAD/CAM system.

Named CMM Interface, the new link increases productivity on the shop floor by enabling users to create a CMM inspection path and evaluation program on the CAD/CAM design terminal for measuring various part features in three dimensions. The probe and the path can be verified by graphically displaying them on the design terminal. If the path needs to be changed to avoid probe collisions or to meet inspection requirements, the user can make the changes quickly and interactively in real time.

CMM Interface helps users inspect more complex parts easier and with greater accuracy. The long and tedious process of writing complex CMM programs manually is no longer necessary and the conventional turnaround time required to create and test a CMM program is drastically cut.

Using the three-dimensional model in the CAD/CAM database, part coordinates, feature locations and feature sizes are automatically sent to the CMM computer for feature checking.

Computervision post processors then produce the machine-readable programs to drive the direct computer-controlled CMM. Inspection paths can be easily documented with hard copy and distributed to operators of manual CMMs.

Talking digitizer speeds up the drawing process and prompts the operator.

Talking digitizer

An added check on the accuracy of data entry is provided by a talking digitizer introduced by a California firm, Design Aids Inc. The device is used in conjunction with a drafting system software package that produces electronic schematics.

The talking digitizer is used as a data capture station where the operator can digitize non-grid, freehand schematics in a form which is saved on the floppy disc of an attached IBM personal computer. Through headphones, the attached vocal output unit gives the operator positive feedback as to the data that is entered.

The talking digitizer allows the operator to concentrate on the drawing data that is being entered, rather than constantly having to shift attention back and forth between the drawing and the CRT display. The vocal output unit also prompts the operator for data to be entered and notifies the operator when a mistake has been made.

New aid to industrial automation

The new 32-bit Eclipse MV/4000 computer introduced recently by Data General (Canada) Inc. is claimed to be the only one of its kind to offer both a real-time operating system for dedicated applications and a compatible, general purpose virtual operating system for multi-user applications and program development.

The company has also announced enhancements to its 32-bit real-time operating system, AOS/RT32, which extend communications device support and simplify the user interface.

The new system is designed for a wide variety of scientific and industrial automation markets, including CAD/CAM, supervisory control and automatic test equipment (ATE).

"The introduction of this low-cost member of our 32-bit MV/Family is another step in our strategy to address the 32-bit cost and performance needs of the high-growth industrial automation markets," said Brent Cahill, acting national sales manager.

"Within this market, the Eclipse MV/4000 offers users the computational power, I/O handling, and address space particularly suited to CAD/CAM, ATE and supervisory control applications," added Cahill.

The Eclipse MV/4000 features an advanced, microprogrammed architecture on a two-board central processing unit. Reliability is further built into the MV/4000 with ROM-based power-up diagnostics and on-board fault isolation diagnostics.

Improved output

The ERGOS 240 systems introduced by Omnitech Graphics Systems Inc. are said to provide improved design and drafting productivity. The systems introduce a raster scan and stroke/refresh capability and provide users with a multi-station distributed processing and networking capability. The problem of degradation in multiterminal central processing systems caused by terminal overload is reportedly eliminated.

Display output is on dual screens and is available either stroke/refresh or high resolution (1280 × 1024) raster scan. The second screen at the ergonomically designed workstation carries scrolled alphanumreic data and operator instructions.

A major customer benefit provided by the systems, the company states, is the distributed processing concept, which does not require high cost dedicated data transmission links to remote locations. As a result, a number of ERGOS 240s can be networked together in a cost-effective solution for both multiple office companies and for different companies working together on the same project.

Each company or office can, therefore, ensure its own drawing control and file security, clearly establish drawing origin and ownership and eliminate the problems of control and cost allocation that arise with multiterminal systems.

The ERGOS 240 systems use a 64K byte computer automation central processing unit with 8M bytes of virtual memory stored on a Control Data 32M byte high speed disc drive. 16M bytes of storage is removable and disc drive capacity can be increased up to 96 bytes.

The ERGOS 240 systems can be used in a wide range of engineering applications. They include: agricultural design and mechanical layout; structural engineering; surveying and municipal engineering; urban and cablevision mapping; power grid layout; mechanical engineering; electrical system design and printed circuit artwork.

Intelligent CAD workstation

A family of powerful, intelligent workstations just introduced by Prime Computer of Canada Ltd. is designed to improve productivity in computer-aided mechanical design environments.

The Prime Workstation 200 Series (PW200) is the only stand-alone workstation in the industry that performs solids modelling, the company said. The single-unit price is as low as $87 840.

Prime Workstation 200 Series needs no special environmental controls. The design station can be powered from any standard 110 v, 20 amp wall socket.

Based on a 32-bit, virtual memory processor, the PW200 Series incorporates dedicated modules of Medusa, an integrated, mechanical computer-aided design system. Medusa offers two-dimensional design and drafting and three-dimensional solids modelling capabilities.

"The PW200 combines the power of a 32-bit processor with full graphics capabilities and proven CAD software in one, easy-to-use, low-cost design station" said Roy Bond, director of marketing communications for Prime Canada. "It provides each user with a complete mechanical design environment.

"All these capabilities make the PW200 design stations an outstanding productivity tool for a single-user environment or in a multi-user design environment," he added.

Using Primenet, Prime's networking software, a user can link PW200 systems with any of Prime's 50 Series of 32-bit minicomputers, creating a design network to meet his needs. Each user in the network retains his own interactive Medusa design environment, while having the capability to share programs, information and resources stored or managed by the Prime host system.

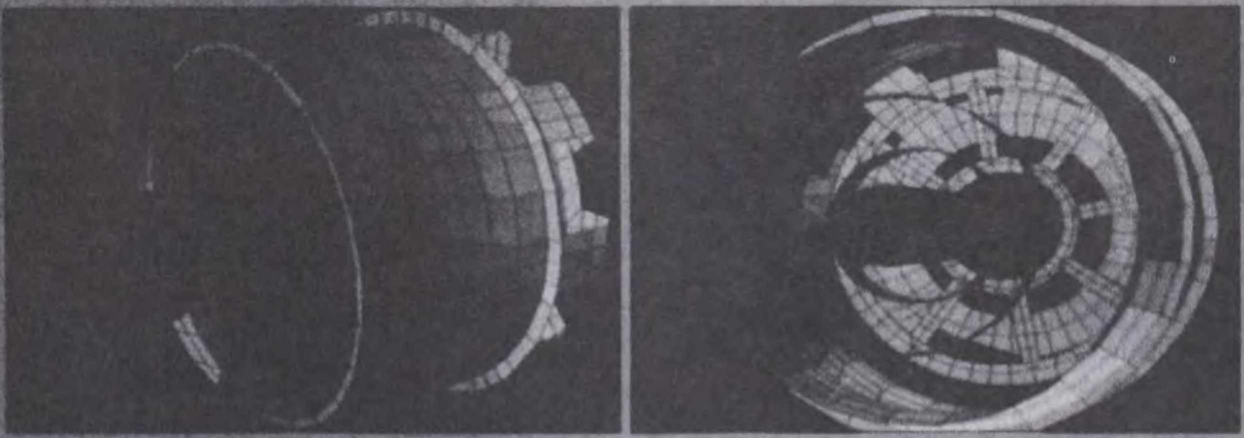
The PW200 hardware consists of a graphics unit comprising a 19-inch, high resolution (1168 × 860) color raster display monitor; a data entry tablet; an alphanumeric keyboard; and a joystick for easy manipulation and control of the screen cursor.

Powering the PW200 is a 32-bit, virtual memory processor with one megabyte of main memory; one sealed 68-megabyte Winchester disc; and a 15-megabyte cartridge tape drive for easy storage, back-up and transport of data.

The 32-bit graphics processor drives a microporcessor-based display controller over a high-speed, direct memory access (DMA) interface. The display controller supports six serial ports (RS232-C), four of which are dedicated.

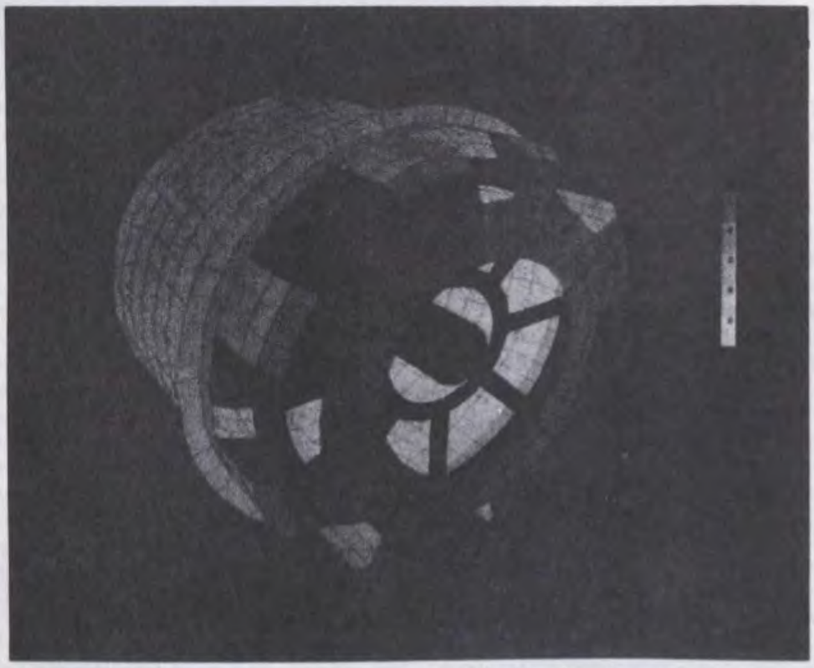
The monitor serves as both a graphics monitor and a system console. A text area can be scrolled on the bottom of the screen, or users can select full-screen text displays.

All of these components are housed in a desk-height unit that fits easily into any standard office or light manufacturing environment. Because it uses sealed Winchester disc technology for storage, no special environmental controls are required. The design station can be powered from any standard 110 v, 20 amp wall socket.



JOHN K. KROUSE
Staff Editor

SOLID MODELS FOR



Solid model of a Bendix electrical generator for an aircraft was built in two and one-half days with the Patran program from PDA Engineering. Colors are assigned according to material and part thickness (above). Pieces of the aluminum housing are shown in blue, and steel parts are denoted by red and yellow. The assembly of parts is checked with various views of the shaded model (top of page).

CAD/CAM is taking a giant step forward with the refinement of solid-modeling technology. Avoiding the incompleteness and ambiguities of wire-frame and surface modeling, the solids approach provides an easier transition from design to analysis and manufacturing.

MOST solid modeling programs in 1980 were still in prototype development at universities and research institutions. And the few commercially available programs at that time were expensive, cumbersome to use, and operated only on large in-house computer systems. As a result, the use of solid modeling packages was largely restricted to large corporations that purchased the programs more for evaluation and research than for practical use.

Now a rapidly growing number of commercial programs are available. These packages are less expensive

COMPUTER GRAPHICS

than their predecessors and can be easily implemented on minicomputer-based graphics systems. Moreover, today's software constructs models in far less time and with less difficulty than earlier programs. Consequently, solid modeling is becoming increasingly practical for a broad range of tasks in design and manufacturing. Although solid modeling is far from pervasive, the technology is being used in a growing list of applications and promises to become the predominate method of geometric modeling. The consensus of most experts is that solid modeling is the "wave of the future" in geometric modeling.

In spite of the significance of this technology, there is considerable confusion among potential users as to just what solid modeling is. For example, three-dimensional wire frames with hidden lines removed or shaded surface models are often confused with solid models because of similarities in appearance. Also, many users perceive solid modeling only as a means to produce realistic graphic displays. Often overlooked is the greater potential of solid modeling to provide a more complete part description for design and manufacturing. As one observer says, "Solid modeling is more than making pretty pictures. It's a way to completely describe the solid nature of a part in the computer."

Comparing modeling methods

Solid modeling is the highest level of sophistication in geometric modeling, which also includes wire frame and surface modeling approaches. Each method represents part geometry a different way.

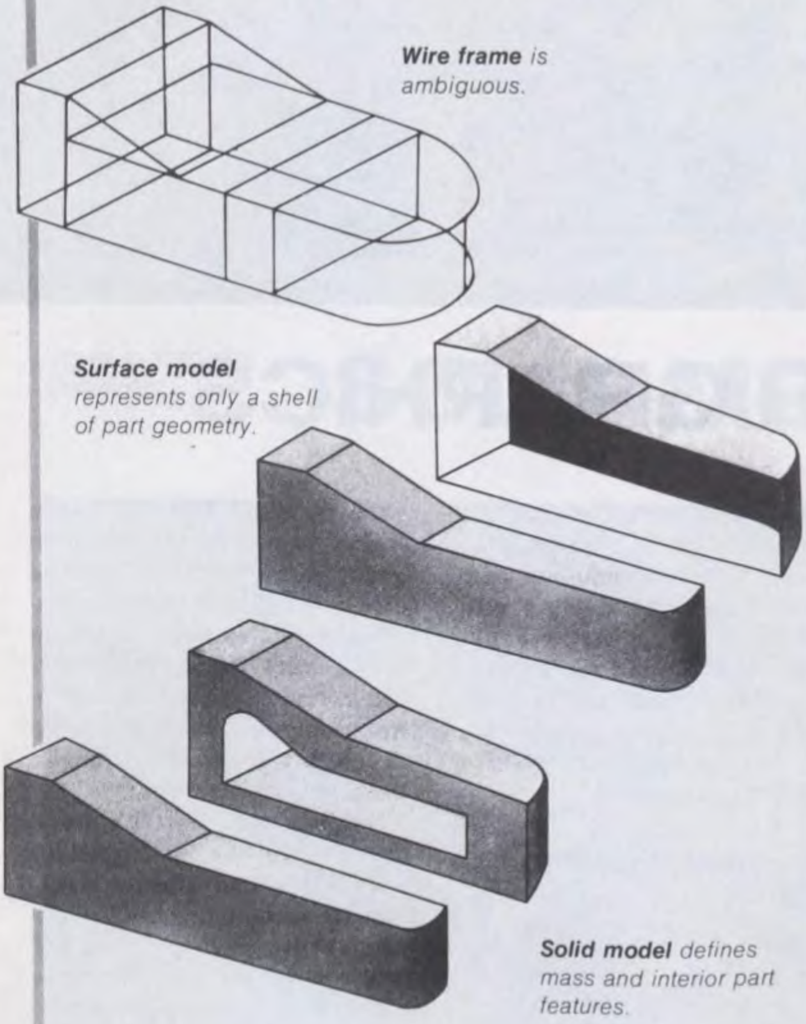
Wire frames represent part edges with interconnected line elements. Wire frames are the simplest models to create and they expend relatively little computer time and memory. Moreover, they provide precise data about surface discontinuities on the part. Consequently, wire frames are widely used for part drawings and detail work in automated drafting. In fact, most geometric modeling today is done with wire frames. However, wire frames contain no information about part surfaces and do not differentiate between the inside and outside of parts. As a result, wire frames representing complex geometries often are ambiguous and may leave much interpretation to the user.

Surface models, the next highest level of modeling, avoid many of these ambiguities. Surface models are created by connecting various types of user-selected surface elements to represent part geometry. Surface models generally contain sufficient data to define NC machining instructions and other applications where part boundary definition is important. However, these models contain no information describing part interiors. And mass properties are difficult to compute.

Solid models overcome the drawbacks of wire frames and surface models by defining parts mathematically as solid objects. Unlike wire frames and surface models, solid models can determine if a specified point lies inside, outside, or on

Why solids are best

The three types of geometric models are wire frames, surface models, and solid models. Wire frames show only the outline of parts and often may be interpreted several ways. Surface models accurately define outside boundaries of parts but provide no information about interiors. Solid models overcome these drawbacks by describing parts mathematically as solid objects. These descriptions provide accurate definitions of interior as well as exterior features. As a result, geometries are described more accurately and mass properties are easily computed.



Wire frame *is ambiguous.*

Surface model *represents only a shell of part geometry.*

Solid model *defines mass and interior part features.*

the surface of a part. In fact, this test is commonly used to determine whether or not a program is truly a solid modeler.

Solid models require more computer processing time and memory than do wire frames or surface models. But solid models are easily used to compute mass properties such as weight, moment of inertia, and center of gravity. And cross sections can be cut through the model to expose internal details. Moreover, solid models are more readily used as a basis for creating finite-element models. In addition, solid models can be used in kinematic studies to check the action of moving parts in three dimensions. And solid models can be used to study the positions of parts in a complex assembly.

One common feature of most solid modeling packages is the ability to generate shaded displays on a raster-scan CRT. This capability provides a realistic display of proposed part geometry. The predominate method for producing these shaded displays is with a technique called ray tracing. In this method, a line is projected from an imaginary eye (viewing) position for each pixel of the CRT. The intersection of the line with the closest point on the model is then made visible. The angle between the line and the surface normal determines color intensity and the amount of shading. Another shading method uses a network of polygons to approximate the visible part surface. The angle of each polygon to the viewing position determines the brightness of that particular facet of the polygon.

Building solid models

Most commercially available solid modeling programs construct models in either of two ways: with primitives or with a boundary definition.

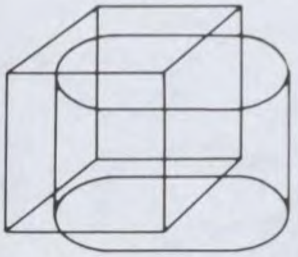
In the primitive approach, models are constructed by combining simple shapes such as cubes and cylinders in building-block fashion. These so-called primitives are combined by a mathematical set of Boolean or logic operators of union, intersection, or difference. The user positions primitives as required and then enters the proper logic command to produce the required shape. For example, a round hole may be produced in a part by subtracting a cylinder from the geometry. With these successive operations, the user constructs a complex model.

Most commercial primitive modelers contain 12 or more basic shapes. But the four most commonly used are the block, cylinder, cone, and sphere. These so-called natural quadrics represent the types of surfaces produced by rolling, milling, turning, cutting, drilling, and other general machining operations used most commonly in industry. As a result, primitives can be used to model most industrial parts. Geometries with sculptured surfaces and other complex contours, however, require extensive user interaction and consume large amounts of computer time to construct with primitives. Parts in this category include automobile exhaust manifolds, aircraft flight surfaces, camera cases, and hand-

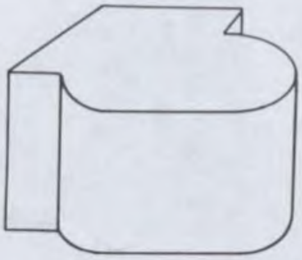
Modeling operations

Solid models are built through either the primitives or boundary-definition approach. In the primitive approach, simple shapes are combined in building-block fashion. With boundary definition, a solid is represented by an enclosed surface. In practice, the simple operations shown here for the two methods are generally extended in much more complex fashion to develop complicated geometries.

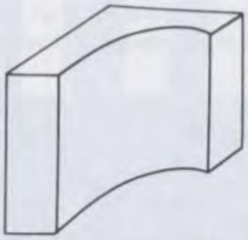
Primitives



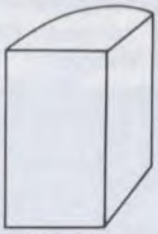
***Primitives** are located in appropriate positions as illustrated here, for example, by a block and cylinder.*



***Union** operation combines the two forms.*

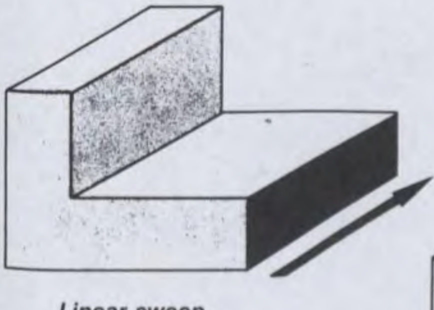


***Difference** operation subtracts the cylinder from the block.*

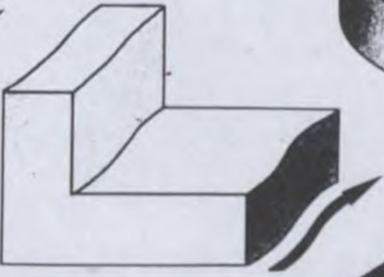


***Intersection** operation produces a volume common to both primitives.*

Boundary definition



***Linear sweep** translates a surface to produce an "extruded" volume.*



***Compound sweep** moves a surface through a specified curve.*

***Rotational sweep** makes a part with axial symmetry.*

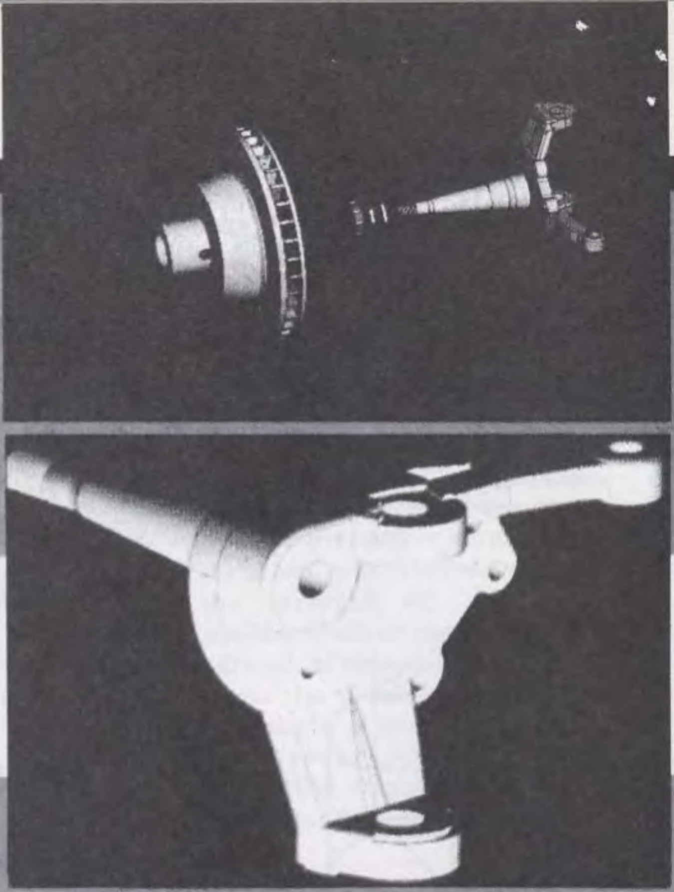
***Tweaking** makes changes to an established geometry.*

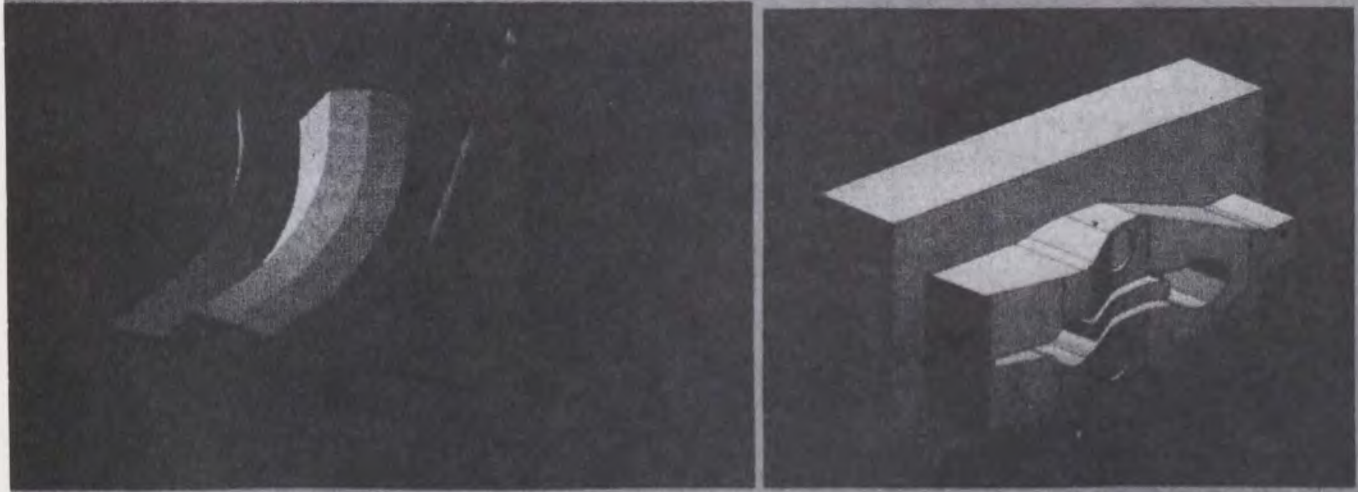
***Gluing** joins two solids with a common surface.*

Solids in design and manufacturing

Solid modeling is a powerful tool for developing the geometry of parts in design engineering. And the technology proves equally useful in manufacturing for designing molds and dies, positioning clamps and tools, and other tasks. Models produced by the Applicon Solids Modeling program illustrate a range of such applications.

Solid models in design realistically display the geometry of an automotive wheel spindle (bottom right). A disk brake rotor assembly is illustrated in exploded view (top right) to show how separate parts fit together. And a cross-section view of an electrical connector (far right) reveals interior features of the design.



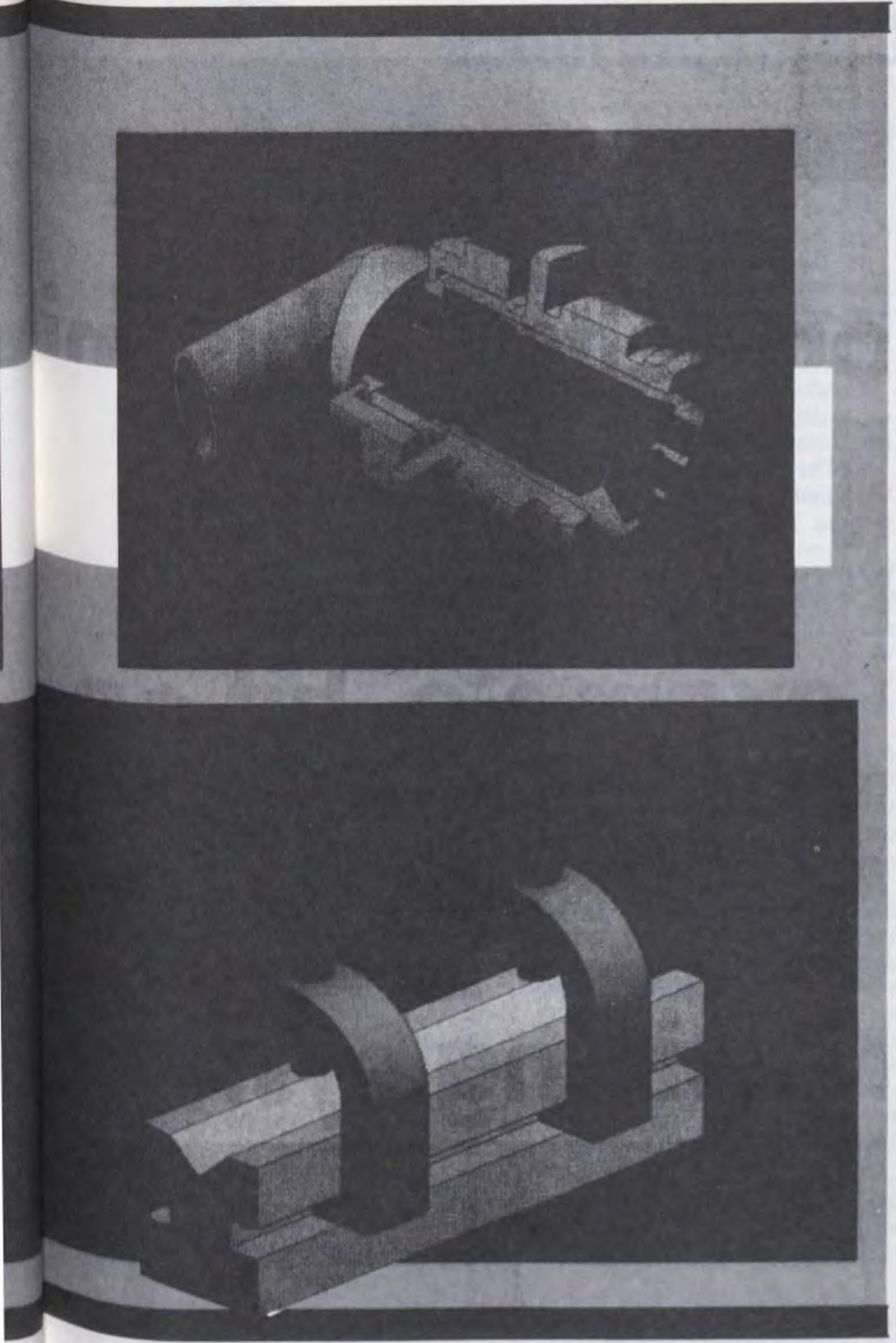


In manufacturing applications, solid modeling is used to develop a die for an intake manifold (above). Clamp locations are shown on a V-block (right). And the position of a weld gun (left) is studied in a tooling clearance simulation.

tool housings.

Parts with complex shapes such as these are more readily modeled with the boundary approach. In this method, a solid object is represented by its spatial surface boundary. Techniques to define this boundary typically include several types of sweeping operations in which a two-dimensional surface is moved through space to trace out a volume. For example, a surface may undergo a linear sweep operation to produce an "extruded" part with constant thickness. Or a surface may be revolved about an axis to create a "turned" part with axial symmetry. In a variation of these techniques a surface may be swept through a specified curve to generate a more complex solid.

Another boundary construction technique is called gluing. This is a method where two



previously created solids are joined at a common surface to produce a new unified object. And a technique called tweaking makes local changes to an overall shape. Boolean operators can also be used in a manner similar to that of primitive modeling to unite, intersect, and subtract solids.

Both the primitive and boundary methods of solid modeling have advantages and drawbacks. As a result, considerable research is aimed at developing solid modeling software that combines these two methods. MD

For more information

Information on specific solid modeling programs may be obtained from the following software suppliers.

Catia
IBM Corp.
Data Processing Div.
1133 Westchester Ave.
White Plains, N.Y. 10604
CDC-Synthavision
Control Data Corp.
Box 0
Minneapolis, Minn. 55440
DDM Solids
Calma Co.
Mechanical Products Div.
527 Lakeside Dr.
Sunnyvale, Calif. 94086
Geomod
General Electric CAE
International
300 Technecenter Dr.
Milford, Ohio 45150
ICM Geometrical Modelling
ICM Inc.
Box 3015
Lynchburg, Va. 24503
ITS-10
Marc Software International Inc.
525 University Ave.
Suite 810
Palo Alto, Calif. 94301
Medusa
Prime Computer Inc.
Prime Park
Natick, Mass. 01760
PADL-2
University of Rochester
Production Automation Project
Rochester, N.Y. 14627
Patran-G
PDA Engineering
1560 Brookhollow Dr.
Santa Ana, Calif. 92705
Romulus
Evans and Sutherland Corp.
580 Arapeen Dr.
Box 8700
Salt Lake City, Utah 84108
Solidesign
Computervision Corp.
201 Burlington Rd.
Bedford, Mass. 01730
Solids Modeling
Applicon Inc.
32 Second Ave.
Burlington, Mass. 01803
Synthavision
Mathematical Applications
Group Inc.
3 Westchester Plaza
Elmsford, N.Y. 10523
TIPS-1
CAM-I Inc.
611 Ryan Plaza Dr.
Suite 1107
Arlington, Texas 76011

How to select a CAD/CAM system - NRC's experience

based on an article by
K.A. Steele,
Division of Electrical Engineering
V.J. Thomson,
Division of Mechanical Engineering
National Research Council

As might be expected, interest in CAD/CAM has been gathering a lot of momentum at the National Research Council for several years - both for internal use and in NRC's efforts to assist and advise Canadian industry. This organization's experiences in acquiring a system appropriate to its needs offer some valuable insights on system selection.

A survey to determine the extent of interest in CAD/CAM as well as potential applications took place in July, 1979. Questions were asked about current and planned involvement, benefits and difficulties, primary application areas, and system characteristics. The results? Accurate perceptions of CAD/CAM in general, but a fairly low level of system awareness. There was a strong feeling that CAD/CAM could benefit lab activities and should be in use.

Potential applications included parts fabrication, computer-aided modelling, design analysis, drafting, industrial process management, and structural design.

Anticipated benefits included better capability to handle new tasks, incresed productivity, better quality control, more thorough examination of alternative designs, and easier design modification.

The major deterrent seemed to be cost, since cost-benefit wasn't perceived as a priority in a research environment like NRC's.

Three goals were established for the prospective system:

1) The system should be utilized immediately by groups providing design and manufacturing services to research programs within the laboratories;

2) NRC should be able to demonstrate the technology to government and industry;

3) The system should be state-of-the art, to save development time and money.

Opening moves

In 1980 NRC staff consulted a number of companies which had or were considering acquiring CAD/CAM technology. It became obvious that if NRC were to provide meaningful assistance to Canadian industry, it could not avoid CAD/CAM involvement. However, the cost for a system of the necessary capabilities was too high for any single division to handle by itself

During the winter of 1980/81, interested NRC staff met to discuss the capabilities of various systems and to define the needs of NRC laboratory staff. Considerations included system characteristics, capabilities, the prospective users, training, and administration.

In 1981, a more formal investigation began. Representatives from the Divisions of Mechanical Engineering and Electrical Engineering, the National Aeronautical Establishment, and the Computations Centre formed a core committee. Mechanical design and manufacturing was to be a principal interest.

The committee had to choose from a number of possible configurations. Assembling software packages and obtaining the necessary hardware was ruled out, as this could have become a development program with no benefits to designers.

Time sharing was eliminated because it was too expensive for the amount of work involved. It has some attraction for performing assessments, however.

The idea of acquiring several independent turnkey systems for NRC's various regional locations had merit, as access to the technology would be enhanced and a range of systems could be tested.

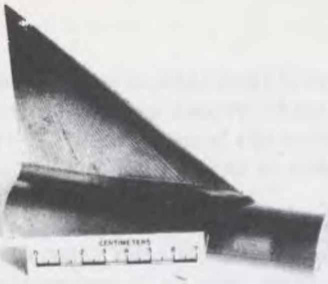
The concept of using one system for Ottawa, where there's a heavy concentration of work, and another for locations outside Ottawa was attractive on the basis of reduced communication costs, but it was felt that the additional complexity of administration, training, data transfer, licensing and maintenance could have posed problems.

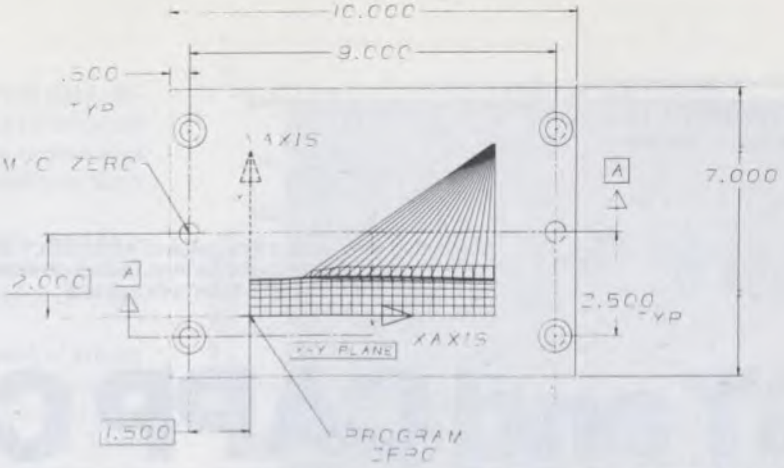
Another alternative was to acquire one large system incorporating distributed processing for economies of scale - yet which could still provide service on location.

A literature search was carried out. Demonstrations of recently installed systems in Montreal, Ottawa, and Toronto proved helpful. The Canadian Institute of Metalworking was retained as consultant to discuss and assess CAD/CAM and estimate its potential for NRC. CIM had recently acquired its own system for use in education, demonstration, and parts manufacture.

Three categories of requirements were compiled: 3-D mechanical design, NC tool path generation, and CAD/CAM system features (see checklist). A survey of the available mechanical design systems was made and the features of the different systems were delineated. A list of 20 or

Below, a four-view drawing, showing the vacuum cleaner cover model used as a benchmark by the National Research Council.





This drawing shows the wing-fuselage model used as a benchmark for the tests. Benchmarks were selected to be representative of NRC's typical design work.

so systems was developed and six systems were chosen as being preferable to NRC.

Benchmarks

A set of benchmarks, representative of NRC's work, was assembled for the vendors to perform. These included a viscometer body and cover, a drafting task of 2½-D parts; a wing-fuselage model and a 3-D design and machining of a fixed-wing, variable-diameter fuselage model of an experimental fighter aircraft; and a complex 3-D surface vacuum cleaner cover model.

CIM performed the benchmarks on its own system in July, 1981, and machined the wing-fuselage model. As consultant, it commented on the suitability of the benchmarks for evaluation and pointed out those features of the benchmarks which would help NRC judge system performance.

The six vendors were notified of NRC's interest. Five vendors responded and performed the benchmarks in October, 1981. Before testing, a table of evaluation criteria was formed and given to the people who were to review the systems.

Four categories were established: general system capabilities; how each system addressed NRC's particular needs; benchmark peformance; and state of the technology used. This last category was especially important to NRC, since it does development work on CAD/CAM system design and applications, as well as research in the basic technologies exploited by CAD/CAM. The system selected would serve as a standard against which future CAD/CAM developments could be compared.

The decision

McDonnell Douglas Automation Co.s CADD system was selected.

Some important differences should be noted in assessing NRC's approach to selection. Cost performance criteria were not a significant factor for NRC. The scope of design problems is large compared to most commercial companies and the system had to be extremely adaptable. In terms of workload, NRC can be compared to a very large company, and its choice reflected this factor. Since R&D is a priority, the choice was slanted towards this field - a different system might have been selected by an organization which was strongly production-oriented.

A more detailed report on this subject is in the works and can be obtained by writing to NRC.

Here's NRC's CAD/CAM checklist

Mechanical drafting design

● Essential features
☐ 3 dimensional drawing
☐ text scaling
☐ line weighting
☐ line typing (chain, dot, etc.)
☐ dimensioning (metric, imperial)
☐ cross-hatching
☐ user library of standard parts
☐ generation of cross-sectional views
☐ tolerance and error checking
☐ moment, mensuration, etc. calculation
☐ assembly checking on separately drawn parts
☐ developable surface layout
☐ access to geometric data base via software (vendor supplied language or FORTRAN)
☐ output of 3-D geometry in IGES data base
● Desired features
☐ automatic dimensioning
☐ grid generation for 2-D finite element work
☐ kinematics
☐ vendor supplied finite element analysis package which is linked to CAD/CAM geometry
☐ architectural drawing capability
☐ gear tooth generation
☐ structural stress analysis

Numerical control

● Essential features
☐ NC tape production for up to 5-axis contouring machines
☐ cutting path generation for milling machines with pocket and boundary routines, lathes with boundary routines, planers, and flame cutters
☐ cutting with drill, tap, threading, profiling and boring tools
☐ capability to drive machines using controllers with parabolic, in addition to circular, interpolation
☐ tolerance setting
☐ regulation of cusp height between cuts
☐ validation of cutting path, including boundary recognition and fixture avoidance
☐ inclusion of tool change and auxiliary functions in cutting path file
☐ availability of post-processors for a wide variety of modern automatic machine tools
● Desired features
☐ output of APT source with extended surface geometry
☐ output of cutting location file

CAD/CAM system

● Desired features
☐ task accounting
☐ secure filing system
☐ archive management
☐ ability to set process priorities and virtual memory management characteristics for the system
☐ data storage on magnetic tape
☐ output of paper tape at user stations
☐ flexible user station hardware
☐ use of present computing machines
☐ data communication via RS232

Part 1

Reprinted from June 1978 issue of ASSEMBLY ENGINEERING

GT and CAPP Cut Work-in-Process Time 80%

Group Technology and Computer Aided Process Planning can help both large and small companies, and you don't need to leap in all at once. In Part 1 we'll see what GT is and look at the story of a company that tried a little GT first, then a lot—and likes it.

Ask a design engineer—chances are he can tell a story about another engineer who had an amazing talent: he could not only remember practically every part ever designed, he could identify its part number and tell where it was used. That memory made him very valuable.

But the trouble with valuable people like that is that they aren't always available, and they have a frustrating habit of changing jobs or retiring just when you need them most. That's where group technology (GT) comes in.

GT provides that terrific memory, but it never retires. It has no memory lapses and it's always available. Best of all, you can try it out on a small scale, then expand when it's been proven. GT is the basis for most computer-aided manufacturing systems.

Group technology is a manufacturing philosophy that takes advantage of the similarities among parts and in the processes used to manufacture them. Instead of treating each part as unique, parts are grouped in families. To do this, a part coding system is used. The code for each part identifies such things as part size, shape and material, and the manufacturing processes used. Coding systems generally form families based either on (1) similar shape within specific dimension ranges, or (2) common manufacturing operations, regardless of shape.

Coding Systems

Information desired by designers may be different from information desired by manufacturing engineers. Both types of information can be included if the code is set up to accommodate them from the start.

Where a designer is concerned with such things as shape, size, tolerances and materials used, the manufacturing engineer is also concerned with manufacturing operations used—how will that hole be formed?—and with the capabilities of machinery on the shop floor. If the data base includes manufacturing information, such things as process data, costs, setup and run times, and tool, jig and fixture data can be retrieved.

GT systems may use monocodes, polycodes or mixed codes. Monocodes, sometimes called hierarchical codes, are a sort of family tree coding system; each digit divides the category identified by the preceding digit into subcategories.

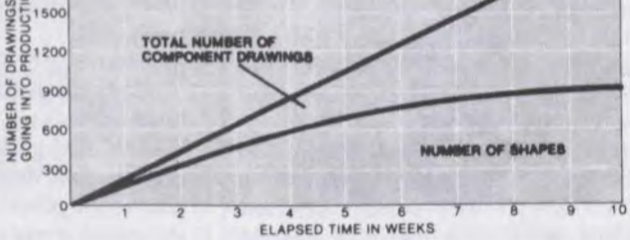


Fig. 1 The upper line in this graph marks the number of new drawings released to the shop over a ten week period. The lower line marks the number of new shapes in these parts, showing that, after a while, most new parts are only revisions of old parts. GT helps keep the revisions to parts simple and fast by allowing easy access to similar parts on file.

To decode, the number must be read from left to right, decoding each digit to discover where to go on the information "tree." An advantage of this system is that a tremendous amount of information can be coded into a relatively short number.

A polycode, sometimes called an attribute code, uses each digit to code a different piece of information, and each digit is independent of all other digits. Thus a search of these codes is relatively easy.

The mixed code combines these: it is composed of groups of monocodes within a polycode. Sections can be used to identify almost anything needed by the user company, and codes as long as 36 characters per part are in use. Even longer ones could be used.

Reinventing the Wheel

One of the most popular comments from engineers involved with a GT system is that it helps keep them from "reinventing the wheel." When a designer needs a part, his best move is to see if the part is already somewhere in the system. In many companies without a GT system, it's easier to just go ahead and draw up the part and assign it a new part number than it is to search the files for a similar part.

But with a GT system, all a designer needs to do is take a few minutes to figure the basic code for the part he needs, and then sit at a computer terminal and see what similar parts are already available. For example a designer might specify a certain thickness of a part—like a washer or a gear—when a similar part that would function equally well is in the system. Two engineers could design similar parts at different times, with the only difference the specification for tolerance, in both cases chosen arbitrarily because it was noncritical. GT systems help prevent proliferation of similar parts because easy access to every part in production is available.

GT in Manufacturing

Advantages accrue not only to the design department, but to almost every other operating unit in the company, particularly manufacturing. Because GT classifies parts into groups with similar shape or manufacturing processes, the parts can be manufactured in these families, rather than individually. This reduces downtime for setups and brings the advantages of long part runs to operations producing relatively small lots.

This is significant. The great majority of U.S. metalworking is performed in lots of less than 50 pieces. Indeed, the trend in manufacturing is toward smaller lots, because manufacturers are finding they must produce more models of their various products, requiring more runs of fewer parts.

GT helps reduce machine setup time by reducing the scope of tooling changes. A surprisingly small portion of machine time is actually spent making chips. It is estimated that 95% of the time parts spend in the shop is in waiting and being moved around. That leaves only 5% of the time for actual production on the machine.

But that 5% isn't all used either. When loading, positioning, gaging, and wasted time are accounted for, only 30% of the time on the machine actually involves machining. What we end up with is a meager 1.5% of the time the part is in the shop—only in that small time are we adding value to the workpiece.

One of the changes under GT can be a move from the departmentalized machine shop to the cell system. Here, the machines are arranged in cells, each of which has all the machines required to produce one or more families of parts. Each cell operates as a shop within a shop.

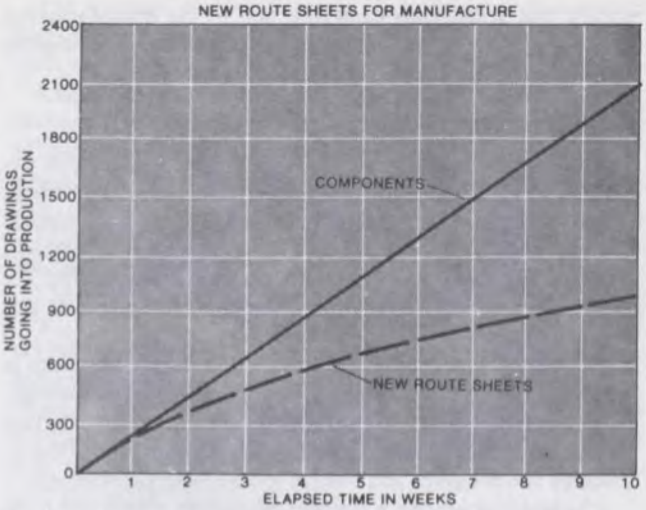


Fig. 1A This graph is based on the same sort of situation seen in Fig. 1. The upper line represents new components moving into production, with the lower line representing new routings. Again, GT helps keep revisions simple and fast.

The cell system and its GT parent are so successful in one company operating three plants that people frequently ask the GT line planners for favors: "Could you slip these parts on your GT line? . . . you guys get parts out so much faster than anyone else . . ."

The man who supervised GT implementation at those plants comments that the most basic problem with GT is changing people's *minds*, getting them to see that there is a better way than "the way we've always done it."

Personnel Advantages

GT, and the manufacturing cell concept in particular, are responsible for better labor relations in many installations. One reason for this is that products are processed from raw material to finished product within a single cell. The members of the cell work force feel more a part of a total manufacturing operation than is possible in most other facilities. They are able to see the relationships among various operations in the manufacturing process, and can react to unusual situations more comfortably. Additionally, the foreman or group leader is more easily able to keep abreast of the status of jobs under his supervision.

Is It Worth It?

Is coding really an advantage? Take a look at Fig. 1. This charts 2100 randomly selected drawings taken from a single company in a 10 week period, from among all component drawings moving into production. Note that after 6 or 7 weeks the number of new shapes had nearly leveled off. Most of the new shapes were already in the coding system by that time. Although the curve will never completely level off, it shows that with GT a great deal of design work can be saved by simply retrieving data from the file and making slight changes in parts already in production. Imagine the continued savings as the upper line continues to rise and the lower line remains nearly level.

The same sort of phenomenon can be seen in the routing sheets that accompany each new part to the manufacturing floor, Fig. 1A. Again, the GT system produces savings in manhours spent producing the routings.

Getting Started in GT

The best place to start in GT is to get some early experience by visiting plants using the technique. A number of companies offer GT systems commercially, and have considerable expertise in setting up GT programs. The systems vary in approach and in some cases are specialized for specific industries. Some companies develop their own systems in-house.

No matter which system is used, one primary necessity in implementing GT is a strong commitment from top management, communicated to everyone in the company. Another important factor is assignment of one top level person to manage the program and ensure it's moving successfully.

Cooperation among a number of groups within the company will be necessary. Design, production planning, scheduling, tooling, manufacturing and quality assurance must understand their interdependence and the effects of their activities on the other groups.

Communication is crucial. To alleviate the natural suspicion growing out of major changes, *everyone* should be kept informed about changes before they are made. A committee with representatives from every department can carry the word to personnel about progress of the system, explain what's happening and why it's necessary, and maintain momentum of the GT implementation.

Just as GT is applied in machining operations, it can be applied on the assembly line, although this is still a fledgling technology. A few companies are coding assemblies just as they code parts, providing data on what individual parts make up each subassembly, what parts and subassemblies make up each assembly and what techniques are used to assemble the finished product.

Probably the best way to see the benefits of group technology is to look at a company using the system. Langston Div. of Molins Machine Co., Inc., Cherry Hill, NJ, was probably the first major job shop plant in the United States to convert to GT.

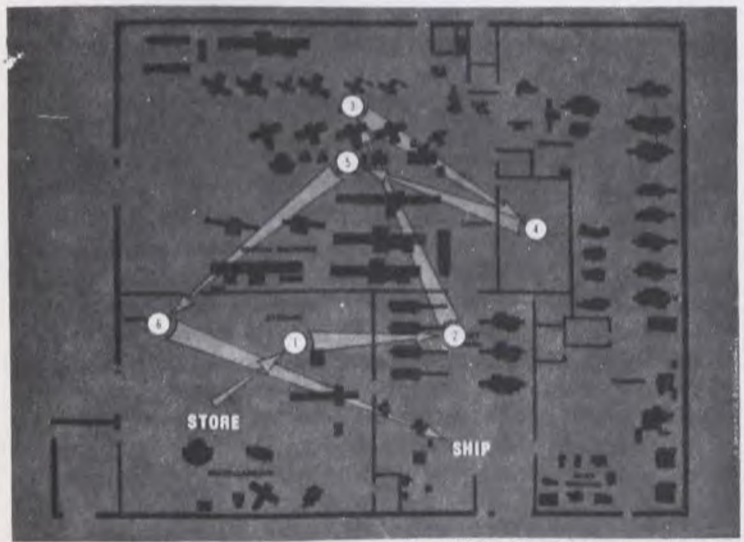


Fig. 2 Work flow in a conventional job shop involves extensive material handling, and long waits between machines.

The Langston Story

Langston is a manufacturer of semi-custom heavy machinery for the paper converting and paper mill industries. The manufacturing facilities consist of two machine shops in Camden, NJ, one for small parts and one for large parts, and an assembly plant at Cherry Hill, 10 miles away.

The machine shops manufacture some 60,000 different parts for the assembly plant. As requirements for any one part are generally small, parts are typically produced in small lots of four to six pieces. Three shifts operate in order to shorten lead time.

Until GT (called Family Parts Line Production at Langston) was introduced, the layout and operations of the machine shops were typical of the conventional job shop.

- Functional grouping in work centers of machine tools that perform similar processes and operations.
- Preparation of loading schedules for each machine with jobs sequenced by "run" day or week.
- Transporting of parts for processing from one work center to another in accordance with machine loading schedules.

The layout of the small parts plant as it was and the actual movement of a small cylindrical part through it are shown in Fig. 2.

The average time to make a part was long—from 4 to 6 weeks, based on from 4 to 6 operations/part and 1 week/operation. This created many problems in terms of the assembly plant's production schedule, which depends on on-time delivery of small quantities of a great variety of parts. Although production control and scheduling techniques were good, most of the in-process time for parts was spent in queues for machining or waiting to be moved to the next work center.

The Move to GT

Family Parts Line Production was initiated at Langston by company president John F. McLaughlin in 1967, when he was vice president for manufacturing. He had previously experimented with the concept at another company. The result was a decision to test the workability of GT by establishing a prototype line in the small parts shop; if the test was successful, the system would be established in other shop areas.

Thomas C. Karanzalis, then McLaughlin's assistant and now vice president for manufacturing, was made project manager; a foreman and an industrial engineer were assigned to assist him.

Grouping Parts into Families

Langston chose visual examination of parts as a quick, inexpensive method to group parts in families (it was not concerned with the broader goal of linking production with product design, which would have called for a classification and coding system).

The task of grouping parts manufactured in the small parts shop was begun in August 1968 and completed 4 months later. Polaroid pictures were taken of every seventh part on the common stock parts list. Each part was placed on a 1 in. grid to establish its size in the photographs. Approximately 400 photographs were made and sorted into families according to size and configuration of the part. Some 93% of the parts fitted into families:

(1) small cube shaped parts
(2) medium cube shaped parts
(3) small bar stock parts—up to 3 in. dia.

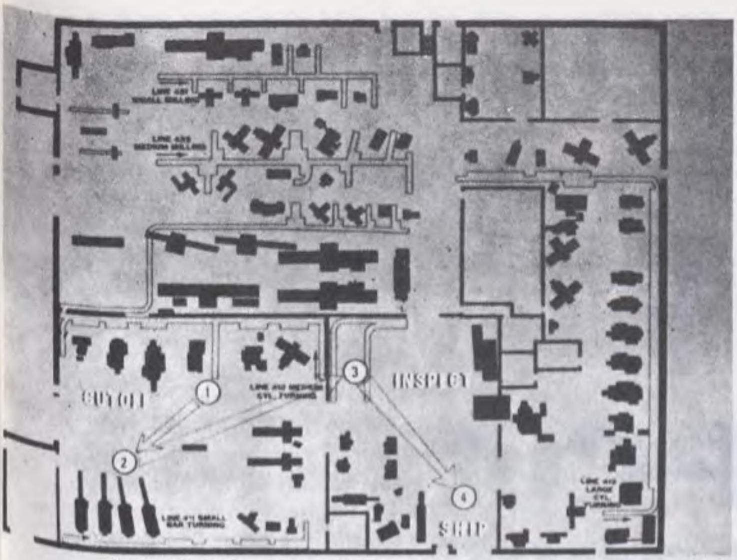


Fig. 3 Work flow through a GT cell requires much less material handling and greatly reduced waits between machines. At Langston, the time it took to get a part through the shop was reduced from 4 to 6 weeks to 2 to 5 days. Productivity—parts/direct labor hour—increased 50%.

(4) small cylindrical parts—3 to 6 in. dia.
(5) medium cylindrical parts—7 to 8 in. dia.
(6) large cylindrical parts—8 in. dia. and up

Setting Up the Prototype Line

A small milling parts line was selected for the test in early 1969 because it would require the least floor space and the least amount of rearranging of machine tools, and thus would cause minimum disruption of production. It was decided that the production line should consist of three milling machines, a numerical control (NC) drill press, a sensitive drill press, a layout table, and a contour saw. These were placed to enable the normal process flow and were linked by a gravity conveyor system.

The foreman and the industrial engineer assigned to the project were responsible for establishing the line and coordinating supporting staff efforts. One of their first tasks was to identify and assign the proper parts for manufacture on the line. They went about this by touring the shop frequently to identify parts that should be processed on the small milling parts line and by reviewing all parts which were scheduled for relese to the shop for processing. Shop workers responded to the project with enthusiasm and helped to identify parts for the prototype line.

The amount of production assigned to the line increased over a period of several months, during which the actual machine tool requirements were more firmly determined and several changes were made in the tool lineup.

Success!

The test was judged to be successful from many aspects. The prototype line was installed without disrupting plant operations and a substantial reduction in in-process time for small milling parts was realized almost immediately—the average time was reduced from 4 to 6 weeks to 2 to 5 days. For those parts assigned to the line, detailed scheduling, expediting, and material handling were virtually eliminated. Floor supervisory problems were minimal.

The success of the prototype line led to a decision in August 1969 to convert the entire 40,000 sq ft small parts shop to GT.

Karanzalis was named full-time project manager under McLaughlin's direction with responsibility to:
(1) Plan and coordinate the rearrangement of machine tools and obtain the material handling devices to support each line.
(2) Develop simplified systems of tool control, line scheduling, and load control.
(3) Make recommendations to revise the supervisory structure.
(4) Work with the personnel department to develop indoctrination programs for operators and anticipate and plan to meet personnel problems.
(5) Coordinate, with the manufacturing development section, the implementation and debugging of each family line as it was established.
(6) Develop and coordinate, with manufacturing services and production control, methods for assigning parts to the family lines and change paperwork systems as needed.
(7) Effect a timely turnover of each family line to the regular manufacturing organization.

On the basis of data from the original sample of 400 parts and experience gained on the prototype line, the parameters of four more families were established; one original family was eliminated in the review process by regrouping cylindrical parts from three groups into two. Alternate layouts for the small parts shop were revised and reviewed until they were finally accepted. This took about a month.

Cooperation between management and the work force was critical. Management held monthly meetings to brief the shop committee on plans, discuss personnel and other problems that might arise, and obtain their views and suggestions. Indoctrination meetings were held for all employees. Foremen cross-trained machine operators to operate several types of machines within a line (or series of lines). The work force rearranged machinery and equipment into the four family parts lines in stages, principally at night, so that there was little disruption of production.

At this point, precision was not considered to be too important, since revisions could be made after a line started. Langston's goal was to move ahead keeping maximum flexibility. In March 1970, the plant had been completely reorganized.

Plantwide Improvements

The new production system resulted in a 50% improvement in productivity, based on the number of parts processed per direct labor hour, in the first year of its operation in the small parts plant. In-process time for a part was substantially reduced; the amount varied in the different family lines, with the greatest improvement occurring in the small milling parts (prototype) line.

Operations improved and efficiency increased throughout the plant. The rearranged layout of the small parts plant and the actual movement of a small cylindrical part through the shop are shown in Fig. 3, for comparison with Fig. 1.

Next month, Part 2 will cover the specifics of the conversion, list improvements and problems encountered, and go into computer aided process planning. □

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Part 2

GT and CAPP Cut Work-in-Process Time 80%

Group Technology and Computer Aided Process Planning can help both large and small companies, and there's no need to leap in all at once. In Part 2, we'll look at the results of Langston's move into GT, explore the development of CAPP and list some sources of additional information.

Richard D. Holtz
Managing Editor

Part 1 of this article, which appeared last month, discussed what Group Technology is and explained some of its advantages. It also covered conversion to GT at Langston Div. of Molins Machine Co., Inc. We begin Part 2 with the second half of the Langston story.

Functional Improvements

Shop Dispatching. Under the traditional setup, Langston's central dispatch and expediting consisted of 13 employees. All jobs were scheduled individually by operation and then had to be followed up by expediters. Work-in-process time averaged 4 to 6 weeks.

Now central dispatch and expediting is performed by 3 people. Central dispatch holds work until 1 to 3 days before it is started on the line, allowing for greater control; preload in the shop is minimal. Individual operations need not be posted after the part is released for manufacture. Since sequencing is automatic, no further scheduling or material handling is required once a job is started on the line. Expediting is by run week rather than by part number. Foremen are responsible for implementing the schedule.

Tooling. Under the conventional operation, trips to the tool crib were required for each job because tools were provided only when jobs arrived for processing. Now usually only one machine tool of each type is in a line, and each line works with a narrow range of parts. Standard tool kits covering about 95% of tooling requirements are provided for each machine. Required tools which are not in the standard kit are specified on the routing sheet by operation number and can be obtained without a tool card. Tool crib attendants now put together tool kits in the time they formerly spent servicing the window.

Parts Processing. A simplified parts processing method was designed by industrial engineering. It eliminates about 90% of the process engineer's writing time. Each of the family lines has a fixed number and variety of work centers, so that the process or routing sheet for each line can be preprinted. On the processing sheet for each part, the process engineer can check off the work centers he intends to use and their sequencing, and indicate the need for special tooling not in a standard kit. The information can be keypunched onto a master form.

Shop Operations.

- Machine setup time is reduced due to use of similar setups for similar parts.
- Lot sizes are reduced because of shorter lead times, avoiding line bottlenecks.
- Questions about proper sequence of jobs are eliminated because the line queues on the feed conveyors of the machines are clearly visible.
- Operator performance has improved due to proficiency gained by working only on similar parts within a family.
- Trips to the tool crib are reduced by using standard tool kits.

- Work assignments have become more meaningful since each line manufactures a complete product which can be seen and appreciated by the operators.
- Waist-high conveyors minimize material handling and the need to stoop or bend.
- Foremen became better trained because each has his own general shop. They also became more sensitive to machine center balancing and learned to move operators more rapidly to meet changing load requirements.

Machine Requirements. According to Langston's findings, a conventional shop tends to buy too much machining capability in order that a wide range of parts can be handled. Because family lines define machining requirements more exactly, less costly equipment is acquired. Langston management feels that this probably more than offsets some duplication that occurs in family lines of low-cost auxiliary machine tools which may be underutilized.

Floor Space. A substantial saving in floor space was accomplished by running the conveyors along the building columns and by moving the machine tools (which were no longer dependent on crane support) closer to the conveyors. Out of a total of 90,000 sq ft (8400 m^2) in both the small parts and large parts shops, an estimated 8,000 to 10,000 sq ft (750 to 930 m^2) were saved. Management credits this, along with higher productivity, for eliminating the need for a larger plant.

Advantages Gained

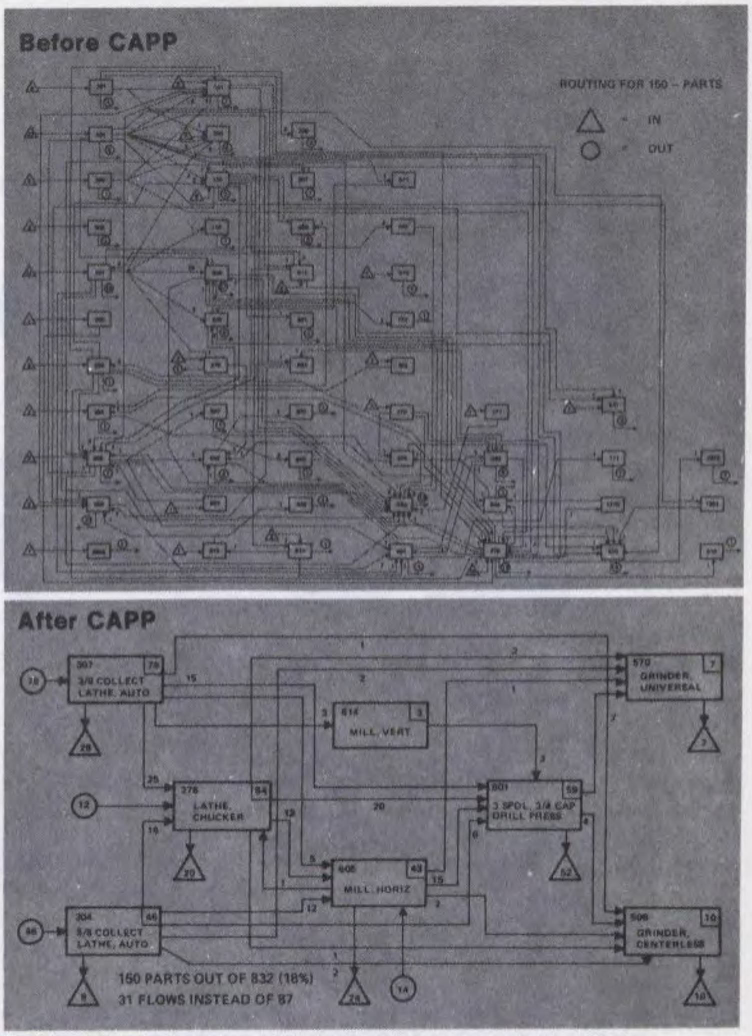
Langston management sees the following advantages:

- Simplified method for processing of parts by industrial engineering.
- Simplified tool control through using tool kits and storing jigs and fixtures in the line area.
- Improved production control and reduced lead and in-process time for small parts.
- Reduced clerical workload in production planning; less expediting.
- Reduced material handling and machine setup costs.
- More accurate costing.
- Improved operations control; less divided responsibility.
- Improved selection of machine tools due to better clarification of work center machine requirements.
- More versatile operators, increased job satisfaction and decreased costs, all from cross-training.
- Stronger, more versatile and responsible foremanship.
- Because this constituted a basic systems change, management was able to correct outmoded practices and abuses which had crept into the old system.

Problems Encountered

Langston encountered the following problems:

- Professional employees resisted the change, perhaps because the concept is deceptively simple and its benefits may have been underestimated. Many traditional procedures of the manufacturing engineer were also challenged by the new method. As a result, several professional employees left the company. There was more support from direct labor than from the manufacturing staff, with constructive ideas having come from men on the shop floor. Management made a major effort to involve the machine operators and keep them informed of changes and the reasons for the changes. "Survival in the face of foreign competition" was cited often.
- Sorting parts into family groups involved considerable time and cost.
- Preparation of new process or routing sheets for each part was a large, time consuming task for process engineers.
- Rearranging machines into family parts lines without temporary productivity loss was difficult. Duplication and underutilization of conventional auxiliary machine tools also occurred.
- Power distribution had to be recalculated and modified to meet the requirements of the new production lines.



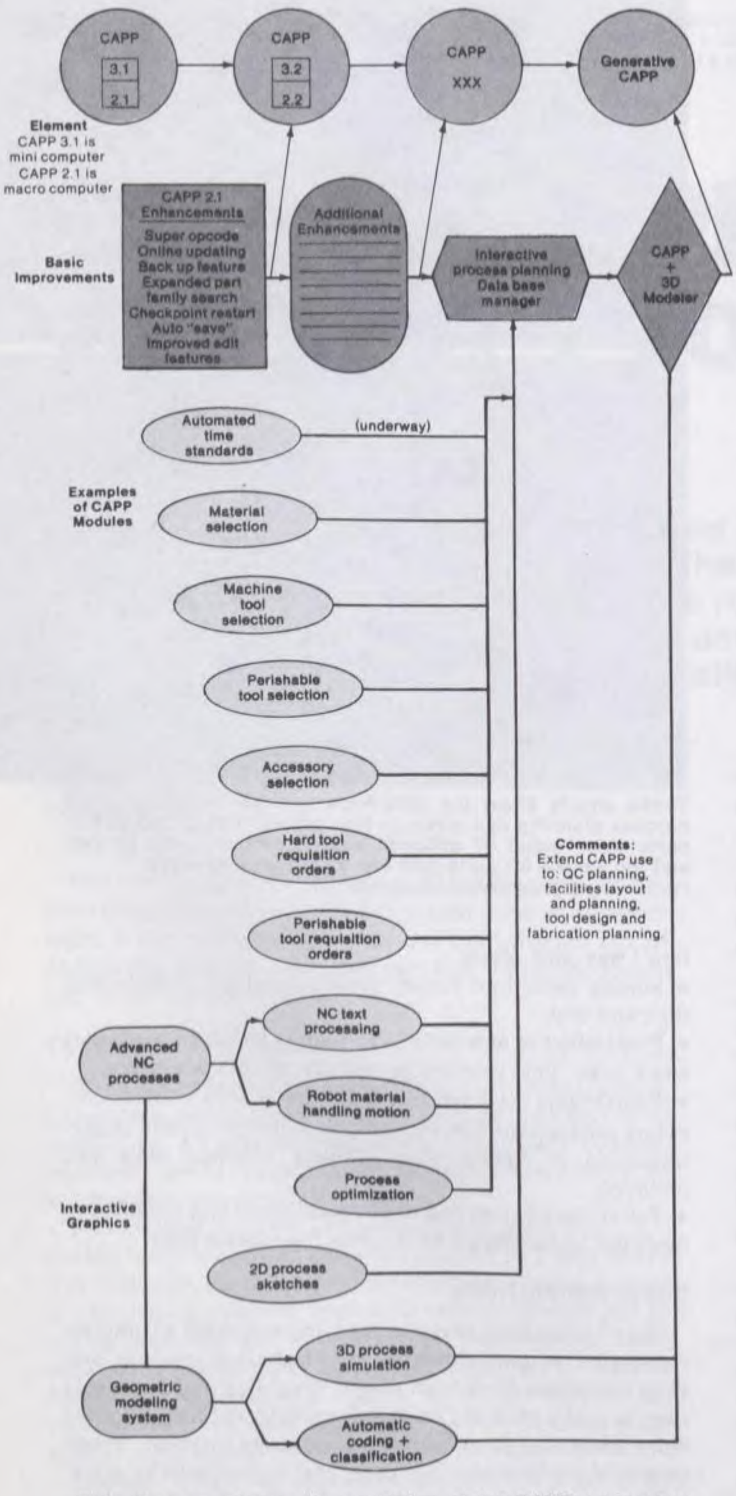
These charts show the difference optional computer aided process planning can make. In the "before" chart, 150 similar parts were routed 87 different ways. CAPP changed all that, and the same 150 parts now are routed only 31 ways.

Charts courtesy of General Dynamics Pomona Div.

Some Conclusions

Over 7 years have passed since Langston made a complete conversion to group technology. Production controls and shop operations have been greatly simplified and in-process time to make parts has been substantially reduced. Work is more interesting for machine operators and foremen, whose improved performance has been vital to productivity gains.

The greatest gains were achieved in the small parts shop, where the system was first installed. Improvements were also experienced in the large parts shop and assembly plant,



CAM-I Staff View: CAPP Evolution—Variant to Generative System

Comments: Extend CAPP use to: QC planning, facilities layout and planning, tool design and fabrication planning.

This diagram shows the evolution of the CAPP program expected by the CAM-I staff. The material has not been presented to the CAM-I membership, but the staff members expect that it will be approved essentially as shown here.

which adopted applicable elements of the system in 1970-71. Layout modifications in the large parts shop resulted in benefits of straight-through line flow; assembly plant productivity improved when a subassembly area was established as a separate function from general assembly, as well as from the more timely delivery of parts by the small parts shop.

Langston management has pointed out that GT is a "deceptively simple" concept. Substantial time and effort and some funds are required to make the conversion to the system, with the following actions critical to success:

- Advance planning regarding grouping parts into families and rearranging machines into family parts lines.
- Consultation with organizational units whose operations will be affected.
- Development of new work force.
- Development of new procedures.
- Indoctrination and training of workers.

Moreover, the complete support of top management is crucial. As McLaughlin said, "You have to ramrod it through. You need somebody to face down resistance." He also said that it is essential to have a tough project manager with full authority to carry out the program and another totally committed person to control paperwork.

From GT to CAPP

Computer aided process planning (CAPP) is derived from GT part classification and coding. The CAPP system was originated and is under continuous development by Computer Aided Manufacturing—International, Inc. (CAM-I), a not for profit research organization which calls the programs it develops "CAM-I Automated Process Planning." CAPP uses a computer to organize and direct the production system from design through final shipping.

In actuality, computer control of the entire manufacturing operation is still only a dream. The present CAPP system doesn't have many frills, and falls between GT and total computer control. Present and future modules, each of which is a step toward complete control, include:

- Material selection
- Machine and cutting tool selection
- Standard component and accessory selection
- Feed and speed calculation
- Product assembly
- Work standard analysis
- Tolerance analysis
- Cost estimation
- Tool control
- Equipment control

Later modules will provide:

- Preparation of process sketches
- Quality assurance planning and reporting
- Routing alteration for machine load balancing
- Order generation
- Material handling control
- Schedule control
- Plant layout

Final steps will result in a system that automatically produces plans based on best technology within the user's manufacturing capabilities.

The present system requires 105K bytes of memory and can be used on IBM 370/168 or PDP 1145 computers with standard time sharing. The system has been adapted by users to CDC equipment.

Variant and Generative Systems

Process planning systems could be divided into two groups: variant systems and generative systems. A variant system is the less complex device—it produces plans by modifying (varying) standard plans already on file. A generative system requires a great deal more information and programming: it generates plans based on the total picture by going through a series of complex operations, unrestricted by standard plans.

The CAPP system that has evolved thus far is a variant system. While a generative system is desirable, the variant system is a highly feasible and very workable beginning, a simple system ready to use now. Later developments will add to present programs, making the system increasingly generative without obsoleting the extensive work already completed.

In the CAPP system used today, attributes of parts already classified and coded are analyzed and the parts are grouped in families based on common fabrication methods. From these data, a standard manufacturing plan is developed for each family. The standard plan takes into account such things as requirements for precedence of operations. The resulting menu of sequences, composed of operations codes (opcodes), is edited by the process planner. Specific operations required are chosen and the rest deleted.

The major step made here is replacement of man-based memory with machine memory. The process planner can depend on the machine to remember the sequence of operations for parts similar to the part being worked on.

Presently, the designer provides all missing data and all data relative to the specific part. Later CAPP systems will have increased capability to provide some of the missing data and aid in the decision process. Later yet, with additional capability, the computer will generate its own plans using memory, internal computations and decision-making ability. The ultimate system will generate complete process plans without specific aid from humans.

That last step is still a long time away, and will require a great deal of development work. Nonetheless, the present CAPP system has been proven in operations producing aircraft, computers, automobiles and trucks, electronics and communications equipment, metalworking machinery, missiles and machined components. CAM-I members have extensively tested the prototype CAPP systems, as have a great number of other companies whose personnel attended various CAPP seminars where the CAPP program was distributed. As difficulties with the programs are pointed out, they are solved by CAM-I or companies under contract to CAM-I. Each "enhancement" makes the CAPP programs more complete and more useful, and takes them a step closer to the ultimate system.

Since that ultimate system is still far in the future, should you wait for it to be developed? That can only be decided by you and your company. The absolute ultimate system will probably never be finished—we rarely run out of things to improve in anything we develop, be it a computer aided process planning system or a mousetrap. The present CAPP system, basic as it is, is saving money for its users right now.

Both GT and CAPP involve investments of money and manhours, but they come one step at a time. You must have a GT system to base CAPP on. If your company can benefit from a GT system, and you install one, you've already made the first step to a CAPP system.

Investigating GT and CAPP isn't comparing one brand of pie in the sky with another. You can discuss the benefits with users. Even enthusiastic users recognize the problems, and they'll discuss them with you, too. Their companies are using GT and CAPP to increase profit. While few claim that the systems were a snap to implement, users seem to feel they were worthwhile. Once companies see some success with the systems, they want more. There are so many companies interested that development is continuing as rapidly as testing will allow.

GT and CAPP Seminars

For those interested in attending seminars on group technology or computer aided process planning, SME and CAM-I are cosponsoring two seminars in the near future. The GT course will be August 16-18 at Pheasant Run Lodge, St. Charles, IL; SME coordinator is Mark Stratton. The CAPP course will be September 25-29 at the Sheraton Atlanta, Atlanta, GA; SME coordinator is Bill Yeates. For details, contact the course coordinators at SME, 20501 Ford Rd., Dearborn, MI 48128; phone (313) 271-1500.

For More Information

If this brief look at GT and CAPP makes you want additional information, there are several excellent sources.

The Society of Manufacturing Engineers, through its Computer and Automated Systems Association, sponsors seminars in GT and CAPP, the latter in cooperation with CAM-I. SME and CASA of SME may be contacted at 20501 Ford Rd. Dearborn, MI 48128; phone (313) 271-1500.

CAM-I, Inc. cosponsors regular CAPP training courses in major cities. Special training manuals and a 9 track magnetic computer tape containing the CAPP 2.1 system are included in the CAPP courses. CAM-I may be contacted at 611 Ryan Plaza Dr., Suite 1107, Arlington, TX 76011; phone (817) 265-5328.

The National Center for Productivity and Quality of Working Life, which provided the Langston story, maintains a clearinghouse which will provide a bibliography of GT and CAPP information sources. The bibliography is available on request to Clearinghouse, NCPQWL, 2000 M St. NW, Washington, DC 20036.

The Machinability Data Center, a Department of Defense sponsored information analysis center, publishes *Group Technology, An Overview and Bibliography.* Price is $7.50 prepaid. Contact MDC at 3980 Rosslyn Dr., Cincinnati, OH 45209.

Prof. Inyong Ham of the The Pennsylvania State University and Walter J. Reed, managing editor of *Machine & Tool Blue Book,* cooperated in a survey on GT in metalworking. The survey results covered geographical locations of users; number of employees; products manufactured; operations performed; lot sizes; average cost to introduce a new part; years using GT; department responsible for GT applications; specific areas where GT is applied; and use of classification and coding systems. A copy of *Machine & Tool Blue Book's* "First Group Technology Survey" is available at no charge by circling number 205 on the reader service card inside the back cover. ☐

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THE FINITE ELEMENT METHOD AFTER TWENTY-FIVE YEARS: A PERSONAL VIEW

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Abstract—The purpose of this paper is to examine the current state of development of the finite element method with regard to engineering applications. First is presented a personal view of the origins of the method, describing the sequence of events at Berkeley. Next is a discussion of the state-of-the-art of structural dynamic analysis, with mention of important recent advances. Finally, two examples drawn from earthquake engineering experience are discussed which demonstrate some limitations of present capabilities. Specific areas requiring new program development are mentioned; the need for a combined analytical-experimental approach is emphasized.

1. INTRODUCTION

It is now over twenty-five years since the finite element method first was used in the solution of practical structural engineering problems. Therefore, it may be appropriate at this time to examine the accomplishments of this past quarter century of phenomenal development. This task has been undertaken with trepidation because the subject has grown in breadth and refinement to the point where it cannot be evaluated adequately by any one observer. Nevertheless, it is hoped that this highly subjective view may be of some value because it is a product of a continuing interest in and contact with the finite element method during this entire period.

Admittedly, taking a backward view like this suggests that one is no longer looking ahead, and this implication is at least partially valid in the present case because the direction of my research has changed. Almost a decade age I became concerned that the advancement of structural analysis capabilities was progressing much more rapidly than was knowledge of the basic material and structural component behavior mechanisms, at least for the nonlinear response range. This deficiency of experimental data was particularly evident in the field of earthquake resistant design, where the structural performance must be evaluated during large cyclic excursions into the nonlinear range. Therefore, during most of the past decade I have followed this alternate path of dynamic experimental research, and have been involved only peripherally with recent developments in the finite element field.

At the outset of this review, it is important to express my concern over the tendency for users of the finite element method to become increasingly impressed by the sheer power of the computer procedure, and decreasingly concerned with relating the computer output to the expected behavior of the real structure under investigation. This concern is similar to that expressed last August by Oden and Bathe in their "Commentary on Computational Mechanics"[1], wherein they decried the complacency and overconfidence of "number-crunching" experts. They illustrated this attitude by the opinion of one such expert that "within the next decade the only use aerodynamicists will have for wind tunnels is as a place to store computer output". To the technologist who communicates only with a computer this may seem like a reasonable assessment; but the opinion certainly is not shared, for example, by engineers designing for wind loading on buildings who can estimate such loads only from boundary layer wind tunnel experiments. In fact, experimental evidence on how structures actually behave is usually the surest cure for overconfidence on the part of computer enthusiasts, and I am pleased to note that there is a growing trend toward experimental verification of the results of extensive computer calculations.

In order to provide a broad commentary on the development of the finite element method, this paper has been divided into three parts. First is a look back to the early days of the finite element development, when the method was viewed in the context of an extension of standard methods of structural analysis. This emphasis on application to the solution of real problems of engineering practice is reflected in the remainder of the paper as well. The second part is an assessment of "recent" advances in structural dynamic analysis capabilities, where the point of reference is a pair of "state-of-the-art" papers written 10 and 7 years ago. Emphasis is placed on dynamic analysis because the static response may be looked upon as a special case of the dynamic problem. In the third part of the paper, difficulties encountered in the analysis of two types of structures will be discussed. The purpose of this section is to demonstrate that major problems still remain to challenge the ingenuity of the finite element researcher, and also that experimental research is essential to discovering, defining, and eventually solving many of these problems. In this latter opinion, I tend to differ from the viewpoint expressed in the paper by Oden and Bathe[1] which emphasized the necessity for fundamental research in applied mechanics and mathematics as the primary approach to a wide range of unsolved problems in computational mechanics.

2. EARLY DEVELOPMENTS

As with any major development in engineering or mechanics, the early history of the finite element method (FEM) can be traced along several paths; certainly no single view of the origins can cover all facets of the development. Moreover, as more individuals and organizations began working with this engineering tool, the advances become increasingly diffuse—so detailing the history for more than a few years quickly becomes a task for specialists in the history of engineering science. Accordingly, this account does not pretend to provide a definitive history of the FEM; instead it merely gives some personal observations on the early days as seen by one of the participants.

It was the words "Engineering Application" in the name of this Conference that encouraged me to prepare this historic summary because the early development of the FEM with which I was involved was continually directed toward engineering applications. Initially, it was a tool designed and developed to solve real engineering problems, even though that outlook is quite distinct from much of the research presently being done in the finite element field.

It isn't possible to identify the exact starting point of the finite element method; and to spend time in conjecture on this question is a meaningless exercise, because the method makes use of many theories and techniques drawn from mathematics and continuum mechanics. One aspect of the FEM, mathematical modeling of continua by discrete elements, can be related to work done independently in the 1930s by McHenry[2] and Hrennikoff[3]—formulating bar element assemblages to simulate plane stress systems. Indeed, I spent the summer of 1952 at the Boeing Airplane Company trying to adapt this procedure to the analysis of a delta airplane wing, the problem which eventually led to the FEM; but because the technique could not effectively deal with plates of arbitrary configurations this effort was soon abandoned.

A more significant preliminary to the development of the FEM was the matrix generalization of structural theory in which the analysis was formulated as a form of coordinate transformation. The earliest known references to the assembly of structural elements by a matrix coordinate transformation were by Falkenheimer[4] and Langefors[5]. However, the classic work which completely stated the matrix formulation of structural theory, and which clearly outlined the parallel procedures of the force and displacement methods, was the series of articles first published in Aircraft Engineering by Argyris *et al.*[6]. It was this work which demonstrated that the concepts of classical structural analysis can be generalized for application to assemblages of any type of structural elements, not only to the traditional beams, struts, etc.

However, the true finite element concept is concerned primarily with the discretization process, not with the procedure used to analyze the system after the discrete elements have been identified and evaluated. Specifically, the FEM discretization involves the assumption of strain or stress fields defined on a regional basis, rather than replacement of the actual continuum by a set of substitute elements. Of course, this general concept applies to well known approximation methods of continuum mechanics, such as the Rayleigh-Ritz method, and it is true that the FEM may be looked upon as a special form of such methods. But the unique feature of the FEM was the idea of defining the strain field independently for the various regions or elements into which the continuum was divided.

Although this regional discretization concept had been proposed earlier[7, 8], it was only when it was used by an engineering organization as a means of avoiding the difficulty of physical discretization by bar assemblages that the method really began to develop. In addition, the concurrent availability of effective digital computers and of the matrix formulation of structural analysis were essential factors in the early development. Also, to maintain proper perspective on the early days of the FEM, it is important to realize that its utilization did not take off explosively; during the first six or seven years the application of the method spread very slowly indeed.

The work which I associate with the beginning of the computerized FEM was done during summer 1953 when I was again employed by Boeing Airplane Company on their summer faculty program. Again, I was assigned to Mr. M. J. Turner's Structural Dynamics Unit, to work on methods of evaluating the stiffness of a delta airplane wing for use in flutter analysis. Because the bar assemblage approach tried during the previous summer had been unsatisfactory, Mr. Turner suggested that we should merely try dividing the wing skin into appropriate triangular segments. The stiffness properties of these segments were to be evaluated by assuming constant normal and shear stress states within the triangles and applying Castigliano's theorem; then the stiffness of the complete wing system (consisting of skin segments, spars, stringers, etc.) could by obtained by appropriate addition of the component stiffnesses (the direct stiffness method). Thus, at the beginning of the summer, 1953, Mr. Turner had completely outlined the FEM concept and those of us working on the project merely had to carry out the details and test the results by numerical experiment.

Our paper describing this initial effort was presented at the New York meeting of the Institute of Aeronautical Sciences in January 1954[9]. I have never known why the decision was made not to submit the paper for publication until 1955, so the publication date of September 1956 was more than two years after the first presentation and over three years after the work was done. As was mentioned, this is graphic evidence that the FEM did not attain instant recognition. Undoubtedly, a major factor which limited its acceptability was that the original work was done in the Structural Dynamics Unit, where the objective was limited to stiffness and deflection analysis; it was several years before the concept was accepted and put to use by the stress analysis groups at Boeing. Thus, it is possible that the orientation of this initial step toward a specific engineering application tended to obscure the general applicability of the FEM concept, even though the individuals working with the development at Boeing were quite aware of its broader implications.

Although I maintained close contact with several of my Boeing colleagues for many years after 1953, I did not work there again and I had no opportunity for further study of the FEM until 1956–57, when I spent my first sabbatical leave in Norway (with the Skipsteknisk Forsknings Institutt in Trondheim). This "Norwegian connection" also was a factor in my decision to prepare a historical summary for this Conference; it was this period which made possible my continued contact with the finite element concept. Lack of computer facilities in Norway limited the type of work I could do at this time, but I was intrigued by plane stress applications of the method and I carried out some very simple analyses of rectangular and triangular element assemblages using a desk calculator. Although this work was too trivial to warrant publication, it convinced me of the potential of the FEM for the solution of general continuum problems.

About the time I returned to Berkeley from my sabbatical leave, the Engineering College acquired an IBM 701 Computer (replacing the old Card Programmed Calculator) and we began to develop structural analysis capabilities with this machine. For educational purposes, a Matrix Interpretive Program of the type pioneered in England[10] offered the best means of making the computer capabilities accessible to the students, and most of my early efforts went into developing such a program[11]. Then it was possible to continue my work with the FEM, which had been undergoing continuing development at Boeing but had attracted only little attention elsewhere.

Early FEM studies at Berkeley were greatly limited by the two thousand word central processor capacity of the IBM 701, but by utilizing the seven 2000 word drum storage units it was possible to carry out some creditable analyses. Our first concentrated effort toward plane stress analysis was in response to a challenge by one of my continuum mechanics colleagues who was sceptical of the validity of the procedure and wanted to see a solution of some classical problem. To me it seemed obvious that the method could solve any plane stress problem to any desired accuracy—limited only by the time and energy one wished to expend on the calculations. But in the hopes of attracting wider interest toward the FEM concept, I allocated part of a small NSF research grant to the solution of a few sample plane stress problems. The results were as good as I had expected, so a paper was prepared. The principal problem that arose in writing the paper was choosing a suitable name for this analytical procedure and I decided finally on the Finite Element Method. This name first appeared in that paper[12], and I can only conclude from subsequent history that it was an apt choice.

In retrospect, the next red letter event in my personal FEM history occurred in December 1960, when Professor O. C. Zienkiewicz invited me to Northwestern University to give a seminar lecture on the new procedure. We were friends from previous meetings, and I knew that he had been brought up in the Southwell finite difference tradition, so it was apparent that his invitation was prompted by scepticism and a desire to discuss the relative merits of finite elements vs finite differences. Certainly, we did have such discussions during my visit, but Professor Zienkiewicz obviously is a very intelligent person and was quick to recognize the advantages of the FEM. During that short visit an illustrious convert was won to the cause, and I think it is not coincidental that rapid worldwide acceptance of the FEM started almost from that moment.

The 1960 paper was not a major work because it described no new ideas; it was useful mainly in introducing the FEM to the Civil Engineering profession. My principal interest at that time was in developing the method as a general purpose tool for the analysis of arbitrary shell structures. One of my students already had worked on the FEM analysis of plate bending, but when we were about to prepare this paper for publication I learned that my former associates at Boeing already had prepared an internal report on plate bending analysis using finite elements. So this report was merely filed with my sponsors at NSF[13] and my student continued with the next step of combining plate bending and plane stress stiffness to obtain flat plate shell elements. Rectangular elements were derived for analysis of cylindrical shells and triangular elements for shells of arbitrary geometry. Significant results were obtained[14], but even in this early work it was apparent that an *ad hoc* approach to extending the FEM left much to be desired. Specifically the triangular plate bending element was not performing satisfactorily and it was necessary to go back for another look at that problem. Results of a follow-on study[15] were still less than satisfactory and it was not until 1964 that an adequate solution had been obtained for this problem.

The other important FEM development at Berkeley in the early 1960s was that we obtained a research contract from the U.S. Corps of Engineers for a practical engineering investigation; specifically they were concerned with the state of stress in a concrete gravity dam that had developed a major internal crack during construction due to temperature effects[16]. This contract provided us for the first time with enough money to support the development of a general purpose plane stress analysis program[17]. It was this program that subsequently proved to many engineers the great power of the FEM; even more important, writing the program allowed my student at that time, E. L. Wilson, to develop and demonstrate his great flair for finite element work. We at Berkeley are greatly indebted to the Corps of Engineers for their contribution to this cause, as well as for support of our finite element research through many years.

One other aspect of the early development of the FEM should be mentioned—the important role played by international conferences. To a large extent, the rapid worldwide expansion of interest and activities in the method is attributable to these conferences, which allowed for formal presentations of ideas and for personal meetings between the active researchers. To my knowledge, the first truly international conference dealing extensively with computer analysis of structures was held in Lisbon in September 1962[18]. The subject of this conference was Numerical Methods in Civil Engineering, and the FEM was the central theme of only one paper; but the conference provided a good forum for discussion of the relative merits of the finite difference and finite element procedures in structural analysis. By 1965, when the first Conference on Matrix Methods in Structural Mechanics was held at the Wright Patterson Air Force Base[19], the expansion of interest in and activity with the FEM was phenomenal. This milestone event brought together from all over the world nearly all researchers who had done significant work with finite elements. At the conclusion of the Conference, it was evident that the FEM had come of age; its potential for solving practical problems had been demonstrated in many structural disciplines, and powerful computer programs had been described which could deal routinely with problems of every description. Of course tremendous advances in understanding and in computational capability have been made since 1965, but this Conference, held only about a decade after the first preliminary applications, showed that the FEM should be recognized as the major analytical tool in the field of structural mechanics.

3. RECENT ADVANCES

Advances in finite element methodology since 1965 have been so rapid and diverse that it is impossible to chronicle them here, even considering only a very limited segment of this rapidly broadening field of mechanics. However, it may be useful to continue this personal view with a very limited discussion of the directions in which more recent work has been headed. The point of departure for this review is the 1969–72 state-of-the-art of structural dynamic response analysis, as summarized in two papers prepared for the U.S.–Japan Seminars on Matrix Methods of Structural Analysis[20, 21]. As was mentioned earlier, this is about the time that my interest turned toward experimental research; so it is evident that my comments on these recent developments present the views of an interested observer, but not an active participant in finite element research.

The field of dynamic response analysis is appropriate for the present discussion if the static case is considered merely as a special case of the dynamic problem, in which inertial and damping effects are not involved, and where equilibrium need be satisfied only at one time rather than at a succession of times during the response. In the 1969 and 1972 papers, the response analysis procedure was divided into two phases: (a) formulation of the equations of dynamic equilibrium, and (b) solution of these equations in response to the given condition of dynamic loading. It will be convenient to discuss these two phases separately here.

3.1 *Formulation of the equations of motion*

Establishing the equations of equilibrium in a finite element analysis involves three essential steps: (1) idealizing the actual structural system as an assemblage of discrete elements, (2) evaluating the mechanical properties of the elements, and (3) assembling the element properties to obtain the corresponding system properties. By 1969, the concept of finite element discretization was well developed, a wide range of element types was available for providing reasonable idealizations of arbitrary structures, and efficient coordinate systems and interpolation functions had been established for evaluating the element mechanical properties.

Moreover, procedures of assembling the element properties to obtain the system properties were well understood in 1969. To a great extent, these procedures are more closely associated with computer program coding than with finite element theory, and little need be said about them here. The only exception is the concept of substructuring, or more specifically the recognition that substructures can be looked upon as "superelements" and thus may be incorporated directly into the finite element assembly sequence. The substructure idea was well understood in 1969, but great progress has been made since then in designing programs that use multilevel substructuring as a routine feature of the analysis procedure[22].

Thus the only phase of formulation of the equations of motion remaining to be mentioned is the evaluation of the element properties, which for a dynamic analysis include the stiffness, mass, damping and external load. In this discussion each of these properties will be treated in turn.

3.1.1 *Stiffness.* By far the most significant mechanical property in most structural problems is the stiffness; accordingly the majority of finite element research has been devoted to developing more efficient elements which provide a better approximation of the actual structure stiffness at less computational cost. By 1969 great progress had been made in this direction, and although much research has gone into this area since then, I think it has been with considerably diminishing returns. Although some significant improvements of element types have been made, these have had little influence on most practical engineering applications. A recent paper by Olsen[23] supports this opinion; he noted that the old triangular flat plate element still remains competitive in analysis of general thin shells, in spite of extensive work done with refined shell elements.

3.1.2 *Mass.* An effective description of the inertial resistance of a structure is fundamental to a dynamic response analysis, and the consistent mass concept[24] was introduced early in the history of finite elements to provide a rational basis for forming mass matrices. However, a strong case was made in the 1969 paper for lumped mass representation rather than consistent mass, on the basis that inertial effects required a less refined discretization than did the elastic resistance. Subsequent research has supported this opinion, and some recent research has been concerned with developing procedures for effectively lumping the mass of arbitrary elements[25].

3.1.3 *Damping.* In contrast to the other mechanical properties, definition of damping or energy loss characteristics continues to be an elusive problem. Because so little is known about the actual damping processes, the damping property generally is defined at the assemblage level rather than for individual elements. In most cases a viscous damping mechanism seems to give adequate correlation between observed structural behavior and analytical predictions; experimental data usually is too limited to warrant development of more refined mathematical formulations.

Effective procedures were described in the 1969 paper and subsequently[26] for explicit definition of a proportional viscous damping matrix. Considerable interest has arisen since then in non-proportional damping, due in part to concern over "radiation damping" effects associated with soil-structure interaction. The classical techniques of treating non-proportional damping (based on mode-superposition using the complex mode shapes) have been employed in some finite element analyses[27]; but a preferable approach in most earthquake engineering problems is to transform to a reduced set of undamped modal coordinates, and then to solve the coupled modal equations[28]. The cost of solving the complex eigenproblem associated with non-proportional damping, and the subsequent cost of expressing the response in complex modal coordinates far exceeds the cost of calculating the response with a coupled set of coordinates.

Another major recent development in treating damping, which will be mentioned later, is through the use of a frequency domain solution. But the major fact which continues to limit the treatment of damping in dynamic systems is the paucity of experimental data concerning the actual energy loss mechanisms in real structural systems.

3.1.4 *Load.* Definition of the load terms in the equations of motion also generally is done at the level of the assembled structure rather than with respect to the elements, and the principal problems with this factor usually are due to lack of knowledge of the true loading mechanisms rather than with the discretization process. Therefore, progress in this area depends more on obtaining experimental data than on finite element research, and little change can be reported since 1969. Significant advances have been made recently in related areas involving fluid-structure interaction and foundation-structure interaction, especially in response to earthquake excitation; these topics will be mentioned briefly later, but generally they are outside the scope of the present discussion.

3.2 *Solution of the equilibrium equations*

In discussing the second phase of the finite element analysis, the solution of the equations of equilibrium, it is useful to divide the subject into several types of categories. First, static and dynamic problems will be separated because of the radically different analytical procedures that may be employed in the solution of the dynamic problem. Then the dynamic analyses may be separated according to the type of coordinates used in the solution: modal or discrete system coordinates. Another classification concerns the "domain" of the analysis procedure: time domain or frequency domain.

An alternative approach to categorization would be to separate linear problems from nonlinear. In discussing the nonlinear analyses, a generally similar approach could be adopted for both static and dynamic cases, the latter merely requiring the inclusion of extra terms to represent the effects of inertia and damping. However, the first approach is more satisfactory for the purpose of this paper.

3.2.1 *Static analysis.* Because the development of efficient algorithms for the solution of large equation sets has been a primary objective for finite element researchers since the method first was put to practical use, the capability in this area already was quite advanced by 1969. Powerful equation solvers were available then, and extensive research since 1969 has further advanced the state-of-the-art. Undoubtedly many of the most significant recent advances have pertained to analysis on nonlinear structures because the nonlinear analysis cost for large practical systems has been almost prohibitive. The continuing active interest in this subject is evidenced by the many major international conferences recently devoted to it[29, 30]; also it is significant that two sessions of this present conference deal with nonlinear analysis.

3.2.2 *Dynamic coordinates.* The first major decision to be made in planning a dynamic response analysis is the type of coordinates to be used. One option is merely to solve directly the equations of motion expressed in the original system coordinates, but this has the disadvantage that the original equation set may involve hundreds or thousands of degrees of freedom. An alternative is to transform to the natural or modal coordinates of the structure which describe the dynamic response more efficiently, and therefore, may be reduced in number. Each of these approaches will be discussed briefly.

(a) *Modal coordinates*

If the structure is linearly elastic, it is usually desirable to transform the equations of motion to modal coordinates and then to evaluate the response in terms of a truncated modal set. Solution of the structure eigenproblem to obtain the modal coordinates is a major computational task, and very effective eigenproblem solvers were developed quite early, as is described on the 1969 and 1972 papers. Research in this area has continued since then, and further refinements of technique are being made, but it is not likely that a major breakthrough will result.

The principal decision facing the analyst in a modal coordinate solution is the number of modes to be included. Clearly this depends on both the spatial distribution and the frequency content of the applied loading. If the load pattern is distributed widely over the structure, it tends to excite mainly the lower modes of vibration which may have distribution patterns similar to the loading. However, if only a small portion of the structure is attacked by the external load, many modes will be excited.

In the past it generally has been assumed that all modes which are excited significantly must be included in the dynamic response analysis. However, it is evident that the amplitude of the dynamic response in any mode depends on the frequency content of the loading. The higher mode response to a low frequency excitation may be essentially static in character, and recently[31] it has been demonstrated that these modal contributions can be accounted for adequately by a static correction term. Thus a standard mode superposition response is performed for only those modes which are subject to dynamic amplification; the response to the load associated with the higher modes is evaluated by a static analysis, and this static correction is added to the dynamic response.

In general, the modal coordinate approach is not recommended for nonlinear analysis; however, some studies have shown that efficient nonlinear solutions can be obtained with modal coordinates[32, 33]. Clearly this approach can be effective only if the dynamic response can be expressed conveniently by superposition of the mode shapes, and therefore it is applicable to systems in which the nonlinearity does not drastically modify the vibration shapes. In principle, one would expect good performance where the nonlinearity is widely distributed over the structure, but not where local concentrations such as plastic hinges are involved.

(b) *System coordinates*

Integration of the equations of motion expressed in system coordinates is the standard approach to nonlinear analysis, but significant savings may be effected if the structure has only localized nonlinearity[34]. In this case a substructure analysis procedure may be adopted wherein all nonlinear parts of the structure are included in a single substructure. The elastic portions of the system are included in other substructures, and the degrees of freedom not required for interconnection to the nonlinear component are removed by condensation. Thus the number of degrees of freedom required for consideration in the nonlinear analysis may be greatly reduced from the original coordinate set.

3.2.3 *Dynamic domain.* The other basic option open to the dynamic analyst is the domain in which the analysis will be performed. In 1969–72 this question seldom arose—step-by-step integration of the equations of motion was the only technique capable of dealing with large scale dynamic applications of the FEM. During the past decade, however, the extremely efficient Fast Fourier Transform (FFT) programs for numerical evaluation of Fourier transforms have been discovered by structural engineers, and have proven to be advantageous in many practical cases. Comments on both frequency domain and time domain analyses follow.

(a) *Frequency domain*

Frequency domain analyses involve the superposition of the response of a structure to various harmonic excitations; therefore, they are only applicable to linear systems. Moreover, because the analysis must be performed for many hundreds of frequencies it will be extremely expensive when dealing with systems having many coupled degrees of freedom. Therefore, frequency domain calculations generally are performed upon uncoupled modal coordinate sets.

One of the principal areas of application of the frequency domain approach to dynamic structural analysis is in situations involving liquid-structure or soil-structure interaction, because the continuous medium can be treated without discretization and coupled directly to the finite element model of the structure. Many important applications of this type of analysis have been reported in recent years[35, 36], and this is one of the significant areas of advances since 1969. Another practical application of frequency domain analysis is deconvolution, i.e. evaluating the input loading history from measured response data[37]. Such analyses can be performed easily in the frequency domain but are very difficult to do satisfactorily in the time domain. Except for special types of problems such as those mentioned above, however, frequency domain analyses seldom are superior to direct time domain integration of the equations of motion.

(b) *Time domain*

Improvement in understanding of the process of direct integration of the equations of motion is one of the most significant achievements of structural dynamics research during the past decade. The step-by-step analysis procedures described in the 1969 and 1972 papers are still valid and widely used, but research done subsequently[38–40] shows that these methods are merely members of much broader families of analysis techniques. These more recent studies (and the references cited above are merely arbitrary examples of numerous papers in this field) show that it is possible to design a step-by-step procedure to have desired approximation characteristics with respect to such factors as period elongation and artificial damping. However, the older methods, even going back 20 years to the pioneering work by Newmark[41] still serve well in many current applications.

4. EXAMPLES OF CURRENT PROBLEMS

Although remarkable progress has been made with the FEM during its first quarter century, and the basic procedures of structural dynamic analysis have advanced to the point where solution of arbitrary dynamic problems appears to be routine, it is obvious to those working with general engineering applications of the method that new problems and difficulties are encountered regularly. In this section of the paper two examples of problems that have confronted the author during the past year are described. These problems are viewed from the standpoint of an FEM user rather than a program developer; they illustrate limitations of analysis capabilities presently available to the user, and therefore, are offered as challenges to those involved in program development.

The two examples are drawn from earthquake engineering and concern the seismic response of (a) thin shell metal cylindrical liquid storage tanks, and (b) thin shell concrete arch dams. Although both involve liquid-structure interaction, the problems identified in the two cases are fundamentally different. However, both demonstrate that "number-cruncher complacency" is premature at this stage of development of the FEM, and that experimental research is essential to further progress—both in understanding of mechanical processes and in verification of analysis procedures.

4.1 *Response of liquid storage tanks*

Examples of damage to ground supported liquid storage tanks are noted after nearly every major earthquake, and designer efforts to improve their earthquake resistance have been under way for over twenty years. The present design procedure is based on an approximate evaluation of the hydrodynamic pressures induced by the earthquake, assuming that the tank is rigid. From these pressures the base shear and overturning moment are determined, and then the resulting shell stresses are calculated by elementary beam theory, treating the tank as a vertical cantilever.

An obvious limitation of this approach is the rigid tank assumption; a thin metal tank can be expected to deform sufficiently during the seismic response to permit significant dynamic amplification of the liquid pressures. Accordingly, several investigators have developed finite element programs[42, 43] which are intended to account for this seismic fluid-structure interaction. The basic assumption of these programs, drawn from hydrodynamic theory, is that a horizontal base motion along one axis will produce only a first Fourier harmonic ($\cos\theta$) distribution of pressure and deformation. Thus a single term axisymmetric shell analysis procedure has been adopted.

In order to verify results of such analyses (which are applicable only to fixed base tanks) and also to provide quantative information on the response of unanchored tanks, a group of tank manufacturers and designers sponsored an experimental study at the University of California using the 20×20 ft shaking table facility[44]. Figure 1 shows a "tall" tank on the shaking table, surrounded by (but not in contact with) its reference frame. It may be noted here that unanchored tanks are used frequently because they do not require the expensive foundations needed for anchorage, but even moderate earthquake motions will induce rocking uplift of the tank walls from the foundation and only very crude estimates of this dynamic response mechanism are presently available to designers.

Probably the most significant and surprising result of this test program was the observation that fixed base tanks did not respond only in the first Fourier harmonic; important $\cos 2\theta$ and $\cos 3\theta$ components of pressure, displacement and stress also were observed in tests of both short[44] and tall[45] tanks. Some of the tall tank results are included here to illustrate this unexpected response behavior. Figure 2 shows deflected shapes of the tank cross section at several times during a typical test, and Fig. 3 depicts the relative maximum amplitudes of the Fourier components contained in various response quantities. These figures clearly show that the standard finite element analysis, which recognizes only the $\cos\theta$ component, cannot provide much understanding of the actual fixed-base tank response.

In the case of the free-base tank, out-of-round response was expected because the axial symmetry of the base support condition is destroyed by uplift. However, comparison of the axial stress distribution about the base of the unanchored tank with an estimate based on a current design procedure, shown in Fig. 3, demonstrates the need for complete revision of the present design concept. Clearly the rocking mechanism concentrates the base section axial stress in a much narrower arc than had been expected, with the result that the measured stress exceeds the design estimate by a factor of about 4. The behavior in this case is highly nonlinear with regard to the support forces about the base, but no effort yet has been directed toward developing a nonlinear analysis procedure to deal with this important problem.

In the context of this paper, the first conclusion drawn from this example is that experimental verification is essential for ensuring reliability of finite element programs. The test of the anchored tanks had been looked

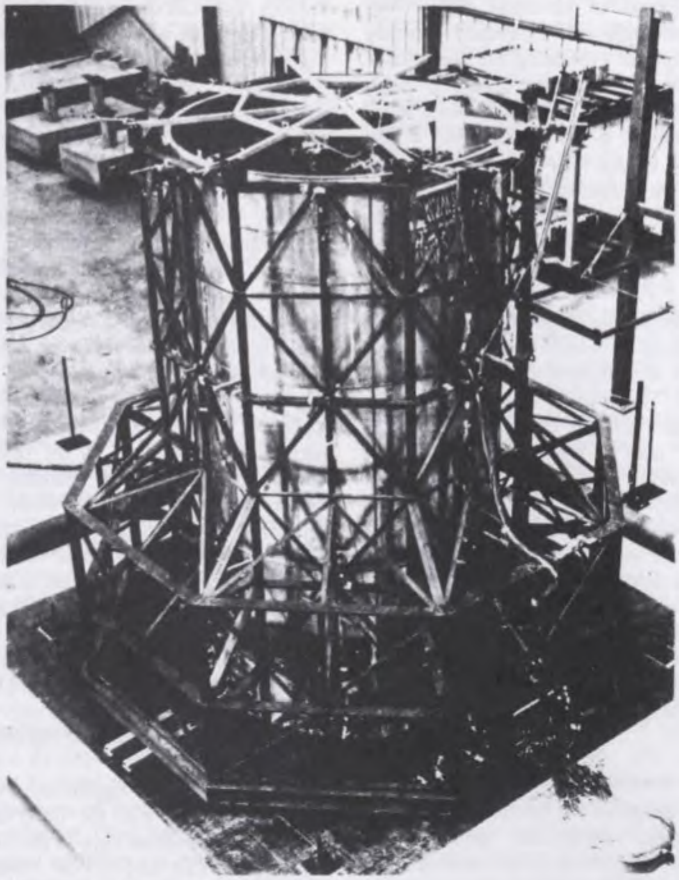


Fig. 1. 7 − 3/4 × 15 ft tank with reference frame on shaking table.

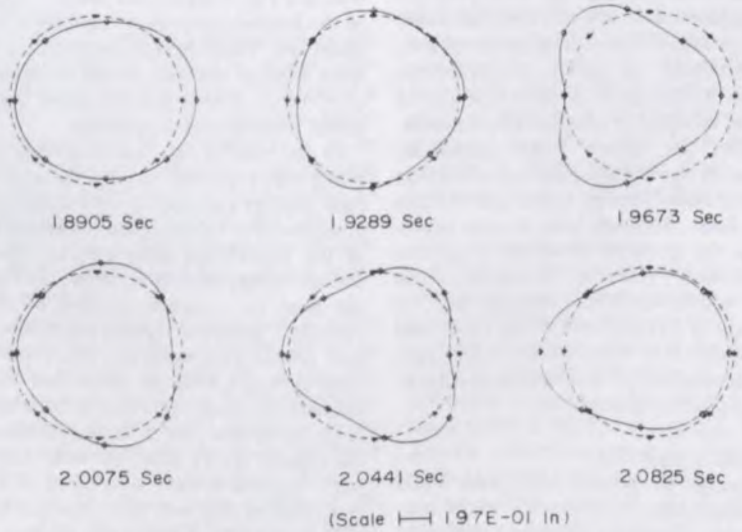


Fig. 2. Deflected shape of tank top during shaking table test.

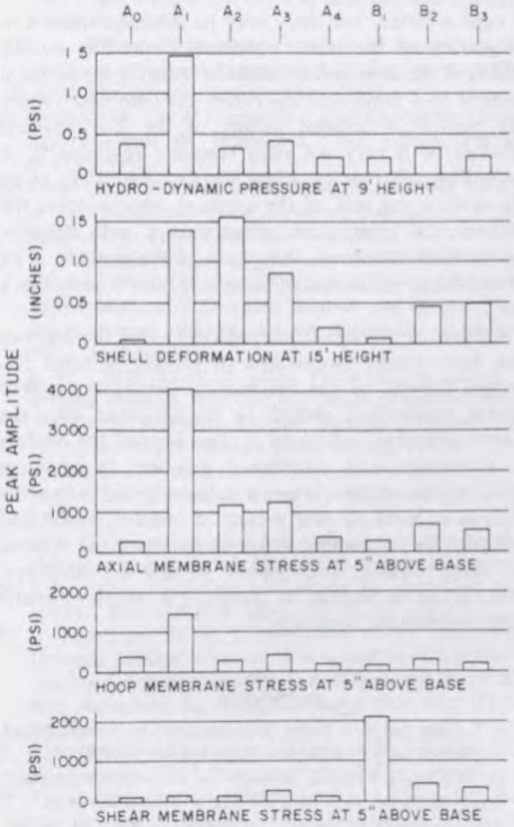


Fig. 3. Peak amplitude of Fourier components shaking table test of tank.

upon only as a routine check of the finite element approximation; the observed out-of-round response was totally unexpected. Theoretical mechanics has not yet provided a basis for predicting these response components, and of course, the finite element analysis cannot go beyond its theoretical origins no matter how refined the mesh or capable the computer. A second closely related conclusion is that experimental data is essential for developing adequate numerical approximations when theory is lacking. Certainly, future improvements in analysis techniques for either anchored or unanchored tanks will depend heavily on experimental results such as those mentioned here, and development of a finite element program which can deal effectively with either of these design problems is a major challenge to the profession of computational mechanics.

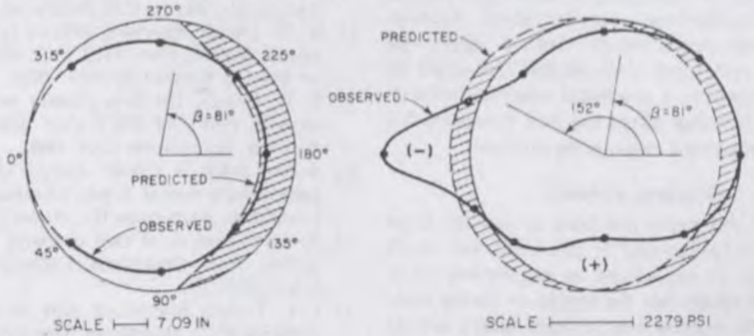
4.2 *Concrete arch dams*

The seismic performance of concrete arch dams is a problem of even more critical concern to engineers and the general public because a large reservoir could constitute a major hazard to the people living below it. Although the past earthquake performance of arch dams has been excellent, non-earthquake failures such as those at Malpasset, France and Vaiont, Italy demonstrate that dams embody a significant potential for disaster. Therefore, great emphasis presently is being placed on seismic safety evaluations of major dams in many regions having active seismicity.

Superficially the analysis of earthquake stresses in a concrete arch dam would appear to be well within the present state-of-the-art of dynamic finite element analysis. Indeed, computer programs have been written for that specific purpose[46], and general purpose programs such as SAPIV also have been used extensively in such studies. However, when these analyses are examined in detail their serious limitations become apparent. For example, reservoir interaction is treated only approximately at best—using "added masses" derived by means of incompressible liquid elements. However, two-dimensional gravity dam analyses have demonstrated the importance of liquid compressibility in the earthquake analysis of such structures[44], and it should be equally important in a three-dimensional arch dam analysis; yet no program accounting for arch dam-compressible liquid interaction is presently available.

Possibly even more critical in this arch dam-reservoir interaction behavior is the fact that added mass analyses indicate negative net fluid pressures in response to a severe earthquake. In other words, the peak negative dynamic pressures momentarily exceed the hydrostatic pressures, and therefore cavitation should result. However, no analysis procedure is available to deal with this nonlinear interaction mechanism, either for compressible or incompressible liquids.

The other major limitation of present seismic response studies for concrete arch dams is that they all treat the structure as a linearly elastic system. For the static design conditions this assumption is reasonable, but the response to a major earthquake is expected to include two significant forms of structural nonlinearity. The first results from the fact that typical arch dams are con-



(a) UPLIFT OF BOTTOM PLATE

(b) AXIAL STRESS DISTRIBUTION

Fig. 4. Comparison of observed and predicted performance during test of unanchored tank.

structed as a series of independent monoliths separated by joints extending from foundation to crest and from upstream to downstream face. These joints are intended to minimize cracking due to shrinkage and temperature change during construction; after construction they are closed by grouting and/or the reservoir pressure on the upstream face, and no movement of the joints occurs during normal static load conditions. But during a severe earthquake, tension and bending effects are induced in the arch rings which can overcome the static compression and cause joint opening. Consideration of this joint behavior is essential to understanding of the seismic response; the tensile arch stresses indicated by linear dynamic analyses obviously are inconsistent with the actual jointed construction of the dam. Inclusion of this type of nonlinearity is well within present finite element analysis capabilities, but it has not yet been applied in any significant practical investigation.

The second type of structural nonlinearity expected during a major earthquake involves cracking of the concrete. Because the tensile strength of concrete is only about 10 percent of its compressive strength, stresses indicated by linear response analyses for a major earthquake often exceed the cracking limit. As was mentioned above, the vertical construction joints would prevent development of arch tensile stresses, but cracking would be expected on horizontal planes due to "cantilever" tensile stresses in the monoliths. Thus, during a severe earthquake an extensive network of horizontal cracks might develop, which could combine with the vertical joints to divide the dam into a system of separate blocks. Because the cracking tendencies are associated with high frequency vibrations, little relative displacement would be expected between the blocks; thus one would intuitively expect that the arch mechanism of the dam would not be adversely affected by such damage and that it would continue to support the gravity and water loads after the seismic input ended. However, such intuitive estimates seldom are convincing to Boards responsible for public safety; analytical procedures which can follow the history of cracking, joint opening, and block displacement, and can then evaluate the stability of the system, are urgently needed.

In concluding this discussion, it may be noted that the three types of nonlinearity identified in the seismic response of an arch dam—cavitation, joint opening, and cantilever cracking—each present formidable obstacles to a finite element analysis, and experimental data on the actual behavior would be required before any such program could be accepted for routine use. On the other hand, the difficulties of conducting a valid experimental study of these mechanisms also are great, because dynamic similitude requirements cannot easily be satisfied with the very small scale models that could be employed. Consequently, a combined analytical-experimental approach probably offers the best prospects for dealing with this important engineering problem.

5. CONCLUDING REMARKS

The purpose of this paper has been to provide some perspective on the background of the FEM and on its current capabilities in application to engineering problems. It is well to recall that the emphasis during early development of the method was oriented totally toward practical application. At present it probably is fair to say that the state-of-the-art has advanced to the point where solution of any structural engineering problem can be contemplated, but there may be a wide variation in the quality of the result obtained. Depending on the validity of the assumptions made in reducing the physical problem to a numerical algorithm, the computer output may provide a detailed picture of the true physical behavior or it may not even remotely resemble it. A controlling influence on where the final result lies along this scale is the skill of the engineer who prepares the mathematical idealization; when dealing with complex and unusual structures, this phase of the analysis is an art and the program cannot be treated merely as a "black box".

Because of the significant possibility that the analysis may have totally overlooked or misjudged some important aspects of the mechanical behaviour, experimental verification should be incorporated into the analytical process whenever it steps beyond the borders of experience and established practice. In addition, experimental studies often will be required when the analysis is breaking new ground in order to define and quantify the parameters which characterize the system. For these reasons, investigations of new structural systems should be planned by means of a combined analytical-experimental approach.

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Small shops break the NC barrier

Many small shops are starting to get into numerical control in a big way. Five NC authorities tell us why this trend must continue.

The technology of numerical control is no longer a novelty in Canada's small shops. For many, it has become a matter of survival. Hurdling the barriers to effective use of NC can be a tough job, but the alternative in most cases is low productivity, a lack of flexibility, and declining profitability in today's highly competitive industrial scene.

"There is no longer any point in investing in conventional machines if you can avoid it," says Garnet Bush, general sales manager for Williams & Wilson Ltd. "Small sub-contractors need the flexibility that NC can give them. They face a wide variety of work, and they can't predict what they'll be confronted with next." Bush sees no let-up in the pressure towards increased flexibility in manufacturing. Within ten years, he predicts, small shops will be starting to use flexible manufacturing systems based on group technology.

Another advocate of rapid computerization of the small shop is CANdata Systems Ltd.'s Valerie Wright, who is professional development vice-president of the Central Ontario chapter of the Numerical Control Society. "Many shops have said, in effect, 'It's either go to NC or close down.' " An escalation of NC technology is inevitable, she says, because ambitious firms will continually move into increasingly sophisticated technology to maintain their competitive edge.

"There is no longer any point in investing in conventional machines."

Many small shops are finding the road to NC tough going. A lack of resources—in capital, personnel, and expertise—is at the root of the problem.

"A small shop seldom has the time or resources to do all the research needed for intelligent decisions on NC," notes Wright. "They have to learn from other users. The problem with this is that the manufacturing processes involved are often quite different."

Certain NC equipment, such as MDSI's Series 300 system shown above, was designed for manufacturers with small-to-medium sized operations. The Series 300 replaces NC part programming with simplified NC part processing, so users won't have to learn a programming language.

"Personnel is an important issue," notes Paul Bayer of Bayer Business Machines Ltd. "How many owners can afford the time to have their staff trained? The small shop owner loses a lot of production time as they go through the learning curve. There are also scrap costs—there is bound to be the occasional accident due to operator error."

Small shop owners do have access to certain information resources. Manufacturers' presentations, open houses, trade shows, technical societies such as the NC Society, and various governmental programs such as the NC facility at NRC's Western Lab in Vancouver should be exploited.

Simplified programming languages and sophisticated machine tool controls can substantially reduce the need for extensive training.

"One way to avoid hidden costs is to buy self-contained units with powerful controls," says Terry Butlin, technical director at Ferro Technique Ltd. and chairman of the Central Ontario Chapter of NCS. "Simpler units appeal to the small shop because you don't need a lot of extras. Self-training kits are available with certain systems which make programming very easy to learn."

Hidden costs can be a significant factor in implementing NC. The tooling itself can represent a major cost to the small shop owner.

"People usually don't get enough information when they purchase NC equipment, especially with regards to cost of tape preparation," notes David Burnett, president of Manufacturing Data Systems International—Canada Ltd. and a past chairman of NCS. "The customer has to ask whether the vendor can support his needs and keep the system running."

Tape preparation can bring headaches to the unwary shop. "In some small shops, I've seen a half a million dollars worth of machine tools using manual data input systems," says Paul Bayer. "This means that the operator is typing tapes into the machine for four hours a day when it should be cutting metal."

The owner must decide the quantity, complexity, and variety of parts he will produce, now and in the future. If many different, complex parts are planned, he's going to need very powerful programming tools.

There are alternatives. "For certain parts, a programmer doesn't need computer assistance. In certain circumstances, time-sharing or contract programming can be advantageous," observes Valerie Wright.

Small shops enjoy certain strengths resulting from their size, as well, and it's up to management to capitalize on these.

"Decisions can be made quickly in a small shop, by the owner. A small shop can get equipment up and running more quickly and more efficiently than many larger shops. Operators are often very highly skilled, and the owners usually know where their money is going," says Terry Butlin.

Small shops are often more innovative than larger shops. They can often find profitable application for the equipment undreamed of by the manufacturer.

> ***"A small shop can get equipment up and running more quickly and more efficiently than many large shops."***

"One idea for the small shop is modular systems," says Valerie Wright. "Start with an intelligent terminal, then upgrade it as it becomes necessary. You can add peripherals as required. Another approach is the multi-user computer, which is capable of handling other functions besides tape preparation, such as accounting."

David Burnett insists that the entry into NC can be affordable for the small shop owner if he exercises all his options. "Why do so many people insist on buying their own systems when they can time share?" he asks. "We call it the Atari syndrome—everybody wants his own screen."

Full knowledge of his alternatives and a clear idea of where he wants the technology to take him will help make the entry into NC painless for the small shop owner. "Small shops have to investigate the technology thoroughly," notes Garnet Bush. The designers didn't necessarily have small shops in mind when they designed the equipment."

Cutting costs with do-it-yourself NC

"You have to learn everything yourself." That's how Harmut Brumberg, president of Brumall Manufacturing Corp. in Scarborough, Ont., sums up NC and the small shop.

Brumall specializes in manufacturing electrical parts. The 20,000 ft^2 plant employs about 22 people and does about $3 million a year in sales.

Brumberg made his first venture into NC in 1980 with the purchase of a Yamazaki H-10 machining center. He followed this up in 1981 with a Yamazaki V-7.5.

These decisions had been well-informed. An electrical engineer, Brumberg designed much of the automatic production equipment in his plant himself and had been following the growth of NC for years.

He wanted his existing staff to be able to handle the NC tools. This required that he become an NC jack-of-all-trades.

The group technology concept was adapted to his tape preparation system. Similar parts share basic tapes, which are modified wherever necessary. This cuts programming time to the minimum.

Every time he had the serviceman in during the first year's free service, he would watch him work, questioning him about what he was doing and learning from him. He also makes regular use of Yamazaki's service hot-line for problems he can't readily solve himself. Result? Service bills are not a problem.

When Brumberg put the machines in, they were running 24 hr. a day. Part of his reason for buying them was to keep labor costs down and increase volume without expansion.

The machines were used mainly for short run work that wasn't feasible for the automatic equipment. "Canada is a country for short and medium runs, so NC is very appropriate here," he says.

Quality was another important factor. "The quality of our machining has now passed the quality of the extrusions we are supplied," says Brumberg. "We've had to start rejecting a higher percentage of extrusions because the NC machines are so accurate that any problems with purchased materials immediately become obvious." Brumberg adds that he doesn't have to compromise with NC, and that having programmable tools makes his production scheduling easier.

Brumberg's total investment in NC was in the neighbourhood of $375,000. He says he won't be content to stop there either—his next ambition is to incorporate robotics into the operation.

NC can be a sound investment for the smaller shop, says Harmut Brumberg, but only if you handle programming and maintenance yourself.

Machine tool technology examined by massive report

Few events have ever been the focus of attention in the U.S. machine tool industry as much as the publication of "Technology of Machine Tools," a massive two and a half year study of the state of the art in machine tool technology. Sponsored by the U.S. government, the study is the outcome of two and a half years work by 120 experts assembled into the International Machine Tool Task Force, which presented its findings in Chicago last month.

What is the status of the U.S. machine tool industry? What are its prospects?

Never have those questions been addressed in a more comprehensive manner than by the International Machine Tool Task Force, which published its findings in a massive report last month.

Sponsored by the U.S. Air Force, the report has left virtually no stone unturned in examining where the industry is at and where it is heading, and it has not always liked what it found. The U.S. machine tool industry, perceived as a small though vital industrial sector, is facing unprecedented challenges, but there are formidable obstacles to be overcome—some of them of the industry's own making—if the demands of the future are to be met.

Although most of the Task Force's observations and recommendations are concerned primarily with the machine tool manufacturing industry *per se*, they include a wide view of current conditions and practices in the machine tool user industry, and here, too, the Task Force has concluded, there is much left to be desired. As for the general economic as well as technological climate, particularly in the U.S., the Task Force sees room for some sweeping changes in the role of government, for instance.

Industry is key element

The U.S. machine tool manufacturing industry accounts for only one-sixth of one percent of the U.S. gross national product, the Task Force observes, adding jocularly that even at its 1980 peak, this is less than that of the paper bag industry. Yet, the Task Force insists, the machine tool industry is one of the key elements in manufacturing industry and its influence is much larger than that indicated by the small proportion of the gross national product it represents.

Until recently, says the Task Force, the automotive industry dominated the machine tool market. The auto makers pretty well determined what kind of machines would be designed, built and sold. But this is changing. In the short term, the Task Force predicts, the "demand shapers" in the machine tool market are going to be the automotive and aerospace industries jointly. Further ahead, other high technology industries can be expected to exert a growing influence on the state of the art. The Task Force specifically mentions computer, telecommunications and energy industries.

The effect of these changes will be pressure to move toward multi-functional machine tools and machining or manufacturing systems. Instead of what it calls a "bi-modal growth" market—either piece part production or mass production—the Task Force foresees a "tri-modal growth" market, with more and more emphasis on smaller and more varied batch production runs.

A conspicuous aspect of the automotive and aerospace industries is that both are diversifying their material mix and part geometries. In the aerospace industry aluminum used to dominate. In the auto industry it was iron and steel. Now, however, both are looking at materials such as titanium, composites (graphite expoxies), aluminum alloys and plastics. This brings pressure for a greater variety of machine tools, or for processing a larger number of different parts on a single machine.

The Task Force identifies rapid progress in computer technology and associated electronic developments as "undoubtedly the single largest force for rapid change in machine tool technology" today. The major problem that confronts both the machine tool user and the machine tool builder is the rapid obsolescence of computer hardware. It is now estimated that an NC or CNC control system has a real life of three to five years only.

The full use of computer control systems has been constrained mainly by the relatively slow production of software (the programs that make computers run), and the Task Force expects this condition to continue until an adequate supply of programmers is available, including machine programmers as well as computer programmers.

Significant modifications of machine tool design will be required by the greater work piece materials mix. The Task Force observes that machine tool structures that were once satisfactory for most applications are no longer stiff enough. As an example, it mentioned aluminum can now be cut at much higher speeds than before, requiring high-speed spindles. Tool chatter, increased tool wear, inadequate chip handling, chips that collect in the machine's moving parts and act as an abrasive, are all examples of problems that need to be solved now. And this, the Task Force says, would seem to indicate some radically different machine designs.

Parts more complex

Part geometries, too, are having an influence. Single parts will be more complex. The experience of the aerospace industry, particularly, indicates that three major adjustments are almost inevitable. First, multipurpose or multifunction machines are required to make a larger variety of different parts; secondly, part feature accuracies must improve; third, multi-access machines are needed for complexly shaped parts.

And then there is the question of part quality. In addition to an increased need for basic dimensional accuracy and precision, there will be other aspects of part quality control. For instance, greater emphasis on product liability will necessitate some kind of proof that machined parts are functionally adequate for their intended use.

Today's new developments are emphasizing more timely communication, more accurate instructions, improved machine utilization, reduced tool cost, and optimized machining

Objectives of the Machine Tool Task Force

"Determining the state of the art of machine tool technology was the MTTF's primary assignment. Since material-cutting and material-removal machine tools constitute the largest portion (by dollar value or by number) of all machine tools, they were selected as the subjects of the MTTF survey.

"Two equally important objectives of the MTTF were, 1) to identify where advances in machine tool technology can be most effective and, 2) to document its findings and provide references for practical use of machine tool users, builders and designers.

"The MTTF was organized into four working groups, each of which investigated a different aspect of machine tool technology:

- Machine Tool Systems Management and Utilization
- Machine Tool Mechanics
- Machine Tool Controls
- Machine Tool Accuracy

(The results of each working group's studies are reported in "Technology of Machine Tools," prepared for USAF Wright Aeronautical Laboratories and Lawrence Livermore National Laboratory; for information, contact: MTTF Project Office, Mail Code L506, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, Cal. 94550; (415) 422-7600.)

Provocative issues

Adaptive control	Are there potential uses outside of the milling (aerospace) and grinding applications? Is it a developed technology for optimizing other cutting processes?
Flexible Manufacturing Systems	What are they? Are they the answer to the need for "flexibility?"
Standards	Who needs them? What kind? Who prepares them? When are they most appropriate to issue?
Accuracy of machine tools and accuracy testing	Correction vs. compensation? When and why should one test? Cutting tests vs. master part trace tests vs. geometric component accuracy measurements
Structural dynamics acceptance testing	Is it useful? Should one use an exciter, a cutting test, or a combination of both?
Government involvement	Support universities and their research? Subsidize (tax incentives, contracts, or grants) specific companies or groups of companies? Establish centres of excellence? Subsidize demonstration projects? Who owns the results? Who directs and controls?

cycle time. The shift is to automated monitoring of performance, computer aided machine shop control, fault diagnosis on the machine, automated work piece handling, computers for linking and controlling groups or series of machines (such as integrated machining systems), and increased accuracy, rigidity, and life of machine tools.

One of the main problems noted by the Task Force is the traditional fragmentation into relatively small, narrowly specialized companies in the U.S. machine tool industry. The Task Force asserts that this remains a handicap to technological advancement. What it often leads to is wastful reinventing of technology already developed elsewhere. Fortunately, the trend toward fragmentation is already diminishing, with some machine tool companies broadening their product lines by internal redirection or through mergers. The immediate result of this will be that some companies will be in a position to sell manufacturing systems and multipurpose machines. It is these "reformed" companies that will be the ones to compete for new user markets, the Task Force notes.

Another major problem to which the Task Force draws attention is the declining numbers of younger workers being attracted to the machine tool industry. The National Machine Tool Builders Association recently estimated a 25% shortage of qualified personnel in the industry at all levels.

The Task Force cites the inadequacy of the flow of technical information in the industry as another constraint on technological progress. Even though a lot of technical information is available, it appears that the industry generally is not taking advantage of it. For instance, standardization is virtually ignored in many areas and even existing standards are not uniformly implemented in the United States. Moreover, the Task Force found that U.S. participation in international standards development is generally inadequate and that domestic development of standards is particularly hampered by the absence of sufficient user participation.

Identify effective advances

The objective of the Machine Tool Task Force was not only to determine the state of the art of machine tool technology, but also to identify where advances in machine tool technology could be most effective and, as well, to document its findings and provide references for practical use of machine tool users, builders and designers, and to guide their efforts.

The Task Force's five volume report contains an extensive and wide-ranging list of recommendations, some of them with the potential of being implemented immediately or, at the most, over the next five years, while others would take as much as ten years to be realized.

The Task Force notes that for the implementation of its near-term recommendations the basic technology is essentially available. The problem is that the ability or desire to implement an action or to use new technology "is not always found among machine tool builders." Some of the recommendations, indeed, may strain a company's resources, and imply increased investment, which may not always be available. The implementation of the recommendations, therefore, are not only a technological matter, but also an economic one, the Task Force cautions.

In the area of computer technology in machine tools, the Task Force sees promise in the following three aspects: 1. Upgrading the capabilities of single machines (machine control); 2. Upgrading the capabilities of systems of machines (plant management); 3. Reducing off-machine processing time.

Computer assistance in the overall operation of the plant as a system of machines also has the potential for significant improvement in productivity and profitability, the Task Force says.

Automation on the way

Both management and machine related improvements were identified. For management functions, the classification and coding of parts and processes (group technology) can yield more efficient use of plant resources. Likewise, in large operations, the use of computer assisted scheduling and work flow control can have significant impact. Growth of automation toward more total plant control is actively on the way today. This growth is typified by flexible and integrated manufacturing systems, and will ultimately evolve into unmanned operation for reduced off-shift machine down time. Automation is also advancing in computer assisted manufacturing. Here implementation will be helped by the development of rational, adequately complete, relevant, and objective data bases, which will replace today's dispersed information from files, reports, and people's memories.

In machine related applications of computer technology, the general trend is for more capability in CNC, more memory and more functions. And some specific items for adapting computer applications that are not, in the opinion of the Task Force, receiving sufficient attention are standardized interfaces and the kind of modularity that would permit gradual growth and retrofit.

Specifically mentioned in the report are tool setting devices, diagnostic devices, automatic fixturing devices, programming and verification, programmable controllers, interface standardization, and exchange of part program data, all having to do with machine control.

A variety of home-made and commercial tool setting devices have been developed and are available for lathes. But integrated tool setting devices are needed for machines other than lathes, such as milling machines, and drilling machines.

Diagnostic devices needed

Diagnostic devices of various forms are now available on some machines, mostly for electronic system diagnosis and some also for mechanical system diagnosis. But, the Task Force observes, the mechanical system diagnostic devices are being developed on a trial and error basis and are often of a go/no-go type. One of the longer-term needs is the rational, logical method of designing total malfunction detection and diagnosis systems.

Automatic fixturing devices, too, exist in many instances, but suffer from limited part geometry applicability and environmental problems such as dirt on the indexing surfaces.

Off-machine process time associated with parts programming and verification are identified by the Task Force as a major growth area, particularly in the aerospace industry. More sophisticated programming tools, such as "bounded geometry" techniques and adequate verification tools would both decrease preparation for machining time and allow machine tools to be utilized for actual production at a high rate, the Task Force says.

An under-used resource for linking normally alien components for manufacturing systems, is the programmable controller, the Task Force says. Programmable controllers applied to machines or in operations where NC or CNC is not required can enhance the capabilities of the more "conventional" machines, which the Task Force says it recognizes will produce the majority of machined parts for the next decade.

The Task Force saw interface standarization as urgently needed to promote automation at the most rapid pace. It says it would encourage entrepreneurship in developing simple add-on devices, which would provide some reassurance to customers that are apprehensive that their new equipment will be obsolete before it is delivered.

Some recommendations are made for standardized plug-to-plug interfaces, standardized post processor software, and standardized communications protocol.

On the mechanical side, the Task Force specifically mentions the promise of stiffer machine tool structures. This would not only allow higher cutting forces, less deflection, better resistance to chatter, and reduced tool wear, but also could lead to the use of less structural material. Some parts made today by rough cut followed by a finished cut can be machined more economically in one pass with a stiffer machine tool. The Task Force says an improved capability to understand, analyze, test and quantify structural behaviour and parameters both statically and dynamically is needed.

Chatter is a significant factor limiting the metal removal rate. Research of chatter in machining has been under way at different organizations for the past 30 years, and the understanding of this phenomenon and of ways to minimize it has increased greatly, but further research will have to concentrate on the effects of work piece material and of cutting conditions and other aspects.

Machine tools under-utilized

The Task Force also notes that many of today's machine tools are under-utilized. It says only 5% to 6% of a stand-alone machine tool's available time is used for actual material removal. Only during that time is value added to the product. The utilization of machine tools can be increased by maximizing the cutting time, maximizing the material removal rate, minimizing maintenance time and shop delays, and reducing disturbances that cause idle time.

If that sounds like a motherhood issue, the Task Force found it necessary to draw more attention to the matter of maintenance.

"Maintenance often receives inadequate management attention, because it does not contribute directly to the value of the product," the Task Force says.

Nevertheless, it points out, maintenance and reliability are crucial to obtaining full utilization, particularly in systems of machine tools where the failure of a single component can shut down a complete line. **CMM**

Canadian participation in MTTF

Two participants in the Machine Tool Task Force were from Canada. They are Prof. Jiri Tlusty (left) Department of Mechanical Engineering, McMaster University, who was chairman of the Working Group on Machine Tool Mechanics and also participated in the working groups on Machine Tool Controls and Machine Tool Accuracy; and Ian Yellowley, Canadian Institute of Metalworking, McMaster University, who contributed as a reviewer in the working group on Machine Tool Mechanics.

MODERN ROBOTICS

The Right Jobs for Robots

Today's industrial robots are capable of handling a variety of jobs, ranging from simple material handling to complex assembly tasks. These guidelines will help you pick the right robot for maximum productivity and return on investment

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TOUGH AND TIRELESS, today's industrial robots are helping to make human drudgery a thing of the past in hundreds of plants throughout the world. And they're helping to improve productivity and reduce manufacturing costs.

Industrial robots can handle loads ranging from a few ounces to several hundred pounds (*Figure* 1). Robots can be trained to perform complex jobs, and through the use of sensors and adaptive controls, robots can cope with changing conditions in the workplace.

But committing to a robotics project, there are a few things that should be kept in mind:

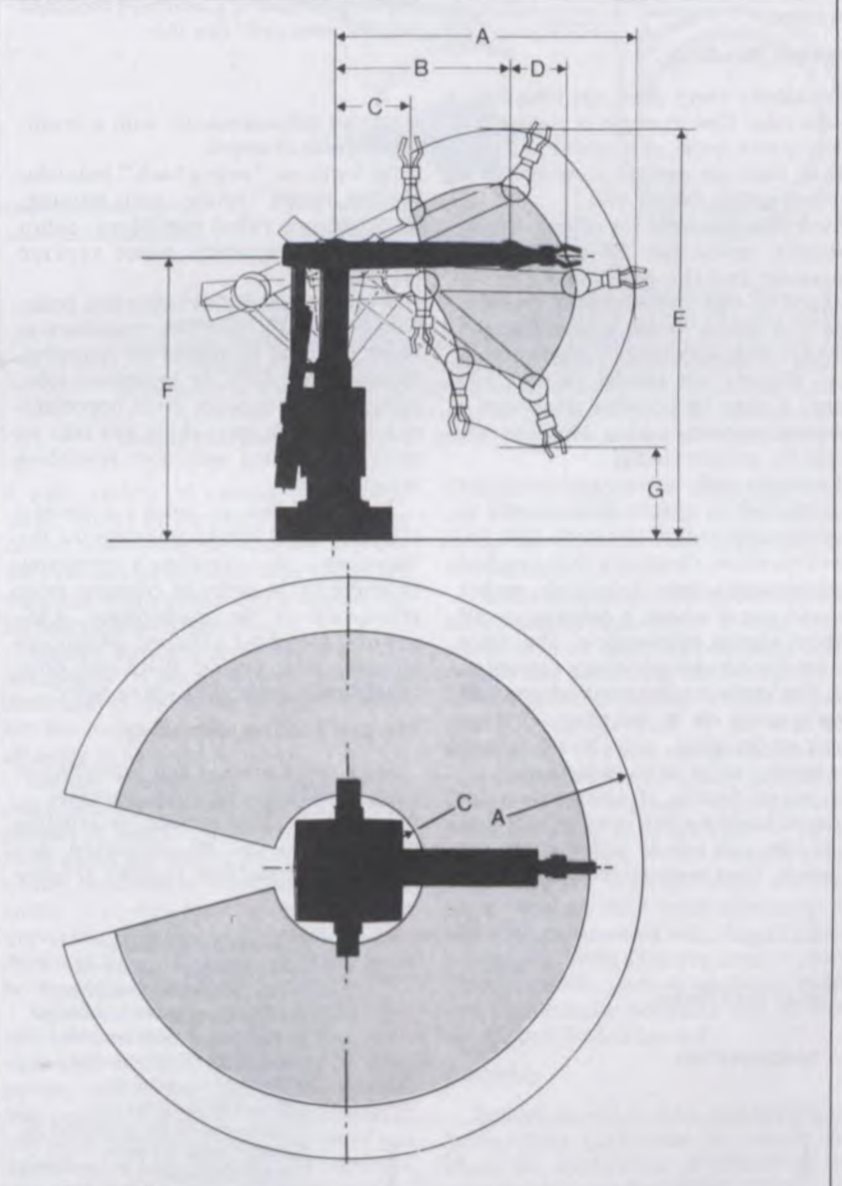
▶ Robots represent a substantial investment — an investment that must be analyzed as carefully as any other investment in terms of short-term and long-term payoff.

▶ It should be ensured that plenty of work exists for each robot. For fastest payback, robots should work three full shifts. After all, idle robots can't be laid off.

▶ Poorly planned production lines or worn out machines usually cannot be made much more productive with robots. Robots should be considered just one aspect of plant modernization, not a substitute for it.

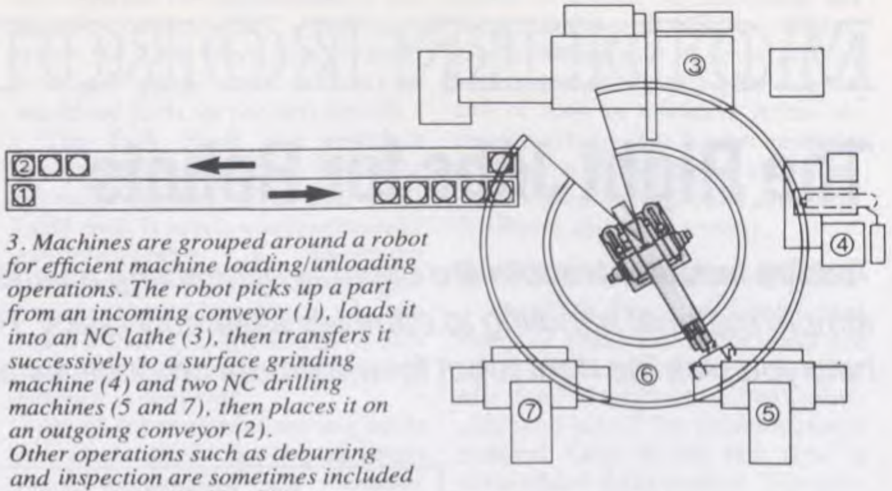
▶ Designs of parts and assemblies may have to be modified for most efficient utilization of robots.

▶ Robots should be put to work on simple jobs first. That way, the people who program, operate, and maintain the



Robot with handling capacity	Dimensions, mm A	B	C	D	E	F	G
6 kg	1159	670	289	200	1620	1150	414
60 kg	2288	1280	989	400	2150	1600	0

1. Operating range of a state-of-the-art industrial robot. The robot can handle jobs anywhere within the range shown. Its reach is greater than that of a person and it is far more powerful.



3. Machines are grouped around a robot for efficient machine loading/unloading operations. The robot picks up a part from an incoming conveyor (1), loads it into an NC lathe (3), then transfers it successively to a surface grinding machine (4) and two NC drilling machines (5 and 7), then places it on an outgoing conveyor (2). Other operations such as deburring and inspection are sometimes included in robot work cells like this.

robots will gain valuable experience. Such experience will increase the chance of early success when robots are put to work on more complex operations.

▶ A first robot purchase should be fully tooled and ready for production. This will help avoid mistakes. After experience is gained with the first few robots, untooled robots, rather than turnkey systems, may be the best choice.

▶ Many different companies offer industrial robots. A manufacturer should be selected that offers comprehensive training programs. And it should be remembered that the availability of service and spare parts on short notice is absolutely necessary to minimize downtime.

Materials Handling

Practically every plant has fatiguing, tedious jobs. One example is picking up heavy parts from one conveyor and placing them on another conveyor or a shipping pallet (*Figure* 2).

Such jobs are ideal for robots. These repetitive tasks can be easily programmed and the programs can be changed as task requirements change. Programs can be stored to eliminate the need for reprogramming of recurrent jobs. If parts are similar in size and shape, it may be possible to design a universal gripper, saving the time required for gripper changes.

Equipped with sensors and computer controls, robots can be programmed to automatically search for parts that are out-of-position. Generally they can find any part that's within their reach, pick it up, and put it where it belongs — all without human intervention. The robot can be wired to a supervisory computer, too, that keeps management informed of what's going on in the plant. If stoppages are frequent, appropriate corrective action can be taken immediately.

A major benefit of using robots for material handling operations is that they don't take rest breaks and don't go out to lunch. Thus material handling operations can be continuous, with a resulting increase in output.

As for those "strong back" individuals that robots replace: with training, they become robot operators, robot programmers, even robot service personnel.

Which brings up an important point: workers usually have little resistance to being replaced by robots for fatiguing, monotonous, dirty, or hazardous jobs, particularly if they are given opportunities to upgrade their skills and take on more challenging and more rewarding assignments.

Another point: in today's economic climate, most workers recognize the importance of a company's improving productivity in order to compete more effectively in the marketplace. Ultimately, the most efficient producers increase their market share and grow accordingly, improving job security.

Machine Loading/Unloading

With robot loading and unloading of parts, standard production machines — lathes, mills, drill presses, or grinding machines — can be converted into automatic production systems (*Figure* 3). While the robot may not load and unload parts any faster than a human operator (the actual load/unload cycle time may be somewhat slower), its tireless operation minimizes delays caused by human factors. As a result, output of the machine may be significantly increased.

Here are some pointers for successful, cost-effective applications of robots to machine loading/unloading jobs.

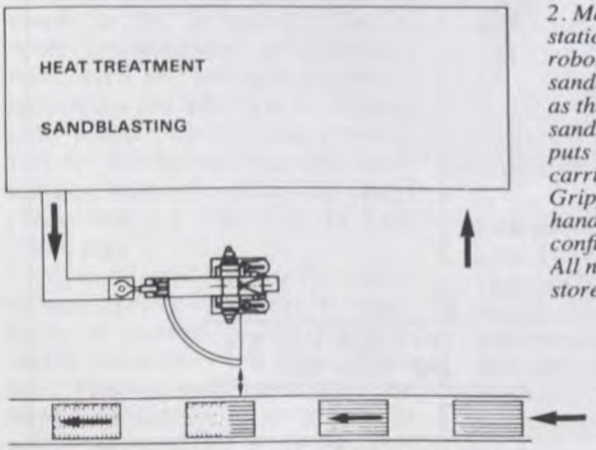
▶ The robot should be kept busy. For maximum return on the robot investment, three or four machines should be grouped so that one robot can serve all the machines in the group in sequence. Often, this will enable one robot to replace three or four human operators.

▶ All operations requiring worker intervention must be completely eliminated. Most machine operators clear chips away from tools and workholding fixtures by hand. Robots can't do this so some other means must be provided for clearing chips. In most instances chips can be blown out of the critical area by an automatic blast of high-pressure air or coolant.

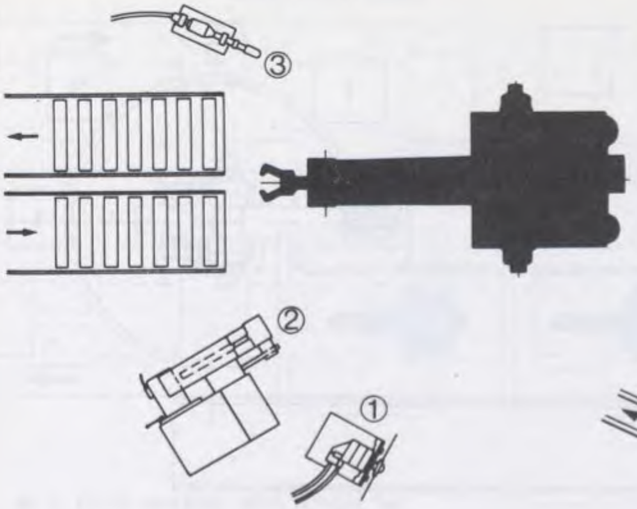
▶ Chucks and other workholding devices used in manually loaded/unloaded machines are sometimes inaccurate. This makes no difference in manual loading/unloading because human operators load parts into chucks and fixtures by sight and always compensate for deviations in chuck accuracy. Robots — unless equipped with sensors and searching devices — can't do this so more accurate chucks or other workholders must be installed before robots can successfully take over the job.

▶ To avoid interruptions in production, conveyors of incoming parts should be kept loaded. With an adequate supply of parts, machines can operate through normal rest breaks and lunch breaks, greatly increasing machine utilization.

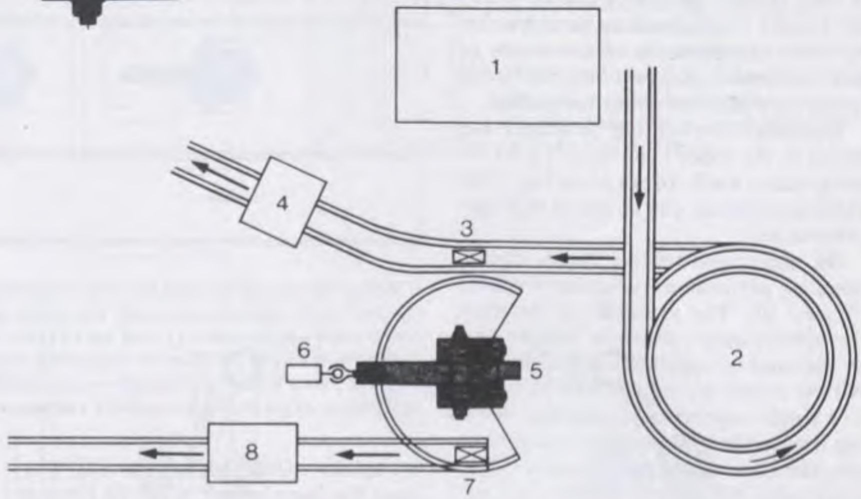
▶ If the shape or size of the part are



2. Material handling station for an industrial robot. The robot picks up sandblasted gear housings as they emerge from the sandblasting booth and puts them on pallets carried by a conveyor. Grippers can be adjusted to handle some 35 part configurations. All necessary programs are stored on a tape cassette.



4. Machine station for cleanup of castings by a robot. The station includes a rotary cutoff wheel or saw for removing gates and risers (1), a floor stand grinder for removing external flash (2), and a grinding head that cleans the interior of the casting (3). Castings are picked up from a roller conveyor and returned to a second conveyor. Mass storage of programs and a universal gripper allow a variety of different castings to be efficiently cleaned with minimal changeover time.



5. Station layout for deburring holes in a machined part. One robot (not shown) unloads parts from a machining center (1) and places them on a pallet carried by a conveyor (2). When the pallet reaches the pickup point (3) it stops and is picked up by the robot (5), which presents it to a rotary file (6) for successive deburring of several holes. It then places the part on a second conveyor that carries it to a honing machine. Elevators (4 and 8) are part of a pallet return system.

significantly changed by the operation, double grippers must be used — one for handling the part before machining, one for handling the part after machining. The gripper must hold the part securely, exerting higher gripping force than that usually exerted by a human operator. The reason for this is that the robot may move the part faster than a human operator and if the part escapes from the gripper, there could be damage to the machine, tools, or tooling. To minimize tooling costs and tooling changes when parts of different size and shape are run on the same machines, grippers should be of the universal type if at all possible.

When machines are loaded and unloaded by robots, one operator can usually tend one or two groups of machines. His or her primary job is to see to it that things go smoothly. Operation intervention is necessary only when there is a problem. With adequate operator training and experience, most problems can be quickly solved.

Cleaning, Deburring, and Polishing

Cleaning of castings, deburring of machined parts, and polishing of parts that require smooth finish are fatiguing, monotonous, dirty, noisy, and sometimes hazardous jobs that should be assigned to robots whenever possible.

When only one simple operation on a part is required, the robot can handle the tool. In most cases, however, several operations are required and it is best to have the robot grasp the part and present it to successive tools, usually in different machines (*Figure* 4). The machines should be grouped within easy reach of the robot.

Robots are especially valuable for cleaning castings. The work station can include a rotary cutoff wheel or saw for removing gates and risers, a floor stand type grinder for removing external flash, and a second grinder for internal cleanup. Stations of this kind can handle a wide variety of casting shapes and sizes, simply by varying programs. The correct relationship between the tool and the work can be maintained by equipping the robot with a sensor and a control that includes a search function.

Shorter throughput times, fewer interruptions (if the supply of castings is maintained) and more uniform quality are the major benefits netted from the cleaning of castings by robots.

Similar benefits are obtained when machined parts are deburred by robots instead of human operators (*Figure* 5). Both metal and plastic parts can be efficiently deburred in robot deburring stations. Use of stored programs and universal grippers will optimize productivity when a variety of parts must be deburred in the same station.

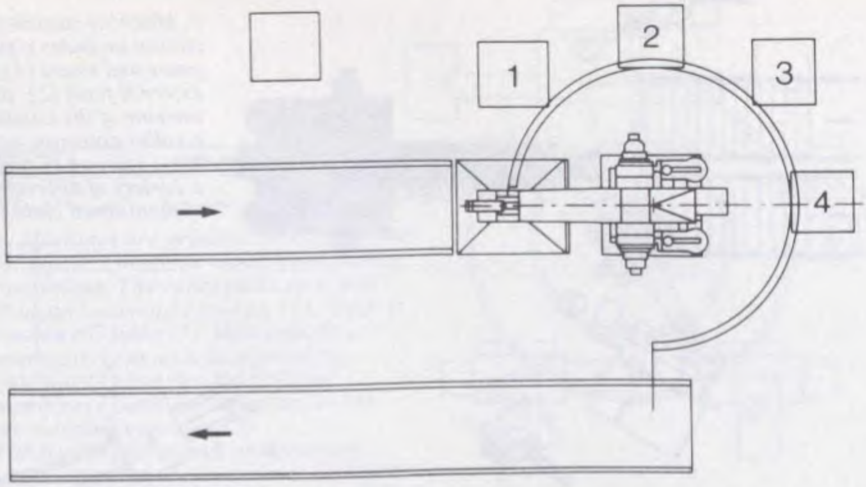
Several control options improve the efficiency of deburring operations with tools such as rotary files (*Figure* 6). One option, soft servo, enables the desired tool contact pressure to be maintained at any point in the program. Tool wear and variations in part shape do not influence the contact pressure. A second option, adaptive control, enables the robot to select appropriate feedrates for various conditions. A fast feedrate is maintained until the tool encounters a burr. At that point, the tool withdraws slightly, then feeds into the burr at the slower feedrate necessary for deburring without excessive tool wear or deflection. When the burr has been removed, the fast feedrate is resumed.

Polishing stations, like deburring stations, usually incorporate several operations such as applying polishing compounds and presenting the workpiece to several different buffing wheels or polishing brushes (*Figure* 7). As with deburring, use of a soft servo enables contact pressures for optimum polishing results to be obtained, regardless of polishing wheel or brush wear, or variations in part shape. When items of complex shape are to be polished, addition of an optional third wrist movement (a sideways movement) will simplify programming. With adaptive control and a suitable sensor, parts of uncertain shape and in indefinite positions can be efficiently polished (*Figure* 8).

Assembly

Typical assembly jobs that are being successfully performed by robots include the application of adhesives for adhesive bonding operations (*Figure* 9), spotwelding, and arcwelding. Less widely performed is mechanical assembly by robot.

In typical assembly applications, the robot usually holds a tool — an adhesive applicator, a spotwelding gun, or an



7. Robot-operated station for the polishing of parts. When a part reaches the end of the infeed conveyor, the robot picks it up, presents it to a polishing compound applicator (1) and successive brushes and buffers (2, 3, and 4). It then places the part on an outgoing conveyor. The robot can be equipped with an extra wrist movement — a sweeping motion — that aids in the polishing of parts with complex curvatures.

arcwelding torch. Component parts are mounted on assembly fixtures or positioners prior to the bonding or welding operation.

The big advantage of robots for spotwelding operations is high speed. When the distance between spotwelds is an inch or two, several spotwelds can be made per second — faster than most human operators. Positioning of the welds is more accurate, too, resulting in better appearance and more uniform quality.

Typically, spotwelding programs are stored in the robot's memory. Up to 30 programs, each incorporating 250 welding positions, can be stored in a tape cassette unit.

On many spotwelding lines, operations are performed by teams of robots (*Figure* 10). For example, in automotive spotwelding operations, robots may be stationed on opposite sides of the line. All the robots on the line can be linked to a single supervisory computer, making it possible to store large numbers of programs and easily re-allocate welding tasks when different assemblies are run through the same spotwelding line. Programming the robots is usually simpler than retraining human operators and robots never forget how to do the job right.

Because robots work quickly and continuously, they are ideal for arcwelding operations (*Figure* 11). It's estimated that robot arcwelders are three times more productive than human operators. All robot-made welds are identical and of uniformly high quality. It is relatively easy to control the weld sequence to avoid problems with thermal stresses in the material. If any distortion occurs, it will be the same in every workpiece. Once an arcwelding program has been set up, it can be rerun at any time.

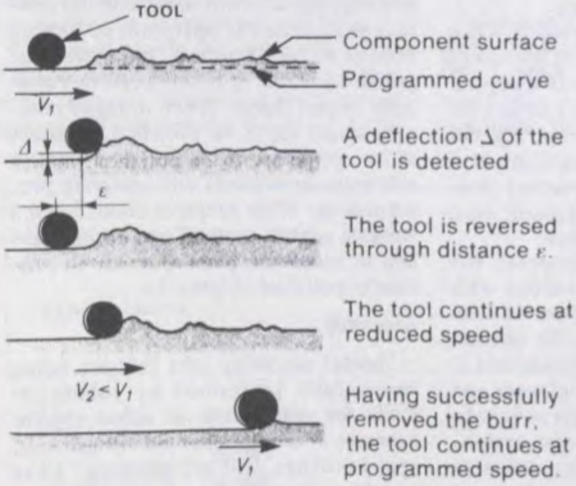
In robot arcwelding, all the human operator has to do is set up the job. If the job is set up on a positioner, the positioner can be controlled by the same program that controls the robot. The operator doesn't have to be in the immediate area when the arcwelding operations are being performed; he can be well away from fumes, heat, and glare.

Incidentally, robots don't have to be stationary. Welding robots (and other robots, for that matter) can be mounted on tracks so that they can automatically move from one welding station to another. This makes it possible to set up one job while another one is being run, or to perform operations on long workpieces with a single robot. The robot typically is positioned by a servomechanism.

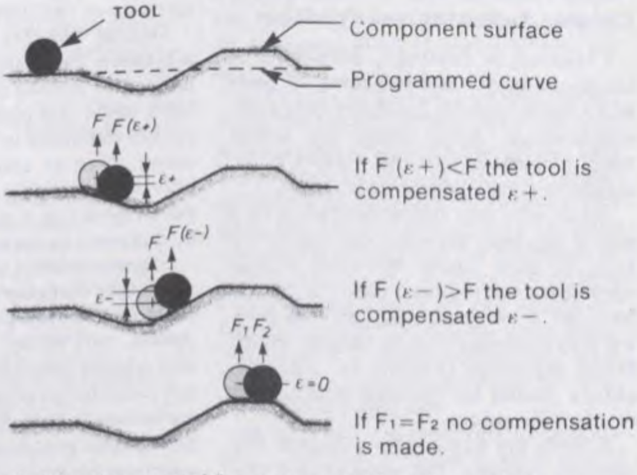
Robot Safety

It's a mistake to assume that when robots are put to work, conditions are automatically made safer for people. True, robots may take over some hazardous jobs. But like all pieces of production machinery, they have to be treated with respect to avoid accidents. The following safety guidelines are pertinent:

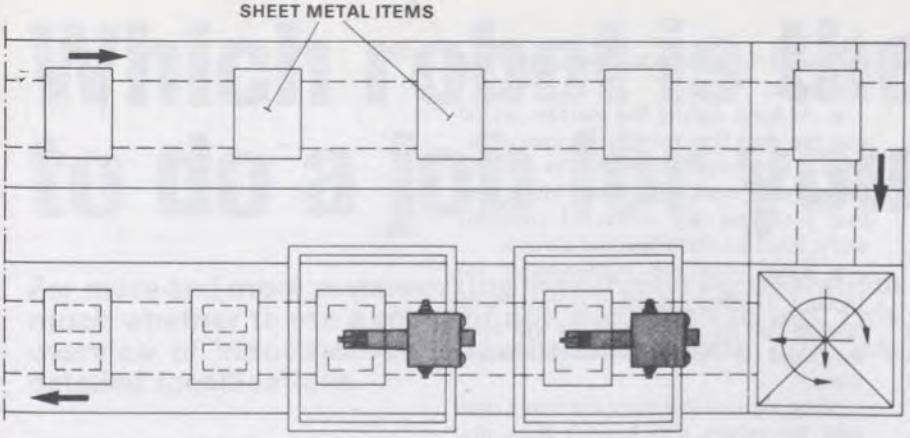
▶ Robot programs, equipment, and sensors must not be solely relied upon to protect human safety.



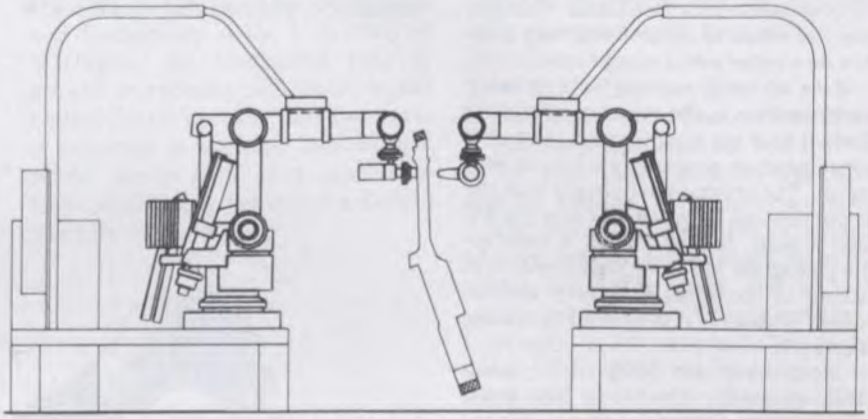
6. Adaptive feed control for a deburring operation. Tool is fed at a fast rate while searching for a burr. When a sensor detects deflection of the tool, indicating the presence of a burr, the feedrate is slowed for efficient deburring action. After the tool removes the burr, the fast programmed speed is resumed.



8. Adaptive control for contour tracking by a robot. This enables the robot to follow a path that is not clearly defined and which deviates from the programmed path. With adaptive control, tools such as polishing brushes can maintain correct pressure for quality polishing, regardless of the changing part contour. Adaptive control also compensates for wear of the brush.



9. Two robots are used to apply adhesive to sheet metal parts on conveyor prior to an adhesive bonding operation. The robots distribute the adhesive from an extrusion head in programmed patterns. The amount can be varied by changing the speed of application or by adjusting a flow regulator in the extrusion head. Stiffening plates are added in the next operation, and bonding is accomplished by a combination of heat and pressure.



10. Setup for spotwelding of automotive body panels by two robots that are programmed to work in unison. A separate programmable control system controls the conveyors and fixtures, and also informs the robot which panel design is to be welded. Programs for the robot are stored in tape cassettes for quick changes.

▶ A robot working area should be enclosed by barriers that prevent people from entering the area while the robot is working. Access gates should be interlocked with the control system. It stops working and is put on hold whenever the gate is opened. The robot should be capable of continuing the program from the point where it was stopped after the intruder has departed, the gate has been closed and the program manually restarted.

▶ Emergency stop buttons capable of stopping all robot motion and cutting off all power to the robot must be provided in easily accessible locations well out of the working range of the robot. All people in the area should know where the emergency stop buttons are located.

▶ Signals and power connections to the robot must not create hazards if they occur at the wrong times or if they are inadvertently cut off during operation of the robot.

▶ Robots must be programmed, operated, and serviced only by trained people.

▶ If it is necessary for people to be within the working range of a robot during programming, great care must be taken to prevent injury that might occur in the event of a robot malfunction.

The most versatile robots are capable of moving with six degrees of freedom.

People should stay out of areas where they might be pinned if the robot moves in an uncontrolled fashion.

▶ Robot operators must know what their robot is programmed to do so they can anticipate its actions. Programs written by others or stored in robot memories must be documented in written form so the programs can be studied by the operator before he puts the robot to work.

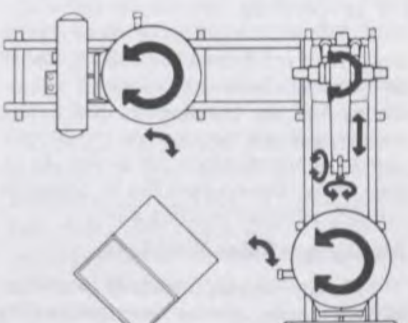
▶ Electric cables and pneumatic or hydraulic power lines must be located where they cannot possibly be damaged by the operation of the robot or robot-related equipment.

▶ The work performed by the robot should not cause safety or health hazards in the workplace. For example, if the operation produces fumes, they should be vented so they do not reach neighboring areas where people work.

Robot operation may require additional safety precautions. It is wise to have a safety engineer with robot experience check out the entire robot installation before regular production operations are started.

Picking the Right Robot

The most versatile robots are capable of moving with six degrees of freedom: rotary movement, radial arm movement, vertical arm movement, rotary wrist movement, wrist bend, wrist sweep, and horizontal travel. These six axes of movement enable movements to be programmed that duplicate those of a human operator in performing a job. If two hands are needed for the task, two robots can be used. Unlike human operators, some robots work just as well upside down as rightside up. If the floor area of a robot workplace must be kept clear, the robot can be inverted and mounted overhead.



11. Robot arcwelding station. Components to be welded are fixtured on either of two rotary positioners. The robot can travel from one positioner to the other so one job can be set up while the other is being welded.

In selecting a robot, make sure it has the number of degrees of freedom, reach, and load capacity required, of course. And speed of movement should meet job requirements. The robot should be capable of keeping ahead of the job.

Pneumatically powered, hydraulically powered, and electrically powered robots are available. Electrically powered robots have the advantage of quiet operation. Their most important advantage, however, is that their servosystems allow the movements of the robot to be controlled with great accuracy. The repeatability of movements of some electrically powered robots is ±0.008″ (0.20 mm).

Controls may be of the point-to-point or continuous-path type. Point-to-point controls are entirely satisfactory for most material handling and machine loading/unloading applications. For applications requiring curvilinear motion, a control system is needed that is capable of continuous-path movement. Features such as adaptive control will help a robot do a better job in many cases.

Ease of programming is a primary consideration in the selection of robots. Robots that are programmed through a teach pendant generally are easy to program. The programmer simply puts the robot through its paces on a new job under manual control. When a satisfactory program has been developed, it is stored in the robot's memory and recalled whenever it is desired to run the same job.

Most robots are designed for maximum versatility. Over their long lives, they can be applied to many different types of jobs. If the robot will be dedicated to the same type of job throughout its life, specialized robots are worth considering.

For example, robots that are designed for spotwelding operations are available. The drive systems of these robots are often modified for rapid, short movements between spotweld positions. And the transformer and power supply unit are mounted on the robot's arm to minimize electrical losses. As an alternative, these robots can be equipped with transformer welding guns.

Managing a Robot Workforce

The big interest areas of manufacturing engineers or manufacturing managers are improving productivity and quality, and keeping them at high levels.

This is why the right robots must be put to work on the right jobs. Robots cannot be managed — after all, they're just unthinking machines. But people can be managed to make robot operations successful. Some tips follow:

- ▶ Make sure that everyone concerned with robots — operators, programmers, service people, engineers, and production supervisors — is properly trained. Unless these people know what they're doing, prospects for successful robot operations are small.
- ▶ Establish preventive maintenance programs for robots and the equipment they work with to reduce problems to a minimum.
- ▶ At least during the startup period and the first few months of operation, keep a close eye on the robots and the people who work with them. Make sure that problems are corrected immediately; don't let them become chronic.
- ▶ Keep your top management informed of robot success stories, with bottom-line information. This will open the doors for more robots in your workforce.

Keep in mind that there are many right jobs for robots that haven't been discussed. Spray painting, for example, automatic inspection, packaging for shipment, or pressworking operations. ■

Which robot is the one to do a job for you?

For more and more metalworking manufacturing operations the question no longer is so much whether to use a robot or not, but which to use. This selection guide provides an overview of industrial robots available in North America, with a comparative list of detailed specifications.

When Canadian Machinery and Metalworking conducted its first Survey of Industrial Robots two years ago, predictions were that robotics technology was about to make major inroads as a production tool in manufacturing industry.

Subsequent events have borne this out. Since that time, the field has burgeoned, and, if anything, this trend can be expected to accelerate.

According to Donald Smith, a director of the Industrial Development Division of the Institute of Science and Technology at the University of Michigan, the compound rate of growth in robotics utilization in the United States over the next five years is expected to average 30% in real terms. Smith drew that conclusion from preliminary results of a Delphi study he is conducting.

What this means in terms of actual numbers installed varies according to different interpretations, but two specific examples serve to illustrate the general trend.

In 1977, General Electric in the United States had 10 robots installed. A year later that number had grown to 70. Last year, the total was 200, and by 1984, G.E. expects to have 1,000 robots in operation. General Motors had 300 robots working in its plants worldwide three and a half years ago, primarily in spot welding. Last year, 1,200 were installed or on order. By 1990, the prediction is there will be 14,000 robots in GM plants, 5,000 of them for parts assembly, 4,000 for machine loading, 2,700 for welding, and 2,300 for painting.

Don't have to be big

These are the sort of figures being cited by large robot users. But what about small companies?

Joe Engelberger, president of Unimation Inc., pointed out to an audience of corporate managers at a conference sponsored by Robotics International of SME in Chicago last fall, that many robot applications are more typical of the small plant environment than they are of large manufacturing operations. He revealed that about half of the machines his company sells today go into large plants and the other half into small and middle-size companies.

Indicating just how small you would have to be not to be able to use robots, Engelberger added a comment that Unimation salesmen are told never to sell a robot to any customer who hasn't the potential for five.

"If it is a small company that runs

Graco OM 5,000 spray painting robot is designed for use in automated painting systems on a one-shift basis, the economics aren't there yet," he explained.

At the same time he pointed out that many small companies can make use of machining centres. "Machine loading is the biggest single application we have," he said.

Besides machine loading, current applications are predominantly in pick and place jobs, and continuous-path manufacturing processes, such as painting, arc welding, drilling, writing and grinding.

More data available

Since an increasing number of robots are installed performing these jobs, more data are becoming available indicating the kind of productivity improvements available.

Last summer, Unimation's vice-president, Stanley Polcyn, gave U.S. government officials an outline of the economies that are realized by utilization of industrial robots. In die-casting, he said, the variety of tasks robots perform include machine unloading, quenching, trimming, spraying, pouring and metal inserts.

"We have documentation of before and after studies that prove productivity increases anywhere from 8% to 35%," he said.

In stamping, he indicated it is common to increase press utilization by 20% to 25% and to directly increase productivity by the amount of that increased utilization.

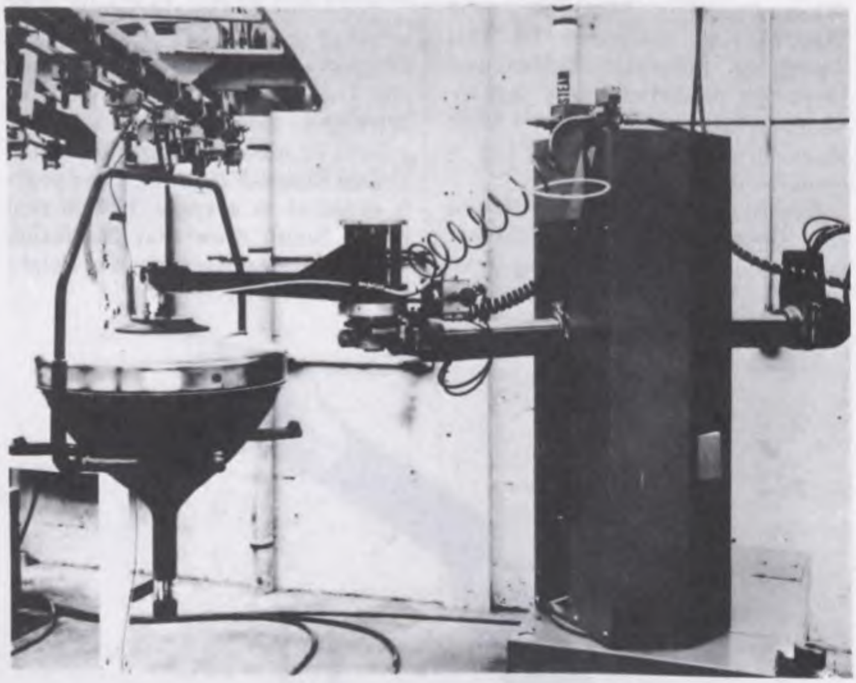
In welding, arc times are increased by two to eight times.

More opportunites are presented by foundries. Manual handling of flame-burning equipment is slow and dangerous. Robots provide not only improved quality and safety but reduce gas consumption by 60%, according to Polcyn.

Forging is another dangerous, hazardous area in which robots thrive. And in investment casting, robots are making moulds, dipping them into slurries and reducing the amount of scrap and rework by 30% to 50% while increasing the output by three to five times.

The attraction of using robots for machine loading lies in the opportunity to utilize a large capital investment without shutting it down for any one of a variety of reasons. A 6% improvement in machine tool utilization is not uncommon.

Many observers in the robot industry are convinced that one of the biggest potentials for robot application lies in the field of assembly, although there are still many problems in this area the robot makers haven't licked as yet.



Prab Model E robot combines servohydraulic power on major axes with electric drive on end-of-arm-axes

Data needed

Many plant managers today, however, no longer need to be convinced of the weird and wonderful miracles robots can perform for them. What they need to know is: can I solve my problems by means of a robot and, if so, which robot?

In any evaluation of a given robot application the moment will arrive, sooner or later, and provided you have decided to go through with it, that you have to match your engineering requirements against sets of specifications. To help you do this, this survey lists the specifications of industrial robots available in North America. It will give you an idea of what is available and what is compatible with your needs and with your financial resources.

Any generalized description of the major function parameters of industrial robots tends, as with any equipment, to be limiting when applied to the individual machine. Various robot makers have their own preferred ways of describing their products. The following should only be seen as an attempt to provide the potential user with a set of descriptive terms on the basis of which a comparative evaluation can be made over the broadest possible range of capabilities. It is, in other words, a means for making the initial assessment of what's in the ballpark and what's not.

Axes of motion

To a great extent, the robot's axes of motion, or degrees of freedom, determine the complexity of the aggregate movements it is capable of. The term, in essence, expresses the number of moving joints.

Arm movement

This defines the robot's "reach," or "work envelope." The work envelope usually has one of three shapes, cylindrical, spherical and spheroidal, depending on the basic configuration of the arm and on the major axes of motion. For practical purposes, the description of the work envelope can be simplified by citing only its three major parameters: Degrees of rotation about the centre axis (*horizontal* arm sweep); *vertical* motion at both minimum and maximum arm extension; and *radial* arm extension, measured from the centre axis. It is a simplification, but it gives a rough idea.

Wrist movement

Although wrist movement can make a minor contribution to the shape and size of the work envelope, its main significance is the ability to orientate the gripper or any other end-of-arm tooling. *Pitch* refers to wrist movement in the vertical plane;

yaw represents movement in the horizontal plane (swing); and the ability to rotate is denoted by *roll*.

End of arm speed

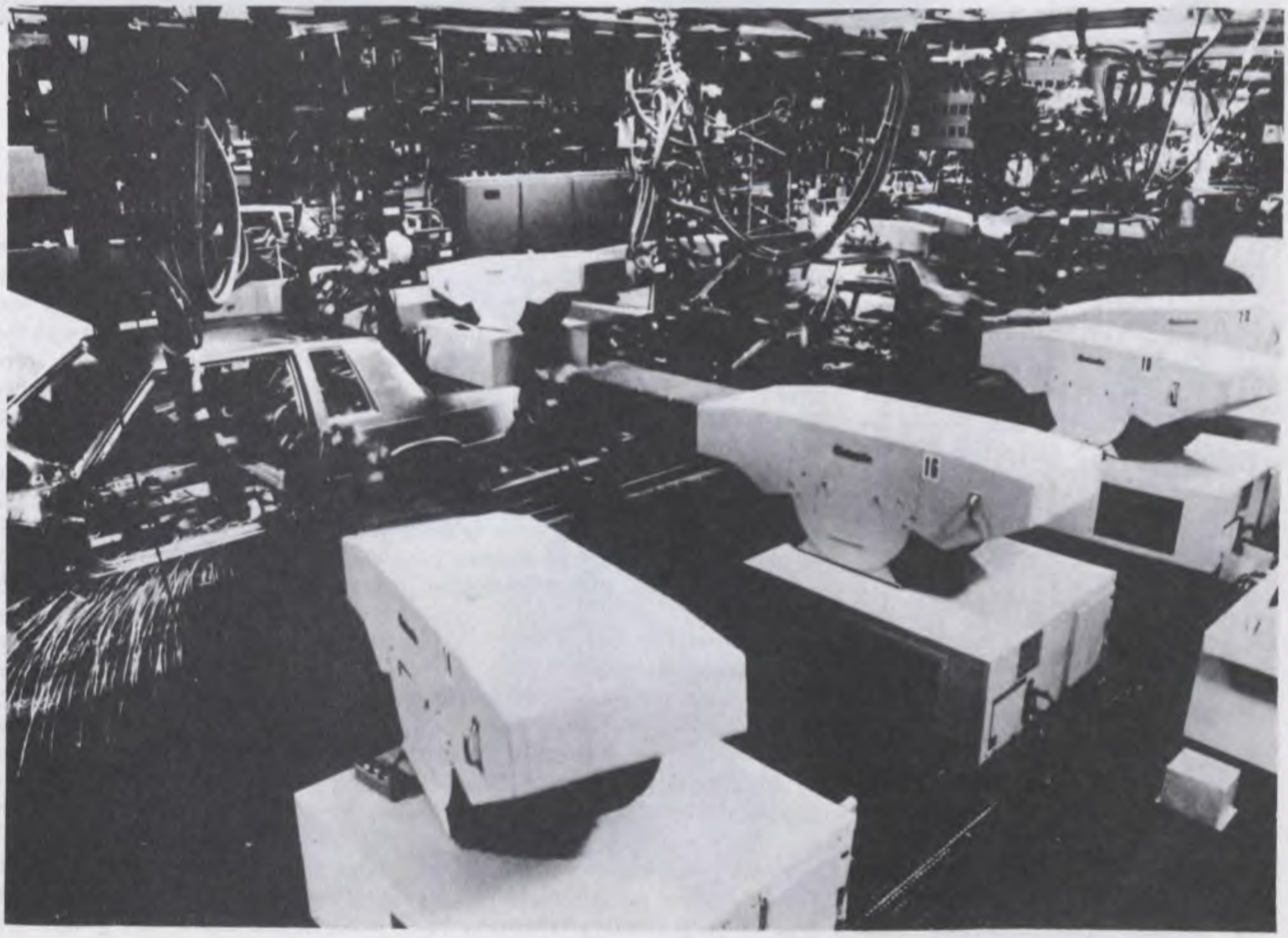
You can get more arguments about a robot's end of arm speed than you can shake a stick at. It varies depending on the axes about which the arm is moving, its position in the work envelope, and the load being carried, to name a few factors. Keeping that in mind, a reasonable, though somewhat simplistic, question to ask still is: How fast can the gripper get from an arbitrary point A to an arbitrary point B in the envelope, empty, and how fast can it move back from B to A fully loaded? The best answer you can expect is a ball-park figure, unless you are willing to accept your answer in the form of a differential equation, or something like that.

Weight carrying capacity

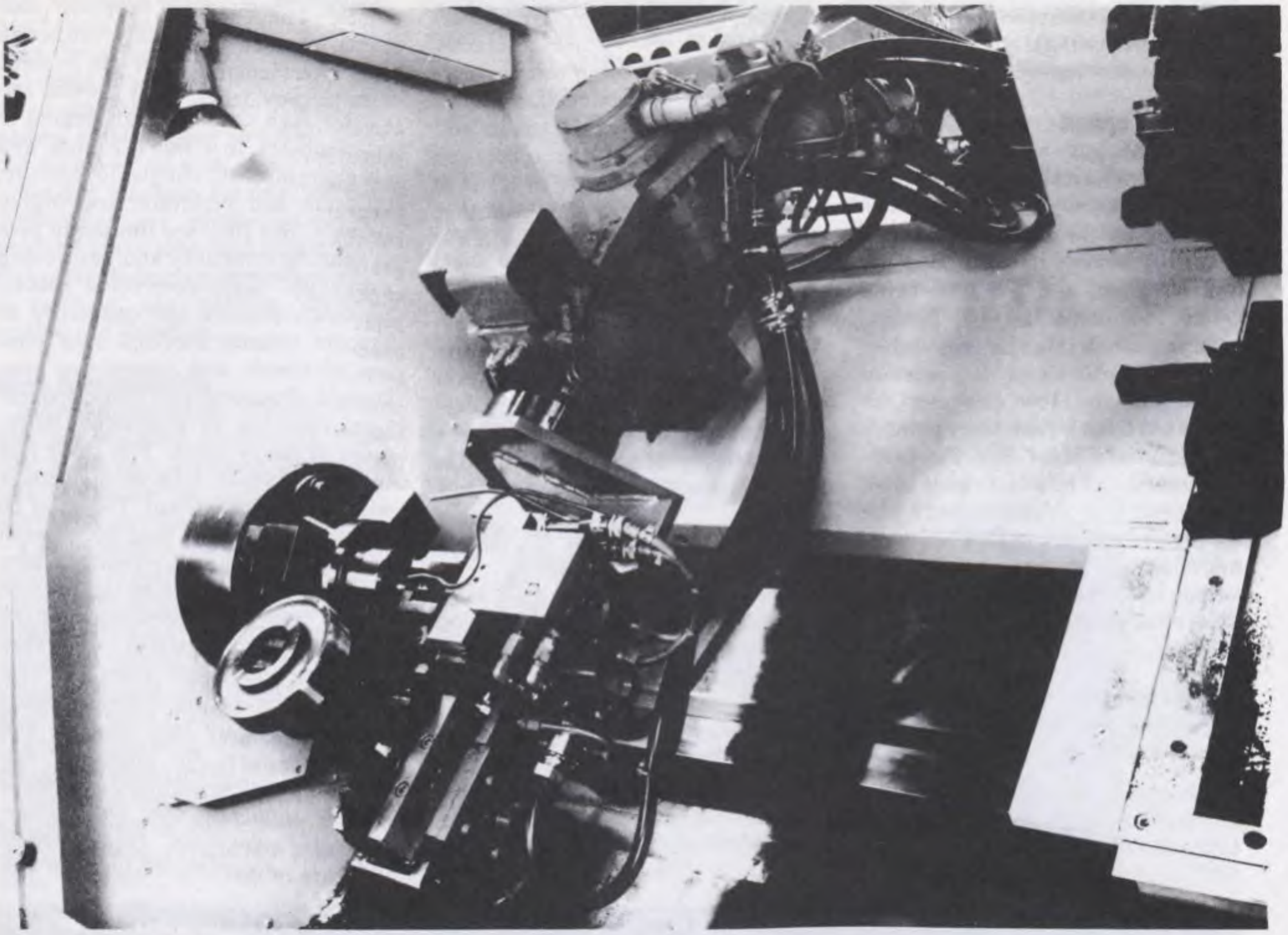
You can get almost as many arguments about weight carrying capacity as about end-of-arm speed, primarily because the two are so closely related. You are still in torque/inertia/momentum/acceleration territory here. Still, it is relevant to ask: What is the weight the robot can practically move from A to B? It is defined as the maximum load that can be carried, at low speed (this is given as a percentage of the maximum speed), and as the load that can be carried at normal operating speed. Again, the answer is a ball-park figure, and you can take it with a grain of salt. (Some robot makers circumvent the issue by stating the robot's static load capacity, but what good is that? You want to get the stuff moved!)

Control

Some people like to talk about low-, medium-, and high-technology robots. The inferiority/superiority inference it carries, well, it just is not fair, and what does it tell you anyway? Much more revealing—and technically precise—is to classify robots according to the type of control employed. *Non-servo* robots are the ones sometimes referred to as "end-point" or "limited-sequence" machines. They move between end-points on each axis only (although some intermediate stops can in some cases be provided). They provide relatively high speed; a high degree of repeatability, to within 0.25 mm; and are low in cost, simple to operate, program and maintain, and highly reliable. But they are limited in programming versatility and positioning capability. *Servo-controlled* robots, typically, provide the capability to execute smooth motions with controlled speeds and sometimes even control of acceleration and deceleration, resulting in controlled movement of heavy loads. You can't just throw a 1,000-lb. load through space without a servo control. They can be programmed to any position on each axis anywhere in the envelope; more than one program can be stored. End of arm positioning accuracy is of the order of 1.5 mm. (0.050 in.). These machines are more complex, and therefore involve more sophisticated maintenance, are less reliable, and more expensive. An important distinction in servo-controlled robots is between *point-to-point* and *continuous-path* machines. Point-to-point robots are programmed for each end



Unimation Unimate robots place over 3,000 spot welds on Chrysler Aries K and Reliant K cars



Cincinnati-Milacron T^3 robot enters machine tool enclosure through rear to remove finished part from chuck

of arm position, without regard for how they get from one point to the next. They are represented primarily by the largest, heaviest-load-capacity machines. In continuous-path machines, on the other hand, the paths that the end of the arm takes through space are defined by the program. Continuous-path robots are smaller and lighter than point-to-point robots, have higher end of arm speeds, and load capacities are generally less than 10 kg. They are used mainly for applications such as spraying paint, arc welding, and grinding and polishing. Some machines, incidentally, act as if they are in the continuous-path category, but really are point-to-point devices; it's just that they provide the capability for defining one heck of a lot of points; each point, nevertheless, must be programmed in.

Memory

The robot memory is part of the controller. It stores the commands that have been programmed in and, through the controller, tells the robot what to do and when. Since the type of memory determines how commands are stored, it gives an indication of the sophistication of the program it is possible to execute, and the degree of flexibility in programming that is possible. *Mechanical step sequencers* include devices such as rotating drums. Other memory devices are pneumatic systems such as *air logic* controllers, electrical memories such as *patch boards* and diode matrix boards and step switches and, finally, electronic memories, which include *magnetic tape* cassettes, floppy *discs*, and *microprocess*-type devices (ROM, RAM, PROM). It should be pointed out that a combination of memory devices is often employed, such as tape cassettes in conjunction with a microprocessor-type memory.

Programming method

There are three basic approaches to telling a robot what you want it to do: Offline—by presetting the cams on a rotating stepping drum, for instance, or connecting up air logic tubing (for non servo robots, programming also includes the setting of limit switches on each axis). This type of programming is usually referred to as *manual*, and is associated with mechanical, pneumatic and electrical memories. As soon as you get into electronic memories, with the potential for more complex programs, you would be all day if you are lucky, or all week if you are not, just wiring up your robot. Instead, what you do is either push buttons, or, and this is almost literally true, you take your robot by the hand and show it what to do. The push-button approach, referred to as *lead-through*, consists of manoeuvring the robot arm from one desired position to the next by means of the control console; all you have to do is push the "record" button at each point, and, once the program is complete, the robot will repeat this sequence from point to point, *ad infinitum*. If you are not so much interested in the exact positions through which the robot arm will sweep, but more in the actual trajectory, you could still program it simply by defining a lot of points. A lot easier would be, though, to use *walk-through* programming; you physically guide the robot arm (or a special teaching arm) through the desired motions, and the robot will repeat *exactly* what you taught it, including any goofs.

Memory capacity

There are several ways memory capacity can be expressed. Simplest is to indicate the number of steps or distinct motions and functions the robot can perform in a single program.

Positioning accuracy

How closely can you program a robot hand to go where you want it to go? Or to put it in another way, how closely should you position a part for the hand to be able to pick it up? Unless equipped with a special sensing device, a robot cannot see what it is doing, so this is an important quantity.

Repeatability

Once you have got a robot hand to go where you want it to go the first time, repeatability will determine how close to that same spot it will return—again and again, and again.

Power

What makes the robot move? It is not a moot question. For one thing, the working environment has a lot to do with the choice of power system. Many of the same criteria apply here as with other types of industrial machinery.

Cooling

Some robots need cooling. The main thing is to make sure you know which type of cooling, and you better talk to your plant engineer, too.

Maximum ambient operating temperature

They say robots can stand the heat of any shop and keep going when a man would long since have dropped in his tracks. Well, there *are* limits. To be sure, end-of-arm tooling may take a lot more before burning its fingers, than the arm and base, and the control console a lot less, particularly if it has a mess of computer logic inside. All of this has got to do also with how much cooling may be required.

End of arm tooling

This is what goes on the end of the arm to do the job. Mostly, it will be a gripper, often referred to as the hand. But it doesn't have to be a hand. Actually, you can put anything you like on the end of the arm. Besides grippers, vacuum pads are the most common off-the-shelf tooling, but put on anything you desire (if you want to pay for custom design)—put on a foot if you like, and you can make it kick the the garbage can.

Interfacing

Except in a few applications, most robots need to communicate and interact with the outside world. This can take the form of simply on/off signals by means of electrical, or pneumatic, contacts, or consist of more complex electronic signals. *Inputs* are the number of lines over which the robot will accept signals from the outside world, and *outputs* are the lines over which it will send signals to external equipment.

Preliminary planning

The objective of this article is to assist the potential robot user in doing some of the preliminary planning. Hopefully, what it will lead to is the possibility to identify two or three serious candidates. That will only be the beginning of the real nuts and bolts evaluation, talking brass tacks with the manufacturers.

One hazard in compiling a listing such as the one that follows is missing someone. From the outset, the objective was to include *all* North American sources of industrial robots and all of the products they offer.

The companies whose names are on the list are, as far as could be ascertained, suppliers of one or more types of industrial robots. Unfortunately, some failed to respond to our requests for information, and their product(s) could not be included. That doesn't mean they might not be worth a try if you are looking for a robot. Perhaps you'll have better luck than we did.

In the case of each manufacturer, an attempt was made to list each available model separately. Only where too much overlap in the specifications for very similar models occurred were they combined. And it goes without saying that in some cases optional configurations are available which space did not permit being listed.

The data in the following pages are based on information provided by the manufacturers in the form of answers to a questionnaire. Bear in mind that in some cases the answers are, of necessity, interpretations and/or approximations. We verified each answer as well as we could, and we believe they will provide the user with a reasonable basis for comparison. But the final proof of the pudding is the manufacturer's own spec sheets.

Thermwood Series 7 pick and place robot is programmed by lead-through teach method, with programmable speed

Source	**ASEA**	**ASEA**	**ASEA MHU**	**ASEA MHU**	**ASEA MHU**
SPECIFICATIONS Model	**IRb-6**	**IRb-60**	**Minior 301**	**Junior 305**	**Senior 415**
Axes of motion	3, 5 or 6	3, 5 or 6	4	6	6
Movement					
arm—horizontal (degrees of arc)	340	330	180	200	360
vertical (min. mm, max. mm)	520-1510	170-1900	150	945-1095	1175-1675
radial (mm)	950	2000	300	1225	1670
wrist—pitch (degrees of arc)	180	195			
yaw (degrees of arc)		360	180	180	180
roll (degrees of arc)	360	300			
End of arm speed					
average max. unloaded (m/s)					
normal operating, loaded (m/s)	1.0	1.0	1.0	0.75	0.3
Weight carrying capacity					
max. at low speed (kg @ %)	10 @ 60	100 @ 60			
at operating speed (kg)	6	60	1	5.0	15
Control					
non-servo			✓	✓	✓
servo—point to point	✓	✓			
continuous path	✓	✓			
Memory					
mechanical step sequencer					
air logic					
patch board (electrical)					
magnetic tape/disc					
microprocessor	✓	✓	✓	✓	✓
other (specify)					
Programming method					
manual			✓	✓	✓
lead-through	✓	✓	✓	✓	✓
walk-through					
Memory capacity (no. of steps)	250-15,000	250-15,000	1000	1000	1000
Positioning accuracy (± mm)	0.1	0.2			
Repeatability (± mm)	0.05	0.1	0.1	0.1	0.1
Power—hydraulic					
pneumatic			✓	✓	✓
electric	✓	✓			
Cooling—air					
water			✓	✓	✓
none	✓	✓	✓	✓	✓
Max. ambient operating temperature (°C)	50	50	50	50	50
End of arm tooling					
off the shelf—gripper	✓	✓	✓	✓	✓
vacuum pad					
other (specify)					
custom design	✓	✓	✓	✓	✓
Interfacing					
Inputs (number)	16+	16+	48	48	48
Outputs (number)	14+	14+	32	32	32
Potential application(s)	1, 2, 3, 5, 6, 9, 14, 15, 16, 17, 18*	4-20*	14, 15, 16, 18*	14, 15, 17, 18*	4, 7, 12, 14, 15, 17, 18*
Number installed—U.S.	not spec'd	not spec'd	not spec'd	not spec'd	not spec'd
Canada	not spec'd	not spec'd	not spec'd	not spec'd	not spec'd
Overseas	not spec'd	not spec'd	not spec'd	not spec'd	not spec'd
Price of basic unit F.O.B. manufacturer (U.S.$)	60,000	90,000	10,000	20,000	35,000
Name of Canadian representative	ASEA Ltd.	ASEA Ltd.	ASEA Ltd.	ASEA Ltd.	ASEA Ltd.
Location(s) of service depot					
parts	White Plains, NY. Troy, Mich., Montreal Toronto	White Plains, NY. Troy, Mich., Montreal Toronto	White Plains, NY, Troy, Mich., Toronto, Montreal	White Plains, NY, Troy, Mich., Toronto, Montreal	White Plains, NY, Troy, Mich., Toronto, Montreal
service	same	same	same	same	same

***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**

SPECIFICATIONS Source / Model	**Advanced Robotics** CYRO 750	**Advanced Robotics** CYRO 820	**Advanced Robotics** CYRO 2000	**ARMAX** LC, VC, LJ, VJ	**Auto-Place** 10
Axes of motion	5	Not spec'd	5	7/9	6
Movement					
arm—horizontal (degrees of arc)	2032 mm	820 mm	2032 mm	270	200 (360)
vertical (min. mm, max. mm)	762	890	2032	to 3225	0-508
radial (mm)	762	240°	2032	1701/2286	940 (1093)
wrist—pitch (degrees of arc)	130	200	130	180	(270)
yaw (degrees of arc)	—	—	—	180	(270)
roll (degrees of arc)	720	380	720	270	270
End of arm speed					
average max. unloaded (m/s)	0.0254	1	0.127	1.3	2.5
normal operating, loaded (m/s)	0.0254	1	0.127	1.3	1.2
Weight carrying capacity					
max. at low speed (kg @ %)	22.72	10	227.27	68	4.5 @ 25
at operating speed (kg)	22.72	10	227.27	68	1
Control					
non-servo				✓	✓
servo—point to point		✓		✓	
continuous path	✓	✓	✓	✓	
Memory					
mechanical step sequencer					
air logic					✓
patch board (electrical)					
magnetic tape/disc	✓	✓	✓	✓	
microprocessor	✓	✓	✓	✓	
other (specify)					
Programming method					
manual					✓
lead-through				✓	
walk-through	✓	✓	✓		
Memory capacity (no. of steps)	64 kbyte	1000	64 kbyte	1000	24 (100+)
Positioning accuracy (± mm)	not spec'd	not spec'd	not spec'd	1.3	1.3
Repeatability (± mm)	0.20	0.3	0.40	1.3	0.6
Power—hydraulic				✓	
pneumatic					✓
electric	✓	✓	✓		
Cooling—air	✓	✓	✓		
water				✓	
none					✓
Max. ambient operating temperature (°C)	50	45	50	50	50
End of arm tooling					
off the shelf—gripper					✓
vacuum pad					✓
other (specify)	bracket	bracket	bracket		Magnetic
custom design				✓	✓
Interfacing					
Inputs (number)	8-32	15	8-32	72	Any number
Outputs (number)	8-32	14	8-32	72	Any number
Potential application(s)	1 2 6 9*	1 2 9*	1 2 6 9*	1 3-20 22*	2 7 8 9 11 14 15 17 18*
Number installed—U.S.	not spec'd	not spec'd	not spec'd	not spec'd	300
Canada					6
Overseas					70
Price of basic unit F.O.B. manufacturer (U.S.$)	99,000	79,000	142,000	50,000-125,000	13,600
Name of Canadian representative	—	—	—	—	A. F. Mundy Associates Canada Ltd.
Location(s) of service depot					
parts	Hebron OH	Hebron OH	Hebron OH	Farmington Hills, Mich.	Troy, Mich. Rexdale, Ont.
service	same	same	same	same	same

***1–arc welding 2–assembly 3–deburring 4–die casting 5–drilling 6–flame cutting 7–forging 8–foundry 9–gauging 10–grinding 11–heat treating 12–injection moulding 13–investment casting 14–machine loading & unloading 15–metal stamping 16–palletizing 17–parts handling 18–press feeding 19–routing 20–spot welding 21–spray painting 22–tracking.**

Source **SPECIFICATIONS** Model	**Auto-Place** **50**	**Binks** **88.800**	**Cincinnati Milacron** **T^3**	**Cincinnati Milacron** **HT^3**	**DeVilbiss** **TR-3000**
Axes of motion	6	6	6	6	6
Movement					
arm—horizontal (degrees of arc)	200 (360)	130	240	240	93
vertical (min. mm, max. mm)	0-127	2134	0-3960	0-3960	2044
radial (mm)	940 (1093)	1219	2465	2615	2185
wrist—pitch (degrees of arc)	(270)	180	180	180	176
yaw (degrees of arc)	(270)	180	180	180	176
roll (degrees of arc)	270	270	240	240	210
End of arm speed					
average max. unloaded (m/s)	1.5	1.02	1.3	0.9	1.7
normal operating, loaded (m/s)	.74	1.02	1.3	0.9	var.
Weight carrying capacity					
max. at low speed (kg @ %)	14 @ 25	not spec'd	45	100	
at operating speed (kg)	4	8.2	45	100	4.53
Control					
non-servo	✓				
servo—point to point		✓			✓
continuous path		✓	✓	✓	✓
Memory					
mechanical step sequencer					
air logic	✓				
patch board (electrical)					
magnetic tape/disc		✓			
microprocessor	✓	✓	✓	✓	✓
other (specify)					
Programming method					
manual	✓				
lead-through			✓	✓	
walk-through		✓			✓
Memory capacity (no. of steps)	24 (100+)	3000/5 min	700+	700+	2 hr.
Positioning accuracy (± mm)	1.3	4	1.3	<1.3	0.35
Repeatability (± mm)	0.6	4	1.3 (0.6)	1.3	2
Power—hydraulic		✓	✓	✓	✓
pneumatic	✓				
electric					
Cooling—air		✓			✓
water		✓	✓	✓	✓
none	✓				
Max. ambient operating temperature (°C)	50	50	50	5-50	35
End of arm tooling					
off the shelf—gripper	✓		✓	✓	
vacuum pad	✓				
other (specify)	Magnetic	spray gun			spray gun
custom design	✓		✓	✓	
Interfacing					
Inputs (number)	Any number	8	8+	8+	13+ TTY
Outputs (number)	Any number	8	8+	8+	5+ TTY
Potential application(s)	2 4 7 9 11 12 14 15 17 18*	paint spraying	5 9 16 19 20 22*	16 17 20 22*	Spray painting, arc welding
Number installed—U.S.	400+		>200	>200	100
Canada					11
Overseas	10				900
Price of basic unit F.O.B. manufacturer (U.S.$)	23,500	45,000	63,000	68,000	95,000
Name of Canadian representative	A.F. Mundy Associates Canada Ltd.	Binks Manufacturing	Cincinnati Milacron Cda. Ltd.	Cincinnati Milacron Cda. Ltd.	DeVilbiss (Cda.) Ltd.
Location(s) of service depot					
parts	Troy, Mich. Rexdale, Ont.	Franklin Park, Ill.	Cincinnati Montreal Toronto Windsor	Cincinnati Montreal Toronto Windsor	Toledo, Ohio Barrie, Ont.
service	same	same	same	same	same

***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**

SPECIFICATIONS Source / Model	**General Numeric M-1**	**General Numeric M-0**	**General Numeric M-3**	**General Numeric A-0**	**Hall Automation Merlin 90**
Axes of motion	3	6	5	3	5
Movement					
arm—horizontal (degrees of arc)	210/300	90	300	300	82
vertical (min. mm, max. mm)	500	180°	1200	300	430-1770
radial (mm)	500/800/1100	not spec'd	1200	300	882
wrist—pitch (degrees of arc)		not spec'd	140	not spec'd	180
yaw (degrees of arc)	3.5	not spec'd	150	not spec'd	180
roll (degrees of arc)	270	90/270	300	360	
End of arm speed					
average max. unloaded (m/s)	1	1	1	1	0.15
normal operating, loaded (m/s)	1	1	1	1	0.02
Weight carrying capacity					
max. at low speed (kg @ %)	20	10	50	10	13.6
at operating speed (kg)	20	10	50	10	13.6
Control					
non-servo					
servo—point to point	✓	✓	✓	✓	✓
continuous path			✓	✓	✓
Memory					
mechanical step sequencer					
air logic					
patch board (electrical)					
magnetic tape/disc	✓	✓	✓	✓	✓
microprocessor	✓	✓	✓	✓	
other (specify)					ROM
Programming method					
manual	✓	✓	✓	✓	
lead-through					✓
walk-through		✓	✓	✓	✓
Memory capacity (no. of steps)	300	300	300	300-1000	40 minutes
Positioning accuracy (± mm)	1	0.5	1	0.05	1.0
Repeatability (± mm)	1	0.5	1	0.05	0.5
Power—hydraulic					✓
pneumatic					
electric	✓	✓	2	✓	
Cooling—air					✓
water					
none	✓	✓	✓	✓	
Max. ambient operating temperature (°C)	45	45	45	45	35
End of arm tooling					
off the shelf—gripper	✓	✓	✓	✓	
vacuum pad	✓	✓	✓	✓	
other (specify)	✓	✓	✓	✓	torch
custom design	✓	✓	✓	✓	
Interfacing					
Inputs (number)	15	15	15	15	16
Outputs (number)	16	16	16	16	16
Potential application(s)	not spec'd	not spec'd	not spec'd	not spec'd	arc welding
Number installed—U.S.	not spec'd	not spec'd	not spec'd	not spec'd	
Canada					4
Overseas	30				5
Price of basic unit F.O.B. manufacturer (U.S.$)	30,000	25,000	70,000	40,000	85,000
Name of Canadian representative	Pavesi International	Pavesi International	Pavesi International	Pavesi International	Programmable Welding Systems
Location(s) of service depot					
parts	Elk Grove, Ill. Burlington, Ont.	Elk Grove, Ill. Burlington, Ont.	Elk Grove, Ill. Burlington, Ont.	Elk Grove, Ill. Burlington, Ont.	Fort Erie, Ont.
service	same	same	same	same	same

***1–arc welding 2–assembly 3–deburring 4–die casting 5–drilling 6–flame cutting 7–forging 8–foundry 9–gauging 10–grinding 11–heat treating 12–injection moulding 13–investment casting 14–machine loading & unloading 15–metal stamping 16–palletizing 17–parts handling 18–press feeding 19–routing 20–spot welding 21–spray painting 22–tracking.**

Source **SPECIFICATIONS Model**	**Industrial Automates** **9500**	**Manca** **(modular)**	**Mobot**	**Nordson**	**Prab** **4200/5800**
Axes of motion		1-7	1-7	6	3-5
Movement					
arm—horizontal (degrees of arc)	90 (120)	100-360	360	116	270
vertical (min. mm, max. mm)	178	10-1,250	761	2788	826
radial (mm)	609	1,250	20,000	1000	1473
wrist—pitch (degrees of arc)	180	to 360	360	240	90
yaw (degrees of arc)	180	to 360	360	240	90
roll (degrees of arc)	180		360	240	180
End of arm speed					
average max. unloaded (m/s)	0.76	1.1	0.5	2.5	1.27
normal operating, loaded (m/s)	0.76	to 1	0.3	var.	1.27
Weight carrying capacity					
max. at low speed (kg @ %)	4.5	to 1,700	200 @ 10	25 @ 30	56.7
at operating speed (kg)	4.5	to 1,700	200	15	45.4
Control					
non-servo	✓	✓	✓		✓
servo—point to point			✓		
continuous path			✓	✓	
Memory					
mechanical step sequencer		✓	✓		✓
air logic					
patch board (electrical)		✓			
magnetic tape/disc			✓		
microprocessor	✓	✓	✓	✓	
other (specify)		prgr. cntr.			prgr. contr.
Programming method					
manual		✓	✓		✓
lead-through	✓		✓		✓
walk-through				✓	
Memory capacity (no. of steps)	1000	optional	unlimited	4h	24-100
Positioning accuracy (± mm)	0.3	0.1	1	2	0.20
Repeatability (± mm)	0.3	to 0.01	1	2	0.05
Power—hydraulic		✓	✓	✓	✓
pneumatic		✓	✓		✓
electric	✓	✓	✓		
Cooling—air				✓	✓
water		✓		✓	✓
none	✓		✓		
Max. ambient operating temperature (°C)	not spec'd	not spec'd	65	43	50
End of arm tooling					
off the shelf—gripper	✓	✓	✓		✓
vacuum pad	✓	✓	✓		✓
other (specify)	magnetic	magnetic			
custom design	✓	✓	✓	spray gun	✓
Interfacing					
Inputs (number)	16	optional	unlimited	8	8
Outputs (number)	16	optional	unlimited	16	8
Potential application(s)	12 14 17*	2 12 14 17 18*	part handling	finishing	4 5 7 8 11 12 14 15 17 18*
Number installed—U.S.	15	50+	100+	20	not spec'd
Canada	1			6	not spec'd
Overseas	5	>400		30	not spec'd
Price of basic unit F.O.B. manufacturer (U.S.$)	11,845	not spec'd	15,000	100,000	30,000-40,000
Name of Canadian representative				Nordson Cda. Ltd.	Can-Eng Mfg. Co.
Location(s) of service depot					
parts	West Allis, Wisc.	Rockleigh N.J.	San Diego	Amherst, Oh. Scarborough, Ont.	Kalamazoo, Mich.; Niagara Falls, Ont.
service	same	Rockleigh NJ Menomonee Falls, Wisc.	San Diego	same	same

***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**

Source	**Prab**	**Prab**	**Reis**	**Reis**	**Rimrock**
SPECIFICATIONS Model	**E**	**F**	**625/650**	**515**	**195**
Axes of motion	3-7	3-7	6	5 (6)	5
Movement					
arm—horizontal (degrees of arc)	240	300	270	300	190
vertical (min. mm, max. mm)	761	to 1520	1200	1950	—
radial (mm)	761 (1068)	to 1520	1500	1600	2032
wrist—pitch (degrees of arc)	220	270	360	260	—
yaw (degrees of arc)	220	180	+180	270	—
roll (degrees of arc)	359	300	360	—	90
End of arm speed					
average max. unloaded (m/s)	1.27	1.27	1.2	1.6	1.016
normal operating, loaded (m/s)	1.27	1.27	1.2	1.6	~1.016
Weight carrying capacity					
max. at low speed (kg @ %)	56.7	to 906	25 @ 50	16	27.21 @ 57
at operating speed (kg)	45.4	to 680	50	10-16	27.21
Control					
non-servo					✓
servo—point to point	✓	✓	✓	✓	
continuous path	✓	✓	✓	✓	
Memory					
mechanical step sequencer					
air logic					
patch board (electrical)	(✓)	(✓)			
magnetic tape/disc					
microprocessor	✓	✓	✓	✓	
other (specify)					prgr. contr.
Programming method					
manual	✓	✓	✓	✓	✓
lead-through	✓	✓	✓	✓	
walk-through			✓	✓	✓
Memory capacity (no. of steps)	4000	4000	800/1600/-3200	800/1600/-3200	23
Positioning accuracy (± mm)	0.76	1.3	0.6	0.2	0.25
Repeatability (± mm)	0.51	1.3	0.6	0.2	0.25
Power—hydraulic	✓	✓			✓
pneumatic					
electric	✓	✓	✓	✓	✓
Cooling—air	✓	✓	✓	✓	
water	✓	✓			
none					✓
Max. ambient operating temperature (°C)	50	50	50	50	80
End of arm tooling					
off the shelf—gripper	✓	✓	✓	✓	✓
vacuum pad	✓	✓	✓	✓	
other (specify)					
custom design	✓	✓	✓	✓	✓
Interfacing					
Inputs (number)	50	50	255	255	6
Outputs (number)	50	50	255	255	2
Potential application(s)	All ex'pt spray paint	All ex'pt spray paint.	not spec'd	not spec'd	Die casting
Number installed—U.S.	not spec'd	not spec'd	2	—	—
Canada	not spec'd	not spec'd	—	—	—
Overseas	not spec'd	not spec'd	30	—	—
Price of basic unit F.O.B. manufacturer (U.S.$)	45,000-60,000	55,000-110,000	55,000	not spec'd	20,000-60,000
Name of Canadian representative	Can-Eng Mfg. Co.	Can-Eng. Mfg. Co.	—	—	Vacumet Ltd.
Location(s) of service depot					
parts	Kalamazoo, Mich.; Niagara Falls, Ont.	Kalamazoo MI, Niagara Falls, Ont.	Elgin, Ill.	Elgin, Ill.	Columbus, Ohio
service	same	same	same	same	same

***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**

Source	Seiko	Seiko	Seiko	Seiko	Sterling-Detroit
SPECIFICATIONS Model	100	200	400	700	ROBOTARM
Axes of motion	4	3	4	5	3
Movement					
arm—horizontal (degrees of arc)	—	90 (120)	—	90 or 120	90°
vertical (min. mm, max. mm)	50	20	100	40	203.2
radial (mm)	200	—	400 (700)	300	—
wrist—pitch (degrees of arc)	—	—	—		optional
yaw (degrees of arc)	—	—	—		optional
roll (degrees of arc)	90-180°	—	(180)	90/180	120°
End of arm speed					
average max. unloaded (m/s)	0.2	0.5	0.57	0.6	0.61
normal operating, loaded (m/s)	0.2	0.5	0.57	0.6	0.61
Weight carrying capacity					
max. at low speed (kg @ %)	1.5	0.3	4	1	272
at operating speed (kg)	1.5	0.15	4	0.5	272
Control					
non-servo	✓	✓	✓	✓	✓
servo—point to point					
continuous path					
Memory					
mechanical step sequencer	✓	✓	✓	✓	
air logic	✓	✓	✓	✓	
patch board (electrical)	✓	✓	✓	✓	
magnetic tape/disc					
microprocessor	✓				
other (specify)	prgr. contr.	prgr. contr.	prgr. contr.	prgr. contr.	prgr. contr.
Programming method					
manual	✓	✓	✓	✓	✓
lead-through		—			
walk-through		—			
Memory capacity (no. of steps)	256	256	256	256	1000
Positioning accuracy (± mm)	0.01	0.01	0.025	0.025	0.1
Repeatability (± mm)	0.01	0.01	0.025	0.025	0.1
Power—hydraulic		✓			✓
pneumatic	✓	✓	✓	✓	
electric	✓		✓	✓	
Cooling—air					
water					
none	✓	✓	✓	✓	✓
Max. ambient operating temperature (°C)	60	60	60	60	Any
End of arm tooling					
off the shelf—gripper	✓	✓	✓	✓	✓
vacuum pad	✓	✓	✓	✓	✓
other (specify)					
custom design	✓	✓	✓	✓	✓
Interfacing					
Inputs (number)	4+	4+	4+	4+	16
Outputs (number)	4+	4+	4+	4+	16
Potential application(s)	Press Feeder	not spec'd	Assembly	not spec'd	4 7 12*
Number installed—U.S.	not spec'd	not spec'd	not spec'd		500
Canada	not spec'd	not spec'd	not spec'd	1500	50
Overseas	not spec'd	not spec'd	not spec'd		15
Price of basic unit F.O.B. manufacturer (U.S.$)	4,000	6,000	7,500	8,000	25,000
Name of Canadian representative	Pavesi International	Pavesi International	Pavesi International	Pavesi International	J. S. Bulmer
Location(s) of service depot					
parts	Torrance CA	Torrance CA Burlington, Ont.	Torrance CA Burlington, Ont.	Torrance CA Burlington, Ont.	Detroit, MI
service	same	same	same	same	same

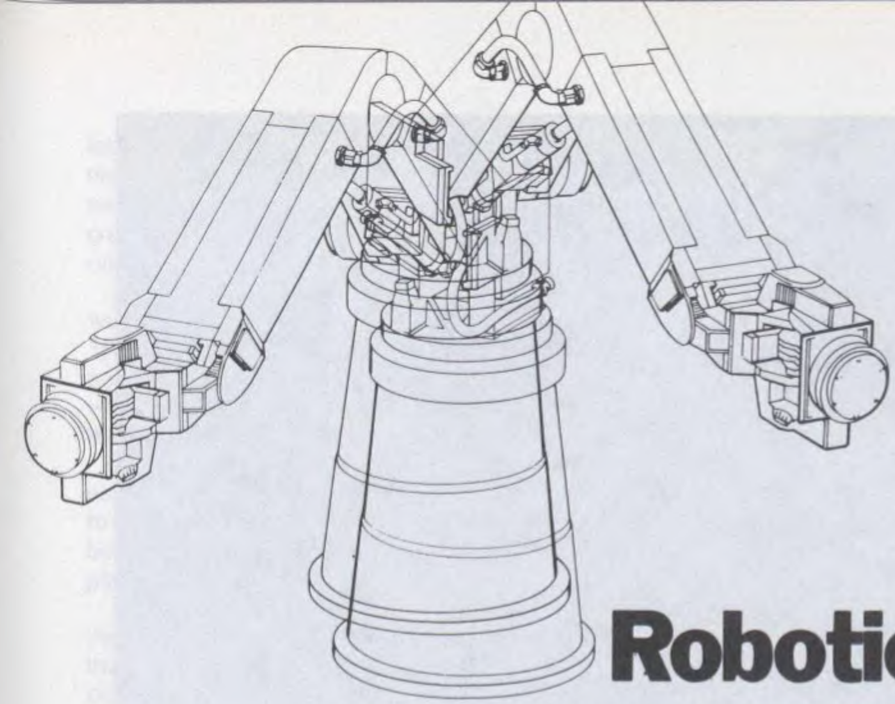
***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**

Source	Thermwood	Thermwood	Thermwood	Unimation	Unimation
SPECIFICATIONS Model	E	3	7	1000	2000/2100/ 8000
Axes of motion		5	6	3 to 5	3 to 6
Movement					
arm—horizontal (degrees of arc)	135	280	280	208	208 max
vertical (min. mm, max. mm)	2134 mm	2489	1930	900-1900	1890/2480
radial (mm)	762, 2108	not spec'd	not spec'd	1060	1041/1365
wrist—pitch (degrees of arc)	180	210	180	90-180	211
yaw (degrees of arc)	180	—	180	90-180	200
roll (degrees of arc)	270	180-360	300		360
End of arm speed					
average max. unloaded (m/s)	1.02	not spec'd	not spec'd	1	1
normal operating, loaded (m/s)	1.02	not spec'd	not spec'd	var.	var.
Weight carrying capacity					
max. at low speed (kg @ %)	not spec'd	not spec'd	not spec'd	22.9	136
at operating speed (kg)	12	22.6	11.3	12	12-50
Control					
non-servo					
servo—point to point	✓	✓	✓	✓	✓
continuous path	✓		✓	✓	✓
Memory					
mechanical step sequencer					
air logic					
patch board (electrical)					
magnetic tape/disc	(✓)		✓		
microprocessor	✓	✓	✓		✓ (8000)
other (specify)				CMOS	Plated wire
Programming method					
manual		✓			
lead-through	✓		✓	✓	✓
walk-through	✓		✓		
Memory capacity (no. of steps)	3000/5 min	200	3000/5 min	up to 256	2048
Positioning accuracy (± mm)	3.2	1.52	1.52	1	1
Repeatability (± mm)	3.2	1.52	1.52	1.3	1.27
Power—hydraulic		✓	✓	✓	✓
pneumatic	✓			✓ (wrist)	
electric	✓				
Cooling—air	✓			✓	✓
water		✓	✓		optional
none					
Max. ambient operating temperature (°C)	50	50	50	50	50
End of arm tooling					
off the shelf—gripper		✓		✓	✓
vacuum pad				✓	✓
other (specify)					
custom design	✓		✓	✓	✓
Interfacing					
Inputs (number)	8	8	8	6	9
Outputs (number)	8	8	8	6	9
Potential application(s)	17 21*	gen. purp.	17*	4 7 12 14 17 18*	1 4 6 7 8 11 12 13 14 16 17 18 19 20
Number installed—U.S.	—	not spec'd	not spec'd	not spec'd	not spec'd
Canada	—	not spec'd	not spec'd	not spec'd	not spec'd
Overseas	—	not spec'd	not spec'd	not spec'd	not spec'd
Price of basic unit F.O.B. manufacturer (U.S.$)	45,000	not spec'd	not spec'd	28,500	46,000-64,000
Name of Canadian representative	—	—	—	CAE Morse Ltd.	CAE Morse Ltd.
Location(s) of service depot					
parts	Dale IN	Dale IN	Dale IN	Danbury, Ct. Farmington Hills, Mississauga	Danbury, Farmington Hills, Mississauga
service	same	same	same	same	same

***1–arc welding 2–assembly 3–deburring 4–die casting 5–drilling 6–flame cutting 7–forging 8–foundry 9–gauging 10–grinding 11–heat treating 12–injection moulding 13–investment casting 14–machine loading & unloading 15–metal stamping 16–palletizing 17–parts handling 18–press feeding 19–routing 20–spot welding 21–spray painting 22–tracking.**

SPECIFICATIONS Source / Model	**Unimation** **4000/9000**	**Unimation** **Puma 250**	**Unimation** **Puma 500/600**	**Unimation** **Apprentice**	**United States Robots**
Axes of motion	3 to 6	3 to 6	5	5	5
Movement					
arm—horizontal (degrees of arc)	200	330 waist	320	90	355
vertical (min. mm, max. mm)	1672-2830	not spec'd	not spec'd	1000	—
radial (mm)	1321	not spec'd	not spec'd	not appl.	1372
wrist—pitch (degrees of arc)	226	240	200	50	210
yaw (degrees of arc)	320	630	300	180	—
roll (degrees of arc)	370	630	270	165	355
End of arm speed					
average max. unloaded (m/s)	1	1.5	0.3	0.01	—
normal operating, loaded (m/s)	not spec'd	not spec'd	not spec'd	0.01	1.4
Weight carrying capacity					
max. at low speed (kg @ %)	205	not spec'd	not spec'd	—	
at operating speed (kg)	90			5 at 100	11
Control					
non-servo					
servo—point to point	✓	✓	✓		✓
continuous path	✓	✓	✓		✓
Memory					
mechanical step sequencer					
air logic					
patch board (electrical)					
magnetic tape/disc					
microprocessor	✓ (9000)	✓	✓		✓
other (specify)	Plated wire			semi-cond	
Programming method					
manual					
lead-through	✓	✓	✓	✓	✓
walk-through					
Memory capacity (no. of steps)	up to 2048		not spec'd	not spec'd	350
Positioning accuracy (± mm)	not spec'd	not spec'd		1	not spec'd
Repeatability (± mm)	2.03	.05	.1	1	0.01
Power—hydraulic	✓				
pneumatic					
electric			✓	✓	✓
Cooling—air	✓	✓		✓	
water	optional				
none					✓
Max. ambient operating temperature (°C)	50	45	45	50	60
End of arm tooling					
off the shelf—gripper	✓	✓	✓		✓
vacuum pad	✓				
other (specify)				torch holder	
custom design	✓	✓	✓		
Interfacing					
Inputs (number)	9	8	8	1	8
Outputs (number)	9	8	8	4	8
Potential application(s)	1 4 6 7 8 11 12 13 14 16 17 18 19 20*	2 14 17*	1 2 3 5 14 16 17 20*	Arc welding	1 2 14 17 21*
Number installed—U.S.	not spec'd	not spec'd	not spec'd	not spec'd	5
Canada	not spec'd	not spec'd	not spec'd	not spec'd	
Overseas	not spec'd	not spec'd	not spec'd	not spec'd	
Price of basic unit F.O.B. manufacturer (U.S.$)	64,000-74,000	41,000	41,000-47,000	38,500	34,000
Name of Canadian representative	CAE Morse Ltd.		none		—
Location(s) of service depot					
parts	Danbury, Farmington Hills, Mississauga	Danbury, Conn. Farmington Hills, Mich.	Danbury, Conn. Farmington Hills, Mich.	Danbury, Conn. Detroit, Mi.	Conshohocken, Pa.
service	same	same	same	same	same

***1—arc welding 2—assembly 3—deburring 4—die casting 5—drilling 6—flame cutting 7—forging 8—foundry 9—gauging 10—grinding 11—heat treating 12—injection moulding 13—investment casting 14—machine loading & unloading 15—metal stamping 16—palletizing 17—parts handling 18—press feeding 19—routing 20—spot welding 21—spray painting 22—tracking.**



Robotic Animation

"Animate" permits verification and debugging of robot programs written in Manufacturing Control Language; "Place" is designed to create, analyze, and edit cell descriptions

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Robotic Animation

This paper reviews some of the results achieved at McDonnell Douglas Automation Company with the robotic animation systems Place and Animate. Work by Heginbotham [1] predates the work reported here and has been a significant influence. Work in this area has also been performed and reported by Soroka [2,3] and Meyer [4]. As these authors report, there are a number of uses for these types of systems. New robot designs can be analyzed and experimented with before investing the time and expense in prototyping. Potential robotic applications can be modeled, ensuring that all required motions can be accomplished by the robot and that cycle time requirements can be met. An analysis of this sort yields, essentially, a verified robot type, tooling design, and shop floor layout, prior to the decision to invest. These are the applications for which Place was implemented.

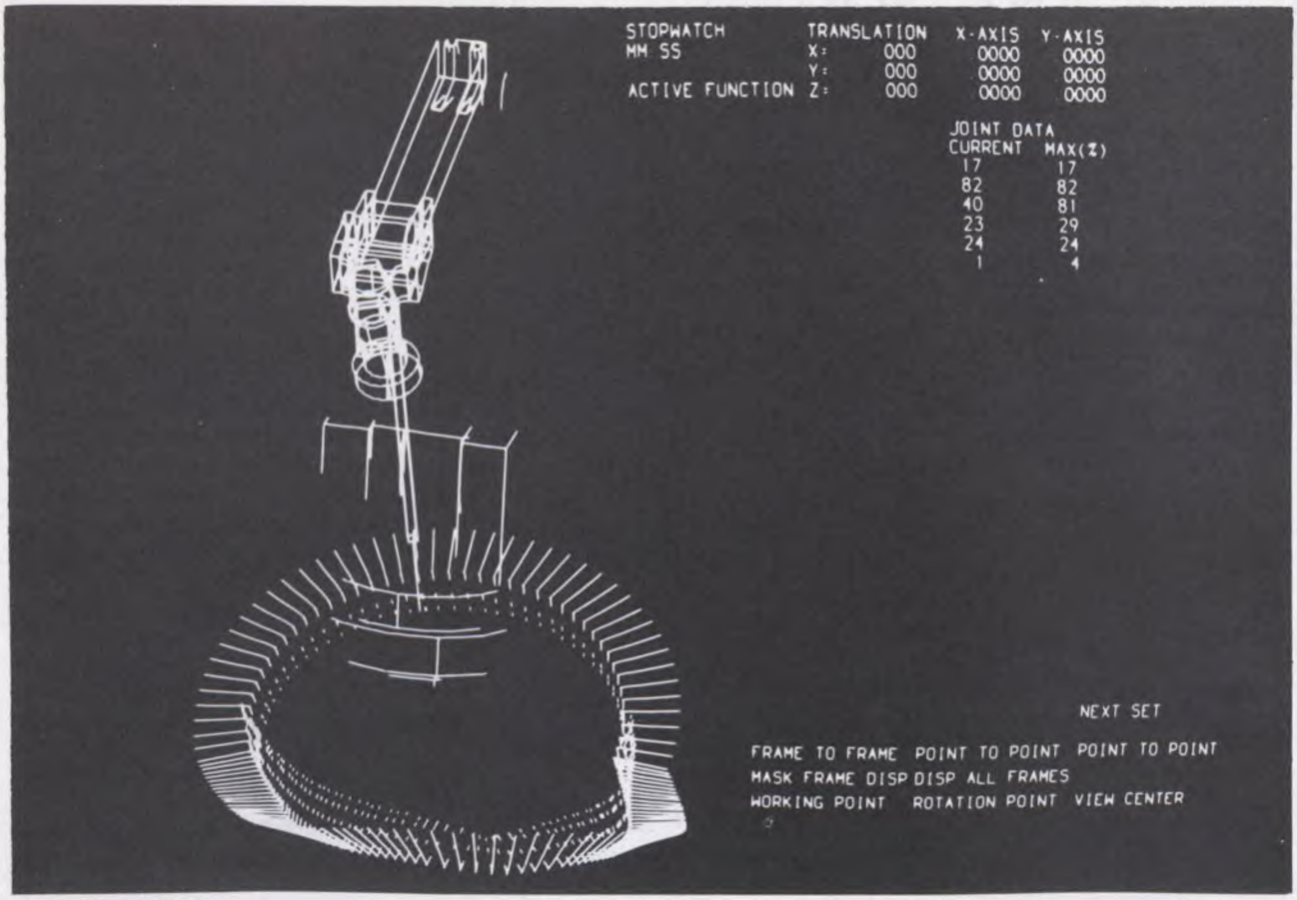
Robotic animation also is an excellent debugging and verification tool to assist in the development of offline robot programs. Animate is an example of such a tool, which is essential to make offline programming practical, since debugging robot programs developed offline with an actual robot defeats much of the purpose of offline programming. Finally, robotic animation in general provides an excellent robotics training tool and can be expected to be exploited for this purpose in the future.

Kinematic Versus Dynamic Simulation

These systems model motion of the robot and other devices using a kinematic description rather than a dynamic one. Meyer emphasizes this distinction by characterizing Emula as an emulator rather than a simulator. There are two main reasons for this situation. A serious attempt at a robust dynamic model of a robot and associated devices would involve orders of magnitude more complex than the kinematic model alone. Even worse, if models of robot loading characteristics, vibration, rigidity, etc., were accurate, they would be different for different copies of the same robot. To complicate matters even further, these models would change over time as a function of the robotic application, environment, and maintenance. Therefore serious attempts to model robot dynamics in the context of an industrial application face difficulties in implementation as well as application.

The second reason why robot dynamics have not been graphically animated to date results from the current level of computing and graphics technology. The CPU, the graphics interface, the graphics display, and the software each provide a certain bandwidth for graphic data communication. In the case of a low speed serial graphics interface or a vector storage graphics display, the bandwidth is so low as to make animation of any sort all but impossible. The advent of high-performance intelligent graphic displays, however, invites attempts at true robotic animation, such as that performed by the Place and Animate systems. These systems use the Evans and Sutherland Picture System 2 graphics display. This is a high-performance vector refresh terminal with a high degree of resolution yielding a high quality display. The computer these systems currently use is the DEC PDP-11/70. A separate CAD software system, Unigraphics, is used to provide geometric models and data.

Development of Place and Animate was motivated in



```
STOPWATCH           TRANSLATION   X-AXIS  Y-AXIS
MM SS               X:      000     0000    0000
                    Y:      000     0000    0000
ACTIVE FUNCTION     Z:      000     0000    0000

                                  JOINT DATA
                                  CURRENT  MAX(%)
                                    17       17
                                    82       82
                                    40       81
                                    23       29
                                    24       24
                                     1        4

                                           NEXT SET
FRAME TO FRAME  POINT TO POINT  POINT TO POINT
MASK FRAME DISP DISP ALL FRAMES
WORKING POINT   ROTATION POINT  VIEW CENTER
```

Fig. 1 Place display.

large part by McAuto's development of Manufacturing Control Language (MCL) [5]. This language was developed under contract to the United States Air Force ICAM program. As part of this effort, an MCL compiler was implemented on an IBM mainframe computer.

MCL is an extension to the Automatically Programmed Tool (APT) language for numerical control (NC) programming. APT is used to direct the motion of a tool having five degrees of freedom. Thus, it has a well-developed capability for specifying geometry. Since robots perform motion, the relationship is obvious. APT, however, lacks the ability to specify anything beyond the simplest of real-time control. The enhancements provided by MCL, to a great extent, fall in this area.

Capabilities have been added for real-time computation, iteration, alternation, concurrency, I/O, and sophisticated sensor control. In addition, the capability to specify a sixth degree of freedom was added. The result is a language of considerable capability. Like any language, teach or textual, which is used to manually encode instructions, errors cannot be prevented. This experience provided the motivation to supply tools to augment offline programming languages such as MCL. Place is intended to automate otherwise difficult activities for robotic application designers. Animate, likewise, is used as a verification tool for MCL robot programs developed offline.

Place

The Place system is designed to create, analyze, and edit *cell descriptions.* A cell description is a collection of CAD information which describes the components of a robotic application. This includes the robot, tooling, parts, end effectors, NC equipment, etc. *Primitive cell descriptions* are those consisting of a single device or object and used to create other more complex cell descriptions. Primitive cell descriptions are generated using geometric modeling data for display generated by a CAD system. If the kinematics of a device is also to be modeled, a software routine that expresses the kinematic relationships must be incorporated into Place. Since most motion can be described as either a simple translation or rotation, models of this sort are not difficult to create. These include conveyors, doors, grippers, rotary tables, etc. Robots, however, require that different kinematic descriptions be derived and encoded into software routines.

Output from Place is illustrated in Fig. 1. Objects are displayed in a wire frame fashion. The view of the application and the scaling can be changed by manipulating function knobs. This is useful for determining interferences. Points are displayed with orientation and roll vectors. A special point in every cell is the "world" origin. This point is distinguished for the user by making it blink. Points and lines are grouped into frames, which generally correspond to rigid bodies. Associated with each frame is a coordinate system managed by Place. Relationships between frames can be fixed, as in the case of an end effector and the robot face plate, or variable, as between the various linkages of a robot, or nonexistent.

In the upper right are a number of indicators used to record quantitative data about the state of the cell description being analyzed. The joint data is an awkwardness measure of the robot configuration. The column labeled CURRENT is the robot's awkwardness as currently displayed on the screen. The column changes instantaneously with the robot motion. The MAX column is the greatest awkwardness that the robot has encountered over one or more of the most recent moves.

"Awkwardness" is defined as a percentage toward what would be a joint limit on a real robot. A value greater than 100 percent indicates that a particular joint has exceeded a joint limit. A joint is at the middle of its range of motion when it registers 0 percent. The greater the percentage, the closer the joint is to a limit.

There are a number of CURRENT and MAX percentages associated with a robot. The topmost percentage refers to the joint nearest the base. For a six-axis robot, the bottommost percentage refers to the joint at the faceplate.

For convenience, Place permits robots to be driven past their real world joint limits. Knowledge of a joint limit error thus requires a cursory look at the MAX column of percentages. Due to their latching.nature, a joint limit will never be missed. For example, consider a straight line robot move of its tool tip from point A to point B. Although all the joints may be well within range at A and at B, there can easily exist points between A and B at which a joint temporarily exceeds its physical limits. At point B, the CURRENT column would show no joint limit error, but the MAX column would reveal that an unreachable location was attempted before reaching B.

In the lower right of Fig. 1 is one of a number of menus used to select functions. The current function is displayed in the center top of the display.

The MERGE CELL function retrieves an existing cell description and merges it into the one being currently edited by Place. After selecting this function, the user must identify the name of a cell to merge by keying it in. The user can also select a target point where the origin of this cell is to be located. The default is the origin of the current cell being edited. The merge cell is the primary function used for generating new cell descriptions. In order to generate an arbitrary cell description, the user can sequentially merge in a number of primitive cell descriptions for each of the constituent objects. To empty the current cell, the CLEAR CELL function can be used.

Repositioning objects in the cell is accomplished by the MOVE FRAME function. This function permits translation or rotation in an arbitrary fashion with respect to any other frame. Motion in any combination of the six degrees of freedom is performed by using the Evans and Sutherland function buttons. Frames having fixed relationhips have that relationship maintained. If the user does not specify a translation or a rotation reference frame, default ones are determined and the function executed.

Frequently, one wishes to move a frame so as to cause a point in one frame to align with a point in another frame. The ALIGN POINT function is used to perform this operation. After alignment, the orientation and roll vectors are coincident. The relationships between all points in each frame remain the same. This function is particularly useful in affixing end effectors onto a robot's faceplate. The user simply identifies an appropriate point on the end effector and corresponding point on the face plate and the alignment takes place immediately.

In order to cause a robot to display motion, three pieces of information need to be provided to Place. Since a cell being analyzed can contain a number of devices capable of motion, the user needs to specify which device is to receive motion commands. This is accomplished by executing the ACTIVE DEVICE function. With this function, the user simply makes a light-pen pick of any of the constituent frames for the device to be selected. From that point, until another device is selected as active, all further commands are directed to that device.

The next piece of necessary information is the definition of a *working point*. The working point is the point of operation on the robot that is to be aligned at various points in space. The working point is defined and selected by using the WORKING POINT function and indicating, again using the light pen, which point on the robot is to serve this purpose.

Finally, in order to display motion, the user must specify points at which the working point is to be aligned. This is done by using the GOTO POINT function and making a series of light-pen picks. As each point is selected, the robot moves in an animated fashion. Throughout its motion, the joint positions are displayed for user analysis. Should a limit be exceeded, motion is permitted to continue, even to the extent that a grasped part is removed from the gripper. The user can easily backtrack to a legal configuration by selecting a goto point yielding a legal configuration.

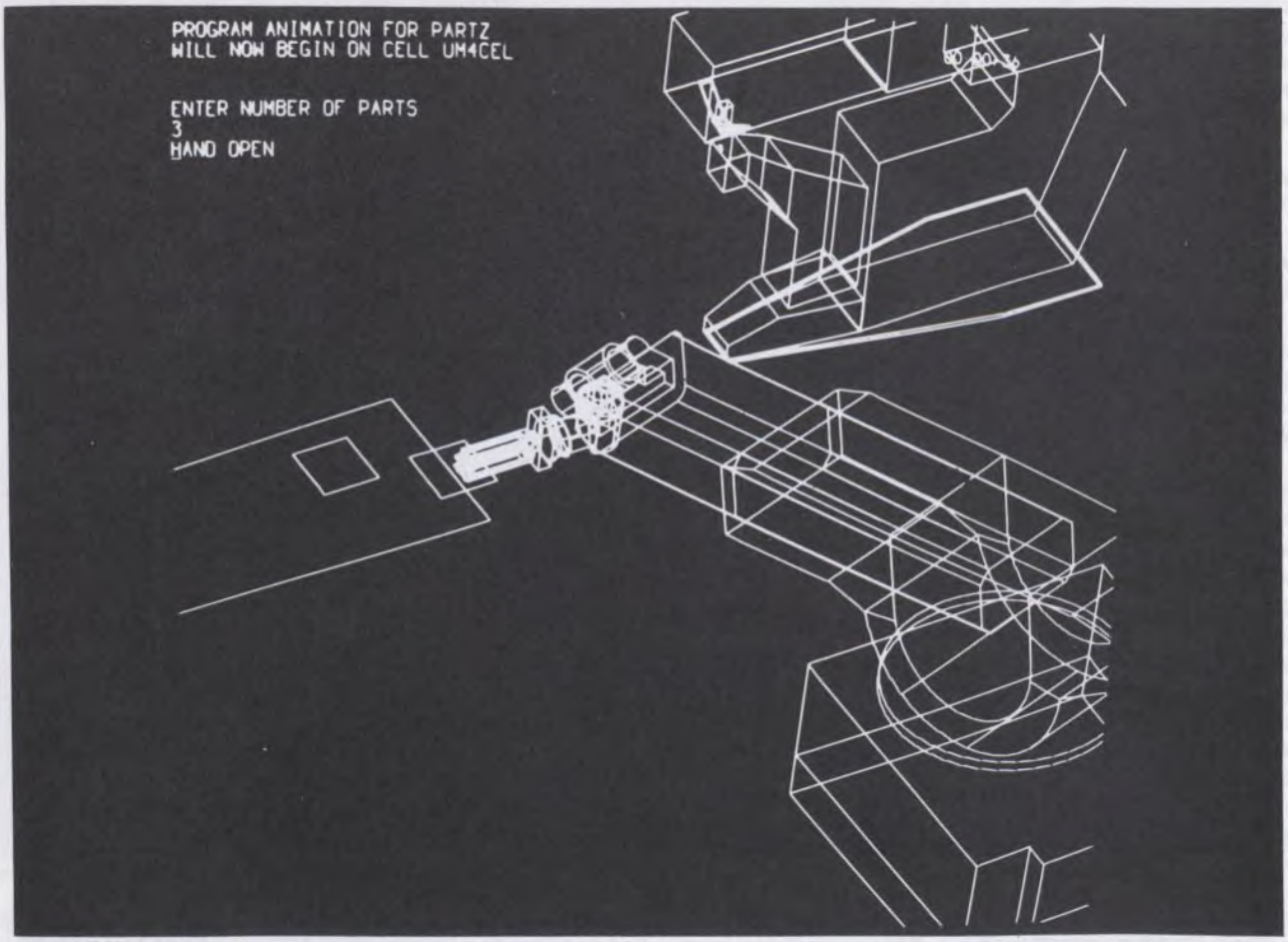
The user can go one step further and display the robot performing tracking. The TRACKING function is toggled on and off by light-pen picks of the menu. When tracking is toggled on, the user can use the move frame function to cause motion of the goto point and the robot will alter its configuration to maintain the working point-goto point alignment. This is of particular use in analyzing conveyor line applications for robots, but it also allows the user to directly control the position of the working point by use of the function buttons.

The results achieved with the Place system have been very encouraging. A variety of industrial applications have been analyzed and the ones that have been implemented have been successful. The experience gained in using Place has been very useful and further refinements are planned.

Animate

As indicated earlier, the Animate system is used for the verification and debugging of robot programs written in MCL. There are two kinds of inputs to this system. One is a description of the operations to be performed. This is the object code, called CLDATA, which is generated from the MCL source program. The second input is the cell description generated via the Place system. The graphic display information necessary to animate the operation of the robotic cell is included here. An example of the Animate display is shown in Fig. 2. The robot and other devices are modeled using the same kinematic description discussed for Place.

A number of user functions are available to assist in verifying and debugging MCL programs. Function knobs permit easy view changing and scaling. Function buttons are used to select from a variety of other capabilities. The state of the program can be saved at any point in its execution by using the CHECKPOINT function. This state can be returned to later by selecting the REPLAY function.



```
PROGRAM ANIMATION FOR PARTZ
WILL NOW BEGIN ON CELL UM4CEL

ENTER NUMBER OF PARTS
3
HAND OPEN
```

Fig. 2 Animate display.

Collision detection is accomplished using these functions. The user must visually determine adequate clearance for all motion by examining different views. An obvious area for improvement is to make this automatic. Assisting the user is a SPEED TOGGLE function that allows the user to speed up or slow down the display speed. Slower speeds permit better verification, while faster speeds reduce operator fatigue. Critical states of the program execution can be examined by halting all activity with the INTERRUPT function. Resumption is performed with the CONTINUE function.

To better assist the user in debugging MCL programs, a number of additional functions have been designed. The *control units* or devices in the robotic cell can be displayed via the CONTROL UNITS function. MCL tasks can be displayed by selecting the TASKS function. The values of real-time variables can be obtained with the REALTIME VARIABLES function. Finally, hardcopy plots can be generated from the current display by selecting, in sequence, the CREATE HARD COPY and PLOT HARD COPY functions.

Findings to Date

A number of McDonnell Douglas component companies are investigating robotic applications that might benefit from offline programming. The Animate system has provided some assistance, but actual industrial experience on implemented systems remains to be done. Animate has proven itself to be effective as a debugging tool for MCL programs, particularly in the areas of detecting joint limit errors, interference problems, and incorrect sequences of operations. As more experience is gained with this tool, more sophisticated enhancements will be made, such as hidden line removal and automatic collision detection.

The Place system has been a more notable success, since it has been used for a number of actual applications. Place has succeeded in finding robot cell layouts faster and better than the current trial-by-error methods. It has even succeeded in at least one application where a solution was thought not to exist. Conversely, potential applications that might have been implemented were determined to be impractical or impossible. This type of useful information is essential if robotics is ever to become widespread.

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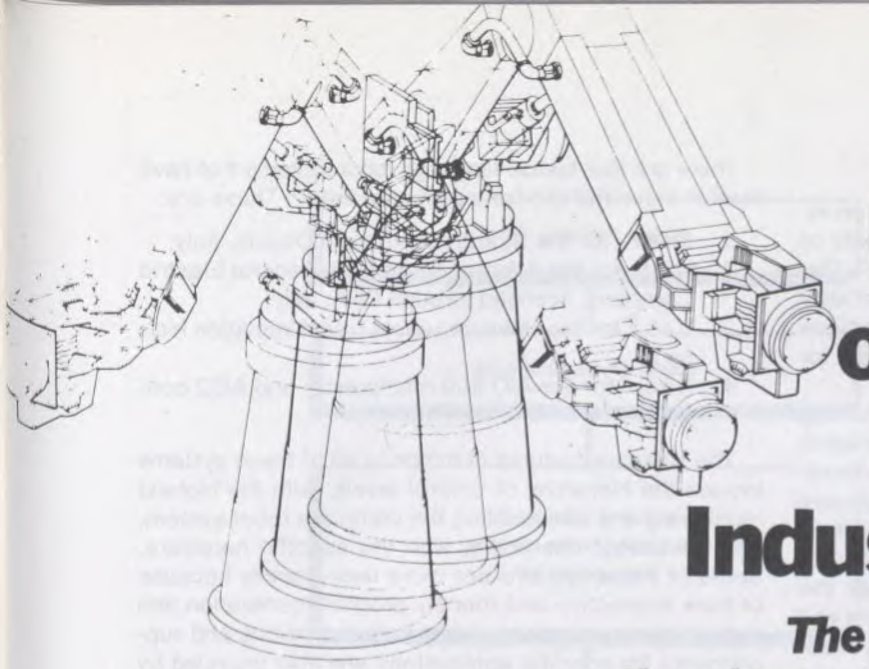

Development of a Software System for Industrial Robots

The proposed model contains the elements of an operating system and facilities for robot program development and testing

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Since the introduction of industrial robots, the methodology for programming them has seen a great deal of improvement. In general, two mainstreams of software organization have been pursued for the control of robots. The first is the "explicitly programmed" system, which makes the user primarily responsible for every control action and requires explicit instructions. The second type is "world modeling," which makes the robot system responsible for knowing specific facts about the objects it works with. In this respect, explicitly programmed systems force the user to decide exactly what sequence of library routines the robot must use to perform a given task. World modeling systems make some of these decisions based on a more goal-oriented description of the task.

Software systems in industrial use are the explicitly programmed type. In these robot systems three different programming techniques are popular:

1 Manual Lead-Through Programming
2 Teach Pendant Programming
3 Textual Language Programming.

Each technique offers unique application advantages over the others. For this reason, the industrial robots in use today tend to have similar teaching techniques for specific applications.

Although the world modeling software is the trend for future robot systems, the demand on present industrial systems is to support user needs. Features such as ease of programming and debugging, Englishlike command language and flexibility for extensions, and supplements to computer-aided design (CAD) and vision systems are a few of the important requirements.

Common Robot Programming Techniques

Manual Lead-Through Programming. In addition to the basic components of a robot system—manipulator, control unit, and power source—this type of programming system requires a lead-through aid. Two lead-through aids are in use: special attachments for the manipulator wrist, and a special teaching arm.

This programming technique is very common in the robots used for spraying applications. To teach the robot a task, switches and pushbuttons on the control panel are set by the operator. These include selection of a program number, sampling rate at which points are to be recorded onto mass storage, remote on/off, and synchronization of the program to a conveyor. The operator then manually leads either the teach arm, or the manipulator (with teach aid) through the motions, switching the spray gun on and off as required.

The software organization for this type of robot system basically consists of an interpreter. In the teach mode it samples and records position and spray on/off data onto mass storage. During playback it reverses the process and transmits position data to the servo drives. When a tachometer signal is used for conveyor synchronization, this signal is used to adjust the program playback speed accordingly.

The major advantage of this type of software system is the ease of program application. The operator is only required to set the correct switches and pushbuttons on the control panel and then manually lead the manipulator (or teach arm) through the required motions. No knowledge of a robot language is required.

All the robot systems using this programming technique have a major drawback. None have good editing capability. This is because all of them record a large number of points to produce the continuous path. Any editing of these points would create discontinuities in the path. Thus the only effective way to edit a path is to reprogram it.

Teach Pendant Programming

This programming system is the most common on industrial robots. Besides the three basic components of the robot, this system includes a teach pendant. Depending on the robot manufacturer, the teach pendant may have just the motion pushbuttons or may also include function keys (for example, time delays, outputs, wait for inputs, etc.).

To teach a task, the teach mode is initiated by setting the correct switches on the control panel. Using the teach pendant the manipulator is moved and the position is recorded by pressing the record button. Various parameters such as gripper state, time delays, output states, wait for inputs, and travel speed can be set and recorded. Unlike the manual lead-through technique which records the complete path, this teach technique records only the end states of the path. The path replayed by the robot in automatic mode is dependent on the control algorithm used to generate the position data for the servo drives. In the more advanced robots, the operator can specify straight-line motion, circular arc interpolation, joint interpolated and/or continuous-path motion.

The software structure is also interpretive. Unlike the manual lead-through technique which records the position data at the sampling rate, this programming system records only the endpoints. In addition, the interpreter has the capability to execute special library routines that allow for some logical branching and other useful functions. The interpreter also allows for going through the program one step at a time. Since library routines are used to provide instantaneous position information to the servos during playback, editing features such as step deletion, modification, and insertion become easy to implement.

The most important advantage from the user's perspective is the large number of functions—such as time delay, output signal states, travel speeds—that can be programmed. Another important advantage is the superior editing capability over the manual lead-through technique. Because of the discrete endpoints programmed, the main memory capacity allows for longer programs.

The disadvantages of the teach technique are that it generally limits the operator to simple programs with limited branching capability. Historically many of these systems provide no easy means of documentation. In addition, for most robot systems these programs have to be taught on line.

Textual Language Programming

So far we have discussed the nontextual techniques of programming the robot. The operator who understood the application was able to program the robot by leading it through, either manually or by means of a teach pendant. Because of the complexity in assembly-type applications, the industrial robots in this category are equipped with textual programming. This teaching technique provides instructions to move the manipulator, read sensors, send signals to external equipment, set counters, perform logical branching, and many other instructions that make the task of programming the robot simpler. This technique of teaching then becomes a program in the classical sense and is either compiled or interpreted by the robot software system.

There are four textual language robot systems that have been in industrial use for a period of time. These are:

1. SIGLA, for the Sigma robots from Olivetti, Italy;
2. HELP, for the Allegro[1] robot from General Electric Company, licensed through DEA, Italy;
3. VAL,[2] for the Unimate robots from Unimation Inc.; and
4. RAIL,[3] for the AID 800 manipulator and AI32 controller from Automatix Inc.

The software features common to all of these systems include the hierarchy of control levels, with the highest monitoring and coordinating the complete robot system, and the lowest interacting with the specific hardware. Some of these systems are more user-friendly because of their interactive and friendly program generation and debugging environment. Language extensions and supplements for specific applications are also provided by some of the vendors.

User advantages in the textual language teaching method include all of the typical advantages of the teach pendant methods such as editing and special function commands. In addition, features such as logical branching and use of data structures provide useful tools to develop large and complex programs. In general, these programs tend to be self-documenting and a hard copy can easily be obtained.

The disadvantages of a purely textual mode of programming is that it restricts the user to communicate through a terminal. In complex assembly applications, this is the most efficient way to program. But for many process-type applications, a combination of the teach pendant or lead-through technique with a textual language format proves more efficient. Languages such as VAL and RAIL support a limited-capability teach pendant.

Software Organization for an Industrial Robot

Recent robot software systems are moving toward supporting the user needs. This is being approached by providing programming aids that allow a combination of textual mode with a teach pendant. In addition, CAD systems are being considered for improved programming efficiency.

To fully integrate the industrial robot into the manufacturing system requires that its software structure consider the user needs as primary. In this regard, the robot software system at the user level must be interactive and friendly, be extensible to allow user-generated subroutines and functions, and also provide an Englishlike command language for various applications. In addition, specific application software should provide various features that ease the task of programming the particular application. As an example, consider a spray application. Here the software structure should support a textual mode combined with a manual lead-through teaching aid or teach arm to provide an efficient programming environment. If a CAD system is available at the user facility, the robot software system should provide the capability of receiving geometry information from it and use it for the robot task.

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[1] Allegro is a trademark of the General Electric Company.

[2] VAL is a trademark of Unimation Inc.

[3] RAIL is a trademark of Automatix Inc.

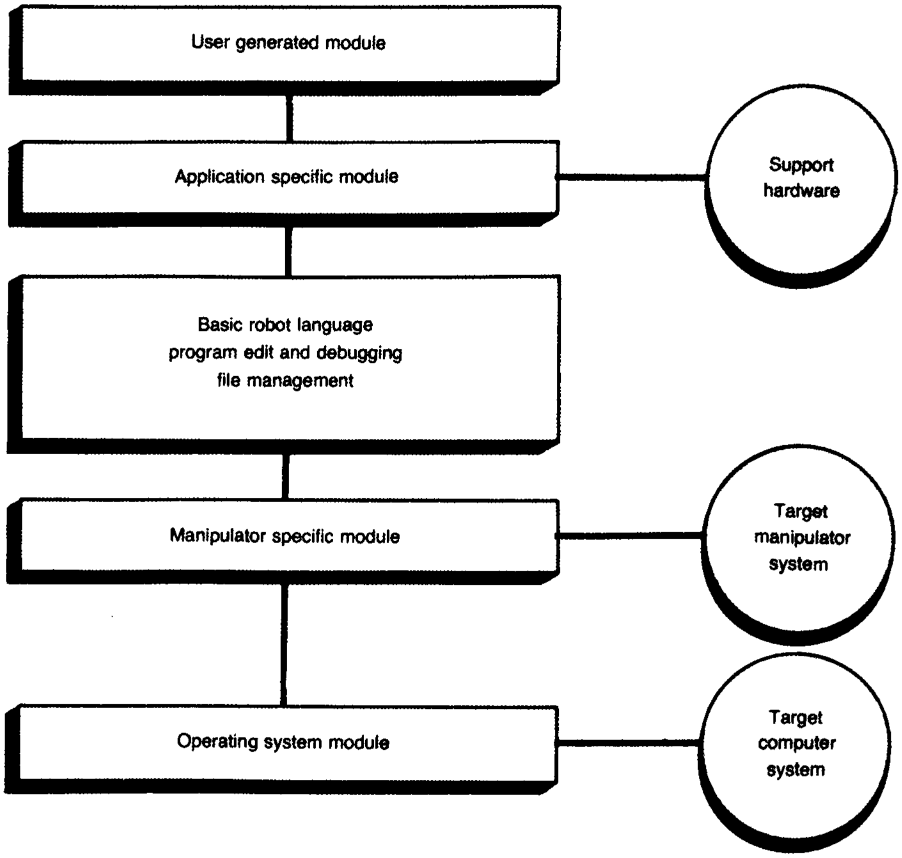

Fig. 1 Modular implementation of the robot software system.

An attempt to define the structure of a software system that will meet these user requirements is shown in Fig. 1. It consists of five major modules, each building on the capability of the lower level modules. The goal of this implementation is to provide flexibility so that substitution of any module with a new or different version has the effect of requiring no reprogramming at the higher or lower levels.

Suppose that a program has been written by the user for an arc welding task. Two years later, when a higher-speed processor is available, the user substitutes the vendor-supplied lowest level module with the new version. This consists of replacing the processor board and associated software. The old program should now execute without modification. The only effect visible to the user should be more accurate tracking due to the higher processing power. Similarly, replacing a jointed-arm robot with a spherical type arm and the associated software module, should have no effect on the execution of the old program.

Operating System Module. At this lowest level in the structure is the operating system that provides the tools to coordinate the target processor, and peripherals such as main memory, input/output, mass storage, and communication. It must also support utility routines and a structured high-level language to be used for development of the robot language and support functions.

To simplify the implementation on various processors and user peripherals requires that the operating system be simple, portable, and extensible. These requirements are important for two major reasons. First, to provide for the implementation of this software system on various robots using different processors. Second, to remain competitive in a highly aggressive robot market requires that the industrial robot vendor be able to adapt new processors and peripherals with relative ease.

Manipulator Specific Module. Various manipulator configurations are in popular use due to the inherent flexibility they provide for specific applications. This module of the software structure provides the translation of the robot language and application-specific commands into executable commands for the particular manipulator. For example, a move command from the next higher module would require a different joint coordinate transformation for a cartesian manipulator than that required for a jointed arm manipulator. This manipulator-specific module should be coded in the structured high-level language to provide self-documentation, maintainability, and portability. Commercially available high-level languages such as C, Forth, or Pascal should be used. Reverting to assembly language for hardware or execution speed consideration must be avoided.

Robot Language Module. The key requirement for this module is that the robot language be Englishlike, extensible, and provide for structured and self-documenting programs. In addition to the typical robot language

ROBOT COMMANDS:

MOVE.TO, MOVE.STRAIGHT, MOVE.ARC,
APPROACH, DEPART, ACCELERATE, PRINT
SPEED, OUTPUT, DELAY, WAIT
DIGITAL.INPUT:, DIGITAL.OUTPUT:,
ANALOG.INPUT:, ANALOG.OUTPUT:

CONTROL STRUCTURES:

BEGIN . . . . . END
IF . . . . . THEN . . . . . . ELSE
WHILE . . . . . . DO.BEGIN . . . . REPEAT
FOR . . . . . . DO . . . . LOOP
GOTO

ARITHMETIC AND LOGICAL:

*, /, +, −
.EQ., .NE., .GT., .GE., .LT., .LE.
.AND., .OR., .XOR.

DATA STRUCTURES:

CONSTANT:
INTEGER:
REAL:
POSITION:
SET:

Fig. 2 Basic robot language commands.

commands shown in Fig. 2, this module must also contain an interactive and user friendly text editor, a program debugger, and a file management system. In this module only those features and commands should be provided that are generic to all robot systems. This will lend flexibility to tailor the application level module more appropriately. Because of safety concerns, this module should be the lowest level to which the user can gain access. Also, user-defined values for speed, acceleration, and servo gains should not override safe maximums.

As with the previous module, the robot language module must be coded in the structured high-level language.

Application-Specific Modules. The majority of industrial robots in use today were installed for a specific application. These robots are performing the same type of task for which they were originally purchased. Each of these application areas has specific needs for which the robot system has to be tailored. Spray painting applications require continuous path motions, conveyor tracking, control of multiple paint nozzles or colors, etc. In material handling some of the same commands are applicable. For example, conveyor tracking is required. But there are a few application needs that are quite distinct. Figure 3 illustrates some typical commands that are useful for spray and material handling applications.

As robots make further inroads into industry, the demand for more application flexibility will grow. Rather than provide all of these capabilities as part of a general language, this software system will support modular packages that can be added or deleted as required. These packages are not only software modules, but also include application-related hardware. For spray applications, a teach arm or lead-through aid should be provided. For material handling, force sensors and a teach pendant would be more applicable.

SPRAYING APPLICATION:

TRACK:	Tracks a conveyor using a tachometer.
TEACH:	Sets up a teach mode for using teach arm.
SMOOTH:	Spline interpolation for smoothing path.

MATERIAL HANDLING APPLICATION:

PALLET:	Name and define a pallet
PALLET.SIZE:	Row and column size
PALLET.COUNT:	Name and initialize a counter
PALLETIZE	Computes next pallet location
TRACK:	Tracks a conveyor
OPEN.GRIPPER	Open the gripper
CLOSE.GRIPPER	Close the gripper

Fig. 3 Application-specific commands for spraying and material handling.

The application-specific module should be coded in the high-level language rather than the robot language. This will not only provide the required portability, but also be highly flexible and speed efficient.

User-Generated Module. This is the highest level in the software structure. Application programs developed by the user of the robot language commands form this module. Since it it impossible to foresee all the various types of commands, control algorithms and sensors that could be used, it is essential that the robot language be extensible, to provide the basis for the development of this module.

Future Software Needs

One of the major requirements of the user is the need for the software system to be interactive, friendly, and have one common Englishlike robot language for a variety of robot systems. In addition, special applications developed by the user or third parties must be easily implemented and transportable to new systems with little or no modification. The software system introduced possess the capabilities to meet these needs.

For the robot vendor, this modular and flexible software system provides a number of advantages, the major ones being the relative ease of transporting and maintaining this software on new manipulator/controller designs. Also, the introduction of new high-speed processors and peripherals can be incorporated into the controller with only the lowest level module having to be redeveloped. Since the development cost of software is a major consideration when introducing or incorporating new designs, vendors using this software system gain a technology edge over their competitors.

Because of the general inflexibility and nonportable structure of present robot software systems, CAD and vision systems are only slowly gaining inroads into the robot domain. This software system aims to provide the flexibility that is essential for communication between CAD, vision, networks, and any other new technology that will be developed, thus paving the way for the robot to become an integral part of the automatic factory.

Based on a paper contributed by the ASME Computer Engineering Division

State-of-the-Art

Some Critical Areas in Robotics Research [*]

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The general field of robotics is briefly reviewed. Two important areas–computer vision and compliance–are identified and discussed at some length. Some comparisons between the various approaches to the vision question are made, and active and passive force measurement are contrasted. Finally some other important areas including hierarchical control, manipulators, grippers and fixtures are considered. It is concluded that significant developments in robotic technology, particularly as they apply to batch manufacturing, will be forthcoming in the near future.

Keywords: Robotics, Adaptive Control, Computer Vision, Laser Range Finding, Light Stripping, Force Sensors, Tactile Sensors, Compliance, Manipulators, Grippers, Flexible Fixtures.

1. Introduction

In the industrialized nations of the world batch manufacturing methods of parts, sub-assemblies and finished assembled components dominate manufacturing industry. In such an environment the use of fixed automation involving cams, jigs and fixtures requires long lead times and is generally uneconomic. Hence, a high level of manual labor is used, particularly in final assembly but also in materials handling and inspection. This has resulted in the use of off-shore cheap labor available in less developed economies, and therefore a net export of jobs. Also, many manufacturing operations are performed in hazardous environments–the foundry and forge shop serve as good examples–and more stringent safety regulations require that these tasks be performed remotely from human operators.

Consequently, considerable research is now being undertaken in the United States and elsewhere aimed at improving productivity by the use of industrial robots. This is taking place in government laboratories, corporate research and development centers, universities and affiliated non-profit research institutes. In this paper some of the recent developments in robot technology are presented.

Currently industrial robots, which are available commercially in several levels of sophistication, are used predominately by the automotive industry for repetive spot welding, machine loading and painting operations [1]. These robots operate in an "open-loop" control mode. The operator leads the robot

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[*] This paper is based in part on: "Advances in Computer Controlled Robots for Use in the Manufacturing Industry", *International Conference on Manufacturing Engineering*, Institution of Engineers, Australia, Aug. 1980, pp. 241–246.

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through a sequence of operations either by actually manipulating the robot arm directly or by using a remote control. A point-to-point sequence is then established in the robot controller memory and the robot can repeat the task almost *ad infinitum.* Because the control is open loop the robot is unable to adapt to any changes in its environment. Errors in parts presentation and orientation and those due to drift cannot be accounted for. Hence the use of these devices has been restricted to situations where tolerances are coarse and the operation is somewhat less than delicate. A tabular summary of the specifications of almost all commercially available robots has recently been given by Koekebakker [2], who also addresses a number of the practical difficulties associated with robot instalations.

Recent advances in computer vision systems -- including binary, gray scale and stereo, compliant devices for the mounting of grippers and other end effectors and the science of gripping or prehension have resulted in considerable technological development. Combined with the drastically decreased cost of computer hardware, largely as a result of VLSI (Very Large Scale Integration), it is expected that significant advances in computer assisted manufacturing, particularly in the field of flexible automated assembly, will result. Spinoffs from other research areas, especially the development of tele-operators and robot manipulators for the space missions of the eighties and the nuclear industry are also expected to have considerable impact [3].

The majority of the research into Flexible Manufacturing Systems and Robotics is being undertaken in Japan, West Germany and the United States. The MUM (Methodology for Unmanned Manufacture) project was conceived in the mid-seventies in Japan, and is expected to go on-line in the early eighties [4]. It is envisaged that this plant will be able to produce automatically up to 50 assemblies, such as gear boxes and hydraulic motors. It has been claimed [5] that machining, forming, laser processing and assembly have all been integrated in this system. On a larger scale, the U.S. Air Force's ICAM (Integrated Computer-Aided Manufacturing) program has set as its long-term goal the development of a highly automated factory for aerospace systems production with integrated management and control [6]. More directly related to the question of batch production and the direct use of the industrial robot is the APAS (Adaptable Programmable Assembly System) pilot system under development by Westinghouse Electric Corporation [7]. This system has as its goal the demonstration of a line which can assemble many styles of electric motors, the changeover from one style to another being accomplished under computer control in a matter of minutes. This system makes extensive use of computer vision and compliant mounts for grippers.

At Carnegie-Mellon University research towards the factory of the future is currently receiving great emphasis.' A *Robotics Institute* has been formed whose current thrust areas are in the field of manufacturing technologies, including adaptive control of a machining cell, assembly of circuit boards, dimensional measurement by light striping and laser scanning, manipulator and sensor development and computer vision. Plans include additional programs in underwater, aerospace, nuclear and prosthetic applications. Indeed the first of these is already receiving attention. The Institute has the largest "Robot" population of any North American University.

Clearly there is great potential use for industrial robots in an adaptable automatic manufacturing sequence. This paper will discuss some of the necessary technology bases for this and specifically address some of the means of closing the feedback control loop so that true adaptability can become a reality. The resent excellent review paper of Barash [8] discusses the more general question of Computer Integrated Manufacturing Systems and the factory of the future.

2. Robot Control by Computer Vision

A number of computer based vision systems are available today, the forerunner being that developed at SRI International [9]. This consists of a solid state TV camera interfaced with a DEC LSI-11 microcomputer by means of a pre-processor. The system is capable of analyzing a binary (as distinct from a gray scale) image in the microcomputer. The Unimation Company is planning to market this vision system with their recently introduced PUMA robot [10]. Software supplied with the system includes packages for connectivity analysis (i.e., distinguishing and defining the part), extraction of shape and size descriptors, extraction of position and orientation descriptors, automatic recognition using families of these descriptors and training for recognition by showing. The system has empirically controlled threshold selection which is necessary for converting gray scale data into binary (black and white) data, and hence necessary when distinguishing a part from its background. Automatic threshold selection is currently an important area in the computer vision research community. Processing time for a typical image is about 1.4 seconds and it is expected that future developments may reduce this by a factor of two.

For the determination of size and shape Agin [11] has listed the following descriptors: area, perimeter, second moments of area, radius vector statistics, hole counts, possible straight line approximations and dimensions of circumscribing rectangles. These may be obtained in dimensional or non-dimensional form. The list of position and orientation descriptors is shorter: center of gravity, center of circumscribing rectangle, angular position of maximum and minimum radius vectors and angular position of minimum second moment of area.

The SRI system, as currently available, is not capable of depth perception. The descriptors mentioned are all obtained from two dimensional silhouette information. The requirement for manual threshold selection also presents some difficulty. Agin [11] has discussed this and concluded that automatic threshold selection by means of the vision computer should be shortly achieved. Until such time, it is likely that systems such as this, based on binary vision and diffuse lighting, will not perform adequately in some industrial environments where sufficiently contrasting backgrounds are not always available. The two dimensional limitation means that information required for successful bin picking, and other operations where part overlap is likely, cannot be performed.

Nevertheless, algorithm and software development for analysis of two-dimensional vision data is being vigorously pursued at present. Connectivity Analysis has been defined by Agin [11] as a procedure for breaking a binary image into its connected components. He has also suggested that binary shape analysis principles tend to be universal. When a solid state camera with 128 X 128 resolution – and improvements here will be rapidly forthcoming – is used, obvious methods of extracting necessary information are very time consuming. Hence, the emphasis in much of the current research is directed at the development of algorithms which reduce the necessary computation.

One such example is the use of *run-length coded* data. Here, the initial 128 X 128 array, containing binary information, is reduced to an array containing only the position of the transition points. This results in considerable data compaction. Other developments, including the use of a single top-to-bottom pass, instead a complete pass for each connected region have resulted in algorithms capable of performing the analysis in between n and n^2 operations for an array of size $n \times n$. This compares favorably with the n^3 operations necessary for the multi-pass procedures [11].

An alternative system has been developed by General Motors and is known as *Consight* [12]. This is based on two planes of light being focused into a strip on a moving conveyor. The principle of operation of the system is illustrated in Fig. 1, where the second light source has been removed for clarity. By replacement of the linear array camera with an area camera, and some software modification, this method is capable of perceiving depth. There is a requirement that parts do not touch. In addition to the depth perception capability, *Consight*, although based on a binary picture, has no threshold problems and is therefore suited to an industrial environment. Nevertheless, as currently developed this system is incapable of generating bin picking information. Conceptually this would be possible if the light sources and camera were made mobile, for instance by locating them on a second arm. This may well lead to some reliability problems however.

Geschke [13] has described a stereo-binary vision system used to guide a robot in an insertion task. The

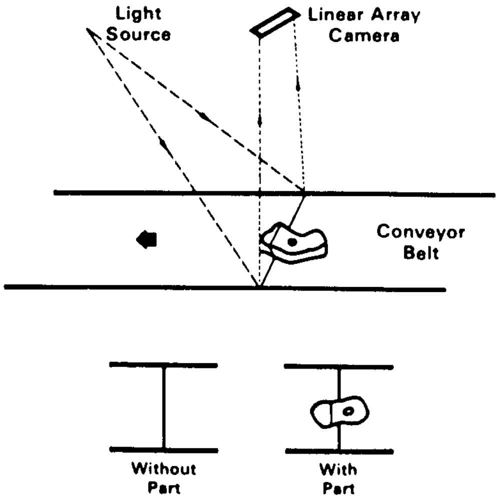

Fig. 1. *Top*: The principle of operation of the General Motors *Consight* system. *Bottom*: Camera's view of parts showing displaced line indicating depth, after Ward *et al* [12].

system is novel in that mirrors are used to obtain three dimensional information from a single camera. As with the SRI system, contrasting backgrounds and parts are necessary and diffuse rather than planar light is used. The robot control algorithms have a soft decay feature which safeguards against a failure of the vision system. Additionally, the control algorithm uses signals from a pair of capacitance based tactile sensors, located in the fingers of the gripper, for precise control in the final stages of the insertion task. Thus, although still limited in a number of ways, this system approaches a true adaptive control.

Vanderbrug, *et al.* [14] have described a vision system in which the camera is mounted in the robot hand and a stroboscopic light source is used. An image of line segments, similar to those obtained with the *Consight* method is produced. The main advantage of the stroboscopic approach is that a moving conveyor is not necessary. The wrist/camera is able to home in on an object for acquisition. The system has been shown to be able to successfully acquire a box, a cylinder and a cast bearing from a random pile of these objects. The unique feature of this system is the arm-mounted camera and flash combination which permits real time image processing and depth perception without gray scale imaging or the necessity of a moving conveyor.

Space exploration and concomitant orbital construction is likely to become more automated as costs and distances from Earth increase. Williams, *et al.* [15] have described the state of the art in vision systems developed for this purpose. A stereo system has been developed which allows a rover to acquire a rock while avoiding other obstacles. It seems that much of this developmental work overlaps that being undertaken by researchers more concerned with earth bound robots. It is suggested that much can be gained by careful study of both approaches.

Kelley, *et al.* [16,17] have developed a two camera gray scale based vision system for use in control of robot bin picking, subsequent orientation and placement into machines of components. In terms of capability and amount of data, this is currently the most sophisticated system known to the author. One camera is mounted on the robot arm and therefore this camera is capable of significantly better resolution than that obtainable with a fixed camera. Light sources also mounted on the robot arm, are computer controlled. The second (fixed) camera is used for pose identification and subsequent re-orientation of the work piece. The major disadvantage with this approach is, of course, the cycle time. Processing of the gray scale data from two cameras requires about 20 seconds compared with 1.4 seconds for the SRI binary image. Additionally, the gripper used for bin picking is vacuum based. While it is conceded that for demonstration this serves adquately, it is doubtful whether such a gripper would be useful in many harsh industrial environments. It may be concluded that the question of gray-scale *vs.* binary input for computer vision systems is far from resolved by researchers in the field. Gleason and Agin [9] have demonstrated the speed of a binary based system and the inherent ability of such a system to recognize parts using various descriptors. Ward, *et al.* [12] have, to some extent, solved the depth perception problem using binary vision, although as currently configured, *Consight* does not use this capability. An equally valid and alternative approach taken by Geschke [13] involves the use of a stereo-binary vision system. On the other hand, Kelley, *et al.* [16,17] have found it necessary to resort to gray scale imaging for successful bin picking. The order of magnitude increase in data results in an equivalent increase in processing time.

At Carnegie-Mellon University research is being conducted into several alternative methods of 3-D range finding [18]. These have grown out of the specific needs of an industrial sponsor. For profile measurements of complex shapes a four-camera light striping technique is being developed. This uses conventional light sources and a single SRI type vision module with four cameras. As with the system developed at the National Bureau of Standards [14], depth can be perceived by analyzing the shape of the resulting light strips. Issues being addressed in this project are: 3-D image representation, correcting for perspective and strip matching.

Another approach uses analog area position sensor chips and laser and infrared light sources for medium (50 cm) and short range (5 cm) sensing. The technique uses active illumination and triangulation. Initial studies indicate that use of the area position chip offers considerable speed advantages over a conventional camera. Combined with a microcomputer and simple optics devices these systems offer new possibilities in non-contacting 3-D ranging.

It may be concluded from this discussion that vision systems as currently available are capable of limited part identification and location and hence low level robot control. Further research will result in improved hardware and software together with superior image processing algorithms. This will lead to fast response and may allow gray scale image processing, even by slower microcomputers. Of course, the developments currently being made in binary image processing algorithms will impact grey scale vision and developments in laser scanning and light striping will increase the resolution obtainable. Wide spread use of these systems will result in higher level languages and hence more rapid and easy user access.

3. Compliance – Passive Force Sensing

While it is clear that the potential of robot vision is only now beginning to be realized, it must be pointed out that even the most advanced vision systems will still be inherently limited in some respects. Paul [19] has stated that vision is no help in fine assembly work, where, if an insertion process is necessary, the important part features are likely to be obscured. This has been confirmed by experimental studies at Carnegie-Mellon University, where the capability of an assembly station for the manufacture of electronic circuit boards, which uses computer vision based on the SRI module as the primary means of adaptive control, has been considerably enhanced by the addition of transducers capable of measuring insertion forces. For such reasons it will be necessary to pursue research on force and tactile sensing methods.

Seltzer [20], Rosen and Nitzan [21] and Abraham, *et al.* [1] have each reviewed various methods of force measurement. The major methods developed to date are remote sensing of reaction forces at manipulator joint drives, wrist force sensing and pedestal force sensing (i.e., sensing reaction forces on a workpiece table). For tasks such as peg insertion using each of these methods, an on-line computer is necessary as part of the control loop. Seltzer [20] has stated that control by such an approach can be time consuming and cumbersome. Remote joint sensing (by measuring drive motor armature currents) has the advantage that no separate force sensor is necessary. However, inaccuracies result from arm inertia, which varies with position, gripper and part, and joint friction. Wrist and pedestal sensing methods involve use of a slightly compliant member instrumented with strain gauges, piezoelectric or other transducers. It is necessary to measure three forces and three torques independently for a complete description of assembly forces.

An alternative approach to force measurement and on-line control is the use of a passive device known as the RCC (Remote Center Compliance). This is a device with a pre-determined compliance which can accommodate position and alignment errors. Whitney and Nevins [22] have described in detail the capabilities of the device and Whitney [23] has demonstrated its use in the assembly of an automobile alternator by means of a computer controlled robot. The main advantage of the RCC is its ability to accommodate position and alignment errors without on-line servoing. It therefore obviates the need for extremely accurate position control of the robot. The importance of this capability is understood when it is rea-

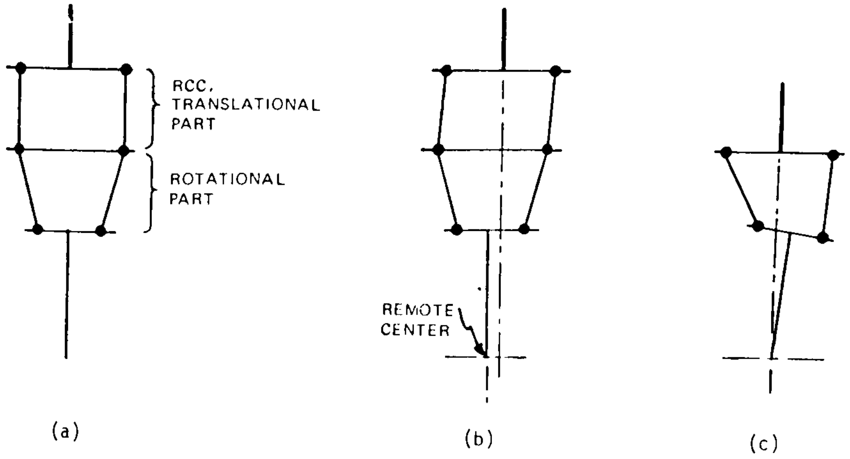

Fig. 2. The principle of operation of the Remote Center Compliance: (a) Planar representation showing rotational and translational parts, (b) Position error accommodation by displacement of the translational part, (c) Alignment error accommodation by displacement of the rotational part, after Whitney, *et al.* [22]

lized that the clearance between a bearing and its housing may be typically 0.013 mm whereas the most accurate commerically available robot with continuous path control has a position repeatability of 0.1 mm [10]. The RCC accomplishes the peg insertion task by effectively pulling the peg through the hole, while actually pushing it. This is achieved by clever location of the center of compliance within the cavity into which the insertion is being attempted. When a force is applied at the center of compliance of a body, only translation results. On the other hand, when a force is applied away from the center of compliance the body rotates about that center. The geometry of the RCC ensures that these translations and rotations correct rather than exacerbate errors due to incorrect alignment. It is necessary for both the peg and hole to have a suitable chamfer, and for the assembly robot to be able to control position to within the chamfer area. The principle of operation is illustrated in Fig. 2 and the actual arrangement of an RCC is shown in Fig. 3.

A commercial version of the RCC and some of the associated technical considerations have been described at length by Rebman and Miller [24]. Some details of suitable elastomeric materials and the properties and applications of these materials have been given by Rebman [25] where use of these devices as critical suspension components in aircraft mounts is also discussed. Seltzer [20] has described an instrumented version of the RCC, which allows an operator or the controlling computer to monitor the insertion forces. This is useful when a gross error which may result in part damage has occurred which the RCC alone cannot accommodate. Watson [26] has described a new device, the RAA (Remote Axis Admittance) which is similar to the RCC but has superior alignment capabilities.

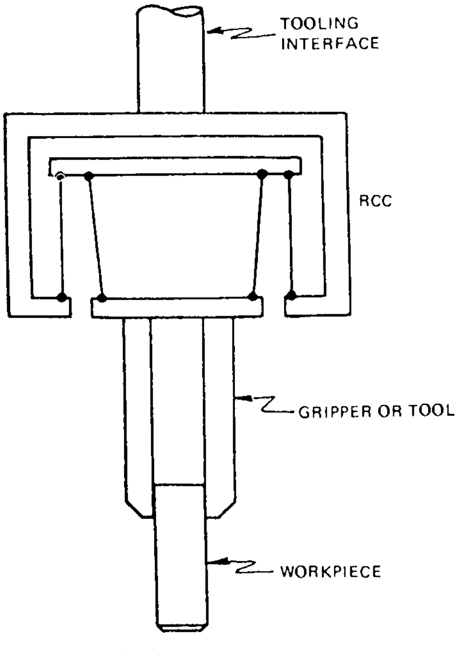

Fig. 3. Physical arrangement of the RCC elements and their relationship with the tooling and workpiece. After Whitney [22].

Notwithstanding these developments, there will be a role for active force and tactile sensing, and it is appropriate to mention some aspects of these areas within the current context. There is some controversy over the definition of tactile sensing. On one hand a tactile sensor is defined as a binary (on-off) device which may, say, indicate the presence or otherwise of a part within a gripper. On the other hand, tactile sense has been defined as local force measurement, usually at the inner surface of gripper fingers. It is interesting to note that the human hand can be considered to have twenty-two degrees of freedom and that each finger is fitted with a highly sophisticated tactile sensor capable of measuring over most of its surface force, temperature, texture and wetness, in addition to operating in a simple binary mode. It is not surprising therefore that researchers are having great difficulty accomplishing some tasks easily and routinely performed by human operators using only tactile sense. To date no commercial robot or gripper is available with either type of tactile sense, however, as noted, Geschke [13] has successfully used a capacitance based analog device in a gripper system for peg insertion. This was coupled with a stereo-binary camera as discussed earlier. This tactile sense was used essentially for protection, i.e., it detected presence or absence of the peg, and caused special action to be initiated when forces exceeded some preset threshold level. In West Germany Warnecke, *et al.* [27] have developed a gripper in which a graticule field of switches is placed. This allows identification of the workpiece position as well as the capability of measurement of some workpiece characteristics.

As part of the research towards the factory of the future at Carnegie Mellon University, the use of vibration, force and dimensional signals together in an adaptive control loop is being investigated. Adaptive control based on vibration signals seems to offer great potential as machine tool resonances and other undesirable conditions can be avoided. Additionally it is anticipated that diagnostic algorithms will be developed and that automatic maintenance procedures will follow [28]. The rational for this work is that if maximum benefit is to be derived from automation of loading and unloading by robots, then other operator functions, including the almost subconscious monitoring via hearing and touch, must be duplicated. Work towards this end includes modal analysis [29] and dynamic force sensing. Concerning this latter aspect, previously developed frequency domain methods are being used [30] and a new approach involving only output data is being studied [31]. The possibility of using semi-active force generators [32] which do not require power amplification is also being considered.

In summary, active and passive force and tactile sensors are available today, and their use has been demonstrated in the laboratory. It is essential to use this type of feedback if delicate assembly sequences are to be carried out. The RCC constitutes an important development, and indicates the importance of careful mechanical design and ingenuity in the whole robotics field. It seems that this type of device will be an essential feature of future robotic assembly lines. Abraham, *et al.* [1] have stated that wrist force sensing and passive compliance devices are ready to be incorporated into the APAS system discussed. On the other hand these authors suggest that direct measurement of manipulator forces is of use only for limiting and protection purposes and that pedestal force sensing and binary and analog touch sensing are not yet ready for practical implementation in their program. Finally, it is noted that no commercial robot is yet available with sensory feedback for adaptive path control.

4. Other Technological Developments

Abraham, *et al.* [1] have identified four other areas where further research and development is being undertaken and where developments will be necessary if the automatic factory of the future is to evolve. These are computer hardware and software, manipulator arm technology, end effectors or grippers and parts presentation or fixturing.

The current developments in computer hardware, such as VLSI (Very Large Scale Integration) have already been alluded to and will not be pursued here. Clearly the driving force for this development is much greater than just that required for robot control.

On the other hand software development is currently presenting some difficulty. Paul [19] has discussed these problems and noted that no language exists which is capable of describing the intricacies of an assembly task. Humans perform these tasks at a reflex level and do not explicitly think of the exact sensory input/output information necessary for a corrective action. Of course, automatic software generation is difficult without such a language base. The binary *vs.* gray scale debate alluded to is indicative of the complex descriptive problems that it is necessary to confront. It must be understood also that programming errors in the manufacturing environment may well lead to physical damage and concomitant downtime. Advances are being made, however. Voelcker and Requicha [33] have developed PADL (Part and Assembly Description Language) for geometric modelling of mechanical parts and processes. This results in descriptions of unsculptured parts in terms of aggregates of distinct solids. Complex parts are built up by operations analogous to arithmetic addition, subtraction and multiplication. In the area of physical design the high level language GLIDE (Graphical Language for Interactive Design) has been developed [34]. This deals with problems such as database administration and may ultimately prove useful in handling the assembly task intricacies. Issues concerning representation involve both space and time tradeoffs. These, together with the merits of various languages have been examined by Baer, Eastman and Henrion [35].

At the control software level advances are also being made. Barbera, *et al.* [36] have described a hierarchical control strategy using microcomputers for arm manipulation. Additionally, a microcomputer is used at each transducer location. Thus a vision signal can be immediately interpreted. A larger main frame or minicomputer can then be used in a supervisory capacity and indeed is able to deal with a number of robots sequentially in a time sharing environment. This allows, theoretically at least, the interaction of two or more robots each with sensory feedback and error recovery. To date no such system has been demonstrated.

The capabilities of manipulator arms have been reviewed in detail by Abraham, *et al.* [7]. As noted previously the most accurate commercially available robot arm has a repeatability of 0.1 mm. This arm is driven by electric DC servo motors. the repeatability of the larger hydraulic servo arms available is typically 2 mm. Two types of motion are required of an arm, namely, gross motion for part transportation or material handling and fine motion for the assembly sequence. Most of the commercially available arms are large, slow and relatively too cumbersome for delicate assembly tasks. This is so as the manufacturers have, to date, addressed the material handling problems. Reduced inertia and increased speed are necessary if manipulators are to become economic in the assembly environment. The possibility of introducing non-conventional materials such as composites suggests itself as a possible solution path, however, the author is unaware of any such developmental work. Features such as automatic acceleration and path optimization depend primarily on software development, but arm capability must be considered at this stage.

At Carnegie-Mellon the use of direct drive arms with built in rare-earth DC torque motors is being investigated [37]. To date a feasibility study has shown that such an approach is possible and likely to offer substantial performance improvements over currently available DC servo indirect drive arms. A design methodology for various joint arrangements and arm sizes has been developed and a prototype arm is currently being constructed. It is anticipated that this arm will overcome, to a large degree, problems associated with conventional arms including coulomb friction, backlash and compliance.

In the circuit board assembly experiment mentioned above two arms have been incorporated, a less precise but flexible arm for part acquisition and a point to point, but precise arm, for component insertion. This approach seems to overcome some of the difficulties mentioned.

The gripper or tool at the end of the manipulator arm is an essential part of the assembly system. No general purpose tool is available and it is the view of one research group that some tailoring to the particular parts will be necessary in most situations [1]. A multipurpose gripper for the acquisition of generic parts was presented by Rovetta [38], which consisted of conformable fingers. In the automobile alternator assembly demonstration [23] it was necessary to use seven different end effectors including three fingered grippers, power screwdrivers and insertion shafts. Some of these were mounted on an RCC, and each could be automatically selected by the single manipulator arm. In contrast, the approach selected for the APAS system [7] is to use one end effector only for each of the seven arms of the system. Each of these end effectors is sufficiently versatile to ensure that all operations at that station can be performed without a tool change. It may be concluded that the desirability or otherwise of tool changes has not yet been established. Nor indeed has a criterion for this decision been given. Also, it is noted that most researchers proclaim at the outset that a universal gripper is impractical. Nevertheless, it is felt that little research is being conducted at present in the important area of end effectors.

One exception is the work of Asada [39] who considered the question of stable prehension. This researcher developed a condition for stable prehension of an object based on minimum potential of the prehension state. Following this theoretical development, adaptive prehension was demonstrated using a computer vision system for input of data to the prehension algorithm. A variety of two dimensional objects were then acquired and manipulated. This work is particularly significant as the technique can easily be developed to clamping of workpieces for machining and other operations. Here, the same stability rules would apply, the stiffness of the gripping fingers being much greater. In the vibration adaptive control work mentioned above, it is intended to study the possibility of dynamically adjusting the clamping configuration during a machining operation. The potential theory approach may well apply here.

Another example is the contour adapting vacuum gripper developed at the University of Rhode Island [40] and mentioned above. This device incorporated a number of sophisticated features including a surface adapting vacuum cup, displacement activated vacuum control and rod position sensing. This last attribute was subsequently used for active steering during acquisition, and thus qualifies together with the potential theory based gripper of Asada [39] as one of the few adaptive grippers developed to date.

The area of programmable fixtures is also one that is receiving scant attention. Warnecke, *et al.* [27] and Abraham [7] have each described a number of flexible fixtures used for parts orientation, transportation, and presentation. The common theme here is that adjustments necessary when changing parts are carried out manually. Thus it may be concluded that this particular aspect is the least developed of all areas discussed. At least end effectors can be automatically changed under computer control. Fixtures and related equipment have not yet been developed to this stage.

5. Conclusions

Implementation of true control in manufacturing industry will require development and adaptation of sensors and associated software which are currently under development at many research centers. The most important of these are vision and range finding, vibration and active and passive force sensing. As noted, there are many variations on these themes, and the optimum approach is not always evident.

Important theoretical and algorithmic developments will continue to be made, especially with the increased emphasis being placed on robotics research and related topics by universities. It will be necessary for industries, corporations and indeed whole nations to quickly adopt these developments and techniques if they are to obtain and maintain a competitive edge.

Acknowledgements

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WHY JAPAN IS PUTTING MORE EMPHASIS ON FMC PROJECTS

Jack Hollingum reports why the country is putting a lot of effort and cash into FMC

NEXT YEAR Japan is to start building a batch manufacturing plant to carry automation right through from the production phase of forged and formed blanks to the assembly of complete gearboxes, pumps or other engineering products.

It may be some small comfort to the western world that this government-sponsored 'Flexible Manufacturing System Complex Provided with Laser' as it is impressively called — FMC for short — is purely a development project. When it is completed at the end of next year it will be used only for testing and appraisal.

However, the participating companies will have gained the experience necessary to design and build complete factories for unmanned manufacturing, and have a good opportunity to lead the world in the building and operating of automated batch manufacturing plants — which is the whole object of the exercise.

Virtually the whole cost of the project is being paid for by the Japanese government, according to the Ministry of International Trade and Industry — MITI. However, a rather different view of the cost distribution is offered by some of the machine tool industry participants who are throwing in a lot of their own manpower and other resources.

What is certain is that the Japanese government has shelled out ¥80 million in 1977, ¥239 million in 1978, ¥1 852 million in 1979 and ¥2 324 million in 1980 for the FMC. And it expects the total cost of the seven-year programme to reach ¥13 000 million — £26 million — by the end of fiscal 1983.

Policy. This suggests a significant policy difference between the Japanese and British governments over support for manufacturing technology — insofar as the British Government has any such policy.

Whereas most of Britain's public support, even in the ASP programme, goes to short-term development projects with quick returns, virtually all of Japan's government effort is going into work which will probably see little practical application before the end of the decade.

Short-term development is a matter for Japan's machine tool industry, and to judge from last November's JIMTOF exhibition it is not lagging in this duty.

But the Japanese machine tool men are not all starry-eyed about the FMC programme. At best, they see it as something for the 1990s, and even though 20 companies have signed up as members of the Engineering Research Association for the programme and are participating in its work, some are doubtful whether they will get much benefit from it.

One man who is serving on the programme's committees even went so far as to suggest that it was not a practical project, that companies would get no direct benefit from it, and that there was not sufficient software experience in Japan to get the FMC running properly.

Government officials, he thought, were too obsessed with hardware. He himself was involved with the programme 'only as a matter of public duty'.

However, it would be foolish to underestimate the significance of the programme. Japanese machine tool men can afford to be sceptical about a government programme when they themselves are already deeply committed to the development and building of plant for unattended manufacture.

Sub committees. Kimio Okazawa is the project manager for the FMC programme. He is based in MITI's Agency of Science and Technology in Tokyo and has the task of coordinating the work of the three government laboratories and 20 companies through a network of management and technical subcommittees.

When I met him in Tokyo recently, he was confident that the many contributory projects were on schedule and that the work would continue according to plan.

The basic economic thinking behind the FMC programme runs like this. Batch production accounts for about 70% of Japan's engineering output and is far less automated than automobile and other mass production industry. It is estimated that 60% of batch production industry will be influenced by the work of the FMC programme sufficiently to buy equipment based on the FMC concepts.

Okazawa accepts that the equipment will be costly, though with 40% of Japan's engineering industry investing in it the machine tool industry could gear up to large scale production. And if it meets its target performance, the payoff to the user could be very satisfactory.

Targets set for the FMC plant are that it should include machining of subassemblies of a maximum weight of 500 kg and a maximum of dimension 1 000 mm, and that the number of parts to be assembled should be up to 300. Production time from the FMC should be less than 50% of that from current equipment. The number of production stations should be less than 60% of the number currently needed.

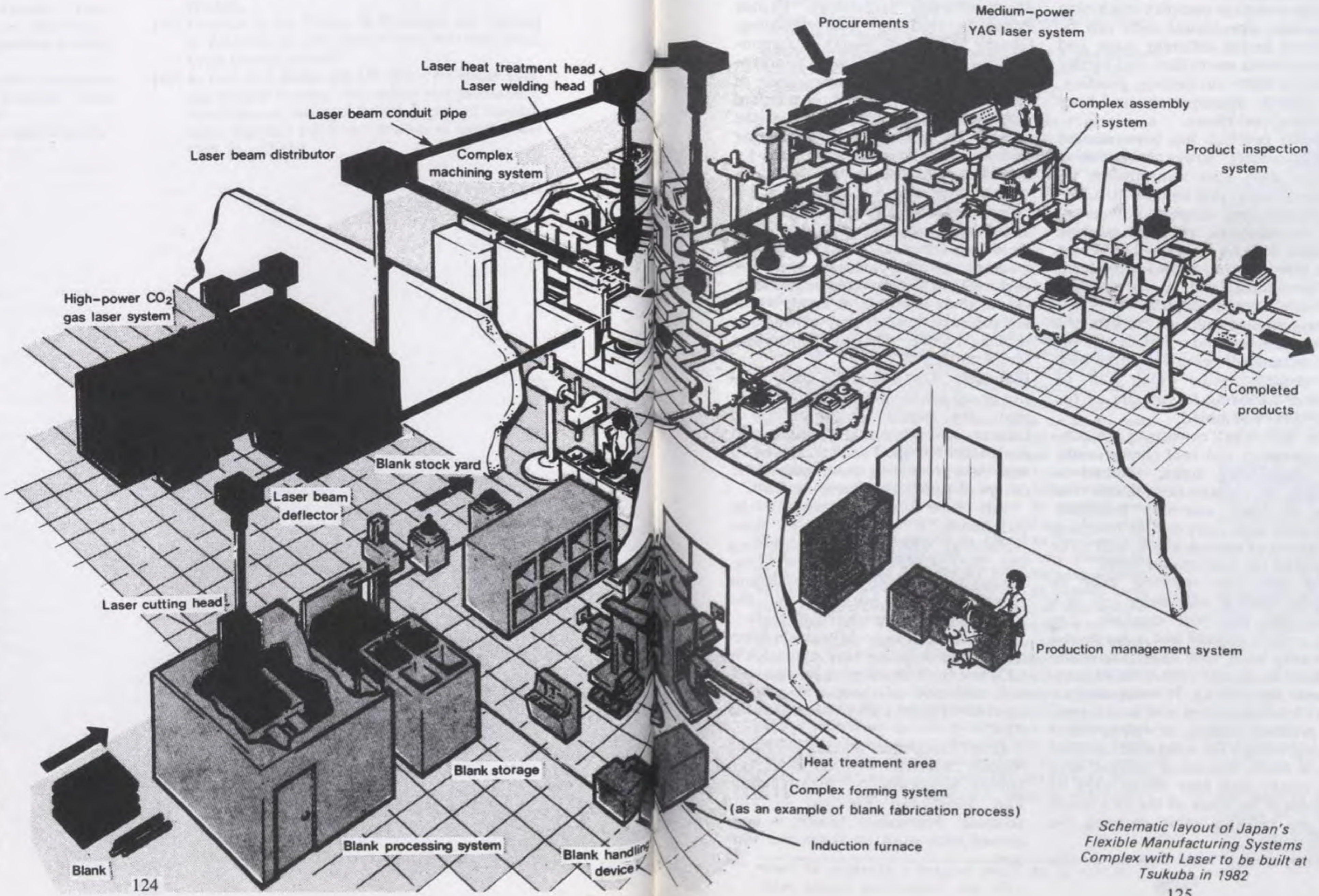
High and medium power lasers are associated with the FMC, and these are to be a CO_2 laser with continuously stable output of 20 kW, discharge tube life of 2 000 hours; a minimum power efficiency of 15%; a 200 W argon laser and a 300 W YAG laser.

Laboratories. Already, a site is being cleared for the building to house the FMC plant at the new Tsukuba Science City, 200 km from Tokyo, where several government research laboratories are now accommodated. This includes the Mechanical Engineering Laboratory and the Electrotechnical Laboratory which are participating in the FMC programme.

The other participating government establishment is the Kyushu Industrial Research Institute on Kyushu Island.

Many of the individual machine cells that will go into the final complex are already built and are under test in the companies that built them, so the individual items of equipment should be thoroughly proved before they are linked up in 1982.

It has been decided not to try to house the entire FMC plant at Tsukuba. The material forming



Schematic layout of Japan's Flexible Manufacturing Systems Complex with Laser to be built at Tsukuba in 1982 machines are heavy and difficult to move, and so will remain in the factories where they have been built. But they will be linked into the hierarchical computer control system by telephone lines.

The material forming group is concerned to develop equipment which will adapt to short batch production of such machined parts as housings, gears and shafts without costly dies and to an accuracy that minimises the amount of machinining required.

Four companies are contributing developments to the programme. These are:

1. **Ishikawajima-Harima Heavy Industries,** which is developing an automatic free forging machine with a pair of rotary turrets, each carrying eight dies, working in opposition, for forming medium and large shafts and spindles.
2. **Kobe Steel** has a hot isostatic press for powder compaction with flexible dies, operating at a maximum pressure of 1 000 kg/cm^2 and 1 200°C, with a pressure chamber 500 mm dia and 1 500 mm long.
3. **Mitsubishi Heavy Industries** has built a disc and ring forging machine to make parts up to 500 kg and 1 000 mm diameter under automatic control.
4. **Aida Engineering** has built a prototype six-axis precision multiple-shaft forging machine for small stepped shafts. It has three opposed pairs of rams working under numerical control — two pairs of 10 tonnes, and the third of 50 tonnes.

Government laboratories have parallel projects on forming with combination dies, powder metallurgy compaction technology and so on. At the heart of the programme is the work being done by the cutting and assembly group, which has six member companies.

Complex. The need here is for a machining complex which can respond flexibly to the manufacture of diverse products, a task to which a good deal of attention has been paid in recent years; and the less thoroughly explored task of developing an assembly station which can carry out complete batch assembly of a variety of engineering products about a cubic metre in size.

An outline description of the machining and assembly units was given last year at a conference of CIRP, the international production engineering association.

The machining complex is built from a number of modular units according to the needs of the particular user. These consist of construction units such as beds and slides; functional units like spindles, grinding heads and laser units; supplemental units — rests, arms, magazines; supporting units — pallets, chucks, mandrels; and tools.

The units are assembled into operational cells of which there are six main types:

A cell — Spindle + axial feed
AL — Spindle + axial feed + lateral feed
AV — Spindle + axial feed + vertical feed
AVL — Spindle + axial feed + vertical feed + lateral feed
RA — Spindle + axial feed + rotational feed
RAL — Spindle + axial feed + rotational feed + lateral feed

In the complete complex machining mechanism, operational cells can be combined in six different ways and combined with controllers and carrier devices to carry out cutting, grinding, gear cutting, measurement and laser processing operations.

Parallel research has been needed on non-contact power transmission between units, data transmission, in-process sensing, chip treatment, adaptive control and accuracy compensation. An automatic assembly machine has been built by Toyoda. The design again is modular to allow for different configurations, and a hierarchical approach is again adopted.

The complete machine consists of a construction cell and a motion cell, the construction cell being built from base and column units which can be selected according to the size of the work to be assembled.

The motion cell consists of positioning, operation and tool change units. The positioning units, themselves modular in construction, locate the parts in their assembly positions. Operation units carry out the fastening operations of various kinds, with tools loaded by the tool change units.

Under test. The machine built by Toyoda which is still under test, is a frame-type four-post machine, 2 m long, with a vertical and a horizontal operating head, able to accommodate work up to 30 mm cube with 30 components up to 30 kg. It incorporates a pallet loading system and uses torque and pressure sensing, as well as vision sensing, using a GE solid state camera.

It is under numerical control, with one rotary and four linear axes of movement for each of the two heads and an indexing table carrying the work pallet.

Co-operating with Toyoda in this project is Yaskawa Electric, which is supplying AC servo motors and control systems. The two companies are working together on the software. Yaskawa has made a 2 kW prototype servo motor and is working on a 5 kW prototype.

Other companies involved in the cutting and assembly group are Toshiba, Makino Milling, Hitachi Seiki and Yamazaki.

Makino, which is working on high-speed spindle mechanisms, has made a 10 000 rev/min prototype and expects to have a 20 000 rev/min 10 hp version running by March for high-speed milling of aluminium and other alloys.

Another small group of three companies is charged with developments in product inspection technology, system control technology and automatic diagnosis/design technology. Fujitsu Fanuc is studying troubleshooting; Okuma Machinery Works is responsible for automatic tool wear compensation and accuracy compensation of modular structures based on standard units; and Shin Nippon Koki has the overall task of building an inspection station corresponding to those for machining and assembly.

This 'inspection mechanism', as it is called, would be better described as an automated test bay in which completed gearboxes, and headstocks made are given a complete operating performance test covering dimensions, shape, shaft vibration, dynamic rotating accuracy, lost motion, starting and rotating torque, vibration, noise and temperature rise.

Diagnosis. Also within the purview of this group are the system control functions, the primary responsibility of Okuma, and automatic diagnosis and design technology. The latter has to do with data processing techniques in the design of products suitable for FMC.

The most surprising part of the programme is the work with laser technology, which is seen as supplying the facility for cutting, welding, hardening and with the laser beams transmitted by mirrors into the machining and other working areas.

Two companies — Mitsubishi Electric and Toshiba — have made 5 kW CO$_2$ lasers which are now being assessed, and one of them will get the contract to build a 20 kW laser for the FMC.

Other companies making lasers are Nippon Electric — 300 W YAG; Horiba Seisakusho — alkali halide; and Sumitomo Electric — zinc selenide. Matsushita Giken is concerned with work on resonance mirrors.

Conférence présentée à la Convention Informatique 1980.

SESSION 44

PROBLEMES FONDAMENTAUX POSES PAR LES ATELIERS FLEXIBLES

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RESUME :

Dans ce papier, il est montré qu'on peut distinguer trois types d'ateliers flexibles : ateliers flexibles pour production de pièces à l'unité, pour les moyennes séries et pour la grande série. Tous ont en commun certains problèmes : fiabilité, correction d'usure des outils, problèmes d'interfaces, commande hiérarchisée, etc..., mais chacun a un problème principal :

- Pour la production unitaire, la condition nécessaire de rentabilité est la normalisation des dimensions et tolérances.
- Pour la moyenne série, produit et atelier doivent être étudiés ensemble.
- Pour la grande série, l'adaptation à des pièces différentes nécessite une quasi identité des gammes d'usinage.

Au total, la rentabilité d'un atelier flexible nécessite un très grand effort de rationalisation et de standardisation. Ne pas accomplir cet effort conduit nécessairement à l'échec.

I. PRELIMINAIRE

On ne peut s'empêcher, nous semble-t-il, d'éprouver une certaine fascination et en même temps quelque malaise à l'évocation des ateliers flexibles. Le terme est à la mode et plaît, indiscutablement; mais la gêne vient de ce qu'il est si vague, si imprécis, si général, qu'il est bien rare que deux personnes lui attribuent la même acceptation. Ce malaise est accru par le fait que bien peu ont vu de tels ateliers, mais chacun en a entendu parler par les revues et par ceux qui ont accompli l'inévitable visite au Japon.* Ceux-ci en sont revenus souvent éblouis et aussi, il faut bien le dire, quelque peu intoxiqués. Il faut reconnaître qu'il y a de quoi l'être quand on vous annonce que le taux d'arrêt total (toutes causes comprises, accidentelles et autres) d'un atelier ne dépasse par 1%! Le malaise s'accroît encore quand on apprend que la plupart des fabricants de ces ateliers, à la suite des échecs retentissants de certains, estiment de tels ateliers invendables, en tout cas inexportables, si ce n'est à quelques clients soigneusement sélectionnés et qui ont l'esprit, le niveau technique, le personnel et l'organisation indispensables pour leur exploitation intelligente et rentable. Pourquoi ces difficultés, ces enthousiasmes, ces échecs ?. Que sont donc réellement ces ateliers flexibles ? Quelles sont leurs caractéristiques et en particulier celles qui les rendent si peu abordables au commun des mortels ? Quels sont les principaux problèmes qu'ils posent tant à leurs fabricants qu'à leurs exploitants et qui doivent impérativement être résolus si on veut en tirer profit? C'est à éclairer quelque peu ces différents points que nous allons nous appliquer dans ce qui suit.

II. TENTATIVE DE DEFINITION

Dans la suite de ce texte, nous nous contenterons d'évoquer les systèmes d'usinage à l'exclusion de tout ce qui concerne l'assemblage, les essais, le réglage, etc... La tâche sera bien assez importante comme cela.

Une définition d'atelier flexible que l'on trouve couramment se formule ainsi : "Un atelier flexible permet la production unitaire de pièces. Sa production et l'engagement des machines sont gérés par un ordinateur". Nous pensons que cette définition est un peu courte. En effet, un tel atelier pourrait incorporer de nombreux opérateurs humains qui obéiraient aux ordres d'un ordinateur. C'est bien ce qui se passe d'ailleurs pour certains ateliers, dans lesquels on utilise le personnel à monter et démonter les pièces des machines (HITACHI 102, par exemple). A notre sens, dans un véritable atelier flexible, l'opérateur humain ne doit pas intervenir directement dans le processus de fabrication. De même, et nous arrêterons là la discussion de cette formulation, on ne voit pas pourquoi un atelier flexible serait dévolu uniquement à la production unitaire. Par contre, on peut déjà prédire de grandes différences entre des ateliers flexibles pour production unitaire, pour petite et moyenne série, et pour grande série. Nous allons donner de ces ateliers flexibles une définition, lourde certes et discutable, mais relativement précise :

> "UN ATELIER FLEXIBLE PERMET LA PRODUCTION AUTOMATIQUE DE PIECES DE TYPES DIVERS ET EN QUANTITES VARIABLES. LES OPERATEURS N'INTERVIENNENT PAS DIRECTEMENT DANS LE PROCESSUS DE FABRICATION ET LIMITENT ESSENTIELLEMENT LEURS INTERVENTIONS A L'ENTRETIEN; L'ORDONNANCEMENT DE LA PRODUCTION EST GERE PAR UN SYSTEME INFORMATIQUE".

Encore n'avons nous pas dit que les machines seront principalement à commande numérique, car on connaît des ateliers flexibles fort évolués incorporant des machines traditionnelles.

III. COMPOSITION DES ATELIERS FLEXIBLES

Il semble clair tout d'abord que des ateliers flexibles ne sont concevables que par familles de pièces. Il est bien évident qu'une même chaîne ne saurait produire des arbres, des boîtiers, des couvercles, des pièces de tôle, etc... .

Un point commun à tous les ateliers flexibles sera donc une organisation de la production par type de produits. C'est un concept très ancien, qui a reçu une nouvelle vigueur du fait de l'apparition de l'ordinateur et aussi grâce au terme maintenant populaire de "technologie de groupe".

Par famille technologique, nous pensons qu'il nous faudra de toute façon distinguer (de façon quelque peu artificielle, mais néanmoins indispensable) 3 types d'ateliers flexibles :

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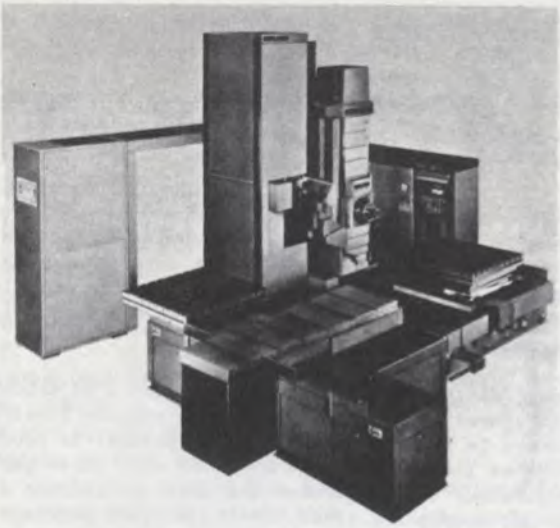
*dont le prestige a éclipsé celui de la visite, bien banale maintenant, aux USA.

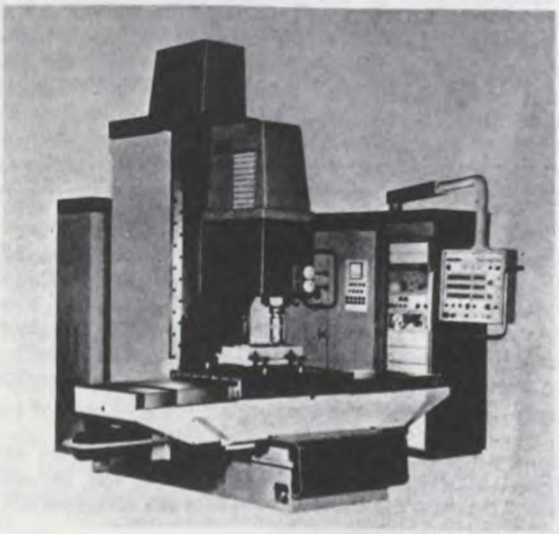
III.1. Ateliers flexibles pour production unitaire de pièces

Fig.I.



La machine de base d'un tel atelier sera le centre d'usinage (fig.I, et II.) et le centre du tournage (fig.III) qui peuvent parfois prendre des allures quelque peu folkloriques de machines à tout faire.

Fig. II



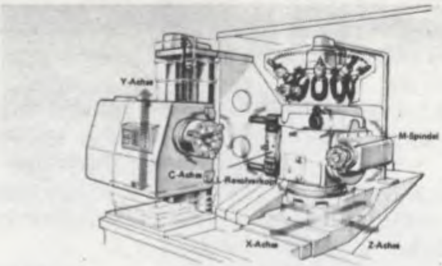
Pour les pièces parallèlépipédiques(les "carters") et les pièces plates (les "couvercles"), le centre d'usinage sera pratiquement capable de venir à bout des formes les plus complexes, si l'on oublie d'éventuelles opérations de préparation pour le montage des pièces sur des palettes.

Pour les pièces de révolution - ou plutôt les arbres, le problème est plus compliqué, car de telles pièces reçoivent très souvent des trous, parallèles à l'axe ou radiaux, filetés ou non. De plus, elles peuvent devoir subir des opérations de taillage, de rasage, de fraisage, des traitements thermiques et, à la suite de ceux-ci, des opérations de rectification, de rôdage ou pierrage.

Dans tous les cas, les machines, afin d'éviter l'intervention directe d'un opérateur, devront être munies de changeurs d'outils et, aussi souvent que possible, de changeurs de pièces. Ce dernier problème ne sera, en général, guère compliqué à résoudre pour les pièces parallèlépipédiques et les pièces plates, car celles-ci seront bridées, hors l'atelier, sur une palette standard. Par contre, pour les pièces de révolution, il n'en sera pas de même. L'automatisation complète passera nécessairement par l'utilisation de manipulateurs programmables munis de dispositifs simples de reconnaissance de forme (si les pièces sont en semi-vrac), que l'on appelle souvent robots. Bien entendu, pour tous les types de pièces, un dispositif de convoyage et de stockage automatique sera indispensable. Pour les pièces parallèlépipédiques, la palette impose presque le convoyeur à rouleaux commandés, économique et fiable, muni des échangeurs, aiguillages et stocks tampons, nécessaires à une utilisation des machines avec le minimum de pertes de temps. Les stocks seront tout aussi faciles à réaliser et les éléments correspondants se trouvent facilement dans le commerce. Au moment de la pose et du bridage de la pièce sur la palette, le code permettant de reconnaître celle-ci est pris en charge par un ordinateur, ainsi que le repère de la pièce à usiner (entré par un opérateur). Les opérations que devra subir la pièce seront alors mises en mémoire dans l'ordinateur et son trajet dans l'atelier sera défini en fonction du plan d'ordonnancement de la production et de la gamme d'usinage. Ce plan lui-même sera établi en fonction des prévisions de production et, bien sûr, modifié en permanence pour tenir compte des aléas : casse d'outil, manque de pièces, panne de machine, modification du plan de production, etc...

Bien entendu, la commande de tout l'atelier doit constituer un système hiérarchisé donnant à chacun des éléments le maximum d'autonomie. En règle générale, on traite localement tout ce qui peut l'être. L'information n'est traitée au niveau hiérarchiquement supérieur que quand il y a interaction entre des éléments de même niveau hiérarchique et aussi quand le traitement nécessite des données (par exemple statistiques globales de panne,

Fig. III



état des autres éléments de l'atelier, etc...) qui ne sont pas élaborées localement. Ce système hiérarchisé ne devra en aucun cas, pour des raisons de fiabilité et de coût, être réalisé dans la mémoire d'un seul gros ordinateur, mais sera effectivement composé de micro et minicalculateurs, certains adaptés à certaines tâches particulières, organisés de façon à permettre l'exploitation la plus simple possible.

III.2. Ateliers flexibles pour petites et moyennes séries

Pour les pièces parallèlépipédiques et les pièces plates, le fait qu'il y a série permet d'accélérer le processus d'usinage par l'utilisation de machines ou équipements plus spécialisés. La fig. IV. montre un centre d'usinage (dont le fabricant a bien malheureusement disparu) qui peut accommoder différentes broches et têtes d'usinage, et en particulier des têtes multiples, permettant de faire en même temps plusieurs usinages. Bien entendu, quand le type de pièce change, on peut garder les outillages généraux (par exemple les outils du changeur de droite, les têtes de fraisage, les plateaux de dressage, etc...), mais les outillages spécialisés sont remplacés par les nouveaux outillages correspondant à la nouvelle pièce. On peut aussi, mais beaucoup plus rarement, utiliser des outillages transformables, par exemple des têtes multiples à entraxe variable. Une forme à peine modifiée de ce type de centre d'usinage, mais adaptée à des pièces de grandes dimensions, est montrée fig.V. Elle représente le "système d'usinage" dit "Head-changer" de la société INGERSOLL, qui a été réalisé pour la société J.I. CASE. La seule différence sensible avec la machine précédente est que 2 unités d'usinage supplémentaires (indice J sur la figure) peuvent être installées, qui pourront faire d'autres opérations (la machine Ingersoll , dans la forme représentée, ne permet pas l'utilisation du carrousel de têtes multiples pour les deux unités complémentaires). On peut aussi utiliser des machines plus spécialisées. Par exemple, il est bien certain qu'utiliser un centre d'usinage à au moins 4 axes à commande numérique pour de simples opérations de perçage et taraudage à l'aide de têtes multiples peut être considéré comme un luxe inutile. On pourra alors utiliser des machines spéciales à un seul axe à commande numérique et munies d'un plateau tournant à 4 ou 8 positions, ou peut être même sans plateau tournant. De même, puisqu'en règle générale on doit toujours fraiser une face (pour des raisons de qualité des usinages et de tenue des outils) avant de faire les usinages qui débouchent sur cette face, on pourra utiliser des machines à fraiser à un axe et demi (le demi axe pour la position du fourreau de broche porte fraise), et munies (ou non) de plateaux tournants à petit nombre de positions.

Fig. IV.

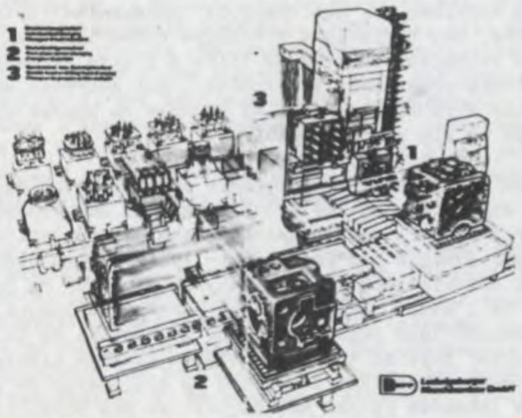
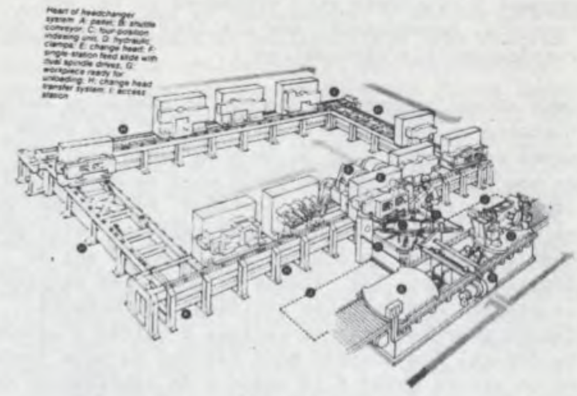


Fig. V.



Pour les pièces de révolution ou arbres, le changement sera moins sensible en ce qui concerne les machines. Par contre, les problèmes de manutention seront considérablement simplifiés, car des "conteneurs" adaptés à la pièce pourront facilement être faits (en particulier à partir d'éléments modulaires adaptables à des plateaux ou paniers standard, ce qui permettra de les traiter avec guère plus de difficulté que les pièces parallèlépipèdiques). Les opérations de chargement et déchargement des machines seront aussi largement simplifiées, car on pourra souvent avoir des appareils cinématiques adaptables, au lieu d'utiliser des appareils programmables beaucoup plus chers. Quant à l'ordonnancement de la production, il sera aussi énormément simplifié par rapport à ce qu'il doit être pour un atelier de production unitaire. Bien d'autres problèmes et en particulier la préparation des pièces avant usinage, le débit, le stockage, etc... seront beaucoup plus faciles à résoudre (nous n'en parlerons donc pas) et il ne faut alors pas s'étonner de ce que c'est ce type d'atelier flexible pour petites et moyennes séries qui a été le plus développé et dont on parle le plus.

III.3. Ateliers flexibles pour grandes séries

Nous abordons là un domaine beaucoup plus neuf (bien qu'on en parle depuis des années) que les deux précédents et pour lequel les discours (en particulier le nôtre) sont très en avance sur les réalisations. Avant d'essayer néanmoins d'en parler, il nous faut, nous semble-t-il, en démontrer l'intérêt. En effet, depuis des dizaines d'années, on développe des ateliers d'usinage en grande série et peu de gens semblent avoir ressenti le besoin d'une réelle flexibilité. Tout au plus se contentait-on de pouvoir faire, par exemple, sur une même chaîne, des pièces de moteurs, par ailleurs presque identiques, mais ayant un nombre variable de cylindre (exemples : moteurs VW Golf, Peugeot 6 cylindres et 8 cylindres en Vé, etc...). Pourquoi, brusquement, des ateliers flexibles deviendraient-ils nécessaires ?

Nous allons essayer de montrer le genèse de cette histoire en plusieurs temps. D'abord, une chose assez peu connue (car on ne s'en vante pas) est qu'une chaîne de grande série voit sa production décroître largement avec le temps. Pour donner une valeur numérique, il n'est pas rare que cette production diminue de plus de 25% après 10 ans de fonctionnement. Les raisons en sont bien simples : la plupart des machines utilisent des moteurs freins pour les avances rapides d'unités d'usinage. Au départ, les courses sont réglées au plus juste et on arrive ainsi à la cadence de fabrication prévue. Malheureusement, après quelque temps, les freins s'usent et les outils arrivent en contact avec les pièces en avance rapide. Ils n'apprécient guère le procédé et le personnel d'exploitation augmente les gardes jusqu'à ce qu'il n'y ait plus de problème (jusqu'au prochain stade d'usure). Les courses supplémentaires (car on se donne en plus quelque sécurité), sont alors parcourues en avance travail et la production chute de façon importante. Si on ajoute à cela une usure progressive d'autres organes, on arrive rapidement à la diminution de production chiffrée précédemment. Ceci n'est guère important dans la mesure où les besoins sont toujours satisfaits par la production, mais s'ils croissent, on va alors à la catastrophe. Nous avons vu de nombreux cas ou des chaînes supplémentaires ont été commandées uniquement pour compenser la perte de production due à un entretien négligent ou impossible. Une solution évidente est de définir de façon "active" la loi de vitesse des unités en fonction de la position, à l'aide de commandes asservies. On garantit ainsi la constance de la production en même temps que l'on se donne la possibilité de modifier facilement les paramètres de coupe, et donc les cadences de production, en fonction de la matière usinée et de l'évolution des outils. Quand on apprend de plus que bien des arrêts sont dus à des défauts de contacts de fin de course (remplis de liquide de coupe par exemple), ou à des pannes (casse d'outils et même de machine) dues à des défauts de ces mêmes contacts ou à leur règlage, on réalise que la seule solution devient la commande numérique. Mais cet argument seul ne suffit pas à convaincre les comptables, car ils ne peuvent réaliser que l'unique obstacle à une commande numérique économique (plus économique même que les traditionnelles commandes séquentielles) est leur faible diffusion, puisque les fonctions à accomplir sont très simples.

Un deuxième argument, complémentaire du premier, est apporté par les changements fréquents que l'on est obligé d'apporter à de nombreux produits qui doivent satisfaire à une législation évolutive. Un exemple frappant est celui de l'automobile, contrainte d'évoluer en permanence du fait des lois antipollution d'abord et pour limiter la consommation de carburant maintenant. Certaines chaînes (les tubulures d'admission et d'échappement des moteurs par exemple) ont dû être refaites trois ou quatre fois à quelques années d'intervalle. Une construction volontairement plus flexible aurait permis d'éviter les énormes dépenses correspondantes. Que l'on ne vienne pas nous dire que la chose est facile à dire maintenant; elle l'était dès le départ. Cet argument, même ajouté au premier, ne peut pas encore suffire,nous nous en rendons bien compte; il en faut donc un plus fort. L'évolution des marchés, perceptible déjà depuis plus de 10 ans, nous donne un troisième argument que nous croyons indiscutable et propre à attendrir le coeur du comptable (physiologiquement incompatible, eut dit Malraux) le plus endurci. Il est bien clair que nul ne peut, dans un marché où l'offre dépasse maintenant largement la demande (ce qui est vrai pour tous les produits de grande consommation*), prédire que tel produit connaîtra le succès, ni l'ampleur de ce succès, ni sa durée. Dans ces conditions, il est bien clair que la seule solution est de faire des chaînes "flexibles", ce qui, dans ce cas, signifiera qu'elles produiront toujours le même produit, mais que celui-ci pourra être facilement changé, même profondément, afin de pouvoir adapter l'offre à la demande. Si on ajoute aux problèmes techniques que cause le sous-emploi d'une chaîne, les problèmes sociaux, on comprend que certains constructeurs se préoccupent de trouver des solutions. Il est connu par exemple que la Général Motors avait envisagé (à un moment, mais nous ignorons l'état actuel de leur réflexion) de fabriquer tous leurs produits sur des centres d'usinage d'un type proche de ceux qu'on utilise pour le travail unitaire. Un tel centre, avec son changeur d'outils, aurait fait quelques carters cylindres par jour ou quelques culasses, mais entièrement, alors qu' un poste de machine transfert traditionnelle fait au contraire une seule opération sur plusieurs milliers de pièces. C'est évidemment, au moins théoriquement, une solution. Nous ne pensons pas qu' elle doive être généralisée. Au contraire, nous pensons que la structure des machines transfert actuelles doit être conservée, mais qu'elles devront être rendues plus "flexibles", en particulier par l'adoption de la commande numérique. Que dire d'autre à ce stade, de telles chaînes ?

Le processus de gestion sera évidemment immensément facilité dans la mesure où le comportement individuel de chacun des outils sera connu, ainsi que celui de tous éléments de la chaîne. Les décisions de gestion en temps réel seront donc faciles à prendre puisque, d'une pièce à l'autre, seuls des paramètres seront à changer. La circulation des pièces à l'intérieur de la chaîne pourra se faire comme maintenant; par contre, la position et le volume des stocks intermédiaires pouvant être amenés à changer (même pendant la durée de la fabrication d'une même pièce, si l'on tient compte de son évolution, de l'évolution des outils et de l'évolution de la demande), on aura intérêt à utiliser des stocks banalisés et centralisés, reliés aux machines par des chariots "indexables" automoteurs. Les opérations d'échange entre le stock et les machines pourront se faire à l'aide de manipulateurs programmables (robots), qui pourront euxmêmes être mobiles afin de pouvoir se porter au lieu où ils sont nécessaires.

Bien évidemment, la fréquence de changement de pièce étant faible, les transformations seront faites par des opérateurs humains. Certaines opérations, - par exemple les fraisages - se feront uniquement par modification de position, de vitesse, de course de l'outil. Là , plus que partout ailleurs, la commande (qui inclut bien sûr la gestion de la chaîne) sera du type à plusieurs niveaux hiérarchiques comportant des aides au diagnostic de pannes (mêmedes pannes mécaniques) et des possibilités

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* bien sûr, dans nos pays; quant aux autres....

de dépannage automatique par échange de l'appareil de secours, placé à côté du directeur de niveau hiérarchique supérieur.

Pour donner un ordre de grandeur, disons qu'une telle chaîne pourrait être adaptée à un nouveau produit pour une dépense inférieure à 10% de la valeur des machines-outils et en un temps inférieur à 1 mois. Rappelons que la reconstruction de chaînes, pratique courante aux USA, permet d'économiser environ 30% du prix d'une chaîne neuve avec un délai de transformation de 8 à 12 mois.

IV PROBLEMES POSES PAR LES CHAINES FLEXIBLES, ET LEURS SOLUTIONS

A lire les lignes précédentes, on réalise que, à l'exception des chaînes pour très grande production, tous les éléments constitutifs des ateliers flexibles existent déjà ou sont faciles à réaliser (y compris les algorithmes et programmes de gestion). Où donc alors est le problème ? . Pour les ateliers de fabrication unitaire, le frein principal sera la multiplicité des outils et outillages. En effet, une PME traditionnelle possède des milliers d'outils différents et des centaines de montage porte-pièces. Les opérateurs, pour passer d'une pièce à l'autre, passeront tout leur temps à déséquiper et rééquiper les machines. Le "rendement" de l'atelier sera alors très bas et sa rentabilisation impossible (Nous avons, par exemple, compté 148 forets différents dans une entreprise de 80 personnes. Ceci donne une idée de l'ampleur du problème). Une condition sine qua non de rentabilité d'un atelier flexible pour production unitaire sera qu'A TOUT MOMENT TOUS LES OUTILS NECESSAIRES A L'USINAGE DEVRONT ETRE DANS LES MAGASINS A OUTILS DES MACHINES. Ceci implique nécessairement une standardisation des diamètres, des tolérances et du nombre de passes (et des diamètres intermédiaires de ces passes). Nous montrons sur le tableau VI ci-après une série de trente diamètres de 8 à 310 mm qui permettent la réalisation de n'importe quelle machine (de type machine-outil). Pour chacun de ces diamètres, il existe 3 tolérances H8, H7 et M6, pour lesquelles il faut 3 ou 4 passes. Un tel choix permet, par exemple, l'utilisation d'outils préréglés et en particulier d'alésoirs à lames flottantes. Ces diamètres doivent, bien entendu, permettre le montage d'une gamme "suffisante" de roulements, circlips, paliers auto lubrifiants, douilles à billes, joints et autres éléments du commerce. Au total, c'est environ 150 outils différents qu'il faudra avoir dans les magasins de plusieurs machines (on a couramment des magasins de 70 outils). Cette solution est, à notre sens, la seule possible. Cependant, s'il est déjà difficile de réaliser une telle normalisation à l'intérieur d'une entreprise, pour ses propres besoins, il est tout simplemenet inconcevable de penser l'imposer à plusieurs clients. Ceci signifie, à notre avis, que la réalisation d'un atelier flexible pour production <u>UNITAIRE</u> est simplement <u>IMPOSSIBLE</u>, sauf sous forme d'atelier intégré.

Pour les ateliers de fabrication en moyenne série, le problème est, à beaucoup d'égard, beaucoup plus simple. Leur développement sera nettement moins tributaire d'une normalisation des usinages (qui est de toute façon préférable). Par contre, la disposition des machines, leur choix, les moyens de manutention et de stockage, dépendront étroitement du produit, qui devra donc être spécialement étudié en fonction des moyens de fabrication et vice versa. C'est l'oubli de cette condition qui a entrainé l'échec de nombreux systèmes, pourtant par ailleurs soigneusement étudiés par des sociétés réputées et compétentes. L'atelier lui-même devra être étudié en collaboration très étroite entre le futur utilisateur et son constructeur. Là encore, si celui-ci est intégré, les choses seront bien plus faciles. Dans le cas contraire, il fera aussi bien, me semble-t-il, de se poser en fabricant d'éléments et de laisser la responsabilité de conception du système au client, s'il ne peut pas obtenir de celui-ci une participation pleine et entière. Un exemple de grande réussite est fourni par l'atelier flexible conçu par la société Sundstrand pour l'usinage des carters d'entrainements d'alternateurs dont elle est elle-même productrice. C'est donc une opération "intégrée" qui permettait, quand nous l'avons visitée il y a plus de 8 ans, l'usinage de 400 pièces différentes sur une chaîne de 8 centres d'usinages reliés par des convoyeurs à rouleaux et dirigés par un ordinateur central. Enfin, pour les ateliers flexibles de grande série, la seule possibilité sera une forte similitude technologique entre pièces. Il sera facile de changer de pièce, même si ses dimensions sont nettement différentes, pour autant que les types d'usinages à effectuer soient très voisins et surtout que les gammes d'usinage soient identiques, ou, plus exactement, qu'elles soient toutes des sous-ensembles d'une gamme généralisée. Nous manquons de place pour développer ici ce concept, mais nous avons pu montrer qu'il était assez facile à mettre en oeuvre, pour autant que le personnel d'étude ne considère pas un nouveau produit comme un banc d'essai de techniques plus ou moins nouvelles et en tout cas différentes. Ceci ne s'opposera pas du tout à l'évolution des produits, mais nécessitera que toute modification soit mûrement réfléchie.

Pour finir, nous voudrions citer quelques'uns des autres problèmes, parfois très difficiles mais souvent communs aux différents types d'ateliers flexibles, qui se posent :

- La correction d'usure des outils. Celle-ci doit se faire automatiquement, avec le minimum d'arrêt des machines. Cela implique une prévision du comportement des outils dont un "modèle" sera présent dans la mémoire d'un ordinateur de commande. La correction se fera suivant l'évolution de la "cote" du modèle et des mesures périodiques permettront d'effectuer des recalages. Ceci permettra de découpler de la correction de la cote la vérification de la présence de l'outil, ce qui est beaucoup plus facile à faire.
- Le renouvellement automatique des outils usés. Il ne suffit plus de détecter un outil usé ou cassé. Il faut aussi pouvoir en trouver un autre dans le magasin et ensuite il faut retirer l'outil cassé du magasin et en mettre un neuf. L'outil cassé retournera automatiquement au département d'affûtage/règlage. Cette technique nécessitera une évolution sérieuse des magasins à outils et des moyens de manutention de ces outils entre magasin et machines.

Fig. VI

8	17	26	47	80	170
9	19	30	52	90	200
11	21	35	58	110	230
13	22	37	62	130	260
15	24	42	72	150	310

- Un problème fondamental est celui de la fiabilité. Si la fiabilité en électronique et informatique est maintenant devenue assez facile à obtenir et surtout prédire, on n'en est pas là en mécanique. Certains croient que la fiabilité est fonction de la précision d'exécution; ce n'est parfois que très partiellement vrai et très généralement faux, du fait que la fiabilité dépend plus de l'environnement que des pièces constitutives d'une machine. Le manque de fiabilité des machines a très souvent pour origine des jeux très faibles, ou des précontraintes, qui conduisent à des boucles de contreréaction internes positives et, de là, à l'instabilité (souvent thermique). Ce comportement étant généralement influencé par l'environnement, on comprend qu'il y ait impossibilité de prédiction de la durée de vie. En fait, sans pouvoir aller plus loin, nous dirons qu'une machine est fiable dans la mesure où on connaît toujours l'état de contrainte de ses pièces et, bien sûr, si ces contraintes sont acceptables. Signalons seulement que la fiabilité se construit au bureau d'études. Malheureusement, ces concepts sont peu connus. De plus, ils mènent à des mécaniques résolument inhabituelles et qui heurtent l'esprit de la plupart des constructeurs.

- Les interfaces : un des points les plus faibles des machines d'aujourd'hui sont les interfaces, et principalement celles qui entrainent un changement de type d'énergie : électrohydrauliques, hydromécaniques, électromécaniques , etc... . Beaucoup reste à faire dans ce domaine.

Nous ne pouvons décidément pas aller plus loin. En matière de conclusion, nous voudrions mettre l'accent sur le fait qu'il ne suffit pas à un industriel, pour baisser ses prix de revient et améliorer sa production, de mettre dans son plan d'investissement l'achat d'un ou plusieurs ateliers flexibles munis de robots et autres engins étonnants. Ceux-ci, non seulement ne seront pas rentables, mais le mèneront vivement à la ruine, s'il n'a pas su auparavant faire cet immense effort de dépouillement, de rationalisation, de normalisation dont nous parlions plus haut. Tout devra être repensé : dessin des pièces, procédés d'usinage, cotes et tolérances; tout cela ne s'opposera en rien à l'évolution des produits, bien au contraire, mais nécessitera qu'ils soient un peu plus et un peu mieux pensés. Tout reviendra, en fin de compte, à faire un effort d'économie.

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ABSTRACT :

In this paper it is shown that three main types of flexible manufacturing systems must be considered: For unit production of parts, batch and mass production. All of them have many problems in common: reliability, tool wear compensation, interfaces, distributed control , etc... But each of them has a specific problem :

- For unit production, a necessary condition for its economic operation is standardization of dimensions and tolerances.
- For batch production, the manufacturing system and the parts to be machined have to be designed together.
- For mass production, several different parts can be machined on the same line if their machining processes are very close to each other.

Finally, if a very important effort of rationalization and standardization is not made prior to buying a flexible manufacturing system, it will result in a complete failure.

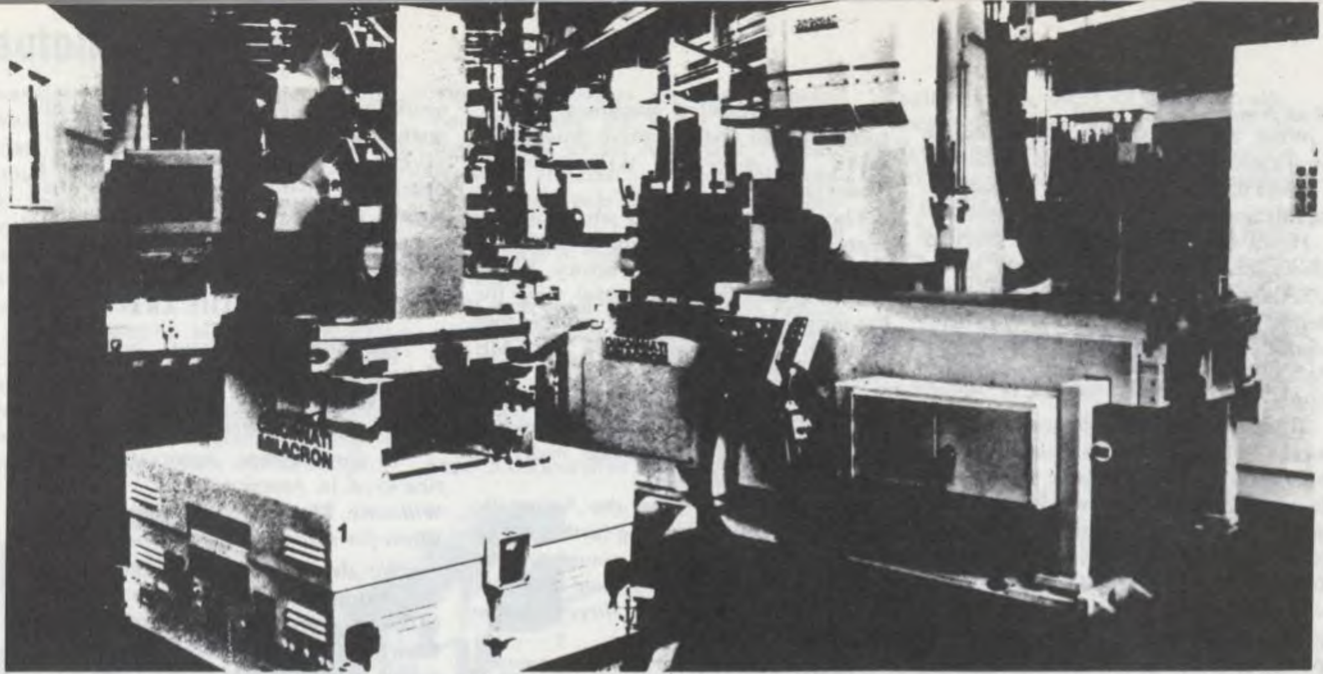
ZUSAMMENFASSUNG :

Es ist die Absicht dieses Artikels aufzuzeigen, dass man zwischen drei Arten von flexiblen Werkstätten unterscheiden kann : die Werkstatt zur Fertigung von Einzelstücken, von mittelgrossen Serien sowie von Grossserien.

Alle drei haben gewisse Probleme gemeinsam wie, zum Beispiel : Zuverlässigkeit, Verschleisskorrekturen von Werkzeugen, Interface Probleme, hierarchische Steuerung, usw. Jede weist aber auch ihr spezifisches Problem auf :

- So ist bei der Fertigung von Einzelstücken die Vereinheitlichung von Massen und Toleranzen Voraussetzung zur Rentabilität.
- Bei der Herstellung von mittelgrossen Serien müssen Produkt und Werkstatt gemeinsam konzipiert werden.
- Und für die Massenverarbeitung erlaubt allein eine Gleichkeit der Verarbeitungsstufen die Anpassung an verschiedene Werkstücke.

Zusammengefasst kann gesagt werden, dass Rationalisierung und Standardisierung die Voraussetzung zur Rentabilität einer flexiblen Werkstatt sind, andernfalls wird ein Misserfolg nicht zu umgehen sein.



Cincinnati Milacron's Variable Mission — a variation on the beginning of the Automatic Factory. This system is designed for total computer control of low and medium volume production. Incoming work can vary in size, shape and quantity.

the advent of the automatic factory

The forthcoming AUTOFACT WEST, scheduled for Anaheim in November, will give exhaustive coverage to the technologies of the Automatic Factory. But what is an Automatic Factory — and what are its technical, social and economic implications? In this article, automation experts — many of whom are scheduled to speak at AUTOFACT IV — provide answers and opinions on this next phase of automation

DANIEL B. DALLAS
Editor-in-Chief

WHETHER WE LIKE IT OR NOT, the industrialized nations of the West — a group that includes Japan as a *de facto* member — are heading into the era of the Automatic Factory. Our imminent arrival at the gates of the Factory represents the culmination of an historical trend that began with James Watt's invention of the steam engine in 1760.

This trend has gone through four distinct phases, the first of which was the utilization of steam as a source of industrial power. The second phase arrived some 40 years later with the invention of interchangeable manufacture, a development generally attributed to Eli Whitney. The third phase, the use of the assembly line, came a full century later with Henry Ford and the Model T. The fourth stage or phase, which began circa 1950, can be termed the age of numerical control. From NC it is but a short series of steps to the Automatic Factory.

Rudimentary point-to-point numerical control made its debut during World War II with the pioneering work of John Parsons. It was — and would have remained — an interesting industrial development had it not been for the almost concurrent development of the computer. It was the advent of the computer that brought numerical control to full maturity in that it provided a lightning fast, systematic approach to the problem of solving the hundreds of thousands of equations involved in establishing a machining routine. Without the computer, continuous path numerical control would have been impossible. There are not enough working days in a lifetime to enable even the most diligent and dedicated of engineers to mathematically describe the cutter paths required for the machining of a complex curvilinear surface.

But the awesome computational power of the computer begged a series of questions. If a computer could so easily provide a punched tape medium for the control of individual machines, might it not also control the machine directly — without the use of tape? Might it not be able to use its surplus computational power to control more than one machine?

The answers emerged with CNC and DNC; a single computer could indeed control a vast array of machines and machine tools. But if this were the case, might not the computer control the entire factory? Again, the answer was affirmative; the computer was the harbinger of the Automatic Factory.

At the same time, a factory run by computers, while theoretically possible, asks more questions than it answers. For one, what would managers and management be like in the context of an Automatic Factory?

What are the social and economic implications of an Automatic Factory in a world that is — according to many — rapidly approaching the limits of growth?

How would the Automatic Factory affect employment, particularly in the USA where high unemployment is endemic? But what are the consequences of *not* utilizing full automation and the Automatic Factory as tools of international competition?

If shorter working hours and work weeks are a twentieth century trend, how would the Automatic Factory affect that trend? Who would share the profits of the Automatic Factory? Stockholders? The government in the form of higher taxes? Organized labor — which, at best, gives grudging approval to advances in automation? The public, which might conceivably be given a choice of better goods at lower prices?

If the evolutionary trends of industry began with a surplus of energy in the form of coal, the burning of which was totally unregulated, how would the Automatic Factory fare in the face of a worldwide energy shortage?

Who would provide the enormous inputs of capital required for the development of the Automatic Factory? Private investors? The federal government? An admixture of the two?

These and numerous other questions surfaced in the course of MANUFACTURING ENGINEERING's study of the Automatic Factory — a study that involved the questioning of numerous experts on the subject of advanced automation.

The first question which required an answer was: What *is* an Automatic Factory?

THE FACTORY DEFINED

"The Automatic Factory is usually considered to be an automated fabrication and assembly facility. However, strictly speaking, an Automatic Factory could be any automated manufacturing facility." — *F. W. Randall, Vice President, Vought Corporation*

"A factory in which production output is controlled by programmed machinery for greater efficiency and productivity." — *George G. Barkley, Machine Tool Systems Product Manager, Acco Industries*

"There cannot be a 'canned' definition. The change (to an Automatic Factory) is evolutionary, not revolutionary. It will be constantly changing as new equipment, new techniques, and new ideas become available." — *R. H. Searle, Applications Engineer, Waterbury Farrel Division of Textron Inc.*

"The Automatic Factory is a production facility which will make use of computer controlled machines to perform planned and repetitive production tasks." — *Roger G. Willis, Arthur Andersen & Co.*

These comments and observations represent a cross section of industry views of the Automatic Factory. While all are good, the most useful view for the purposes of this article comes from Kenneth Treer, Chairman of the SME Assembly Council.

It is Treer's contention that the Automatic Factory must be viewed from two perspectives — that of the *practical* and that of the *ultimate*.

In the practical view, the Automatic Factory is a manufacturing facility which accepts raw materials or components in one end and processes them into finished products *without direct human input*.

In contrast, the ultimate Automatic Factory is a manufacturing facility that operates *without direct human intervention*.

Accordingly, the ultimate Automatic Factory is the stuff of which science fiction is made. That does not rule it out, of course. But it delays it into the indefinitely far future, possibly to the end of the next century. Still, the executives questioned by MANUFACTURING ENGINEERING for this article were nothing if not optimistic. "If we could put a man on the moon . . ." was a recurrent theme.

A view of the Automatic Factory similar to Treer's is taken by L. A. Branaman, manager of OSO Engineering in the Electronics Systems Division of General Electric. Says Branaman:

"The ultimate definition of the Automatic Factory is one in which all operations, including material handling, processing, fabrication and assembly, inspection, and quality control, are performed without direct intervention by human operators. The only people involvement would be in a control center from which all operations could be remotely monitored, and in equipment maintenance.

"Realistically, this objective is decades away; however, in the near term we certainly can look for more automated material handling, for intelligent work stations for processing, fabrication, and assembly, and for integrated in-process automated inspection functions."

It was pointed out by certain of our respondents that the Automatic Factory is already in existence — that the petroleum processing industries and others in the chemical industries have already developed Automatic Factories. However, most respondents insisted that to include any discussion of these facilities in this article would be to becloud the issue. When manufacturing engineers and managers discuss the Automatic Factory, they are speaking exclusively in terms of manufacturing operations involving a variety of materials, processing methodologies, machines and production equipment, and a wide variety of products.

STATE OF THE ART

"The Automatic Factory is like the Holy Grail — something you approach but never reach." — *Philippe Villers, President, Automatix, Inc.*

"To some extent, Automatic Factories exist in America today." — *Cyril Williams, Managing Director, The Institute for Advanced Automation*

"We already have some elements of the Automatic Factory. The Variable Mission system is an example." — *Charles F. Carter, Jr., Technical Director, Cincinnati Milacron, and Vice President of the Society of Manufacturing Engineers*

"At least various segments of the total program have been implemented individually." — *Denes Hunkar, President, Hunkar Laboratories*

As the preceding comments indicate, the Automatic Factory will emerge as an evolutionary development of today's technology. In this, it differs markedly from the previous phases of industrial development (steam power, interchangeable manufacture, the assembly line, numerical control) all of which emerged as revolutionary developments. A recurrent theme disclosed in our research is that most (not all) of the technology required for an Automatic Factory is now in existence. That the Automatic Factory is slow in emerging is attributable to economic considerations and not to technological limitations.

W. A. Carter, European operations manager for CAM-I, has provided MANUFACTURING ENGINEERING with some interesting observations in this regard:

"All the industrialized countries in Europe are working toward the development of Automatic Factories and most countries, including France, Italy, Norway, and Sweden have examples of systems in operation. It should also be noted that almost all the automobile manufacturers are using robots to a greater or lesser extent in body production, mainly welding, which provides them with a high degree of flexibility in body production."

Carter notes that although the U.K. has nothing in the way of an Automatic Factory, several British concerns are about to start building such systems. Significantly, the first abortive attempt at the Automatic Factory was made in the U.K. with the Mollins System 24. Introduced in 1962, the system, which was lightyears ahead of the technology, was designed as a completely automated system for the production of small aluminum parts. As Carter sees it, modern developments in computer technology and material handling plus substantially lowered equipment costs would make such a system eminently practical today.

In the meantime, according to Carter, Eastern Europe is making as much progress as the Western Bloc nations through the development of two flexible manufacturing lines now operating in East Germany. Others are now operative in Czechoslovakia and the Soviet Union. And eight to 10 flexible manufacturing lines are operative in West Germany.

"Perhaps the most impressive automated system is the aircraft manufacturing line at MBB in Augsburg, West Germany," says Carter. "Here are many large machining centers with automatic toolsetting, toolchanging, loaded from central storage where even the tool store is automatically linked by computer to the main system. Parts are delivered to the machine from carts that travel around the shop. This system is in full production and has been fully economically justified."

IBM's QTAT line for the automated manufacture of silicon wafers. You are looking at what could be termed an Early American Automatic Factory. It consists of 100 highly automated computer controlled tools organized into eight sectors, all designed to perform a variety of operations — no matter what the configuration of the electronic component.

Japanese Progress

The greatest progress in implementing the Automatic Factory has been made in Japan. Although a full-fledged Automatic Factory will not make its debut until the mid-1980s, Seiko has developed a system for the automatic assembly of watches. No human input whatsoever is required. Since the individual components must be machined conventionally, the Seiko system does not qualify as an Automatic Factory. However, if Seiko can completely automate the difficult work of watch assembly, there is no reason to believe that automation of the machining process is far behind.

Of even greater significance is Japan's national program designed to develop a "Methodology for Unmanned Manufacturing" (MUM). As reported by Dr. M. Eugene Merchant of Cincinnati Milacron, the MUM program represents a cooperative industry-university-government cooperative R&D program.

Initial planning for this program began in 1972 with annual funding of $100,000 by the Ministry for International Trade and Industry (MITI). Participants include some 10 Japanese machine tool builders, several universities, the Mechanical Engineering Laboratory (of MITI), the Association for Machinery Engineering, the Japan Industrial Robot Association, and the Japan Machine Tool Builders Association.

In Dr. Merchant's words, "The plan which was developed calls for the development, construction and operation of a prototype 'ummanned' machine building by about 1980. The plant would be a 200,000 to 300,000 square foot factory staffed by a 'control crew' of only about 10 persons, as compared to the normal complement of 700 to 800 workers for such a factory. The plant would manufacture some 2000 different machinery parts in lot sizes of 1 to 25 and assemble them to produce some 50 different machine components (gear boxes, spindle heads, turret heads, hydraulic motors, etc.) all automatically. Processes carried out would include forging, heat treatment, welding, presswork, machining, inspection, assembly and painting."

The latest available information indicates that this factory will be fully operative by 1985. Obviously, an Automatic Factory with the capabilities described is of even greater international significance than Seiko's splendid accomplishments in the automated assembly of watches.

U. S. Progress

"To some extent, Automatic Factories exist in America today," is the observation of Cyril Williams, president of The Institute for Advanced Automation. As an example, he points to Walter Kidde, Inc., Belleville, NJ, a manufacturer of fire extinguishers.

"This manufacturing operation is fully automated in that it starts with a billet of steel which is successively drawn and shaped, heat treated, machined, assembled, tested, painted and packaged," says Williams. "It comes off the line as a finished product untouched by anyone in the process."

Williams notes that the same degree of automation is seen in the manufacture of automobile wheels at a West Coast facility of General Motors, ". . . which automatically (without manual assistance) produces a complete wheel. It enters at one end as strip steel and coiled bar, is automatically rolled, cut, formed, welded, punched, assembled, painted, and dried. It emerges at the opposite end as a completely finished product."

Outstanding progress toward the Automatic Factory is also seen in IBM's QTAT (Quick Turn Around Time) manufacturing line. Designed and built for the production of customized logic circuits, QTAT consists of more than 100 automated tool subsystems grouped into eight sectors. Importantly, this is an example of advanced automation that incorporates electron-beam technology.

The workpiece is an 82-mm (3¼") round silicon wafer that contains a standardized set of electronic components (resistors, transistors, diodes) manufactured by the masterslice process. Electron-beam tools define the interconnection on three layers of these electronic components within the chips. The QTAT tools perform the remaining manufacturing operations, including photoresist application, baking, exposure and develop, as well as evaporation, sputtering, etching, and stripping for both wet and dry processes. Many operations in the QTAT line are monitored by automatic measurement tools.

At American Can. One of the most advanced Automatic Factory developments is seen at American Can Co., Greenwich, CT. Here's how AC's system works, according to a description provided by William S. Adams, manager, Automation Technology at American Can.

▶ Raw materials are received by way of rail or truck at an automated receiving dock. Automatic inspection of incoming material is accomplished in two stages. The first involves pattern recognition of the material by size or shape. The second stage of inspection makes use of a bar code reader for items requiring further identification. When materials are fully classified, paperwork acknowledging their receipt is generated.

When the system comes across questionable items, it attempts to resolve their identity by way of voice contact with the individual making the delivery. (Speech recognition and synthesis techniques are used by the computer.) When all else fails, a flag is raised in the front office.

▶ Raw materials which have been received are classified and conveyed to an appropriate storage location. Direct and indirect process materials are automatically sampled and tested for quality. Dimensional checks are automatically made by scanning lasers. Chemical composition and uniformity are checked by a variety of automated analyzers. Acceptable materials are conveyed to the process staffing location. Unacceptable materials are returned to the vendor for credit with appropriate test results.

▶ Production is automatically scheduled, based on market demand and equipment capacity. Material handling, equipment setup, and tool changes are automatically accounted for, minimizing downtime for changeover. Raw material components are available when needed through an advanced forecasting system. A national data service provides current and future market data directly to the business computer system. This data is combined with actual customer data and manipulated so as to accurately project materials requirements.

▶ Raw material inventory, fabrication equipment, in-process inventory, assembly and testing equipment, and finished goods inventory are connected via an array of conveyors, stacker cranes and robots. All material handling tasks are accomplished by dedicated microcomputers and associated machinery under the direction of a master computer. Robots are used extensively for low-speed material transfer applications. High-speed transfer is accomplished by precision turret, vibrator and conveyor assemblies.

▶ Parts fabrication is accomplished on machines which are controlled directly by microcomputers. Extensive feedback is provided through sensors to insure equipment, tooling, and product integrity. In the case of forming operations, lasers are used for precision inspection purposes. Dimensional characteristics and structural defects can be closely monitored.

▶ Final assembly, testing and packing are accomplished by a sequence of robots. Pattern recognition is used to identify and position the various parts which are then assembled and/or tested by manipulators utilizing sensor feedback.

▶ All finished product is palletized and transferred into the automatic/store/automatic retriever warehouse. Shipments are subsequently staged and loaded into trucks, thus completing the automatic production cycle.

At Auto-Place. As a manufacturer of robots, Auto-Place has a vested interest in the integrated CAD/CAM (Automatic) factory. Says company General Manager Richard Abraham, "In our view, an integrated CAD/CAM factory of the future will consist of modular subsystems, each controlled by computers which are interconnected to form a distributed computer system." The modular subsystems Abraham speaks of will perform as follows:

▶ Product design will be done interactively by a design engineer who will specify the design concepts in an ordinary way. The engineer will use a computer that stores data on models, computes the optimal design for different options, displays the results for approval, and allows sufficient iteration of this process.

▶ Production planning, an optimized plan for the manufacturing process (including routing, timing, work stations, operating steps, operating conditions, and so on) will be generated by the computer on the basis of product design outputs, scheduling and line-balance algorithms, and varying conditions of purchased part deliveries, available resources, product mix, priorities, and so on.

▶ Part forming will be accomplished by work stations, each of which will be controlled by a small computer. These stations will load and unload work, make the parts, and employ adaptive control (in-process operation-sensing and corrective feedback), and incorporate diagnostic devices such as toolwear and tool-breakage sensors.

▶ Material handling will be accomplished via computer-controlled devices that handle parts, tools, fixtures, and other materials throughout the plant.

▶ Assembly of parts and subassemblies will take place at computer-controlled work stations. Each station may include a table, jigs, industrial robots,

Measuring increased productivity

"Concerning the increase of productivity which can be attributable to the Automatic Factory . . . If we use as a base measure of production per individual, per unit time, then the increase can be many orders of magnitude. However, if we measure in order to quantify the relationship between the output of current manpower and the output of a workforce where automation is employed based on today's standards, we could start with a minimum of 400 percent. We could then simply increase that number to whatever number was desired, based on the reduced target cost of the product.

"The American standard of living has declined largely due to the erosive effects of inflation on our buying power. The historic effects of the introduction of mass production into our industrial regime . . . had an enormous impact on our standard of living. Our failure to provide the same increase in productivity with these same techniques in recent decades at the same rate has contributed to this decline. The automation of industry today is gradual and based on its ability to absorb these initial costs. Remember that when manufacturing costs are reduced, this money generally falls right to the bottom line. Only a lack of capital money prevents the coming of the Automatic Factory." — *Cyril Williams, Managing Director, The Institute for Advanced Automation*

CYRIL WILLIAMS OF IAA
"Only a lack of capital prevents the coming of the Automatic Factory."

and other devices.

▶ Inspection of parts, subassemblies and assemblies will be accomplished by computer controlled sensor systems during the manufacturing process and at the end of the process.

▶ Production information will be organized by a distributed computer system that stores, processes, and interprets all the manufacturing data. These would include orders; inventories of materials, tools, parts, and products; manufacturing planning and monitoring; plant maintenance; and various other plant activities.

Like some of his colleagues in the business of advanced automation, Abraham sees certain technological voids barring full implementation of the Automatic Factory in the immediate future. Essentially, these relate to insufficient knowledge concerning the flow of business information in an Automatic Factory, a point that is also made by Richard Morley. (See "The inexorable advance of computerization.")

MANAGEMENT IN THE AUTOMATIC FACTORY

"Management must accept some blame for our current situation. It has allowed itself to be impacted too strongly by the government and unions, and by a short-sighted financial outlook that puts too much emphasis on short-term results." — *Richard P. Cottrell, Vice President — Factory Management, The Bendix Corporation*

"A different style of management will evolve with the Automatic Factory. Long-range planning will supersede the 'management by reaction' system so prevalent in industry today. Competition will take place on a much broader international stage, and decisions will have to be based on this scope — including a possible trend among many competing companies to exchange ideas more freely in challenging the international cartels." — *Jack McPhail, Marketing Manager, Automated Production Systems Division, Ingersoll-Rand Co.*

"Managers in the Automated Factory will be graduates of specialized programs in industrial management with an emphasis on technology." — *Frank H. McCarty, Director, Manufacturing Engineering, Raytheon Co. and Chairman of the SME Technical Council*

The transition from conventional to totally automated manufacturing spells the demise of the traditional manager. The most significant difference between today's manager of a conventional manufacturing facility and tomorrow's manager in an Automatic Factory lies in computerization. A working knowledge of the computer will become mandatory. According to Richard E. Morley, president of Functional Automation Gould Inc.:

"The new manager will evolve into fully automated discrete parts process control much as the cottage industry evolved into mass production. The techniques, considerations, and technologies needed will substantially change over the next 15 years. This is not to be feared, however. The existing people have the necessary knowhow, and they can easily adapt to the new situation — if they are willing to do so.

"The one thing that can help is the availability of capital. The immense amount of capital required will slow down the introduction or requirement for new management techniques; the existing management crew will have time to easily adapt.

"Specific management criteria will be the ability to communicate with the computer. Although trivial, the manager will have to be able to interpret the computer data as presented to the manager, and be able to input data or requests for information by himself.

"The new manager will also have to specify and be part of the design of the factory of the future. Converting his requirements to the technology-based designers or architects of the factory will be a job that will not be trivial."

Richard Morley's credentials to speak to this point are impeccable. He is the man who invented the programmable controller and founded Bedford Associates, a company that eventually became Modicon Corporation. In 1977, Modicon was purchased by Gould Inc. Morley remains with Gould as president of Functional Automation Gould Inc. For more on Morley's view of the Automatic Factory, see, "The inexorable advance of computerization."

Donald K. Grierson, senior vice president and group executive, the Industrial Electronics Group of General Electric, takes a view of management that parallels Morley's:

"As for managing the Automatic Factory, there will be some changes," says Grierson. "These will be basically in the managers' educational background. The managers — especially the managers of manufacturing and manufacturing engineering — will be more technically oriented. They will have to know computers, data processing, instrumentation and electronics.

"The most important management assignment will be to hire or train a higher level of engineering talent with which to design, plan the layout, and operate the Automatic Factory. There will be less emphasis on shop operations and expediting, and more concern for studying how to install and maintain automation equipment.

"One of the interesting and challenging problems present-day managers will face will be the transition to the Automatic Factory. And one of the biggest problems may be in getting the shop operations manager to understand and agree to the management objectives of setting up an Automatic Factory. Once the objectives are understood and agreed to, the major hurdles to the Automatic Factory will have been cleared.

"Concurrent with this education process for the shop operations manager will be the training and upgrading of skills for hourly rated employees as technicians to service and maintain the automatic equipment. Once everyone involved realizes that more can be produced with the same amount of people, unfounded threats of lost jobs decrease and productivity increases."

While there is general agreement among the many who contributed to this article concerning the need for a different breed of manager (generally, a humanist steeped in the latest technologies with a working knowledge of computerization), little is offered in the way of discussion on the structure of management itself.

However, it follows that if the Automatic Factory represents the ultimate in computer-integrated manufacturing, the traditional lines of management responsibility will become blurred and possibly vanish. Robert Crowley of Structural Dynamics Corp. pictures an inversion of the conventional management pyramid. Top management would not be invested in a single person, but in a board that would manage by consensus. The descending layers of management would then grow successively narrower until one person is reached in this inversion — the person who presses the button to activate the entire system.

It is also suggested by another respondent that all of middle management would disappear and that the "manager" would be a supersophisticated product designer.

Philippe Villers, president of Automatix, avoids defining the management structure of the Automatic Factory, but asks a key question concerning the future nature of management: "Traditionally, the roles of manufacturing and inspection have been administratively separated. But if a robot performs a manufacturing operation and then inspects its own work, who does the robot report to?"

There is no pat answer, though it is obvious that if the discrete manufacturing functions are to be integrated, management itself must undergo a corresponding integration. As a result, the ranks of management, like the ranks of the hourly rated employees, will undergo a severe thinning-out process. As the Automatic Factory moves toward maturity, a small cadre of super managers will undoubtedly emerge. They will work in an administrative structure that is totally different from anything we have today — and their field of expertise will simply be the Automatic Factory.

PRODUCT DESIGN

"In Japan there is complete cooperation . . . there are regularly scheduled meetings in which product design principles for automatic manufacturing are discussed." — *Frank J. Riley, Vice President, The Bodine Corp.*

"The nature of the fabrication and assembly processes will be important factors in the decision for automation. Consequently, we will see product redesign as a prerequisite to that decision." — *Robert L. Vaughn, Chief Manufacturing Engineer, Lockheed Missiles & Space Co., Space Systems Div., and Vice President of the SOCIETY OF MANUFACTURING ENGINEERS.*

"Products which are today being redesigned for automatic manufacturing have probably already been subjected to redesign for purposes of mechanization. The product's design may be completely changed if the goal is an Automatic Factory." — *Douglas Swanson, General Manager, Swanson Assembly Systems, Swanson-Erie Corp.*

Years ago, Alfred Sloan coined the expression "dynamic obsolescence" to define a product philosophy of the automobile industry. Specifically, dynamic obsolescence involves product changes intended to make the customer unhappy or at least dissatisfied with his present car. As Sloan's chief competitor, Henry Ford stoutly resisted the lure of dynamic obsolescence — and in so doing, managed to lose his company's preeminence in the automobile field to General Motors.

All indicators now point to a return to the basic manufacturing philosophy of

SRI'S DAVID NITZAN
"Emulating man's primary functions with the robot involves artificial intelligence."

Toward artificial intelligence

"It has been suggested by Dr. M. Eugene Merchant that there are seven important basic CAM functions in the Automatic Factory. They include product design, production planning, parts fabrication, material handling, assembly, inspection, and organization. Four of them — product design, production planning, parts fabrication, and organization — have already found their way into the factory. Considerable progress has been made on them, but additional work is still required. We have even farther to go when it comes to material handling, assembly, and inspection. SRI (Stanford Research Institute) is concentrating on these three areas.

"Most of the effort so far in CAM has involved what might be called CAF (Computer-Aided Parts Fabrication). Material handling and inspection are involved in parts fabrication (machining and forming), and robots will be involved.

"The robot is intended to replace man with his three primary capabilities — motor functions, sensing functions and thinking functions. We want to emulate these functions with the robot and that involves artificial intelligence.

"To be cost effective, the system must be fast, reliable, programmable and low-cost. To achieve these capabilities, we must improve upon man's capabilities (via artificial intelligence).

"In batch manufacturing, you can't afford to have expensive fixtures and related tooling — that's why vision is so important. Man's vision is limited; he can't see infrared. The sensors we're working with detect it and enable us to distinguish between metallic and dielectric materials." — *David Nitzan, SRI International*

Henry Ford, which mandates the production of functionally useful products that will not undergo design changes for the sake of change. Products — particularly those produced in the Automatic Factory — must meet customer-acceptance criteria in the context of *producibility*. Once the product design has been accepted and proved in production runs, it can be expected to be frozen into the indefinitely far future. As Richard H. Searle of Waterbury Farrel puts it, "Considering the cost to change automatic machinery, there will be less redesign of products for cosmetic change reasons. Products will be designed with the needs of automatic manufacture in mind."

Speaking to the same point, Janis Church of IITRI says, "Whether one calls it Producibility Engineering, or refers to Designing for Production, this is an often talked-about and little-followed approach . . . Perhaps a simple example will give an example of its potential.

"IIT Research Institute was approached by the maker of a relatively simple medical instrument to develop a system to automatically assemble it. The instrument had nine parts. As the first step in the automation process, it was redesigned to three pieces. The automation project was a failure, however, because it never got beyond that stage. The company decided that the three-part design with manual assembly satisfied their objectives, and they went away happy."

Ms. Church's observations on IITRI's redesign of a medical instrument support a comment from Lockheed's Robert Vaughn concerning the viability of the Automatic Factory for certain products: "The decision to build an Automatic Factory at all will be dictated more by the economics of the situation than by the type of product. Given sufficient expenditure, almost any product can be automated."

On a different aspect of product design, Vaughn notes the coming of a higher degree of standardization. ". . . designers of products will be faced with still another constraint — that of designing for the Automatic Factory. These limitations may take the form of different standards for tolerances, elimination of certain types of fasteners in favor of others, limitation on part configurations to accommodate digital camera recognition methods and similar new considerations."

Speaking on the same subject, Jack McPhail of Ingersoll-Rand says that, "Component parts will become more standardized, taking advantage of higher volumes to justify automated parts machining and making it possible to develop more versatile and flexible automated assembly systems."

SME Director LaRoux K. Gillespie of Bendix notes that, "The design of products for the Automatic Factory must include considerations of finishing operations as well as the primary cutting and forming operations." In this instance, the design considerations are almost legion: deburring; polishing; plating; designing to allow firmly attached small burrs; using part edge configuration to minimize burrs; recognizing where heavy burrs will be rolled into inaccessible locations.

The import of these observations, which typify the views of virtually all respondents to the MANUFACTURING ENGINEERING survey, indicate a far greater role for Value Engineering functions before an Automatic Factory can become a reality.

They also indicate that, of necessity, the divisional lines that have traditionally separated Manufacturing Engineering from Product Design will disappear. Conceivably, the two functions will eventually be merged.

THE APPEARANCE OF THE AUTOMATIC FACTORY

"The Automatic Factory will probably look like a conventional plant during plant shutdown." — *Frank J. Riley, Vice President, The Bodine Corp.*

"The Automatic Factory will not only be larger and higher, but it will penetrate the ground much deeper. Furthermore, I believe it will be nuclear hardened to survive a nuclear attack other than a direct hit." — *Frank H. McCarty, Director of Manufacturing Engineering, Raytheon Co.*

The two views presented above represent the wide divergence of opinion concerning the exterior appearance of the Automatic Factory. Many believe that the Factory will be totally beneath ground to conserve energy and to assist in surviving a nuclear attack. The beneath-the-ground school of thought is a logical one, though none of its proponents offer a suggestion as to the type of world the surviving Automatic Factory will serve.

Some respondents envision the Automatic Factory as the hub of a wheel. Conventional plants on the circumference will be suppliers of raw materials, and certain subassemblies that are more conveniently made with conventional manufacturing techniques. Other plants on the rim would accept completed assemblies from the Automatic Factory for use in other product manufacture. The entire system, says McCarty, could be underground except for the projecting hub of the Automatic Factory.

More to the point is the question: What will the Automatic Factory look like on the inside? The consensus is that it will be quiet — far quieter than current OSHA standards mandate. It will be immaculate as well. One respondent suggests that it will be "clinically clean." All believe that it will be staffed with robots of varying size and capabilities, and that all operations will be supervised from a central control room or "tower".

Says Joel Goldhar of the National Research Council, Assembly of Engineering: ". . . from the inside, the Automatic Factory will look much like a traditional factory, except that it will be cleaner, quieter, and with far fewer people. Moving away from the production floor, we will see a larger concentration of people involved in maintenance and the 'knowledge work' parts of manufacturing, i.e., production control, materials management, purchasing, and the like."

Insofar as personnel are concerned, Goldhar believes that, "More people will walk into the Factory wearing white shirts and carrying toolkits for repairing computers and electronic equipment, while fewer will walk in carrying boxes of wrenches or lunch."

Says Lockheed's Robert Vaughn, "The inside of the Automatic Factory will be similar in most respects to a present day plant. Some differences will be (1) a lower level of general lighting, (2) less attention given to general heating and cooling unless processes are affected, (3) less space allocated to accommodations for people, i.e., restrooms, lunchrooms, parking, and so on, and (4) more space for equipment maintenance. There may well be more effective use of vertical space."

And according to General Electric's Donald Grierson, "Instead of machinists operating machine tools, there will be engineers and technicians programming and servicing the machine tools that are run automatically by electronic control. Work performed by men and women will be in functions requiring skilled training. Rote assignments will be performed by robots.

"The other difference will be in plant layout. Instead of finding groups of manufacturing technologies clustered together, such as all the lathes in one area and the machining centers in another, the Automatic Factory layout will be designed by computer to best facilitate parts movement. Automatic material handling systems, including conventional conveyors, will move parts from one area to another with robots moving components and assemblies from one conveyor belt or automatic cart to another."

In view of the widely divergent opinions concerning the internal and external appearance of the Automatic Factory, it is impossible to arrive at a general consensus. There are, however, well defined areas of agreement as to certain deficiencies in existing technology.

NEEDED TECHNOLOGICAL ADVANCES

"We must see more robots with eye-scanning systems." — *Peter M. Baker, President, Quantrad Corp.*

"A wealth of data will become available through computerization, and a significant challenge will be in determining how to formulate that data into meaningful information which will aid in managing the situation." — *L. A. Branaman, Manager, OSO Engineering, General Electric*

The most dominant theme emerging from Manufacturing Engineering's survey is that robots with varying degrees of capability and sophistication will serve as in-plant personnel in the Automatic Factory. However, the technology of computerized vision is not sufficiently well advanced to make the robots ready to report for work in a totally automated facility. Further, the technology of computerized vision must be accelerated for other applications.

Says L. A. Branaman, "I expect electronic vision to become an intrinsic part of the programmable assembly systems of the future. Not only will the addition of this element increase the 'intelligence' of the system, but it also will facilitate the incorporation of in-process inspection capabilities at critical points in these systems. Solid-state camera technology is a key to progress in this area."

Similarly, Philippe Villers states that, "The artificial intelligence which will be available through the use of advanced computer programs cannot be used unless data is available to the computer. The sense of vision will be the most useful of these sensor systems in the form of digital television cameras.

"Force and proximity sensors of various types will be the next most useful. Also included will be a variety of devices which go beyond the duplication of human capabilities in real-time response. These include infrared, ultrasonic, pH meters, torque sensors, and a variety of other devices which will assume new importance in this type of application."

Villers elaborates on this theme in discussing the impact of robotics on material handling. He points out that, "Material handling systems between cells, between individual machines, and on the machines themselves will call for highly reliable systems integration. But there will be more flexibility through the use of advanced sensors like vision systems. Essentially, we need to develop fault-tolerant material handling systems to assure high uptime. Sensors will tell us what's wrong. Computers will know what to do about it."

Richard Abraham sees a "major deficiency" in a general absence of knowledge concerning the information flow in a business organization. He also sees voids in computer hardware and software in the area of interprocessor communications. More important, he sees a need for a high-level language capable of describing part geometry and form in three dimensions. "Several geometric part modelers have been developed," says Abraham, "but none to a degree suitable for implementation in a working environment."

SOCIAL AND ECONOMIC IMPLICATIONS

"The workforce will decrease in terms of unskilled and semiskilled labor, but the numbers of skilled technicians will necessarily increase. The net effect will be a reduction in the number of people employed in the manufacturing plant." — *Robert Vaughn, Chief Manufacturing Engineer, Lockheed Missiles & Space Co., Space Systems Div., and Vice President of the Society of Manufacturing Engineers*

"The total effect of the Automatic Factory on the size of the workforce will be positive. As we improve our ability to produce and compete, our economy will improve. The resulting increased demand for more products will lead to more jobs." — *Richard P. Cottrell, Vice President — Factory Automation, The Bendix Corp.*

"The Automatic Factory is probably the only means available for raising or at least maintaining the American standard of living." — *S. K. Smith, Manager-Fastening Systems, Eaton Corp.*

The inexorable advance of computerization

RICHARD E. MORLEY
"This pervasive use of multiple computers will be generally invisible to the casual observer."

"Computerization is one of the more interesting aspects of the Automatic Factory. We anticipate that computers will be used throughout the AF. This assumes that each limit switch will utilize a very inexpensive microprocessor. The limit switch, in turn, will be coupled to a localized controller. This localized controller, for example, would then be hooked to a typical servomotor. Each of these levels will contain microcomputers.

"This pervasive use of multiple computers will be generally invisible to the casual observer. This revolution is going on now and will continue to monitonically penetrate all factories whether or not they are called 'automatic.'

"Computerization will allow the mechanical aspects of the factory to be more general purpose and be dynamically configured in control. The mechanical aspects will be more general purpose and will utilize such techniques as adaptable materials handling, robots and machining centers. Materials handling between the various machining centers will begin to upstage the standard transfer line.

"Materials handling with automated pallet trucks, in conjunction with robots, will allow the flow of materials to be dynamically programmed for a family of parts rather than the factory producing a single part.

"Engineering changes for small-lot production will become feasible in the Automatic Factory. Large-scale computerization, such as that being offered by Functional Automation of Gould, will allow the interrelationship of all aspects of the Automatic Factory. This will maintain uptime, audit trails, and maintenance, both scheduled and nonscheduled.

"One of the foreseeable problems with computerization will be the inability of the existing management structure to accommodate and make use of the information base available." — *Richard E. Morley, President, Functional Automation Division, Gould Inc.*

As Joel Goldhar pointed out in a letter to the author, "There is a real need for additional and better focused research on the social and economic implications of the Automatic Factory." The author agrees, noting that the questions asked in the MANUFACTURING ENGINEERING survey were more productive of additional questions than they were of definitive answers. And since most of the questions asked for opinion rather than yes-or-no responses, the answers cannot be tabulated. However, several readings of the correspondence file gives one a sense that — all in all — the Automatic Factory will be a welcome and even necessary addition to American industry.

Proliferation

To what extent will the Automatic Factory spread through industry? There is no absolute answer, since its proliferation is strictly a function of economics. Professor Lamberson of Wayne State University sees it "eventually reaching all facets of industry. The product range is limitless."

Roger Willis of the Arthur Andersen Co. takes a slightly more conservative view, noting that, "It will spread as far as the unions and the government allow it to."

No one regards the Automatic Factory and its proliferation as impossibilities, but one company president wonders whether the concept of the Automatic Factory might not be extreme. "You can attain just about the same results with flexible automation," he observes.

The Conventional Factory

Does the Automatic Factory spell the demise of the conventional factory? The answer is no — although it will thin out their number. As Richard Cottrell of Bendix puts it, "Some conventional factories will remain. The important point is that the Automatic Factory will be more efficient and productive, a condition that will probably lead to a fewer number of factories."

The economics of the Automatic Factory are such that it will make its greatest impact in small-batch manufacturing. It will not take over the manufacture of automobiles, for example. (See "A selective transition in automobile manufacturing.")

Of greater significance is the impact of the Automatic Factory's advanced technology on the conventional factory. Robots, improved material handling, vastly improved inspection and quality control, computer vision, and the like are not developments that will be restricted to the Automatic Factory. The conventional factory will remain, but it will grow in sophistication. The conventional factory will no longer provide income for the unskilled.

Labor Unions

Will labor unions be rendered obsolete by the Automatic Factory? A number of respondents pointed out that labor unions are already diminishing in size, and that the advance of automation (with or without Automatic Factories) spells their demise. Most, however, believe that unions may evolve into different forms, but that they are here to stay. "Unions are in the organizing business," observes one engineer. "As the pool of unskilled labor dries up, they will attempt to organize the professionals of the Automatic Factory, as well as its technicians and maintenance staff."

Workforce Size

What impact will the Automatic Factory have on the size of the American labor force? The consensus is that the labor force will change in character from unskilled and semiskilled to semiprofessional and professional — but that it will not change significantly in size. Says T. F. Fluchradt of Westinghouse, "The Automatic Factory won't have much effect on the size of the American workforce. If we assume that our economy is growing but that our birth rate is not, the size of the workforce is more dependent on the birth rate, and the Automatic Factory will merely allow each worker to have a larger share of influence within the factory."

A selective transition in automobile manufacturing

"Two factors control the incorporation of any new automation — cost effectiveness and the availability of capital for the investment. At the same time that our (the automobile) industry increases the degree of automation, demands upon available capital also increase — for higher R&D expenditures to maintain competitiveness, heavy expenditures to meet governmental regulations, and the like. In addition, governmental financial policies in the areas of tax credits, depreciation rates, and other incentives also have a substantial impact upon investment. Because of these factors, we expect the optimum Automatic Factory to be evolutionary, though specific state-of-the-art technology may be revolutionary.

"We believe that selected segments of the Automatic Factory will be highly, if not totally, automatic. These segments will be restricted to very high-volume products where few design changes occur. The manufacture of various components within a specific facility may be completely automated while the facility in general is not.

"In our industry's continuing quest for productivity improvements, changes will be required in the way we do business in terms of degree and sophistication of automation and management style." — *Paul F. Guy, Director, Manufacturing Engineering and Systems Office, Manufacturing Staff, Ford Motor Co.*

But in the view of William S. Adams of the American Can Co., "Eventually, the size of the workforce and the amount of time that an individual actually spends on the job will decrease. This means that the 'goods and services' supplied by a small group of people will be sufficient to satisfy the needs of a large group of people. This, of course, translates into high productivity, which is good — but at the same time yields high unemployment, which is not so good. A redefinition of work, compensation, recreation, and so forth, will be required."

While virtually all concerned are optimistic as to the stability of the workforce size, the key to the answer lies in T. F. Fluchradt's assumption of an expanding economy. If the economy expands, it will absorb the segment of the labor force that will be displaced by automation. But if the economy continues to stagnate at its present no-growth level, the advance of automation has implications that are obviously disastrous. Needed now and needed badly is a reversal of our decline in productivity growth. The Automatic Factory is one tool for assisting in effecting this reversal.

The Role of Government

What role, if any, will the government play in the development of the Automatic Factory? If there is a consensus in responding to this question, it is that the government **should** take an avuncular interest in the development of the Automatic Factory without becoming bureaucratically entangled in its growth.

Says John C. Williams, "The government will have a role in establishing the Automatic Factory and in taking some of the risk out of it. Manufacturers in this country should be able to operate from a position of U.S.A., Inc. when competing with overseas manufacturers."

In Kenneth Treer's opinion, "Government will have to concern itself more with legislation which aids the long-term development of the Auto-

Labor vis-a-vis America in worldwide industrial competition

"There will certainly be a diminishing workforce, as indicated by the many demographic studies showing population shifts in the 1980s and the 1990s. The fact that we will have fewer entrants into the workforce and also a shift toward the service occupations makes the need for the Automatic Factory even more important.

"It will be incumbent upon the labor organizations to recognize this. Rather than antagonism toward management in developing the Automatic Factory, the labor organizations will have to begin to understand the problems facing American industry in its worldwide competition. It is important that they develop an attitude of cooperation with manufacturing industries — for the benefit of all concerned, especially labor itself.

"The reduced workforce, as forecast by demographic studies, and the fewer number of workers in an Automatic Factory will certainly have a severe impact on the membership levels of labor organizations. This will lead to reduced income from membership dues and consequently to reduced financial support of the unions.

"It is conceivable that reduced financial support could lead to the demise of labor organizations as we know them today. With an awakening need for the reindustrialization of America, the survival of the labor organizations will depend on their cooperation with management in developing more efficient, more productive methods of manufacturing, so that America can again be a leader in worldwide competition." ***— Leon B. Musser, Vice President, Kearney & Trecker Corporation.***

matic Factory and less with the short-term tax returns and ineffectual social reforms."

In the opinion of most, the government will eventually do nothing to assist in the development of the Automatic Factory, although there is definitely a consensus that the Automatic Factory provides many of the answers to America's social, economic and international problems. Says Joel Goldhar, "My guess is that, in the U.S.A., the government will do relatively little to stimulate the widespread development or implementation of the Automatic Factory.

"What we need is a generally accepted set of national strategies for improving manufacturing productivity from which the appropriate goals for industry and government will follow naturally.

"In the absence of this kind of overall strategy, the discussions of government's role are being held in a vacuum." ■

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A SPECIAL REPORT

Distributed Control in Discrete Part Manufacturing— An Overview

Network communications between programmable controllers or minicomputers and remote input/output via data bus in discrete manufacturing is suddenly the hot, new thing. But because it is such a hot, new thing, many users are not yet willing to discuss their distributed control applications for a variety of reasons: some consider their applications highly proprietary; others say their systems are in the final test and acceptance stage; while others are just implementing their systems. *Control Engineering* interviewed several of the leaders in the industrial controls industry to talk about distributed control in discrete manufacturing—where it is today and where it's going. Based on their comments, we will discuss the status of digital controls, data highways and distributed control. We'll also describe several applications of systems involving processor communications and remote input/output.

KENNETH PLUHAR, Control Engineering

Pure distributed control in discrete manufacturing means an independence at the basic functional loop—that is at the station or stations doing the work. The network link can be broken, but each control continues to function; perhaps not as efficiently as before, but function nonetheless. This is the key to distributed control: the work station or independent island functions without being tied to the network.

So we can see that the definition of true distributed control is the same in discrete manufacturing as it is in the process industries: each control loop is local to the work station (process) and operates independently of the supervisory control function of the central processor (central control room). Distributed control is the method of functionally dividing the control requirements into unique applications and distributing the control systems around the manufacturing complex. There is a requirement that the various unique applications must, in most cases, be related by group technology (similarity—in operations) for a family of parts.

Discrete manufacturing includes piece-part production, the assembly and handling of piece-parts, and the testing of assemblies. Nuts and bolts are discrete parts. Engines and transmissions are assemblies using many discrete parts and are, themselves, tested as discrete entities. Automobiles and airplanes are discrete entities made from assemblies involving thousands of discrete parts and assemblies.

Many industrial control manufacturers have provided the tools to make programmable controllers (pc's) work in a distributed system, and they seem to be talking about communications and designing data highways; but few have yet really approached distributed control in discrete manufacturing from the total systems concept. However, there are a lot of things happening out there on the design boards of industry, and there are distributed controls in place or nearly in place: a can production application, a casting/heat treating line, an automated material handling system with interactive crt terminals and robotic pallet carriers, engine and transmission test stands, alignment systems, torque monitoring systems, and others.

Distributed control in the discrete manufacturing industries is hot now because the data highway concept pioneered by the process industries is fast becoming cost effective, and may already be, in the industries that pioneered pc's. The process industries required the distributed approach because of the applications that were being controlled: pipe lines, oil platforms, energy management, and because of the need for reduced wiring costs, increased systems reliability, and management reporting. And that need for management information which, in itself, requires monitoring of machine operating parameters on the shop floor and closer operational control, is the impetus spurring the boom in distributed control in discrete manufacturing.

Some typical networks

When looking at the needs for setting up a distributed system, several factors should be considered. First and probably most important is group technology considerations. It probably sounds obvious, but at this time, networking dissimilar operations will lead to nothing but grief.

Functions of each subsystem must be carefully selected from the overall production scheme to optimize each subsystem. Computation time of each subsystem and communication transmission time are important factors in determining where a function may be placed without affecting system control. Management and data collection should be placed at the supervisory or central processor. Control functions and diagnostics for each work station should remain at that work station with reporting to a supervisory control.

Looking at the hierarchical or tiered network, we see three basic levels. The first level consists of pc's at the work stations. The second is the supervisory pc or mini controlling other pc's or mini's. The entire program of the supervisory pc could be changed by the level three computer while the pc continued to control its work station. The level three computer includes capabilities for management reporting, system diagnostics (diagnostics can also be distributed to the lower levels), error correction, part routing, crt applications, and other data gathering. This network concept seems to be the type that will soon be dominant in the distributed control market.

Another network type is the daisy chain network on which each controller receives a signal from the controller upstream, extracts data meant for it, and passes the signal to the next controller downstream. This network is often referred to as a dependent network because stations doing the work cannot continue to function downstream from a break in the network link. This approach seems to be one of the more popular in industry today.

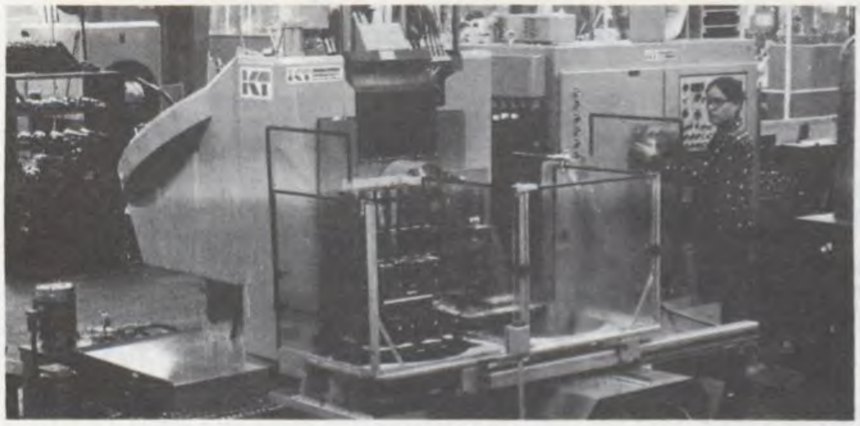
An input/output (I/O) network locates the I/O device in the field to speed data to the pc in the control room. While this approach may be considered a network or data highway, it is not distributed control, rather it might be called distributed communications. Remote I/Os save on wiring costs for applications which are very far from the supervisory function and also allow very high speed data communications.

NC in a distributed system

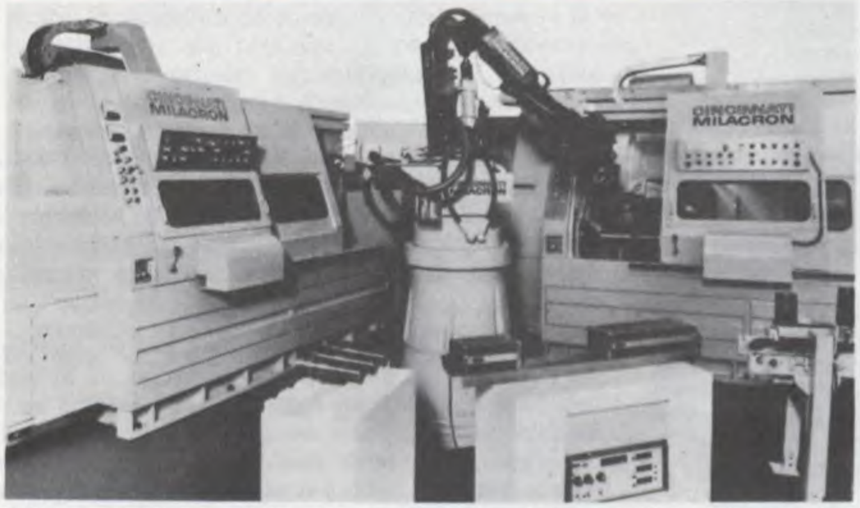
There is an important factor regarding the modern machine shop that must be considered when discussing distributed control. That is the probability of a pc/nc marriage.

The common link between nc and pc's or mini's in a distributed system is probably the need for management information. An additional link might be the need for supervisory control that must take place on the shop floor between the pc and the nc machine control unit (mcu).

There are some pc/nc applications,



A Kearney & Trecker Milwaukee-Matic 180 Machining Center is seen operating under K&T's Computer Numerical Control (cnc) in the machine tool builder's Milwaukee plant. At left note the palleted fixture which is prepared for the next machining cycle.



In this representative robotic production system, a Cincinnati Milacron T^3 computer-controlled industrial robot is servicing two Milacron cnc turning centers. Operations include feeding random sized parts to the machines, removing them, placing them into a laser checking gage, and then stacking them. The T^3 is the robot under development in ICAM's robotics project—Task B (see text).

but nc users don't seem to be prepared for a true distributed control approach except in the area of robotics where the control application is a mini rather than a pc.

But the real link is sophistication. As the machine shop becomes more automated, more dependence is placed on the network. As each nc island or work station becomes more automated, as robotics become a larger factor in the manufacturing process, the more distributed control is needed to manage and control the process.

Robotics in a distributed system

A near future discrete manufacturing technology that also cannot be ignored is the merger of robot controlled systems (robotics) and distributed control. Current robotic applications include arc welding, drilling of aircraft wing panels, auto body spot welding, spray painting, and shot peening.

Robots are now "taught" positions which can be repeated by matching a joint location. Joints are merely swivel or rotary axial points giving the robot pitch, roll, yaw, or sweep motions. The accuracy of repositioning can be affected by tool changes, load distribution, and even temperature changes in the hydraulic oil.

Teaching a robot is done by literally walking the device through its production cycle, usually using a pendant control. Each position is recorded and stored in the robot's computer memory. This on-the-job teaching is time consuming and may tie the robotic work stations up for several shifts.

The Air Force's Integrated Computer Aided Manufacturing (ICAM) program's Robotic Systems for Aerospace Batch Manufacturing Project—Task B will solve many of these problems in addition to placing robots in a distributed system for sheet metal production.

The Task B project, coordinated by Michael Moscynski, Air Force Materials Laboratory, Manufacturing Technology Division, Wright-Paterson AFB (Dayton, OH), involves several items under development including off-line programming techniques which will overcome the problem of on-the-job teaching of the robot. A high order APT (automatically programmed tools)—like language is being developed. Sensors and vision capabilities are being developed to accommodate feedback methods which will close the operating loop of the robotic control thus improving accuracy and repeatability.

The integration plan or control hierarchy of the Task B project includes three levels. The first level is defined as the process, which is an act such as tube bending. The second level is called the station, which is the machine that performs the process—in this case the robot. The third level—and this is where things get interesting—is called the cell. It contains two or more stations related by group technology for a family of parts. Included in level three is inter- and intra-cell automatic material handling. The cell will be supervised by a mini on the shop floor. At some time in the future, the cells will be networked in a method analogous to current dnc methods which use a high level cpu as a system manager. Human intervention via crt is also a future consideration for level 3.

Video display in a Distributed system

The video display terminal—more commonly called a crt—is found throughout the various applications that follow. It is found at the highest level of the network and down on the shop floor. In discrete manufacturing, however, *CE* could only find black and white, alphanumeric applications. Again, there seems to be a lot brewing in the design of color and graphic display crt's as in other areas, but users and manufacturers are keeping quiet until the applications are implemented and proven. ☐

Special thanks to Dale Benedick, Industrial Solid State Controls (York, PA), Joe Cowan, Texas Instruments (Johnson City, TN), James Heaton, Process Computer Systems (Saline, MI), and Peter Zilko, Eagle Systems (Davenport, IA) among the many who contributed background information for this article.

RÔLE DES GRAPHIQUES PRODUITS PAR ORDINATEUR DANS LA CONCEPTION DE BÂTIMENTS

Donald W. Collins
et
Robert Bycraft, ing.*

Résumé

Le présent article décrit les divers usages, passés et présents, de graphiques produits par ordinateur, considérés comme aides à la résolution de problèmes. Nous étudierons la conception de bâtiments assistée par ordinateur (CBAO), dans ses relations avec l'industrie du bâtiment, en la définissant d'abord en fonction de la révolution de l'information et en établissant un bref historique, puis en étudiant certaines lacunes inhérentes aux méthodes classiques de conception de bâtiments ainsi que les obstacles possibles. Nous décrirons ensuite sous forme de résumé bibliographique l'état de la recherche en CBAO et certaines applications de graphiques produits par ordinateur. Enfin, nous présenterons un langage de production de graphiques, ainsi que le rôle du gouvernement et du secteur privé dans la conception assistée par ordinateur (CBAO).

Introduction

L'architecture en est à sa « troisième révolution industrielle » [STINE75], mais le spécialiste en bâtiment utilise des méthodes et des outils qui datent d'il y a cent ans. Les universités du monde entier devraient tenir compte d'une observation de Richard Buckminster Fuller qui dit qu'alors que les médecins s'intéressent aux organes intérieurs de l'espèce, les spécialistes du bâtiment s'intéressent à ses organes extérieurs. Il est nécessaire de créer des laboratoires de recherche en bâtiment, spécialisés en conception, exactement comme il existe des laboratoires de médecine d'anticipation.

Telle que considérée aujourd'hui par les chercheurs de l'industrie du bâtiment, la conception de bâtiments assistée par ordinateur consiste en un système au sein duquel le concepteur et l'ordinateur forment une « équipe » capable de mieux résoudre les problèmes qui se posent et où il y a place pour un véritable travail multidisciplinaire. Un système intégré de conception de bâtiments assistée par ordinateur (CBAO) est en mesure de mouler les différentes disciplines de conception de façon que le bâtiment puisse être considéré comme un système global et non plus comme de multiples systèmes ou sous-systèmes indépendants.

Un système de CBAO vise essentiellement à réduire au minimum les répétitions des données requises pendant le processus de conception et à faciliter l'instantanéité du transfert de données précises entre les différentes disciplines de la conception. En réduisant au minimum les données à introduire en les transférant entre les différentes disciplines par ordinateur, on augmente la productivité et l'efficacité de la conception. De plus, dans un système efficace de CBAO, les tâches comme la répétition des dessins et les calculs compliqués, sont accomplies par ordinateur. Ainsi le concepteur peut se concentrer sur les aspects créateurs.

Au Canada, deux organismes se sont occupés à perfectionner le domaine de la CBAO. Le gouvernement fédéral a institué un programme de recherche de cinq ans en conception assistée par ordinateur (CBAO), dirigé par le ministère des Travaux publics. Au Québec, le Centre des études sur le bâtiment de l'Université Concordia a choisi d'inclure la conception de bâtiments à l'aide de l'ordinateur parmi ses sujets de recherche.

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*M. **Robert S. Bycraft** est chef de la Division de l'élaboration de la conception assistée par ordinateur (CAO), Travaux publics Canada. Ingénieur en mécanique, il fut d'abord spécialiste des installations de chauffage, de ventilation et de climatisation dans le secteur privé. Il a été l'instigateur du programme du gouvernement fédéral visant à promouvoir l'application de l'informatique à l'analyse des installations énergétiques dans les bâtiments. Au ministère des Travaux publics du Canada, il a également joué un grand rôle dans la mise sur pied de la Division de l'élaboration de la conception assistée par ordinateur (CAO) qui incite à employer des aides informatiques de manière à concevoir des bâtiments plus rentables et plus efficaces.*

*M. **Donald W. Collins**, Bac. arch., M.sc. génie de l'information, Ph. D. génie de l'information (informatique-dessin assisté), est depuis septembre 1979, professeur agrégé de recherche en conception assistée du bâtiment au Centre des études sur le bâtiment à l'Université Concordia. Il était auparavant chef du Département d'architecture et professeur au William Rainey Harper College en Illinois. Les recherches de Donald Collins portent sur l'application du dessin par ordinateur à l'architecture et au génie.*

À l'heure actuelle, la CBAO peut aider les concepteurs de bâtiments à préparer en moins de temps un ensemble plus complet et mieux coordonné de documents de construction. De plus, les documents relatifs au fonctionnement et à l'entretien du bâtiment peuvent être aisément préparés à partir des fichiers de données mémorisés dans le système CBAO. Une forte proportion des dessins de travail peuvent être exécutés à l'aide de terminaux à écran cathodique interactifs (CRT) et de traceurs à commande numérique. Lorsque des modifications sont apportées par l'une des sous-disciplines de l'équipe de conception, les corrections à apporter aux autres dessins et documents en mémoire s'enregistrent automatiquement. Dans un système intégré de CBAO, durant le processus de conception, le concepteur peut demander, par exemple, les quantités de matériaux requises ainsi qu'une mise à jour des décisions de conception prises. Ce type d'interaction lui permet d'envisager différentes hypothèses de conception et de comparer le coût de ses différentes décisions. Pour l'analyse des besoins en énergie, la surface extérieure, les quantités de matériaux sélectionnés et le volume intérieur du bâtiment en cours de conception peuvent être calculés automatiquement. Un système intégré peut fournir au propriétaire du bâtiment les guides appropriés rédigés à partir des devis et les dessins définitifs nécessaires au fonctionnement et à l'entretien du bâtiment. Il peut également fournir des calendriers d'entretien préventif pour les matériels mentionnés dans les devis. Tous ces renseignements sont en mémoire et accessibles à chacune des sous-disciplines en vue des décisions de conception. De plus, il est facile d'intégrer aux fichiers les statistiques d'exploitation du bâtiment.

Ces informations peuvent être utilisées pour vérifier si le bâtiment se comporte comme prévu ; elles peuvent également servir pour concevoir des bâtiments semblables.

Lacunes des méthodes classiques de conception

Un des principaux objectifs de la conception automatisée des bâtiments est de les construire de façon plus efficace et d'en réduire les coûts d'entretien pendant leur durée utile, et non de remplacer les hommes par des machines. Il s'avère à l'usage qu'on procède rarement aux calculs manuels précis et détaillés dans tous les domaines de l'analyse de conception en raison du temps qu'il faut pour les faire. L'industrie utilise de nombreuses « règles de l'art » qui consistent à ajouter des facteurs de sécurité pour composer les approximations. Ceci augmente les investissements initiaux ainsi que les coûts de fonctionnement et d'entretien.

Malgré ces facteurs, il se produit parfois des erreurs coûteuses à cause d'hypothèses fausses et de calculs imprécis. Dans l'ingénierie des charpentes, les avantages potentiels des codes modernes du bâtiment sont en grande partie perdus. Par exemple, on tarde à accepter la conception des états limites de l'acier en raison de la difficulté d'appliquer cette méthode. Un grand nombre d'autres méthodes analytiques d'évaluation de la conception comme celles qui permettent de faire des estimations précises en énergie ou d'établir le niveau d'éclairage ne peuvent être utilisées sans ordinateur. Enfin, la facilité et la rapidité avec lesquelles l'information peut être extraite et utilisée sont importantes, parce que la valeur de l'information pour tout projet de conception diminue rapidement à mesure que la conception progresse.

Bref historique et bibliographie des graphiques produits par ordinateur

La première utilisation générale d'un écran cathodique pour la réalisation de graphiques par ordinateur remonte au début des années 60 avec Ivan Sutherland et son système « SKETCHPAD ». Celui-ci a été élaboré par le laboratoire Lincoln du Massachussetts Institute of Technology.

Les graphiques automatisés constituent un outil susceptible de nombreuses applications, ainsi qu'en témoigne Ivan Sutherland [2] :

> *« Je considère l'affichage d'ordinateur comme une fenêtre ouverte sur le monde d'Alice au pays des merveilles grâce à laquelle le programmeur peut décrire soit des objets qui obéissent à des lois naturelles bien connues, soit encore des objets purement imaginaires qui suivent les lois écrites dans son programme. Grâce à ces affichages, j'ai fait atterrir un aéroplane sur le pont d'un porte-avion en mouvement, observé une particule nucléaire heurtant une barrière de potentiel, fait voler une fusée à une vitesse voisine de la vitesse de la lumière et contemplé un ordinateur qui révélait ses travaux les plus secrets. » [SUTHE 70] (traduction libre)*

L'ordinateur et les graphiques automatisés joueront un rôle important dans le façonnage de l'avenir. Il s'avéreront utiles dans les domaines suivants : planification des routes, conception des automobiles et des aéronefs, cartographie, architecture et génie, mise en page, esthétique, analyse numérique et exploration de l'espace, pour n'en mentionner que quelques-uns.

Il existe plusieurs ouvrages importants sur les graphiques automatisés relatifs à l'industrie du bâtiment. Le premier ouvrage sur l'utilisation des ordinateurs en architecture est celui de David Champion [3].

Sur quatorze chapitres, seulement deux traitent des graphiques automatisés. L'un d'eux traite des applications architecturales de ces graphiques et l'autre décrit un programme qui permet de réaliser des perspectives sur un traceur.

En 1969, Neil Harper a écrit un livre alors qu'il dirigeait une collection d'ouvrages qui traitaient de l'utilisation des ordinateurs en architecture. Cet ouvrage est particulièrement intéressant en ce qu'il présente des applications réellement utilisées par des firmes d'architectes et permet au lecteur d'étudier les différents systèmes mis en œuvre. Toutefois, Harper n'indique pas en détail ce qu'il faut faire pour élaborer un système.

L'ouvrage le plus récent sur la CBAO est celui de William J. Mitchell [5] qui traite de la conception architecturale assistée par ordinateur. On y trouve les principes fondamentaux de la CBAO. Il se divise en quatre parties : concepts fondamentaux, bases de données, interfaces et solution de problèmes. Il est recommandé à tous les spécialistes du bâtiment qui s'intéressent à la CBAO.

Les progrès effectués entre le programme SKETCHPAD de Sutherland et la conception architecturale assistée par ordinateur de Mitchell sont considérables ; cependant, l'utilisation des graphiques produits par ordinateur au titre d'outils d'architecture ne fait que commencer. Nous étudierons l'un de ces outils dans la section suivante.

Logiciel et langage de production de graphiques

En 1975, le professeur Collins [6] a démontré la possibilité d'utiliser l'ordinateur dans la conception de bâtiments modulaires. Cet ouvrage est important en ce qu'il utilise un langage spécialisé de production de graphiques, le langage GRASS [7, 8] au lieu de langages de programmation d'usage général comme le FORTRAN IV et le BASIC RSTS/E. Cela lui permet de réduire des deux tiers le recours à la mémoire et d'obtenir presque instantanément des résultats visuels.

Ces études présentent également une approche modulaire à la résolution de problèmes au moyen d'un logiciel. Les élévations peuvent être construites interactivement par un usager et donner des réponses à des questions posées sur un terminal ou en recevant dynamiquement des données d'un autre système. Le système d'élévation peut produire des fichiers de données utilisables pour d'autres programmes. Ceci constitua le début d'un système de gestion de base de données dans l'industrie du bâtiment.

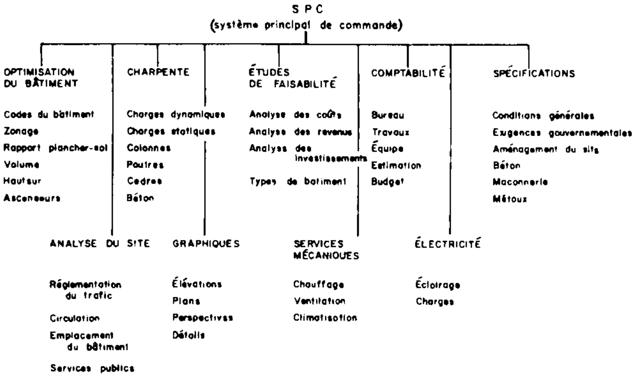


Figure 1

Nous allons maintenant décrire un système de production d'élévations par CBAO. Cela ne constitue qu'une petite partie d'un système intégré (Fig. 1), ce n'est qu'un exemple des possibilités d'utilisation des graphiques dans la CBAO. Les variables introduites sont des termes dont se servent tous les jours les concepteurs et dessinateurs (Figures 2 et 3).

Des variables telles que la largeur des baies et des colonnes, la hauteur des planchers, l'épaisseur des montants, menaux et seuils, la hauteur des menaux horizontaux, le nombre de baies, de fenêtres et de planchers sont introduites dans le calculateur. Il est possible de répéter les calculs initiaux, selon différents critères de conception. Il existe également des variables qui permettent de sélectionner le type de bâtiment, comme les façades en affleurement, verticale ou horizontale.

Les figures 2, 3 et 4 illustrent quelques-unes de ces variables.

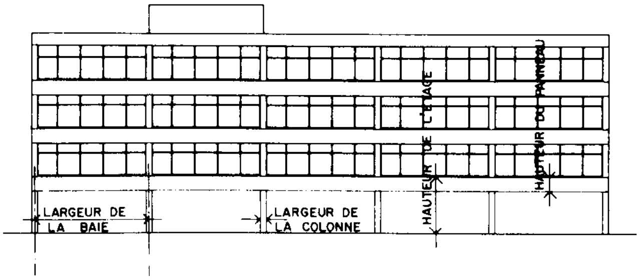


Figure 2

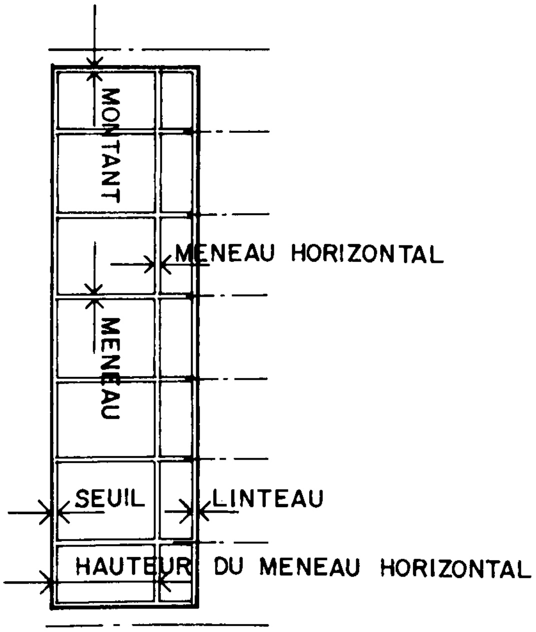
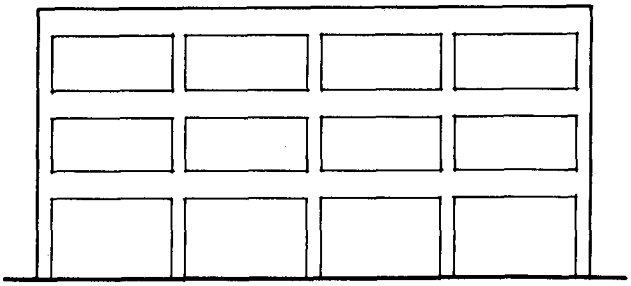
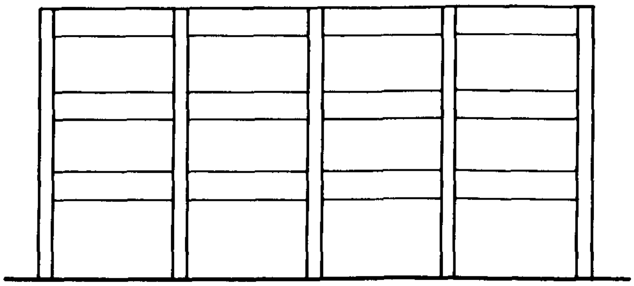


Figure 3

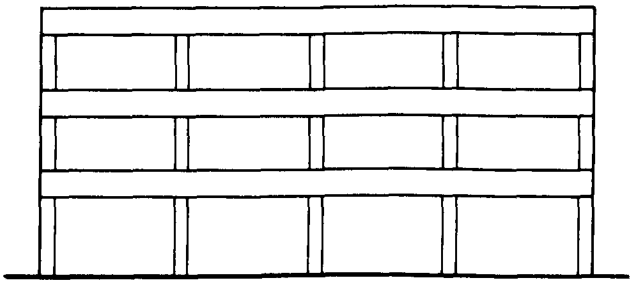
Un fichier de données est produit par ordinateur en 10 à 15 minutes ; l'usager peut alors changer en quelques secondes un code dans le fichier et obtenir une autre conception. En utilisant un terminal interactif comme le terminal à écran cathodique, il est évident que si un code du fichier peut être modifié, il doit y avoir un nombre presque infini de possibilités. Par exemple, la modification de la dimension de la largeur de la baie donne une conception différente, tout comme la modification du nombre de fenêtres par baie. Dans ce cas, le « Système interactif de production de graphiques » constitue pour le concepteur un outil de conception de modèles qui lui permet d'étudier un grand nombre de possibilités. Il importe de signaler que le concepteur peut demander la liste des matériaux indiquant les quantités nécessaires pour les devis et les soumissions. La figure 5 donne une élévation ainsi qu'une liste d'informations relatives à un bâtiment telles que produites par l'ordinateur.



Type 1 Facade en affleurement



Type 2 Facade verticale



Type 3 Facade horizontale

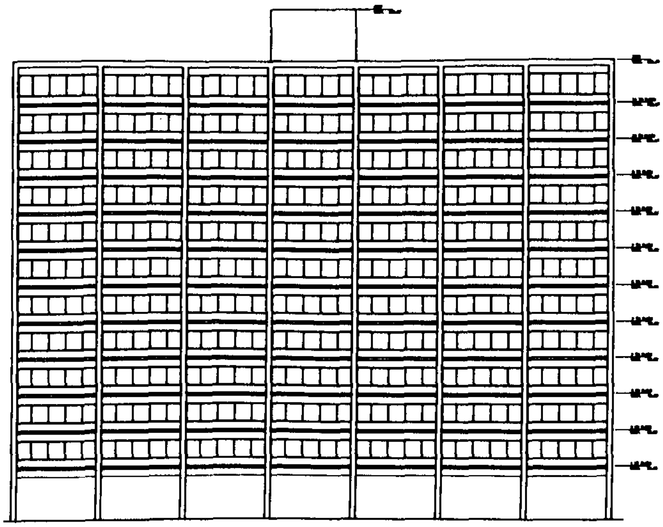
Figure 4 — Types de bâtiment

Ces informations peuvent être données pour le bâtiment entier ou pour chaque étage. Si l'on imagine un système totalement intégré, il est possible de penser que l'information calculée sur la façade d'un bâtiment puisse être utilisée comme entrée dans les programmes d'analyse des besoins en énergie. On peut même aller plus loin : l'information relative aux données des encadrements de fenêtres pourrait être envoyée, sous forme de fichier d'ordinateur, au constructeur de fenêtres avec le dessin des membrures extrudées des encadrements et les longueurs et quantités de membrures à produire, ainsi que les quantités et les dimensions des vitres.

Dans les mois à venir, ce système CBAO de production d'élévation sera mis en œuvre en langage GRAPPLE sur mini-ordinateur au moyen d'un terminal de production de graphiques TEKTRONIX. Ce langage est le résultat d'un programme de cinq ans de recherche et développement en conception assistée par ordinateur, financé par le ministère des Travaux publics du Canada, que nous avons mentionné précédemment.

Au cours des années 1973-1974, le groupe de « conception assistée par ordinateur » du ministère des Travaux publics du Canada et ses conseillers ont étudié l'état des graphiques interactifs d'ordinateurs disponibles. La décision d'adopter le langage de programmation GRAPPLE [9], mis au point par les chercheurs de la Bell Northern, se fondait moins sur les programmes existants que sur la souplesse de ce langage, capable de créer de nouveaux programmes.

Il s'agit en fait d'un langage très structuré, supérieur pour cette raison aux langages FORTRAN ET BASIC, même si l'on ne tient pas compte de sa capacité de production de graphiques. Il s'est avéré d'ores et déjà



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PROGRAMME D'ÉLÉVATION DU BÂTIMENT   LISTE DES MATÉRIAUX  PAGE 1

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                                 1455 OUEST BOUL. DE MAISONNEUVE
                                 MONTRÉAL, QUÉBEC H3G 1M8

NOM DU PROJET .................. ESSAI D'ÉLÉVATION # 1
                                 SOM - JOHN DOE - CONCEPTEUR
                                 B  RUE
                                 A - PROJET
                                 C  VILLE

DÉTAILS DU BÂTIMENT

SURFACE TOTALE DE L'ÉLÉVATION ................................ 29662.30
SURFACE TOTALE DES VITRES DE L'ÉLÉVATION ..................... 15313.20
SURFACE TOTALE DES PAREMENTS POUR L'ÉLÉVATION ................ 14349.30
POURCENTAGE DU VERRE PAR RAPPORT À LA SURFACE TOTALE ...         31.62
POURCENTAGE DU PAREMENT PAR RAPPORT À LA SURFACE TO-
TALE ........................................................     48.30

NOMBRE DE BAIES DANS L'ÉLÉVATION ............................      7.00
NOMBRE DE FENÊTRES PAR BAIE ..................................      5.00
NOMBRE D'ÉTAGES DANS L'ÉLÉVATION .............................     12.00

HAUTEUR TOTALE DU BÂTIMENT ...................................    150.00
LARGEUR TOTALE DE L'ÉLÉVATION ................................    197.3

LONGUEUR TOTALE DES MONTANTS DE FENÊTRES .....................    884.4
LONGUEUR TOTALE DES MENEAUX DE FENÊTRES ......................   1769.9
LONGUEUR TOTALE DES SEUILS DE FENÊTRES .......................   2021.25
LONGUEUR TOTALE DES LINTEAUX DE FENÊTRES .....................   2821.25
LONGUEUR TOTALE DES MENEAUX HORIZONTAUX DE FENÊTRES               0.00

NOMBRE TOTAL DES MONTANTS DES VITRES DE FENÊTRES .............    154.00
NOMBRE TOTAL DES VITRES DES FENÊTRES MODULAIRES ..............    231.00
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Figure 5 — Détails du bâtiment et élévation type

un excellent outil de production de logiciel. La concision de ses codes permet de réduire les espaces de mémoire centrale et de mémoire sur disque ainsi que les temps d'exploitation et le coût des programmes. Les progrès réalisés en une période relativement courte n'ont cessé de confirmer la nécessité d'adopter un langage de base solide avant de commencer les travaux de production graphique. Même actuellement, en dépit des progrès réalisés, il est évident que nous ne faisons que commencer à saisir l'utilité et les possibilités d'application des graphiques produits par ordinateur pour nos travaux. La nécessité d'utiliser un langage souple qui puisse s'adapter aux usagers est encore plus évidente aujourd'hui qu'il y a cinq ans.

DRAWI est un éditeur évolué de dessins écrit en langage GRAPPLE [10]. Il permet d'exécuter des dessins sur un terminal graphique muni d'un réticule commandé par une molette. La liste des fonctions des dessins est affichée sur le côté de l'écran et des fonctions spécifiques peuvent être sélectionnées avec le réticule, ce qui permet au dessinateur de disposer d'un certain nombre de fonctions puissantes. L'une de ces fonctions, véritable zoom, permet d'agrandir une partie du dessin affiché à l'écran.

À l'aide des points du quadrillage, il est possible de créer des dessins très détaillés et d'une grande précision dépassant de loin les capacités des plus grandes planches à dessin. En utilisant une structure fichier/données incorporée à la machine, il est loisible de créer de véritables bibliothèques de parties et d'ensembles qu'on peut désigner nommément et mettre en mémoire en vue de leur extraction éventuelle ou de simple répétition, réflexion ou rotation sur d'autres dessins.

Bien que le programme DRAWI ait été créé pour produire des dessins d'architecture, il est de nature générale et peut être utilisé pour presque toutes les applications graphiques. Puisque les graphiques automatisés ont pour principal avantage la répétition de parties et d'ensembles, la nature de la plupart des dessins d'architecture ne semble pas, à l'heure actuelle, justifier le système d'un point de vue économique, pour la plupart des firmes d'architectes. Un essai effectué auprès du cabinet Murray & Murray & Associés à Ottawa le confirme bien. Les coûts actuels du matériel sont trop élevés en comparaison des avantages que les architectes peuvent retirer de l'utilisation du système.

Logique et rôle du gouvernement dans la conception assistée par ordinateur

Le développement de la CBAO coûte cher et fort peu de recherches peuvent être financées par l'industrie de la conception en matière de construction en raison de la petite taille des entreprises.

Dans le numéro de mars 1979 de *Engineering Digest*, J.H.C. Scrimgeour, de l'ITC, écrit :

> *« Par conséquent, on évitera l'escalade des coûts en se gardant notamment de réinventer la roue. Cela signifie que nous devons nous efforcer de ne garder secrètes au sein de nos firmes respectives que les parties de projets qui doivent absolument le demeurer en raison de leur réelle nouveauté ou de leur caractère secret. »*

La création au Canada d'un centre de CBAO financé par le gouvernement viserait à :

1) créer un centre de communications favorisant l'échange des idées et des informations relatives au développement et aux applications de la CBAO dans l'industrie du bâtiment ;

2) financer et diriger le transfert de la technologie des organismes de recherche et de développement aux praticiens, au moyen de programmes de présentation, cours, sessions de formation, colloques et ateliers ;

3) créer un milieu innovateur et créateur employant un nombre limité d'architectes, d'ingénieurs et de spécialistes en bâtiment chargés de faire des recherches ou de développer leurs idées dans leur domaine de spécialité, notamment les sciences informatiques connexes, et, en même temps, de constituer une source de connaissances techniques ;

4) cette base technique étant créée, indiquer les centres d'excellence au gouvernement, dans les universités et dans le secteur privé ; promouvoir et administrer des contrats de recherche visant à développer l'utilisation de la CBAO dans l'industrie de la construction.

Il est nécessaire d'augmenter les fonds consacrés à la recherche et au développement pour créer des techniques perfectionnées proprement canadiennes et soustraire le pays à une totale dépendance des techniques importées. Nous devons également utiliser notre système d'éducation, sophistiqué et coûteux. Il se peut que nous ne puissions affronter la concurrence dans toutes les industries, mais notre industrie du bâtiment est déjà importante et très en avance, d'après les normes internationales. Il nous faut créer sans cesse de nouvelles techniques de conception et de construction de bâtiments et inciter nos architectes et ingénieurs à utiliser les meilleurs techniques existantes. L'ordinateur est un outil puissant lorsqu'il est convenablement utilisé ; nous devons perfectionner cet outil et former nos spécialistes à s'en servir s'ils veulent rester à l'avant-garde des techniques de construction de bâtiments.

Intégration de l'informatique et de la science du bâtiment

L'un des mythes au sujet des ordinateurs est que la science informatique est déjà bien avancée et qu'il suffit que les architectes et les ingénieurs trouvent des applications et les mettent en pratique. Si c'était vrai, le développement et l'utilisation des ordinateurs auraient certainement progressé davantage dans l'industrie de la construction, durant ces trente dernières années. En fait, il est avéré que l'application finale (par exemple : le traitement des mots) constitue la force qui fait progresser l'industrie de l'informatique. Comme avantage supplémentaire, un centre de CBAO financé par le gouvernement pourrait également aider l'industrie informatique canadienne, encore à ses débuts. C'est le logiciel qui fait vendre le matériel, et les efforts déployés pour mettre en œuvre le logiciel de la CBAO dans un futur ordinateur construit au Canada (même si la plupart des pièces sont importées) augmenteront le potentiel de vente de ce dernier au Canada et à l'étranger.

De plus, la Canadian Advanced Technology Association, dans le mémoire qu'elle a présenté au ministère fédéral des Finances en mai 1978, a écrit :

> *« La création de compagnies axées sur la technologie provoque souvent la création d'entreprises commerciales connexes. Par exemple, un producteur de techniques canadiennes provoquera souvent la création d'entreprises orientées vers la consultation dans le même domaine »*
>
> *« Dans l'entreprise type, membre de la C.A.T.A., un dollar investi en recherche et développement aujourd'hui procure $30 de vente l'année suivante ; ce phénomène peut également être exprimé par une capacité de création d'emplois de 30 : 1 pour les Canadiens chaque année. »*

Il est évident que le marché du matériel informatique restera fortement concurrentiel et sera beaucoup moins important que celui du logiciel pour deux raisons : d'abord, la proportion représentée par sa valeur dans le « système » diminue rapidement et, plus important encore, le matériel n'a *aucune valeur* sans le logiciel. Même si le matériel perdra de son importance dans les années à venir, il demeure nécessaire et la probabilité qu'il soit importé et contribue au déficit de notre balance commerciale est forte. On pourrait améliorer la situation en réexportant du matériel sous forme d'un système global matériel-logiciel destiné à desservir des marchés spéciaux. De cette façon, le Canada pourrait procéder à des exportations nettes de techniques avancées sous forme de systèmes matériel-logiciel vendus clé en main.

Rôle du secteur privé

Enfin, soulignons qu'il serait vain pour les organismes gouvernementaux et les universités d'instaurer des aides informatiques sans la participation du secteur privé, ultime utilisateur de cette technologie. Toute activité de ce type doit être guidée et conseillée par l'industrie privée, au moyen de groupes de travail et de conseils consultatifs. Entre autres choses, ces organismes doivent aider le centre gouvernemental de recherche en CBAO à repérer les spécialistes de leur profession capables d'entreprendre les travaux de contrôle utiles à l'industrie. Ils doivent sans cesse évaluer les progrès du centre et les avantages qu'en retire l'industrie de la construction, et veiller à ce que l'argent des contribuables soit dépensé de façon judicieuse.

Conclusion

Nous sommes persuadés que les années 80 verront l'adoption de la conception de bâtiments assistée par ordinateur.

La recherche et l'aide gouvernementale joueront un rôle important à cet égard et contribueront à transférer cette technique à l'industrie du bâtiment. Au cours des années 80, les experts du bâtiment retourneront à l'université à la fois pour y communiquer leurs connaissances et y apprendre cette nouvelle technique.

La collaboration entre les secteurs privé, gouvernemental et universitaire dotera le Canada d'un programme de conception de bâtiment assistée par ordinateur qui permettra à la production automatisée de graphiques de jouer un rôle de premier plan dans la conception du bâtiment.

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Integrated Manufacturing System for Sheet Metal Parts

By Ryohei MAEDA,* Eigo SEKIGUCHI,* Akira SAITOH,* Katsuhiko YAMAGUCHI*
and Masateru SHIMOZONO*

ABSTRACT This paper describes the Integrated Manufacturing System developed for small quantity and various-shaped sheet metal parts. This system divides five elements, design, production control, process planning, production equipment and DNC system. Each element is included into the overall system, which is based on a computer integrated system.

KEYWORDS **Integrated manufacturing system, Computer integrated manufacturing, CAD (computer aided design), Production control, Process planning, Production equipment, DNC (direct numerical control) system, Sheet metal parts**

1. INTRODUCTION

Many small sheet metal parts of various shapes are produced in NEC. Because of the diversity of customer needs and a reduction in product life cycle, many kinds of sheet metal parts tend to be produced on a small scale. Therefore, the following problems are occurred.

(1) Many skilled workers are required.
(2) Many workers work in a dangerous environment.
(3) It is difficult to retain production quality high.
(4) It is difficult to increase production efficiency.

In order to solve these problems, about six years ago CAD/CAM system development was started for sheet metal parts. In June 1979, it was decided to develop an overall manufacturing system which was based particularly on the digital computer potential as a tool.

This system is divided to five elements, design (for production), production control (scheduling and supervising), process planning (programming), production equipment (NC machines) and DNC (Direct Numerical Control) system. First, individual elements were developed one by one, then they were integrated into an overall system. This system was installed in Tamagawa Plant, Nippon Electric Co., Ltd. It has already started to produce sheet metal parts as an integrated manufacturing system.

2. THE INTEGRATED MANUFACTURING SYSTEM

Any manufacturing stage, especially the production process, is automated by using IE technology, computer, NC machines, robot, etc., on a step by step basis. However, because the manufacturing elements are closely related with each other and plenty of information is needed for them, it is important to consider the total manufacturing efficiency. The economic situation increasingly forces production plants operating on a small scale with large variety production to adopt more automation. This is because it is necessary to develop a total automated manufacturing system, which has flexibility and moment-by-moment optimization in any stage of manufacturing, design, production control, process planning and production. Integrated manufacturing system gives the potential to provide that system eventually. The generic concept of the integrated manufacturing system is defined by M. E. Merchant as follows [7]:

Integrated Manufacturing System – That closed-loop feedback system whose prime inputs are product requirements (needs) and product concepts (creativity) and whose prime outputs are finished products (fully assembled, inspected and ready for use). It is comprised of a combination of software and hardware, whose elements include product design (for production), production planning (programming), production control (feedback, supervisory and adaptive optimizing), production equipment (including machine tools) and production processes (removal, forming and consolidative). It is amenable to being realized by application of systems engineering and has the potentiality of being fully automated by versatile automation and being made fully self-optimizing (adaptively optimizing). The present major instrument for accomplishing such is computer-related technology.

3. DEVELOPMENT SYSTEM OUTLINE

On the integrated manufacturing system concept, the following points were considered on improved system development.

(1) Computer integrated manufacturing system.

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*Transmission Division

(2) Database management system.
(3) Hierarchical computer control system.

Figure 1 shows the system flow. This system is composed of five elements, Design, Production Control, Process Planning, Production Equipment and DNC system, and is based on five data files, PIF (Production Information File), SMOF (Specification of Manufacturing Operation File), POF (Production Order File), MDF (Manufacturing Data File) and SDF (Standard Document File). Each element is working independently. They are connected with each other by the data files.

This system uses ACOS 900 for the central computer. The operator communicates with the central computer by NEAC DATA STATION. NC machines are controlled by the DNC system, which is composed by microcomputers and optical data highway (NEOLINK). Central computer and DNC line are connected by floppy disk. The production process is as follows:

(1) The turret punching machines punches circular, square, oval and special shaped holes, as well as various kinds of notches in the standard size material sheet.
(2) The tapping machine taps screw holes.
(3) The cutting machines cuts parts off with a rectangular punch, which has an L-shaped cutting blade. Parts are temporarily stored automatically in a tray.

Each element is described as follows.

4. DESIGN

The CAD (Computer Aided Design) system is shown in Fig. 2. This CAD system consists of a design data processor, called BEPP (BEnt Parts Processor), and a product information master file called PIF and specification of manufacturing operation file called SMOF. It also involves peripheral automatic drawing equipment. The information flow is as follows:

First, a designer prepares a sketch, for instance, a freehand three-dimensional picture of sheet metal parts with dimensions. The operator defines the shapes in specialized modeling BEPP code and sends these data to ACOS 900 by NEAC DATA STATION.

Second, BEPP is used. BEPP has two basic information tables. One has data on primitive profile patterns and the other has data on punched hole figures. Samples are shown in Figs. 3 and 4, respectively. Both

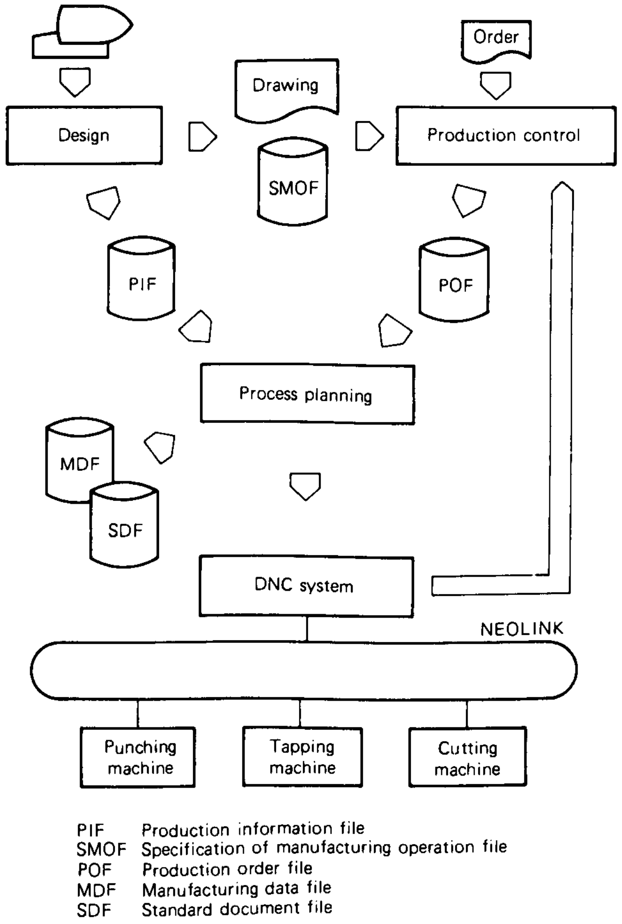


Fig. 1 System flow.

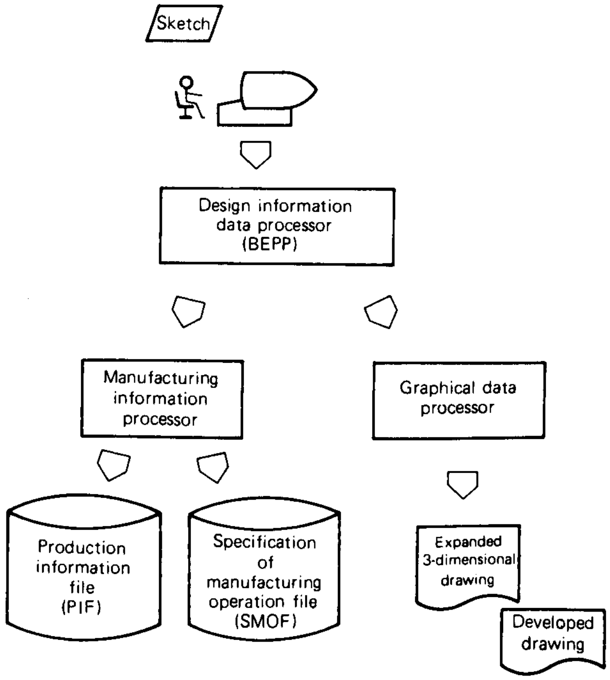


Fig. 2 CAD system flow.

tables do not restrict the final design contents, permitting free setting and selection of patterns and dimensions. These tables are referred to as needed and a set of basic patterns with its numeric codes (BEPP code) is selected corresponding to the primary design image. The coded input data is converted to the numerical data corresponding to the basic information tables. Then, developing calculation from three-dimensional structural shape to two-dimensional plane is accomplished. The data is broken down into detailed items: Blank profile shape, manufacturing code number, figures and locations of the notches, additional or deleted lines to revise the blank profile shape, and the dimensional lines.

Finally, after arrangement and error checking, the data is connected to generate complete exploded three dimensional drawings and developed drawings. This data is registered permanently in the PIF.

5. PRODUCTION CONTROL

The production control system is shown in Fig. 5.

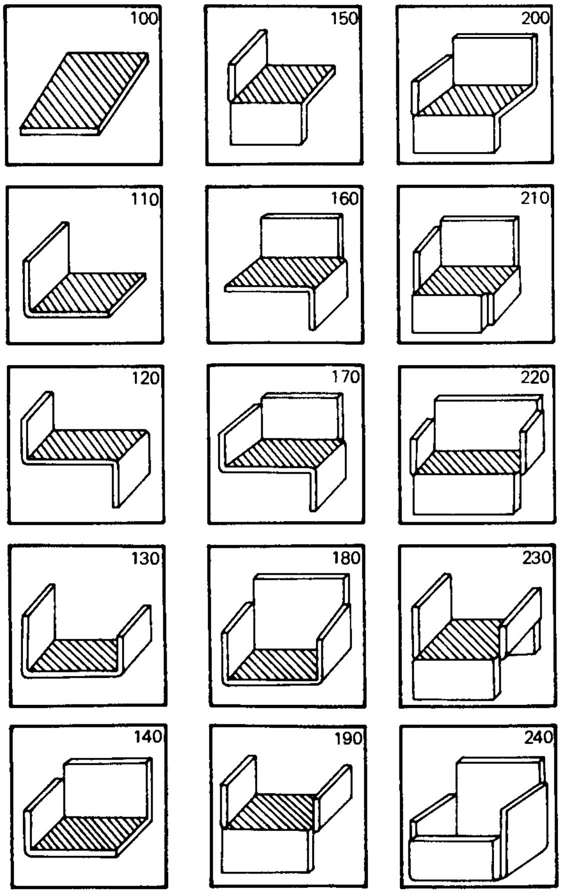


Fig. 3 Primitive pattern examples.

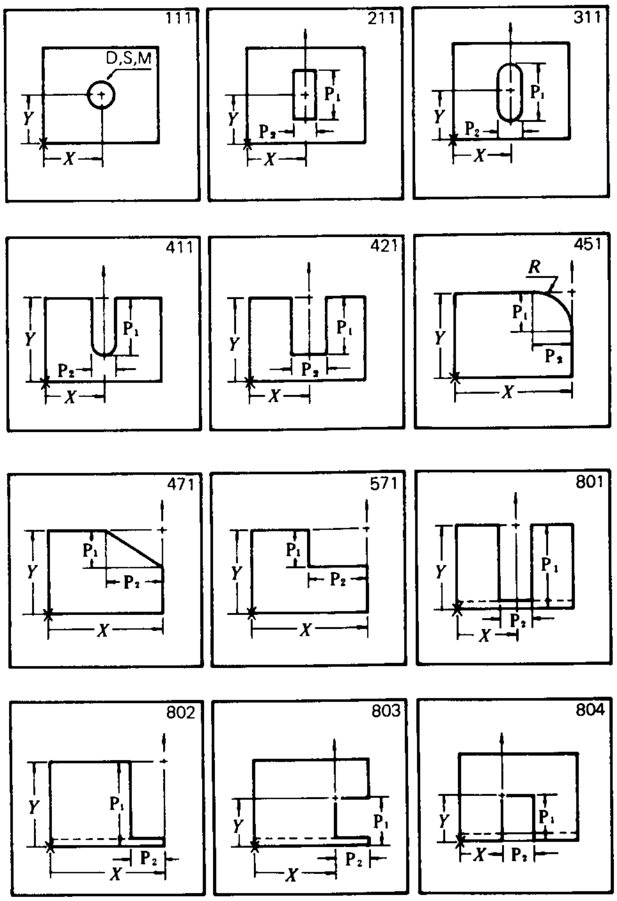


Fig. 4 Selectable punched hole figure examples.

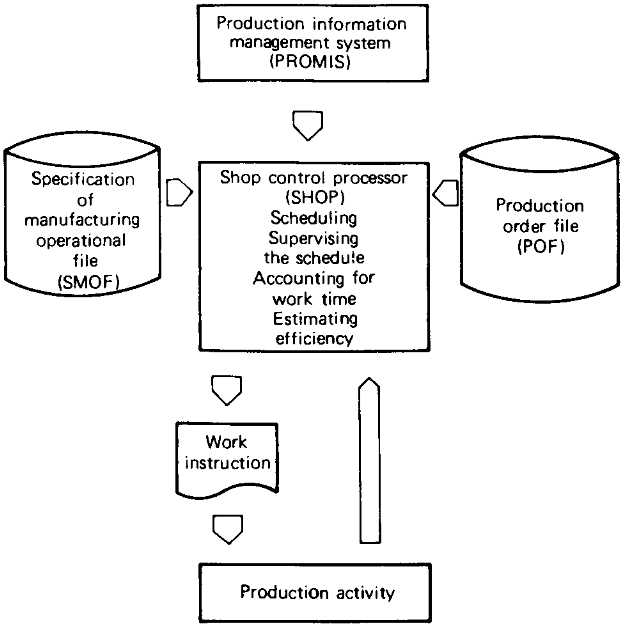


Fig. 5 Shop control system flow.

This production control system consists of a production management information system called PROMIS, a shop control processor called SHOP and production order file called POF. This system is mainly controlled by scheduling production orders. In automatic manufacturing, scheduling is a very important process. Generally, there are three levels in scheduling, as shown in Fig. 6.

- Level 1: Scheduling between shops. In this situation, delivery time which synchronizes each shop is appointed.
- Level 2: Scheduling between work centers in a shop. In this situation, delivery time in each work center is decided in consideration of each load.
- Level 3: Scheduling in a work center. In this situation, orders sequence is decided on, considering the work center high efficiency.

In this system level 1 is processed by PROMIS. Levels 2 and 3 are processed in the shop, as follows.

(1) The NC work center, as shown in Fig. 7, is a flow shop in which punching, tapping and cutting are operated sequentially. The orders for each day are chosen in accordance with the punching load, which is the first operation, and is not affected by other operations.

(2) Then, the orders are arranged in sequence in accordance with optimum arrangement on a standard sized material sheet.

One of the most important aims in scheduling is load adjustment. However, load adjustment requires the following decisions, if possible, concerning whether or not to:

(1) Extend working hours.
(2) Change delivery time.
(3) Change the work from one work center to another.

Scheduling in this system, therefore, is processed by conversational man-machine system. A machine displays load rate and loaded orders in a work center, and an operator inputs such instructions as changing delivery time, etc. Using this simulation, scheduling is almost completed.

6. PROCESS PLANNING

Figure 8 and Table I show the data structure and process planning process sequence.

First, according to keywords assigned to product names in the Production Order File, which contains data such as delivery time and volume for all products already scheduled, the product design information is extracted from the PIF.

Next, process planning, such as nesting, parts layout on a material sheet, design of using facilities and tools and operations sequence decision, is continued to optimize such items as those shown in Table I, quoting suitable data from Manufacturing Data File (MDF) and Standard Document File (SDF).

An example of the process planning output is shown in Figs. 9(a) and (b). Processes are as follow:

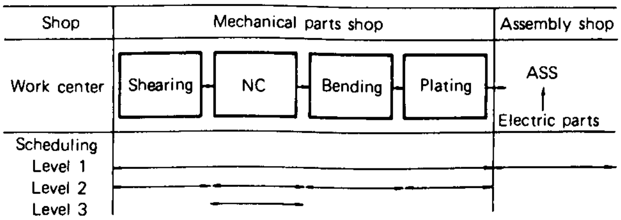


Fig. 6 Scheduling level.

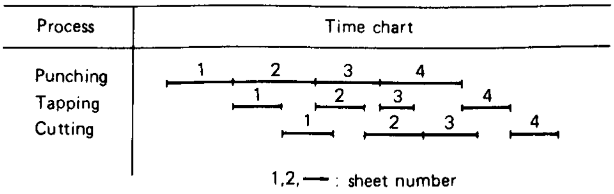


Fig. 7 NC work center process.

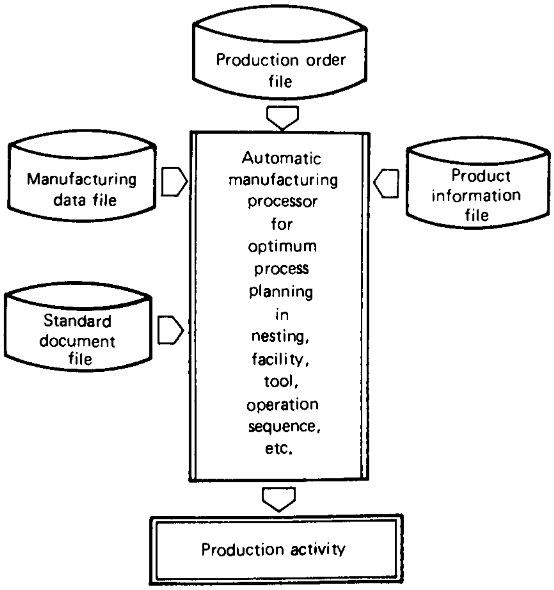


Fig. 8 Process planning system flow.

(1) Nesting

In cutting by a shearing machine, as shown in Fig. 10(a), large oblique areas are all useless. If NC machines with a rectangular punch were used for cutting, this area may be used for many other small parts. In order to use this area efficiently, the oblique areas should be collected in one place.

Three large oblique areas in Fig. 10(b), resulting from investing several groups of products, are very useful. However, one larger oblique area in Fig. 10(c), formed by gathering up three unused areas in Fig. 10(b), is the most useful when a template for small work blanks is used, as shown in Fig. 10(c). Waste data is obtained by nesting with the new algorithm which was developed according to the nesting principle.

(2) Tool Operation

After data on all punched holes in the standard sized material sheet are stored, complete with size and figure in no relation to product names, each hole is referred to tools registered in MDF to pick up a matched tool.

The necessary tools are set on each turret head station for the NC turret punching machine, not only to match the setting specification but also to minimize sequential turret head rotation. Tapping tool operation is the same as punching.

(3) Cutting Process

A rectangular punch, which has an L-shaped cutting blade, shown in Fig. 11, cuts parts surrounded by cutting margin areas in order to furnish support for the material sheet during cutting and to cut all four sides precisely. Parts already arranged in the Nesting Process, for example, as shown in Fig. 11, are cut by three strokes.

Great care must be taken that the same parts may not always be cut continuously, because parts are arranged on a standard sized material sheet, not necessarily placed in order to simplify the cutting sequence, but placed in order to obtain material waste minimization through using the Nesting Process. In Fig. 11, part A-2 must be held over until parts B-1 and B-2 are cut.

(4) Tray Selecting Process

A general flow diagram for the tray selecting process, shown in Fig. 12, is mainly concerned with hardware operation. In this process, first, the products are distinguished from the margin area cutting operation. Next, the tray to store the products is decided upon, in order to minimize tray movement.

As previously described in the cutting process, the same parts may not always be cut continuously. Therefore, in the case of Fig. 12, after the tray stores part A-1, it has to be put to one side temporarily until part A-2 is cut, because the tray to store B parts must be set up next. The tray to store B parts may also be put aside temporarily, while one of the C parts is cut.

7. PRODUCTION EQUIPMENT

This system has turret punching machines, tapping machine and cutting machines. These machines are connected in DNC line using optical data highway and are controlled by the DNC system. The turret punching machine is shown in Fig. 13. The tapping machine is shown in Fig. 14. The cutting machine is shown in Fig. 15. Tapping machine and cutting machine were developed for this system. The tapping machine has the following unique characteristics:

(1) All tapping processes are controlled by NC. Therefore, the operator only needs to set and reset the work.

(2) This machine has six tapping heads (two heads

Table I Data structure and process flow.

	Manufacturing data file	Standard document file	Optimum process planning
Nesting (layout on a material sheet)	Material thickness, standard sheet size, etc.	Sequence of layout, cutting margin area, etc.	Material waste minimization
Facility	Mechanism of turret station, cutting tool, tray, etc.	Setting up turret station, precision compensation, NC instruction, etc.	Minimization of tool changes, turret head rotation, tray movement
Tool	Name, form, size, etc.	Use of shear proof, combination with tools, etc.	Rational use of tools, combination of tools
Operation sequence		Sequence of tool operation, cutting operation, etc.	Tool movement path minimization

above the x-y table and four under it). Two heads are controlled at the same time.

(3) This machine has sensors, which detect tapping head movements. If any accident or malfunction occurs, this machine is stopped rapidly.

The cutting machine has the following unique characteristics:

(1) All cutting processes are controlled by NC. Therefore, the operator only needs to set and reset the work.

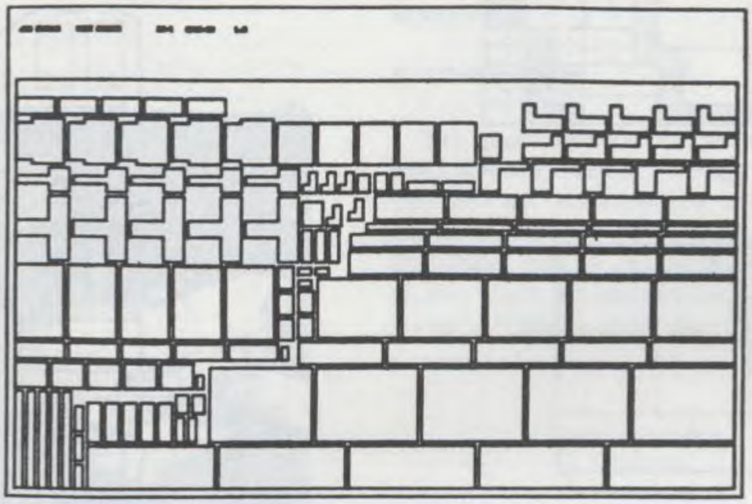
(2) This is a rectangular punching machine, which has an L-shaped cutting blade.

(3) This machine has a tray selection and waste elimination mechanism.

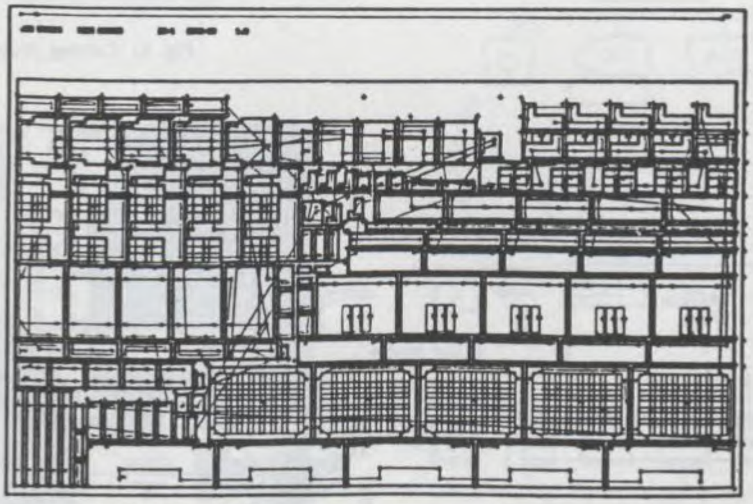
8. DNC SYSTEM

The DNC system was developed in order to increase actual machine working time and to realize on-line production control (feedback, supervisory and adoptive optimizating) with the hierarchical computer system. This DNC system has the following unique characteristics:

(1) NLU is a compact intelligent terminal with



(a) Layout diagram.



(b) Punching, tapping and cutting sequence.

Fig. 9 Layout and operation sequence.

man-machine interface (monitor TV and keyboard).

(2) High speed and high quality data transmission, using an optical data highway.

(3) Low cost system, which is composed by microcomputers and one loop data highway.

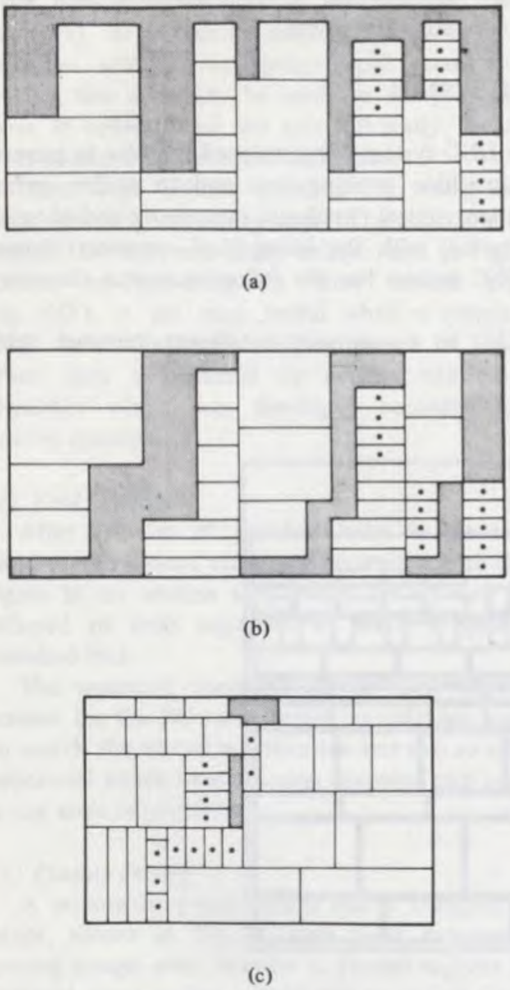


Fig. 10 Nesting process principle.

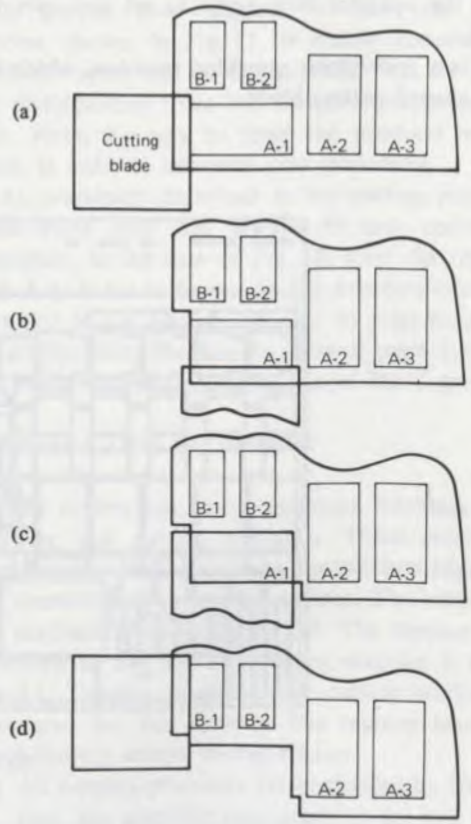


Fig. 11 Cutting process.

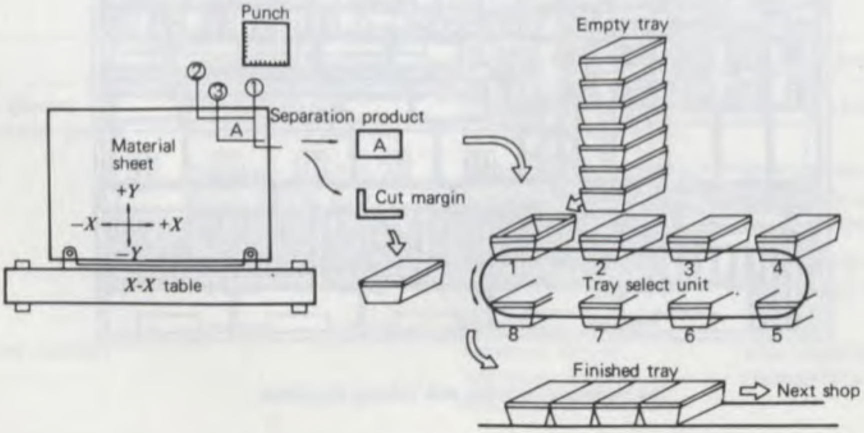


Fig. 12 Cutting machine operation.

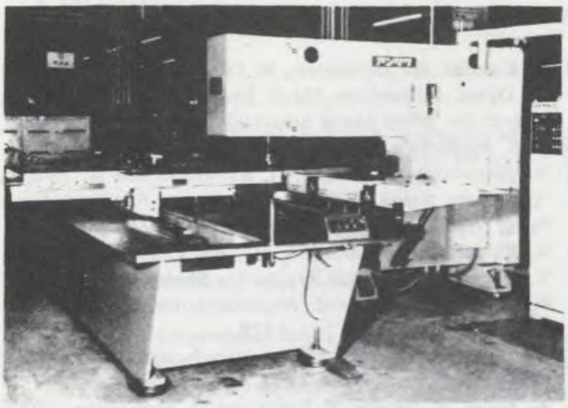


Fig. 13 NC turret punching machine.

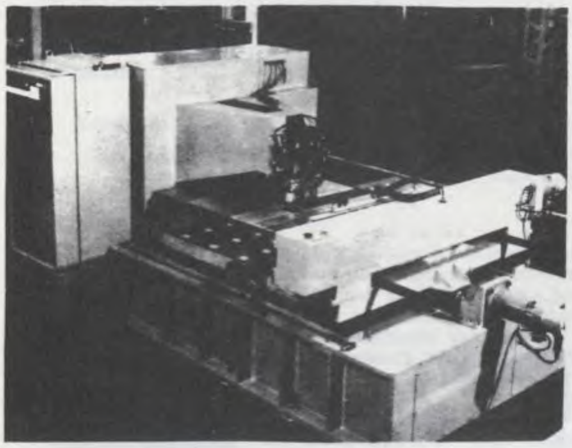


Fig. 14 NC tapping machine.

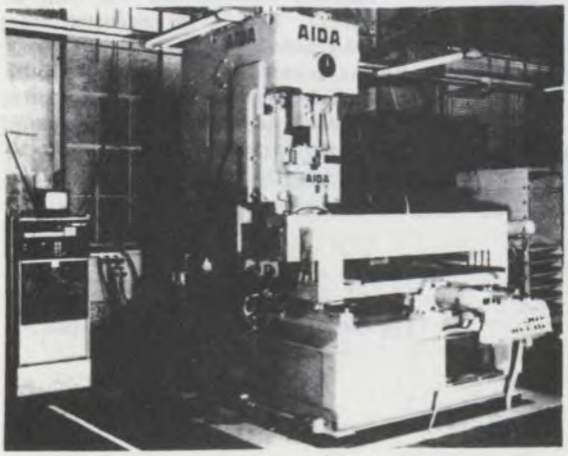


Fig. 15 NC cutting machine.

Figure 16, shows a simple block diagram of the DNC system. The DNC center, consisting of a microcomputer system (MPU-80), stores the command data compiled in a central computer, distributes it to the NC machines, and controls this system. The DLU (Data Linkage Unit) controls the NLUs (NC Linkage Unit) which are connected to the data highway. When an NLU requests command data, the DLU extracts command data from the DNC center and sends it to the NLU. The NLU sends a request signal to the DLU when the NC machine requires command data, receives the data from the DLU and sends it to the machine. The NLU displays the command data on the monitor TV at the same time. An operator can communicate with the DNC center by using the NLU keyboard and monitor TV.

9. CONCLUSION

This paper describes one example of the integrated manufacturing system, which is adapted to small quantity and various-shaped sheet metal parts. This system includes the elements, design, process planning, production control, production equipment and DNC system. Each element is integrated into an overall system, which is based on a hierachical computer

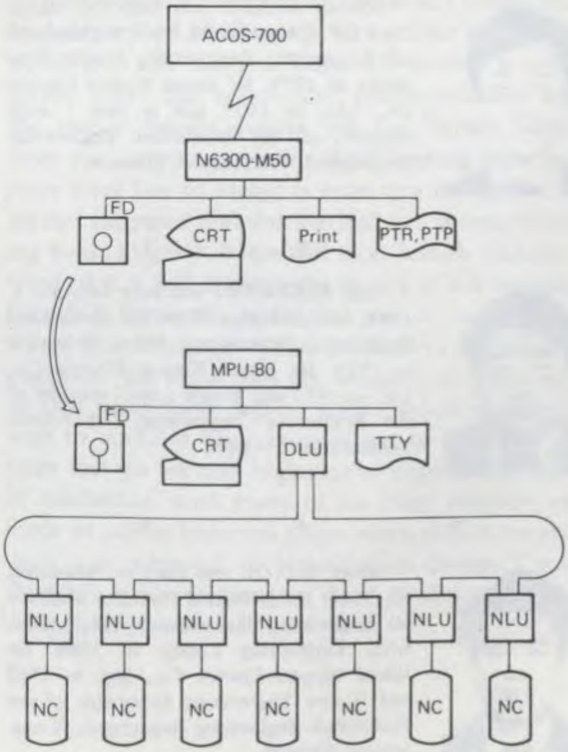


Fig. 16 DNC system.

system. In the near future, this system will be expanded into a more flexible and more automated manufacturing system with robot technology and more satisfactory production control, especially flexibility and moment-by-moment optimizing. Also, it is planned to implement this system to any other shops, rotational parts, package assembly, inspection, etc.

The integrated manufacturing system concept is very important in considering future automated manufacturing systems. Therefore, it is hoped that this concept will be more earnestly discussed and used to implement any other manufacturing system.

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Forum

Some Social Aspects of CAD

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There is a widespread belief that automation, computerisation and the use of robotic devices will liberate human beings from routine, backbreaking, soul destroying tasks and leave them free to engage in more creative and worthwhile activities. Actual experience does not support such a generalisation and there are growing grounds for believing the reverse is frequently the case.

There are now grounds for believing that the computer, as the vehicle for technological change in the field of white collar and intellectual work, is bringing in its wake many of the contradictions experienced at an earlier historical stage when skilled manual work was subjected to mechanisation and automation.

Keywords: CAD, leisure time, technological change, white collar work, unemployment, creativity, suppression, managerial control, trade unions, female values.

Dr. Mike Cooley is an unusual combination of technologist, active trade unionist and academic. He is a Senior Engineer in the Aerospace Industry, and Past National President of the AUEW/TASS, a trade union which organises some 200,000 designers and engineers in the U.K. He is an internationally recognised authority of the social effects of "New Technology" (in particular CAD) and has lectured on these matters in most European countries, the USA and Australia. He has been a guest professor at several West German Universities, and is Joint Director of the CAITS project at the N.E. London Polytechnic. His papers and books have been translated into over 20 languages.

In the light of what I shall have to say I wish to declare at the offset that I am not opposed to technological change rather I believe I stand for the best use of it. I therefore distance myself from those romantics who seem to believe that before the Industrial Revolution the populace used to spend its time dancing around May-poles in unspoiled meadows. It never was like that, and I am deeply conscious and proud as a technologist of the contributions science and technology have made in eliminating squador, disease and filth and providing the material basis for a better standard of living. I do, however, believe that we are at a unique historical turning point, and decisions we make in respect of new technologies will have a *profound* effect upon the way we relate to each other, to our work, and even to nature itself.

I share, with one of the founders of modern cybernetics, Norbert Wiener, the concern "although machines are theoretically subject to criticism, such criticism may be *ineffective* until long after it is relevant".

I do therefore intend to be critical and I hope that by being critical at this stage we can take some steps whilst it is still relevant. There still persists a widespread belief that automation, computerization and the use of robotic devices will free human beings from soul-destroying routine, backbreaking tasks and leave them free to engage in more creative work. It is further suggested that this will lead to a shorter working week, longer holidays and more leisure time. In a word, that it will improve the quality of our working lives. It is frequently added as a sort of occupational bonus that the masses of data available to us from the computer will mean that the decisions we make will be that *much more* logical, scientific and creative. I wish to question those assumptions and attempt to show that we are now beginning to *repeat* in the field of intellectual work many of the tragic mistakes we made at earlier historical stages when skilled manual work was subjected to technological change. I will therefore quite deliberately draw parallels between *manual work* and *intellectual work*.

* This article is an excerpt from unscripted statements made by the author when introducing his invited paper with the same name at the MICAD'80 Conference in Paris, September 23–26, 1980.

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To do this it is necessary to view the computer as part of a technological continuum which has been discernable over at least 400 years. The computer therefore cannot be viewed as an isolated phenomenum, but seen as another means of production and viewed within the context of the political, ideological and cultural assumptions of the societies which have given rise to it.

1. Looking Back

Viewed historically, the first thing we notice about equipment is that it has *an ever increasing rate of obsolescence.* Wheeled transport existed in that form for 2000 years. Watt's steam engine was running 102 years after it was built. High capital equipment in the thirties was written off in 25 years. The type of equipment I describe in my paper will be obsolete in 3 or 4 years time. Economists would refer to this as the tendency towards a shorter and shorter life for fixed capital.

The second discernable feature is that *the total cost of the means of production is going up.* This is in spite of the reduction of cost for micro-processors and micro-computers. Computers are simply controlling means of production whose cost is ever increasing.

Thus, confronted with equipment which is getting obsolete literally by the minute and which has cost massive capital investment, employers will seek to exploit that equipment 24 hours a day. This they attempt to do through *shift working.* – This is not an academic question. Some of the Senior Design Staff at Rolls Royce were told to accept 3-shift working to make full use of the CAD related equipment. A strike took place and the employers were prevented from introducing this.

Resistance to shift work should not be seen as some kind of bloody-mindedness on the part of Trade Unionists. Those who are required to accept *rotating shifts* are likely to have an ulcer rate 8 times higher, a juvenile delinquency amongst their children of 80% higher and a divorce rate about 60% higher. I say that without making any observations about the nuclear family, simply to attempt to demonstrate that the problems that arise at the point of production spread right out to the fabric of our lives, affecting our relationships with our children, our husbands and wives and the communities in which we live.

Then there is *the exponential nature of technological change itself.* In the last century alone our speed of communications has gone up by 10^7, traffic by 10^2, data handling capability by 10^6, energy resources utilization 10^3, weapon power 10^6. Related to this exponential rate of technological change is the rate of obsolescence of *knowledge* which accompanies it. In some fields of activity one would now have to spend 15% of one's time doing nothing else but updating ones knowledge simply to stand still. – It is being suggested that if you could divide knowledge into its quartiles of *outdatedness,* all those over the age of 45 would be in the same quartile as Pythagoras and Archimedes. – Yet there are no sympathetic mechanisms in our society whereby all those experienced workers will have an opportunity to develop new skills and capabilities. This is particularly true in the field of Computer Aided Design (CAD).

Thus technological change can be viewed as a means by which the organic composition of capital is changed. That is to say processes are rendered *capital intensive* rather the *labour intensive.* Human energy and intelligence is replaced by machines. This is done by getting a worker, whether by hand or by brain, to go through a labour process and to objectivize that knowledge into control tapes. This means that the knowledge which previously existed in the consciousness of the worker (which was his or her bargaining power) has now been objectivized into the machine (either as software or as a control tape) and now confronts the worker as an alien and opposite force.

The *capital intensive* nature of technological development over the past 200 years may be judged from Fig. 1. It will be seen that initially about 86% of the population worked in Agriculture, this was subjected to mechanization, use of chemicals and automation. It now means that about 4% of the population can produce an agricultural produce, many times greater

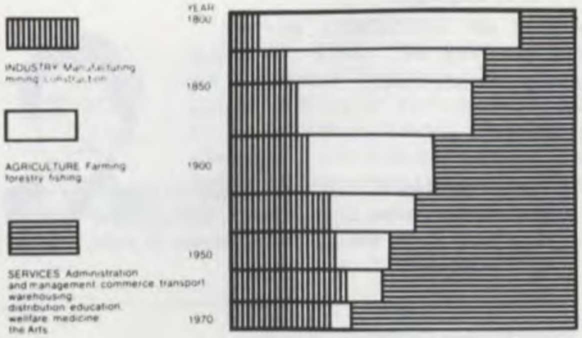

Fig. 1. The Changing Structure of Employment in the USA.

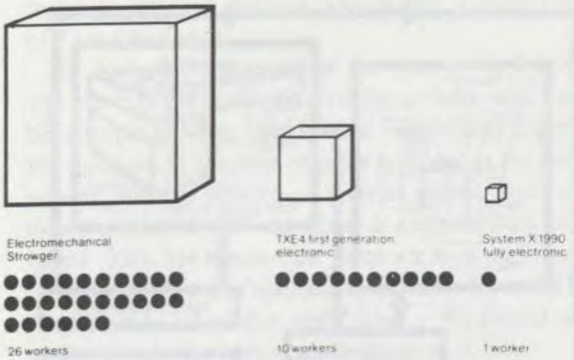

Fig. 2. The Relative Sizes and Labour Ratios Needed to Make Telephone Exchanges.

than that at the beginning of the 1800's. In the meantime, some of those displaced were going into fields such as Manufacturing. However, the increases in productivity that were made possible by new automated and computer-based systems has been such that the numbers employed in those industries have been declining since the beginning of the 1970's.

In the meantime, the administrative, technical and design areas were growing, the so-called *white collar* areas. Gradually they are also being subjected to massive technological change, so much so that the Guardian could say with respect to the field of clerical work "one man and his machine equals 500 typists".

2. Technological Change and Employment

If we look at Fig. 2, we see the change that is taking place in, for example, the manufacture of telephone exchanges. By 1990, four percent of the initial labour force will be able to produce an equivalent switching power (that is, in about eight or ten years time). In addition, by 1990 the skilled diagnostic maintenance work will have been replaced, since the new systems will have *self*-diagnostic routines.

In the field of CAD work, similar changes in human-power requirements are predicted. Generally speaking one can look towards a figure of one CAD operator replacing between four and 11 draftspeople and designers, depending on the given activity. It is to be predicted that this will result in the sort of development that we see in Fig. 3. The cyclical basis of our employment continues to go up. The basis of unemployment rises and the number of jobs vacant remains fairly static or goes down. This has meant that there are now predictions in the UK that there may be 4 million people out of work by *1985.*

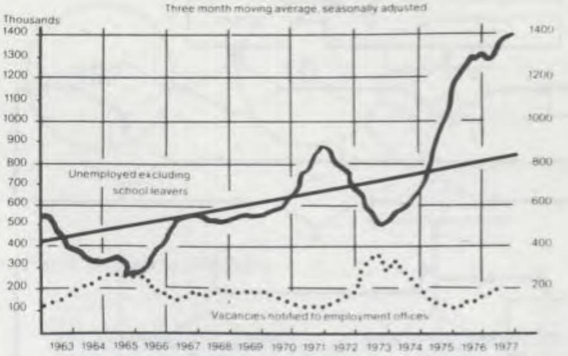

Fig. 3. Vacancies and Unemployment in Great Britain, 1963–1977.

Even in that most optimistic of the technologically advanced nations, West Germany, it is now predicted that there may be as many as 4.2 million people out of work in between five and eight years time. There is an EEC Commission Report which suggests there could be as many as 20 million people out of work by 1990. Whilst this cannot be directly related to technological change, it is none-the-less the case that *technological change* represents a *major* aspect of this displacement of human beings. If we look at the cost of unemployment to the Nation state we see in Fig. 4 that the total of the transfer payments to the unemployed persons and the loss of revenues to the Nation state levels out at an approximate total of 90%. One has to add to this the social cost, the drugtaking, the neuroses, the interpersonal violence, and illness directly related to unemployment (which has been quantified by Dr. Brenner in the United States).

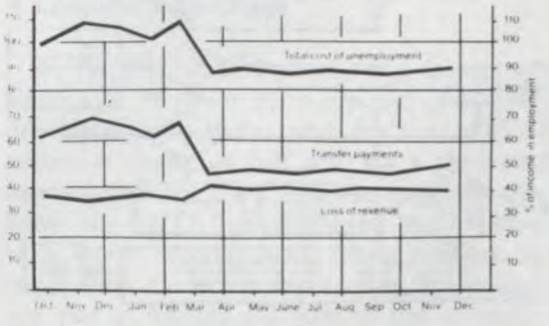

Fig. 4. Unemployment Costs.

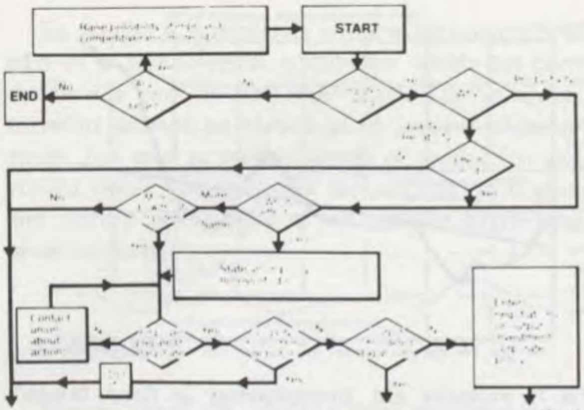

Fig. 5. Trade Union Response to Technological Change (Part 1 of 2).

When we do this we begin to see that the micro-efficiency of large multinational corporations in introducing computer-based systems may mean an efficiency for them, but could well mean an inefficiency for the Nation state as a whole when viewed at a macro level. The Trade Union response to this situation up to now has been as given in Fig. 5 and Fig. 6. This is now rapidly changing with trade unions advocating technology agreements which provide not merely that nobody will be "sacked" but that an establishment of workers will be maintained. This means that if productivity dramatically outstrips production, which it inevitably will, that there should be the possibility of a shorter working week, longer holidays and more leasure time.

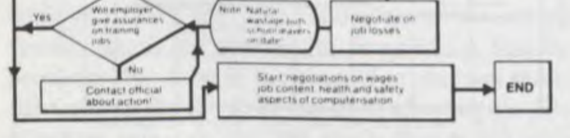

Fig. 6. Trade Union Response to Technological Change (Part 2 of 2).

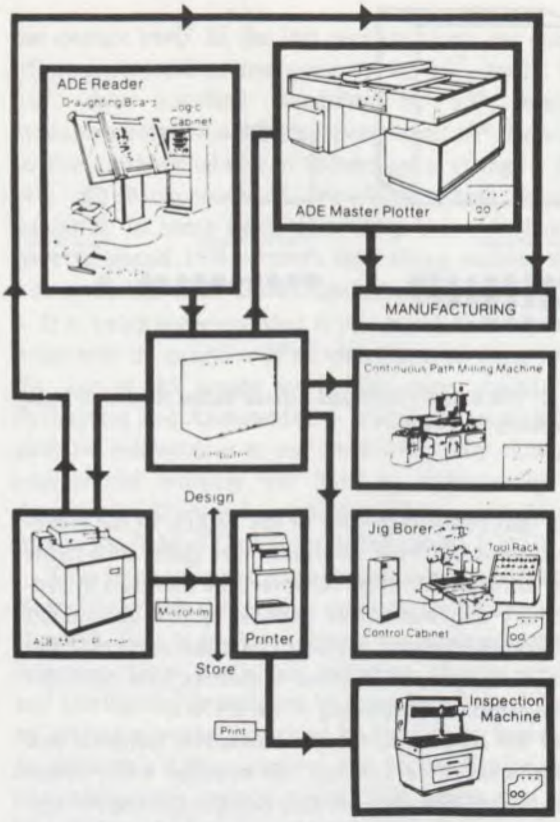

Fig. 7. The ADE System for Engineering Data Processing.

The tendency up to now has been to perceive this situation as one in which there is a problem for those who are displaced, but that at least those who remain are the lucky ones. If we look at Fig. 7 we see a development that will be increasingly common. The draftsperson no longer produces a drawing. This means that the conceptualization, which used to take place as the skilled workers analysed the drawings to decide upon the means of manufacture, is now eliminated and the worker on the shopfloor is confronted with a NC tape. This means that some of the most highly skilled and creative work on the shop floor is permanently eliminated – that of tool making, jig boring, turning, universal milling, even inspection. Some industrial sociologists assure us that when this happens the worker will be elevated to a sort of "manager" where the computer would act as an "integrator" and give them a *panoramic view* of the labour process. In fact the reverse is the case. In a recent issue of the American Machinist it was pointed out that in some NC processes the *ideal* workers are mentally retarded workers; specifically, a mental age of *12* is mentioned.

If, however, we examine the system further we will see that gradually the drawing activity will itself be eliminated. The draftsperson will either digitize the data, or, in the case of some systems, as the component shape is defined on a visual display unit, the data bank for the NC machines is automatically produced. This has meant that there are now some predictions that the draftsperson as we know them will be eliminated in about five years time. – We should not underestimate the historical significance of this.

3. Looking Ahead

Since human beings first drew on cave walls, drawing has been a profoundly *important* part of the cognitive processes by which we *conceptualize* a shape, nature and form of artifacts. It is by no means clear where the *next generation* of skills and designers are going to come from, or who will carry on that *tradition.* In eliminating these human skills, we fail to understand some of the most precious assets any society has: the skill, ingenuity and creativity of its ordinary people. We are so obsessed with *machine-based* systems that we are failing to understand and adequately appreciate the enormous *intelligence* of human beings.

We have been so conditioned by modern science and technology that we no longer even realize that we are treating human beings in this way. In the field of manual work my colleagues and I were recently asked to consider the design of a system which would protect drivers from the hazards of North Sea Oil pipeline maintenance work. Our immediate response was to think of a robotic device which would eliminate the human beings from the process altogether. In fact, the more you think about modern science and technology, the more you will realize that one of its main functions is to eliminate *human* energy and intelligence. So, we thought of a *robotic* device, but when we began to consider the complexity of programming of such a robotic device to recognize which way a hexagon nut was about, much less when it has a barnacle on it we began to realise how *incredibly intelligent* human beings are. They will know exactly what size spanners to select; what torque can be applied, and in applying the torque, they are drawing on those vast bands of tacit knowledge which the philosopher of science Polanyi used to talk about.

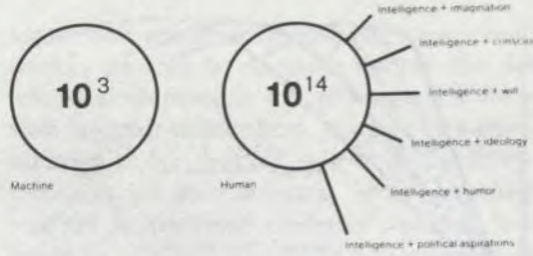

Fig. 8. Human vs. Machine.

If we think for example of a footballplayer intercepting a football in flight, we get some idea of the massive computational powers of a human being that is simple in some fields of sport. If one looks at a highly skilled fitter or toolmaker at work, or raise that to a higher level and view the enormous skills of a designer, we get some measure of the incredible "information processing" capabilities of *human beings.* Indeed if one regards information processing in its totality rather than narrow number crunching, the comparison between a human being and a machine would be then given in Fig. 8. It will, however, be seen that the human being brings together not only vast computational power but also imagination, conscientiousness, will, ideology, humour and political aspirations. These are precisely the so-called *unpredictabilities* that employers seek to eliminate, or as some employers would put it in the United Kingdom, sheer bloody-mindedness. So there is a conscious effort to eliminate human beings from these labour processes.

For those who think that this is an exaggerated view, there are the typical headlines in the engineering press, one of which said recently *"people are trouble, but machnines obey".* Another one pointed out *"robots don't strike".*

4. Computer Aided Design

In the field of CAD there was a famous advert which said "if you've got a guy who could produce drawings non-stop all day, never gets tired or ill, never strikes, is happy on half pay, has a photographic memory, then you don't need systems X". We now all know why CAD is being introduced. It is not because of a shorter working week, longer holidays, more leisure time, nor is it to free us from the boring routine part of drafting and leave us free to engage in more creative work. The reality is spelled out in such

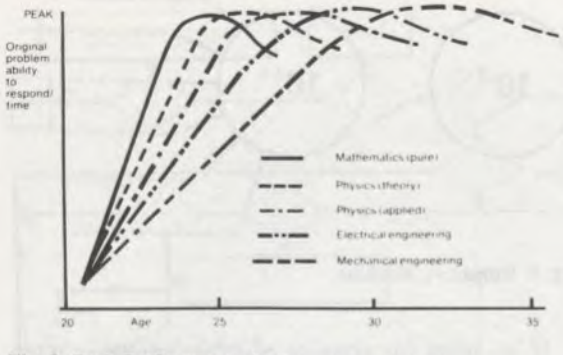

Fig. 9. Peak Performance Ages.

adverts. I have described in my book *"Architect or Bee?"* the manner in which deskilling techniques are spreading right through the spectrum of intellectual work. Engulfing, on the one hand, that of detailed draftsmen as shown above, but spreading right through the spectrum where some of the most artistic and creative aspects of design, such as architecture, are being eliminated by some of these systems.

The extent of this is such that recently there have been suggestions that Universities should be based on factory models. The students are referred to as *commodities*; examinations, as *quality control procedures*; and graduation, as *delivery*. The University Professors are referred to as *operators*. They provide a computer-based model to actually measure the *performance* of the University Professor. This growing tendency is now beginning to be applied in many fields where computers are based and they work out the *peak performance ages* for different groups of workers interacting *with* the computer based systems. See Fig. 9 and Fig. 10.

They can do this because the human being may be viewed as *the dialectical opposite of the machine.* The human being is slow, inconsistent, unreliable, and highly creative, whereas the machine is the dialectical opposite. It is fast consistent, reliable and totally non-creative. It used to be the idea that when you link these two dialectical opposites together, you would have a new whole: a perfect human-machine symbiosis. In fact, as the human being tries to keep abreast of the machine, the stress is truly enormous.

Reports by Bernholtz in Canada suggest that the creativity of the designer is *reduced* by 30% in the first hour; by 80%, in the second hour; and that the designer thereafter is shattered as a result of the rate of this interaction. We should certainly not be surprised that this sort of thing is happening. Robert Boguslaw warned us that it would be done quite some time ago when he spoke about the "operating unit" approach to Systems Design. *"If this provides us with sufficient handles on human materials such that we can think of them as we can think of metal parts, electrical power, or chemical reactions then we have succeeded in placing human material on the same footing as any other material and can begin to proceed with our problems of systems design. There are, however, many disadvantages in the use of these human operating units, they are somewhat fragile, they are subject to fatigue, obsolescence and even death. They frequently are stupid, unreliable and limited in memory capacity. But beyond all this they sometimes seek to design their own circuitry, that in a material is unforgivable. Any system utilizing them must devise appropriate safeguards".*

Fig. 10. Task Response Time and Age Groups.

So in other words, that which is most precious about the human being *the ability to design their own circuitry*, or, *to think for themselves* is now said to be an attribute that should be suppressed by the equipment. Precisely that sort of thing is happening in the field of CAD with the insistence upon optimized subroutines. Concerns about these developments are now widespread and international. Even the biggest union in West Germany, I.G. Metall, recently had on the front page of its Journal "Fliessband im Büro" pointing our that the production line is now flowing into offices. In Australia, Bill Richardson (the General-Secretary of the Federation that covers all white collar unions in that country) stated recently that the computer-based new technologies have three main characteristics: (1) They displace labour, (2) they deskill and degrade jobs that remain, and (3) they increase managerial control.

This *increased managerial control* of the system means that we are no longer able "to design our own circuitry". We are being reduced to perform with a bee-like behaviour. Yet, it is precisely our ability to use our imagination which distinguishes us from "animal forms". "A bee puts the shame on many an architect in the construction of its cells. What distinguishes the worst of architects from the best of bees is namely this: The architect will construct in his imagination that which will ultimately be erected in reality. At the end of every labour process we get the results that already existed in the consciousness of the labourer before the onset of the labour process itself."

People seem to believe that imagination is only significant in the fields of, let us say, literature, music or fine arts. If we look back at the great scientists, technologists and engineers, they all displayed, on the one hand, a sort of child-like *curiosity,* and on the other hand, a vivid *imagination.* Thus the great Newton once said: *"I seem to have been only like a boy playing on the seashore and diverting myself now and then finding a smoother pebble or a prettier stone than ordinary".* Or the great Einstein who said: *"Imagination is infinitely more important than knowledge".* And on another occasion said: *"The mere formulation of a problem is far more important than its solution, which is merely a matter of mathematical or experimental skill. To raise new questions look at new possibilities and regard old problems from a new angle requires creative imagination and marks the real advances in science".*

In coming years we shall see more and more women working in industries of various kinds. Yet, as we look at the adverts in computer journals, they usually show a young "dolly bird"-type of woman leaning suggestively over the equipment. The idea being that they are merely playthings or decorations that you have around the place to sell the equipment. In point of fact, it would be an enormous philosophical and scientific contribution if more women were to come into science and technology, not as imitation men or as honorary males, but to challenge the predominantly male *values* which dominate science and technology, particularly computer science. Our science reflects, predominantly the value system of the white male capitalist warrior hero. It would be a great contribution if the so-called logic and objectivity and rationality of that industry, which are normally regarded as the "male attributes", were to be challenged by *women* – who would emphasize the importance of the *subjective,* the *imaginative,* and the *analogical* rather than the digital, and, in that way, begin to move science in the direction which will be far more socially relevant, humane and caring.

5. In Short

Science and technology is not *given*, it is not like the sun or the moon or the stars. And, if it is not doing just what we want it to do, we have a right and a *responsibility* to change it. Increasingly, we will be required to change ourselves to future technologies. There is a famous advert in Britain which shows a woman suffering from what technology has done to her. She is suffering from "highrise blues", and the advert says very subtly: "She cannot change her environment". I ask, "why not?", and it goes on to say "but you can change her mood with . . . (a tranquilizer). In my view, it is not pills and tranquilizers we need, to deal with the enormous social problems we now see all about us, but a clear view of what we want from science and technology and the courage to stand up and do something about it. Above all, we should realise that the future was not out there in the Centre of America before Columbus went out to discover it. The future does not have predetermined shapes and forms. It has got to be built be people like you and I, and we do have *real* choices. And when we choose, we should never forget as *designers* (whether we are designing CAD or any other kind of system that as we design machines we are in fact designing *social relationships.* We should never allow ourselves to be so fascinated by the *technology* that we forget what it is all about which is after all, *human beings.*

The IGES standard addresses CAD/CAM data-exchange problems the industry faces today. End users as well as developers will be responsible for its success or failure.

Intersystem Data Transfer via IGES

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Within the CAD/CAM community, the constant growth of individual application programs has been balanced by a general call for methods with which to interface applications and share data among design, analysis, and fabrication processes. Interfaces depend on a standard for digital representation of a product; they are a first step toward the real goal, integration. Numerous standards bodies have attempted to provide flexible, yet stable, methods with which to represent products. In many instances, however, these methods are oriented toward the CAD/CAM systems of the future rather than currently operated and marketed products. The result has been an inability to integrate on a significant scale without major rewrite or total replacement of the systems to be integrated.

The Initial Graphics Exchange Specification—IGES—was conceived and implemented for application *now*. It is specifically targeted at the current generation of turnkey interactive graphics systems used to define the geometry of a part. It has received widespread attention as a solution to the problem of exchanging part models.

The purpose of this article is to review the issues involved in exchanging data through IGES and to describe the user's responsibilities, which, if carried out, will ensure IGES implementations commensurate with the community's expectations.

Product definition components

Before considering the exchange of CAD/CAM data, it is first necessary to establish what the data consists of. Three fundamental components of product data—format, representation, and meaning—are described below in order to identify the issues that IGES must resolve.

Format. The huge number of software/hardware systems available is matched by an equal diversity in bit representations for floating-point, integer, and character definitions. This variety of methods manifests itself in the definition of numeric and character-set standards and in the establishment of the basic accuracy of the model. The numeric issues are widely recognized. The character issues of format, which consist of the character set and the mapping of characters to graphics symbols, are more subtle. Graphics applications commonly use the ASCII set as a base and then modify it to provide mappings for the variety of symbols required by the application. This results in a significant problem in both the numerics and the characters from which the basic elements of the product are composed.

Additional difficulty in sharing CAD/CAM data is due to the inability to determine how good the data is. In processing a product definition downstream from the gen-

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erating application, one must be aware of the basic computing accuracy achievable on the generating hardware, and the accuracy sought by the user.

Representation. There are several distinct methods with which to represent the geometry of a part. One is the *edge boundary*, or wireframe, in which the extremes of the part are represented by a collection of space curves. Another is *surface representation,* which allows a more precise definition of the geometry, particularly for locations not on an edge boundary. This method can be difficult to display in graphics. A commonly used hybrid implementation is the *edge-surface representation*. In this method, the principal geometry is defined as a wireframe; surfaces can be developed between edges to provide additional detail.

The representation component provides the specific collection of parameters that make up each data element. This component represents a geometric line by its end points versus its equation and a pair of start and end parameters. Representation does not include the intended use of the line, but (given a numbering scheme, accuracy bounds, and a set of element representations) the representation component makes possible the exchange of a definition between applications, making the definition available for human interpretation. For example, the product definition for a drawing developed in an on-line graphics application can be transferred to a background plotting application.

Meaning. The meaning component expresses the design intent of the data by associating the object representation with the real-world product. Meaning addresses both individual data elements and collections of elements. It is the most complex of the data components and exhibits the least commonality in specific method. In many instances, the meaning of the data is imparted only by the application that uses it. A simple example is a flat panel (Figure 1) composed of straight lines. The design intent is for lines A1-A4 to define the exterior panel edges and lines B1-B4 to define the edges of an interior cutout. The data representation (Figure 2) hints at the intended meaning, but the ultimate assignment is made by the end user.

Additional information can be placed within the product description to support meaning. Generally, this additional information falls into two categories: properties associated with data items, and relationships between data items in a single model. A structure such as that in Figure 3 provides for the intended meaning of the product definition by means of relationships between data elements and the assignment of properties.

IGES methodology and components

Processing functions. Figure 4 depicts the basic IGES methodology for communication between systems. Data from the native format data base of system A is preprocessed into the IGES format. Following communication to system B, the IGES-formatted data is postprocessed into the native format of that data base. IGES is not a copy of any specific native system; thus, it utilizes formatting, representation, and meaning methodologies, each requiring specific processing. In preprocessing for representation, there is not always a one-to-one mapping of the native element to the IGES element. The preprocessor

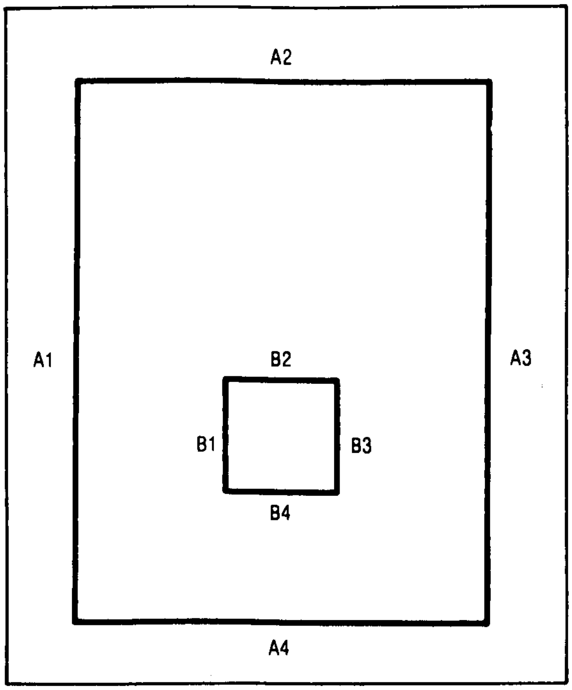

Figure 1. Panel geometry.

```
LINE, A1, 0.0, 0.0, 0.0, 4.0
LINE, A2, 0.0, 4.0, 3.0, 4.0
LINE, A3, 3.0, 4.0, 3.0, 0.0
LINE, A4, 3.0, 0.0, 0.0, 0.0
LINE, B1, 1.0, 1.0, 1.0, 2.0
LINE, B2, 1.0, 2.0, 2.0, 2.0
LINE, B3, 2.0, 2.0, 2.0, 1.0
LINE, B4, 2.0, 1.0, 1.0, 1.0
```

Figure 2. Simple entity definitions.

```
ASSOC, X1, A1, A2, A3, A4
DESCRIBE, X1, *PANEL PERIPHERY*
ASSOC, X2, B1, B2, B3, B4
DESCRIBE, X2, *PANEL CUTOUT*
LINE, A1, 0.0, 0.0, 0.0, 4.0
LINE, A2, 0.0, 4.0, 3.0, 4.0
LINE, A3, 3.0, 4.0, 3.0, 0.0
LINE, A4, 3.0, 0.0, 0.0, 0.0
LINE, B1, 1.0, 1.0, 1.0, 2.0
LINE, B2, 1.0, 2.0, 2.0, 2.0
LINE, B3, 2.0, 2.0, 2.0, 1.0
LINE, B4, 2.0, 1.0, 1.0, 1.0
```

Figure 3. Structured entity definitions with meaning components.

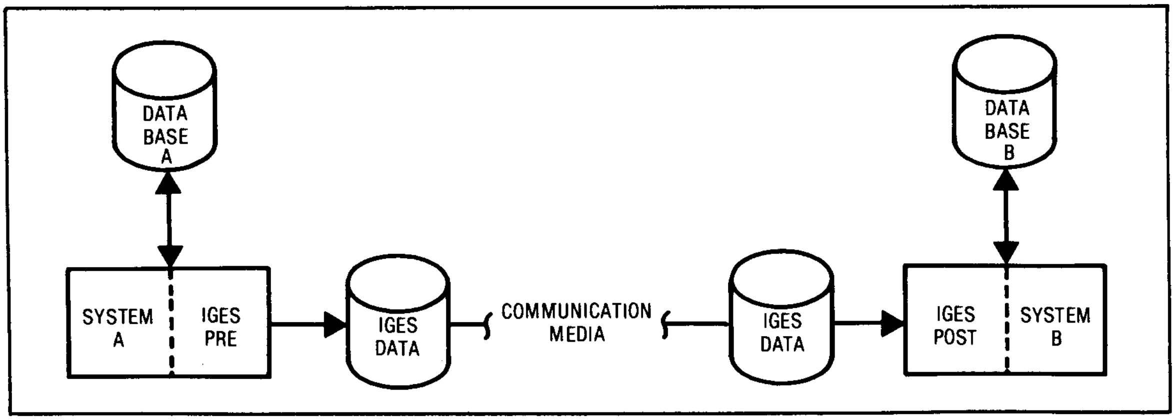

Figure 4. IGES system methodology.

must decide to choose a null mapping (drop the element), a one-to-one conversion, or a one-to-many conversion in which a single native entity is represented by a set of IGES elements.

Postprocessing for representation requires a similar set of decisions. The incoming IGES element might be dropped (null mapping), a one-to-one conversion might be employed, or a set of IGES elements might be converted to a single native element (many-to-one). The last mapping can be enhanced if the preprocessor uses a relational mechanism to note that a one-to-many conversion was employed.

The functions of the pre- and postprocessors are, therefore, the selection of the appropriate entity mapping and the actual conversion. Attention is commonly focused on potential difficulties in conversion, but the selection criteria for the entities to be processed and the mapping to be applied are more critical.

IGES file structure. The basic element in the IGES structure is the *entity*. The IGES structure consists of a data file in five segments: The *prolog* is a block of header data that provides any textual preface for the file. The *global* section provides a definition of the conditions in which the model was developed. These conditions include the numeric accuracy of the originating machine, the relationship between model space and real space, the units of measurement for model space, and a set of maximum/minimum ranges for which the destination system should allocate. The *directory* and *data* sections together comprise the actual entity representations. The directory contains an index of all the entities in the model and a set of attributes of each. The attributes consist of data items such as entity label, line font, views visible, levels visible, and a pointer to the location in the data section in which the actual entity definition is located. The *terminator* is an accounting tool for verifying the total number of records used in each of the other four sections.

IGES format. The format component is addressed in part by using an ASCII-coded 80-character/record file. In essence, the file is a simple card deck. This approach has the advantage of universal compatibility, but suffers from a significant expansion of data bulk due to character encoding of all numeric terms.

The potential problem of file size has received considerable attention during public review of the proposed standard. Clearly, a binary encoding technique would have reduced the volume of data, but at the sacrifice of format simplicity and flexibility; it would also have imposed a processing burden that might have been equivalent to dealing with character-encoded data. In a first implementation, the ASCII technique provides a better basis from which to address the efficiency issues through better communications, better data management, and more compact encoding.

The remaining format components are addressed through the allocation of integer constants, single-precision floating-point constants, double-precision floating-point constants, and character strings. IGES provides mechanisms for detailing the native system's binary word structures for integers and floating-point; this accounts for the theoretical accuracy of the data. Additional mechanisms allow the user to define the intended accuracy of the model. Character strings introduce the question of character mapping. Graphics applications often use the ASCII character set not to represent the characters themselves, but as a base mapped into the various additional symbols required for a particular application. This can be represented via a set of standard mappings contained within the standard or via a user-defined mapping that utilizes a character-font definition entity.

IGES representation. The representation components are addressed by the IGES entity set and entity attributes. The entity set is divided into four basic entity types: geometry, dimensioning and annotation, structure, and properties.

The geometric entities of IGES include the point, line, circle, conic, parametric spline (including linear, quadratic, and cubic forms), face, ruled surface, surface of revolution, and tabulated cylinder.

Additionally, the composite entity representation links multiple curves into a single item, and the copious data entity provides for dense arrays of points or line segments. In essence, both are alternative forms of other entities that associate or group components to impart a specific meaning. They do not constitute fundamentally

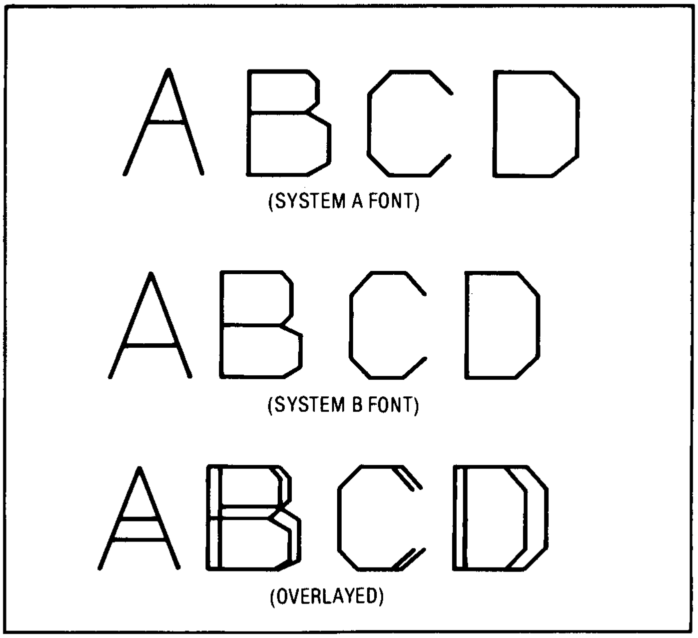

Figure 5. Text incompatibilities.

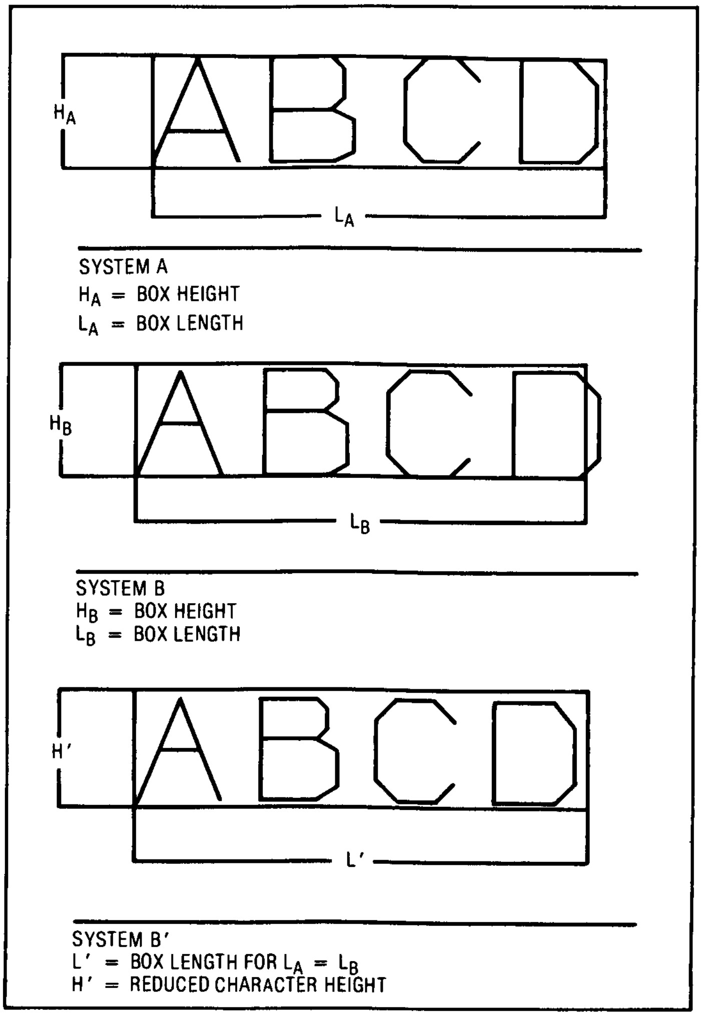

Figure 6. Text extremes definition.

unique units of geometry; thus, they can be selectively applied to reduce date volume or assign special significance.

IGES has three primary dimensioning and annotation entities: text, arrow, and witness line. They are the building blocks for most of the remaining dimensioning entities. A series of dimensioning entities is provided, each consisting of one or more of the building blocks. These dimensioning entities are angular dimension, diameter dimension, general label, linear dimension, ordinate dimension, radius dimension, and flag note. Several special dimensioning cases are defined: center line, point dimension, and section. While the dimension and annotation entities do not represent all the techniques of drawing generation, participating organizations agree that they do represent a major cross-section.

The problems of interfacing a set of wireframe, surface, and solid technology systems are significant. If one considers the individual geometric and dimensioning entities to be converted to/from a CAD/CAM system, a number of problems are evident. The most commonly discussed issue is the treatment of the spline. Even three- or four-member heterogeneous system architectures typically use six or eight spline algorithms. For a common set of input points and conditions, each yields a different curve. Each has a unique set of assumptions and limitations associated with its algorithms; for some potential pairings, there is no mathematics known to perform a direct conversion. The IGES spline captures a wide variety of the forms in use and allows approximations to be developed at the data source.

The topic of splines commonly overshadows that of drawing annotation and dimensioning. For many potential CAD/CAM users, however, the first goal is to achieve a digital representation equivalent to the manual drawing. The standards for annotation and dimensioning commonly consist of but a single criterion: legibility. Each organization within a given company might define and enforce a set of techniques and, in essence, maintain its own style. These styles manifest themselves in the methods of dimensioning and in more subtle areas, such as character sets, character fonts, and line fonts.

Figure 5 depicts the typical problem resulting from differing character fonts. Figure 6 depicts the general IGES solution, in which the issue of legibility is addressed by controlling the boundaries of the text. This method captures the content of the text, but not its precise appearance. A second alternative is provided by IGES, in which the generating and receiving systems share character definitions. The definition of each character is established by the specific appearance of the symbol geometry and a mapping to the ASCII set. Note that drawing/data set equivalence is maintained in Figure 6 but not in Figure 5. The user/implementor of the IGES translators is given the responsibility to choose the appropriate mode and the structure in which to represent that decision.

IGES meaning. The meaning component of product definition is addressed through appropriate utilization of the structuring and property mechanisms. In general, this involves assigning properties to individual entities or collecting entities into structures that highlight logical features of the product. Properties can also be added to such structures.

The structure entity set includes a number of methods for defining both specific relationships among collections of entities and the meaning of the relationships. The most important of these entities are the associativity, the view, and the drawing.

The associativity mechanism. The IGES associativity mechanism consists of an associativity definition entity and an associativity instance entity. These entities correspond, respectively, to the definition of the relationship to be formed and to a specific application of this relationship. The relationships that can be represented by the associativity mechanism consist of one or more lists of entities. Each list corresponds to a class in an associativity definition entity. For example, a simple group in which some number of entities are to be addressed as a single item is a one-class association. If, however, a second set of data, perhaps defining the model from which the first set originated, is to be related to the first, a second class of associativity is required.

There are difficulties to overcome where fundamentally different systems begin to share these types of data. . . . IGES cannot resolve all differences between systems.

Once the relationship has been defined by means of the associativity definition entity, one or more occurrences of the relationship can be represented by the associativity instance entity. This consists of a list of pointers to specific entities being related in any class or list.

An example of the use of an associativity mechanism is the specification of a tool path. A three-class associativity definition determines the structure of the tool path. One class points to a geometric description of the machine tool within the IGES file, a second points to the path to be followed by the center line of the tool, and a third points to the set of geometric entities representing the object to be machined by the tool path. Thus, the associativity points to three different objects: the machine tool, the tool path, and the part to be machined. Each object might consist of many entities.

The view entity. The view entity provides a theoretical cube in which a model is placed. The cube can be rotated and its sides used to clip or limit the model. Additional criteria allow alteration of the display characteristics (line font, blank status, etc.) of individual entities in the view. To completely describe the desired view, there must be some control over how individual geometric entities are displayed in that view. For example, an edge that would be hidden in a real object can be shown on the display in exactly the same manner as other edges, shown as a dotted line, or blanked out completely. This presentation must be a function of the view itself; it cannot be a function of the model because the presentation changes from view to view.

The drawing. A collection of view entities can be collected into a drawing. The drawing entity allows a view or set of views to be placed on a theoretical drawing sheet. In combination, the view and drawing entities allow a 3-D wireframe or edge-surface model to be displayed in a 2-D medium without replicating the geometry of the model.

The IGES property. In addition to the standard set of entity attributes provided on the directory entry portion of each entity, IGES provides a general mechanism with which to define and specify attributes. The feature is called the IGES property. It consists of a unique name and an assigned value or set of values. Once defined, the property can be associated with the model elements that have that characteristic. Color, for example, is a property, and red is a value. The latter can be associated with red model elements. The same property name, "color," and a different value—blue, for example—might be associated with other model elements.

IGES provides the means to allocate user-defined properties (the sender and receiver must agree upon the property meaning and valid value) as well as standardized properties whose meaning and value set can be constrained by the standard. Clearly, widespread *ad hoc* use of properties will not guarantee full exchange of data, but it will form a basis from which the common property meanings and values can be derived and integrated into the standard.

Utilization of IGES

Developer and user responsibilities. The key to successful IGES implementation and use lies in developing a detailed understanding of the relationship between the product the end user perceives, the set of computing elements that represent the product, and the structuring mechanisms that represent the binding of computing elements into a single product definition. These issues require attention from both the application developer or vendor and the CAD engineer responsible for production implementation and operation.

Each implementor must consider the design intent behind the data to be exchanged. In the case of the spline, it might be possible to convert the parameterizations from system A to system B through IGES while retaining the degree of the spline polynomial, similar continuity conditions, and the exact shape of the curve. For other spline pairs, it will be necessary to perform a curve fit—perhaps to the level of substituting a linear spline or composite curve of line entities—and sacrifice selected functionality. The decision to curve fit might be made by either the sending system's preprocessor or the receiving system's postprocessor.

Similar issues exist throughout the annotation and dimensioning area. Text fonts, dimensioning data structures, and dimensioning methods vary widely. In general, it will be possible to represent these methods within IGES without significant loss of data content.

There are difficulties to overcome where fundamentally different systems begin to share these types of data. Specific solutions must be implemented by the vendor or corporate system when a curve form, a particular surface, or an individual dimensioning technique is not present in the system that uses IGES. Data standards such as IGES cannot resolve all differences between systems. The CAD/CAM community faces current application scenarios that demand a practical, near-term resolution of these problems. IGES significantly minimizes the set of such issues by limiting the number of interpretations and mappings that must be considered, thus making implementation of the applications far more practical.

The primary targets of a data standard are

(1) the consolidation of many "foreign" interfaces into a single one, and
(2) the reduction or elimination of the local-system interpretation of data.

Determining and quantifying such interpretations of data are among the most difficult tasks facing developers of corporate networks. Every system has a level of binding between its functions and its data base. In some instances, the data-base representation is complete for all required functions. In other cases, an individual function may key on peculiar data-base conditions to make significantly different use of data. A simple example can be drawn from an existing implementation. Two dash characters (--) in a text string will display as two dash characters when placed in one entity. These same two dash characters display as a subscript condition when placed in a different entity. These issues can readily be addressed by the IGES preprocessor, which provides an interface file in which the data accurately represents the function it had on the generating system and/or application.

The user community must recognize that local optimization of a CAD/CAM application environment will not allow the implementation of a CAD/CAM application network.

The data mappings for a specific application can be considered in terms of the concept of *application protocol*. This is the set of procedures and techniques used on a system to accomplish the design work necessary for a specific application. This concept makes explicit those features of a CAD/CAM system required in a single application and thus allows attention to be focused on them to the exclusion of extraneous features.

Clearly, if a given application can be accomplished on two different systems, there is a correspondence between the application protocols for that application on the two systems. If this application protocol can be precisely stated, a mapping can be defined to handle the translation.

The problem is the precise statement of the application protocol. The concept is new, and little work has been done toward a general understanding of application protocols. Still, it is attractive to contemplate a language capable of describing them. Such a language would permit the design of processors capable of automatically generating necessary mapping software.

The end user of turnkey systems has a parallel set of responsibilities. System developers are pressured to provide both more local functionality and more global integration. The end user wants to share data generated by turnkey graphics with analysis or fabrication applications resident in a corporate network, but resists constraints on his use of local data elements. Imposition of corporate or network data standards is often perceived as a lowest common denominator by the user, who finds himself denied a particular entity or construct of an individual system. A standard such as IGES represents the intersection of the representational techniques used by a set of applications and the union of meaning or design intent. The system developers will provide implementations of the data standard for compatible data items and for data defined by the users as having equivalent meaning.

The end user's responsibility is to provide definitions of the intended purpose of the data. Furthermore, he must apply the known constraints of system interfaces when developing data to be used in a heterogeneous application environment. In many instances, this will entail relatively simple adaptation of an alternate entity or entity form. In other cases, it will require specific local functionality to be traded off for more general data utilization. The user community must recognize that local optimization of a CAD/CAM application environment will not allow the implementation of a CAD/CAM application network. Successful implementations will be based on the functionality required both upstream and downstream of individual applications.

Homogeneous architecture. In considering CAD/CAM system design alternatives, the most commonly presented candidate is a homogeneous architecture. Several factors make this impractical. Larger companies typically distribute responsibility and authority for the development or acquisition of computing systems, generally along the same boundaries as the company's product organizations. Competition among vendors encourages the development of new or enhanced systems, which are often too attractive to ignore. These factors make it extremely difficult to maintain a homogeneous environment. Contractor relationships impose the same difficulties as those found within a single company, but with less chance of initial system commonality. A subcontractor could be given a compatible system, but liability for system use and maintenance is complex. The subcontractor might simply be unwilling to assume a second system due to the investment and confidence in his own. These factors make the heterogeneous environment a natural and unavoidable part of the CAD/CAM industry.

Realistic benefits. In the short term, the benefits of IGES must be addressed with respect to the size and resources of the individual CAD/CAM shop. IGES is a data standard, not a product in itself. As such, it requires the pre- and postprocessors to form a product. These processors, along with their individual mapping schemes, user interfaces, operating constraints, and performance characteristics, are what the user will see. The degree to which an individual shop can adapt to these processors or impact their implementation will determine the degree of benefit achieved.

Small applications. The small, one-system shop with a relatively small number of system users and few locally developed applications is unlikely to expend the resources or contract dollars to tailor an IGES facility to its use. On the other hand, adaptation might be relatively easy for the small-use community. It will be possible to make immediate use of an off-the-shelf IGES interface with which to exchange data with customers and associated contractors. The available entity set might not encompass all the local candidates, but it should be useful in a majority of cases and certainly will provide capability beyond that which could be developed locally.

Large applications. The corporate CAD/CAM shop with a large number and wide diversity of users as well as many in-house applications faces a different problem. This environment typically reflects a high degree of local optimization in which individual applications have been developed and tailored to a specific group and task. These applications require highly specialized user interfaces and data/product relationships. In many instances, innovative users stretch turnkey graphics systems to the limits of their capability. For this community, the early IGES implementations might appear elementary and inadequate; user resistance could be a problem. However, these same users will have previously encountered and perhaps attempted to deal with the problems of exchanging data within company organizations. Even the elementary IGES implementation will provide immediate and useful capability to begin resolving such issues of heterogeneous application. It will give management immediate alternatives for selective application of data standards in areas of greatest return. In-house development and contracted vendor enhancements could address specific user interfaces, additional entity mappings, and complex data/product relationships.

For some, the early implementations of IGES might appear elementary and inadequate; user resistance could be a problem.

Clearly, no data standard is an ultimate solution to the full scope of CAD/CAM data-interface problems the community currently faces. A standard is a tool that can contribute to a solution when applied to appropriate tasks. It can support a variety of disciplines, but is inadequate for some.

IGES Version 1.0 is specifically oriented to mechanical applications. Within the mechanical area, it is most suited to wireframe geometry and drawing applications. More complex mechanical applications—those with specialized use of low-level native data elements—will be more difficult to implement, but are achievable. IGES provides a practical medium with which to satisfy the functional needs of a broad spectrum of applications.

The functional benefits of implementing IGES are paralleled by a second set of benefits, which must not be undervalued. As the standard's title makes clear, this is an *initial* attempt at providing a standard of this type. IGES embodies the experience and proven technology of several corporate networks. Implementation, review, and enhancement by the industry as a whole will provide the experience necessary to pursue a second-generation standard. Attempting to enhance the standard without a wide base of implementations will not lead to a better standard, but only perpetuate the current void in interface experience. This would force individual companies to continue to pursue costly local implementations, which are both redundant and divergent from an industry-wide perspective. IGES is a baseline from which we can derive immediate and continuing functional benefit while gaining the practical knowledge needed for more advanced efforts. ■

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Kennicott has written or coauthored twenty technical papers and articles. He is a member of the Association for Computing Machinery and is a fellow of the American Association for the Advancement of Science. He received the BSc in chemistry from the University of Utah in 1953 and the PhD in chemistry and physics from the California Institute of Technology in 1962.

What's New in Control Standards

The efforts of the professional and trade organizations of USA to promote standards have received fresh impetus with the official adoption of OMB Circular A119, as noted by ANSI. Its policy guidelines will be implemented by the Secretary of Commerce. Earlier developments here and abroad have been mentioned in periodic reviews in Control Engineering of Sept. '79 and '78, May '77, Oct. '74, Sept. '73, June '72, '71, and '70, Nov. '71, Apr. '69, May '68, July '67, Oct. '66, Aug. '65, June '64, and Oct. '61.

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In 1978 the Federal Trade Commission sought the power to regulate the voluntary standards and certification process. However, the proposal was opposed by testimony of ANSI and others before a Congressional Assessment Board. The FTC rule-making procedure was specifically terminated by the FTC Appropriations Bill signed on May 28, 1980.

In January 1980 a national policy of cooperation between federal agencies and voluntary standards bodies in the private sector was established by Circular A119 issued by the U.S. Office of Management and Budget. The Circular calls for heads of federal government agencies to authorize active participation by their employees in the work of private sector organizations that plan, develop, produce, and coordinate voluntary standards. To secure federal participation, an organization must meet the basic criteria provided in the Circular's policy guidelines, must request listing by the Department of Commerce, and must provide DoC with evidence of compliance. The list will be published in the Federal Register, and a group may be challenged for noncompliance. The Secretary of Commerce is required to establish a voluntary service for resolution of disputes, and a central public register with a consolidated cross-referenced subject index. Agencies are encouraged to adopt voluntary standards for procurement purposes, but are not restricted to those developed under the Circular's criteria.

The recommendations of an ANSI-sponsored Study Group for the Implementation of a National Policy of Standards were published in April 1980. They cover the planning of voluntary standards development, the mechanisms for public review and recognition of consensus, and the three approaches currently used by ANSI—the Standards Committee Method, the Canvass Method, and the Accredited Organization Method. An evolution of ISO and IEC coordination is recommended.

American National Standards which have recently been developed by various accredited organizations and accepted by ANSI's Board of Review are listed under the organization name. Those developed by ANSI committees are noted here:

B551M-1979 Preferred SI units for machine tools;
B93.35-1979 Cavities for fluid power exclusion devices;
B93.5-1979 Practice for use of fire-resistant fluids for hydraulic fluid power;
B93.48-1979 Test for tube fittings for pneumatic fluid power applications;
B95.1-1977 Terminology for pressure relief devices;
C37.11-1979 Requirements for electrical control for high voltage circuit breakers;
C63.2-1979 Radio noise electromagnetic compatibility of electronic systems;
MC85.1 Terminology for automatic control—In press, 1980 revision;
PH7.15-1979 Audio recorded magnetically striped information cards;
N544-1968, R1979 Signal Connectors for Nuclear Instruments;
S1.30-1979 Guidelines for Sound Power Standards and Noise Test Codes;
X3.62-1979—Paper for Optical Character Recognition Systems;
X3.64-1979 Additional Controls for use with ASCII;
X3.66-1979 Advanced Data Communication Control Procedures (ADCCP)—Defines means for exchanging data between business machines, computers, connections and terminals over communication circuits.

ANS
American Nuclear Society
555 N. Kensington,
LaGrange Park, IL 60525

ANS 4.5 Functional Requirements for Accident Monitoring in Nuclear Power Plant Generating Stations is a 1980 draft for which ANS and BSR/ANSI have requested comments. Other documents recently approved by ANSI include:

ANS2.10-1979 Retrieval, Review, Processing and Evaluation of Records Obtained from Seismic Instrumentation, Guidelines for
ANS 3.5-1979 Nuclear Power Plant Simulators for Operator Training (being revised)
ANS 6.5 DRAFT STANDARD Glossary of Terms used in Radiation Shielding and Dosimetry
ANS 55.1-1979 Solid Reactive Waste Processsing Systems for Light Water Reactors
ANS 55.6-1979 Liquid Reactive Waste Processing Systems for Light Water Reactors
ANS 55.4-1979 Gaseous Radioactive Waste Processing Systems for Light Water Reactor Plants: Minimum design, construction, and performance requirements
ANS 58.4-1979 Criteria for Technical Specifications for Nuclear Power Stations
ANS 56.6-1979 Ventilation Systems for Pressurized Water Reactor Containment
ANS 3.7.2-1979 Emergency Control Centers for Nuclear Power Plants

DIN
Deutsches Institut für Normung
Burggrafenstr. 4-7 D1000 Berlin 30,
Federal Republic of Germany

Among the standards recently issued:

*DIN 19221, April 1980 Letter symbols in automatic control science and technology
*DIN 19225, Feb. 1980 Terminology and classification of controllers
*DIN 19237, Sept. 1978 Control engineering vocabulary
*DIN 66201, April 1979 Process computing systems—Terms
*DIN/IEC 65B-18 Sept. 1978 Methods of evaluating performance of transmitters for use in industrial process control systems

DIN holds the Secretatiat for ISO/TC 172 Optics, Guidelines published (Beuth Verlag GmbH) for VDI/VDE Gesellschaft Messund Regelungstechnik recently:

*VDI/VDE 3554, Mar. 1980 Functional description of operating systems for process computer systems
*VDI/VDE 3558, Apr. 1980 Design of

process computer systems with redundancy for increased availability of an automated process

*VDI/VDE 3559, Feb. 1980 Extent of documentation on hardware and software for process computer systems

ASME

American Society of Mechanical Engineers
345 East 47th Street,
New York, NY 10017

Comment has been requested on the 1980 reconfirmation of BSR/ASME PTC 19.3-1974 Temperature Measurement for Performance Test Codes; also on BSR/ASME B89.6.2-1973 Temperature and Humidity Environments for Dimensional Measurement. Other documents recently approved by ANSI include:

MFC-1M-1979 Glossary of Terms used in Measurement of Fluid Flow in Pipes

At the Emerging Technology Conferences which featured ASME's Centennial, the new Computer Division discussed CAD/CAM, software for CNC, and a code PEPSE which optimizes the controllable parameters of a steam power plant.

EIA

Electronic Industries Association
2001 I Street, N.W.
Washington, DC 20006

Documents recently approved by ANSI include:

RS-440-1979 Fiber Optics Connector Terminology

RS-455-1979 Fiber Optics Test Procedures

The USA/DoD Std-1678 covers Test Methods and Instrumentation for Fiber Optics. Proposed standard sizes for cables (inner conductor/outer sheathing) are 50/125, 100/140, and 200/240 microns. Size 50/125 is favored by the International Telegraph and Telephone Consultative Committee of Geneva.

IAP

Instituto Argentino del Petroleo
Maipu 645, 3er Piso, Buenos Aires

Current activity in the field of automatic control is concerned with:

Terminology-Publication in 1980 of a revised and expanded ANSI/MC 85.1-1963 in Spanish.

Electrical Symbols—Issuance of a local norm on Graphic Symbols based on IEC 117 and IRAM-IAP antecedents with comparison of related DIN standards.

Technical Specifications—Issuance of Tech. Spec. sheets with examples, based on ISA practice

Intrinsic Safety—Preparation of recommendations based on documents of Canadian EC, CSA, NFPA, and IEC

IEEE

Institute of Electrical and Electronic Engineers
345 East 47th Street,
New York, NY 10017

The following IEEE documents, already approved by ANSI, are being processed as IEC standards on the recommendation of USNC for IEC:

*IEEE 595-1976 Serial Highway Interface System for CAMAC (IEC Publ. 640)

*IEEE 675-1978 Multiple Controllers in a CAMAC Crate (DOE/EV 0007, EUR 6500e)

*IEEE 683-1976 Block Transfers in CAMAC Systems, Recommended Practice for

*IEEE 726-1979 Real-Time BASIC for CAMAC (ERDA TID 26619 and ESONE/RTB)

*IEEE 758-1979 Subroutines for CAMAC

*IEEE 583A-1979 Supplement to CAMAC Standards and Reports (DOE/EV 0009)

The IEEE Computer Society has printed a Dictionary of Computer Terminology, published a draft of Software Quality Assurance Plan, is working with ANSI X3 on P770-PASCAL. Its microprocessor-related draft standards include 694 Instruction Set Mnemonics, 695 Relocatable Code Formats, 696 S-100 Bus, 796 Multibus, 698 Guide for Interfacing Microprocessors and Peripheral Devices, 754 Floating Point Arithmetic, 755 High Level Languages Extensions

IEC

International Electrotechnical Commission
1, rue de Varembe,
1211 Geneva, Switzerland

TC 65 Industrial-Process Measurement and Control chaired by H. Sartorius (Germany) with the Secretariat held by J. Durand (France) has a Working Group 1 Terminology whose chairman is R. Temple (Foxboro). Meeting in October 1979, WG1 made some progress toward terms and definitions describing the characteristics of and operating conditions for hardware and software of the chemical, petrochemical, power generation, food, textile, paper, metallurgical, and air conditioning industries.

Two 1979 publications of TC65 cover Operating Conditions for Industrial-Process Measurement and Control Equipment: 654-1 Temperature, Humidity, and Barometric Pressure; 654-2 Power. Drafts are in hand for Part 3, Mechanical Influences, and Part 4, Chemical and Biological Influences. Publication 584-1 Thermocouples—Reference tables has been issued and 584-2 Thermocouples—Tolerance is in draft form. Drafts have also been prepared for the Process Data Highway (PROWAY) for Distributed Process Control Systems: Part 1 General, Part 2 Functional Requirements, Part 3 Glossary of Communication Terms.

Other recent IEC publications are titled:

*204-3A First Suppl. Electrical Equipment for Machine Tools—Part 3 Diagrams for Electronic Equipment for Industrial Machinery

*4335 Addendum 1 Data Communications—High Level Data Link/Control Procedure

IPW

International Purdue Workshops on Industrial Computer Systems
Purdue University,
West Lafayette, IN 47907

At the 7th International Meeting Oct. 8-11, 1979 V-Ch. for Standards T.J. Harrison (IBM, Boca Raton FL) summarized the status of

Real-Time PL/I, proceeding slowly in ANSI X3J1.4

Real-Time BASIC, minimal in ANSI BZ3.60, ECMA 55, IEEE 726 to be enhanced

Real-Time FORTRAN, ISA S61.2, S61.3 moving toward ANSI and ISO

BASIC for CAMAC, issed as IEEE 726, 675, 583A moving toward IEC

IEEE Microprocessor Standards 694,695,696,796,698,754,755 being drafted

PROWAY progressing in IEC/SC65A/WG6

Process I/O Standard approved by ISO/TC97/SC13/WG1

Channel Interface by ANSI X3T9 rejected as ANS,adopted by USA as FIPS

Open System Interconnect model approved by active ISO/TC97/SC16

TC-1C Industrial Real-Time FORTRAN, Chaired by R.W. Signor (General Electric, Bridgeport, CT) will become inactive after completion of its work on ISA 61.3. However, comment on a related draft standard,Definition of Procedures for the Application of FORTRAN for the Control of Industrial Processes, developed with CEC support, is sought by Wilfried Kneis, KFZ Karlsruhe.

TC-2C Industrial Real-Time BASIC, chaired by Gordon M. Ball (Hatfield Polytechnic, GB) has a cooperative agreement with ANSI X3J2, ECMA TC21 and TC2 for joint work on 14 areas of enhancement Level 1.

TC-3C Long Term Procedural Languages, chaired by Jean Robert (Cap Sogeti Logiciel, Montrange-Cebex, FR) recommends the Green Language for

ADA, and the international standardization of ADA and its strict control.

TC-4C Problem Oriented Languages, chaired by Guenter K. Musstopf (Hamburg Univ. FRG) has completed work on PROCOS and is studying the basic architecture of a generalized interactive program generator.

TC-5C Interfaces and Data Transmission, now chaired by Maris Graube (Tektronix, Beaverton, OR) have examined PROWAY Parts 1, 2, and 3 as developed by IEC/SC65A and proposed an ISA SP72 position defining what PROWAY is expected to accomplish.

TC-6C Man/Machine Communications, chaired by Robert F. Carroll (Goodrich, Cleveland, OH) is reviewing comments on its Guidelines for M/M Interfaces, reviewing JEIDA-30-1979 Design Standard for Operators Console with CRT Display, and preparing a report on alarms to include some basic definitions.

TC-7C System Reliability, Safety, and Security, chaired by Roy W. Yunker (PPG Industries, Pittsburg, PA) anticipates some years of effort. Its European group EWICS plans to develop 4 Guidelines - Glossary and Definitions, Program Construction, Program Verification, and Documentation. It has completed Recommendations for Safety Validation/of Safety-Related Software, and EPOS, a formal specification and design tool for computer controlled industrial automation systems. The Japanese group TC-7J have produced JEIDA-29-1979 Standard for Operating Conditions of Industrial Computer Control System, and will discuss a guideline concerning estimation and evaluation of industrial computer control system reliability.

TC-8C Real-Time Operating Systems, chaired by Th. Lalive d'Epinay (Brown-Boveri, Baden-Dattwil, CH) will "describe functions and provide guidelines for design" in a continuously updated report.

TC-9C Glossary was disbanded.

The Ad Hoc Committee on Distributed Industrial Computer Systems, chaired by Klaus Muller (Kern Forschungsanlage, Juelich, D) assumed the status of TC-10C by combining the European Distributed Intelligence Study Group, the Architecture Subcommittee of the Japan Electronic Industry Development Association, and DICS-A chaired by J.W. Humphrey (Brookhaven Lab, Upton, NY). EDISG has sub-groups concerned with CAMAC, with data communication systems, with bus systems for multiprocessor architectures, and with a bibliography of operating systems. DICS-A will study Functional Distribution of Control via the Purdue Steel Plant Hierarchy Control System. JEIDA is interested in putting BASIC on a chip, and in optical fiber communication for distributed systems.

ISA

Instrument Society of America
67 Alexander Drive,
PO Box 12277,
Research Triangle Park, NC 27709

The 1980 edition of Standards and Practices for Instrumentation includes 750 titles and abstracts from USA organizations, and 210 titles from international organizations, all listed in a keyword index. New ISA documents listed:

*S67.01 Transducer and Transmitter Installation for Nuclear Safety Applications

*S75.03 Uniform Face-to-Face Dimensions for Flanged Globe Style Control Valves

*S75.04 Face-to-Face Dimensions of Flangeless Control Valves

*S18.1 Annunciator Sequences and Specifications, for electrical alarms

*S51.1 Process Instrumentation Terminology, covering analog measurement and control; the new standard SAMA PMC 31.1 Generic Test Methods is closely related.

Committee S60 under Raymond Solk (Comsip Customline) is working on RP 60.5 Graphic Displays for Control Centers, referencing S5.1 Instrumentation Symbols and Identification with definitions from ANSI X3.12-1970. Supplementary Flow Diagram Symbols is the title of dS5.3, now in its third revision by the committee under David Rapley (Stearns-Rogers), that deals with shared displays for instrumentation, computers, internal system functions, and alarms. Both dS5.3 and S5.4 Instrument Loop Diagrams will be on the agenda for international experts from ISO/TC10/SC3 and IEC/TC65/WG5 who have been invited by George Platt (Bechtel), chairman of ISO/TC10/SC3, to discuss various topics on symbol representation in international standards after the October ISA Conference in Houston.

Les Driskell (Pittsburgh) who chairs SP75 has appointed Robert Widdows (Ellsworth, KS) to develop a terminology for regulators. SP75.04 under E.H.C. Brown (Pittsburgh) will study improvements in control valve and system design to better stability. A new subcommittee under Hans Baumann will study rangeability and other control valve characteristics. S39.2 and S39.4 are being combined to form ANSI/ISA 75.02/ SP75.07 under T.V. Molloy (Pacific Gas & Elec.) will examine ways of evaluating control valve noise. Control Valve Capacity Test Procedures. Subcommittee SP75.06 under Floyd Harthun (Fisher Controls) is at work on dS75.02 (ANSI B16.101) Control Valve Capacity Test Procedure.

Knowledgeable representatives are sought by Lois M. Ferson (ISA) to join with ASTM E20 (Ed Zysk, Engelhard) for work in ANSI MC 96 on Temperature Measurement Thermocouples. FORTRAN documents ANSI/ISA S61.1 and S61.2 have been sent to ISO/TC97/SC5 for processing as ISO standards.

Chairman of TSC-1 James Nay (Westinghouse, Oak Ridge TN) is planning reviews of RP25.1 Materials for Instruments in Radiation Service and of dS67.07 Pressure Boundary and Seal Requirements for Nuclear Safety Related Transducers. A Survey Committee SP67.09 chaired by J. R. Harper (Virginia Electric) is to study Replacement Parts for Nuclear Safety Related Instrumentation.

ISO

International Standards Organization
1, rue de Varembe,
1211 Geneva, Switzerland

A review of the basic governance of ISO has been suggested by D.L. Peyton, Managing Director of ANSI. The Executive Committee has appointed a study committee chaired by Vice-president R.L. Hennessy (Standards Council Canada) to consider these proposals. At a 1980 evaluation meeting in Washington, Secretary General Olle Sturen noted problems of quality, quantity, and speed. He said that ISO cannot allow five years for the development of an international standard, and should look into alternatives to the committee method.

For some years, ANSI and the USA National Bureau of Standards have been working cooperatively with INFCO, the ISO standing Committee for the study of scientific and technical information on standardization activity, to provide USA input to the development of a network of national standards information centers called ISONET. This involves information exchange agreements covering national and international standards as well as technical regulations and related "standardizing" documents. Its primary purpose is to promote international trade by providing rapid access to reliable information concerning standards and other technical requirements applicable to exported and imported products. See: Directives for the Technical Work of ISO - 1979.

The Secretariat for a new ISO Committee on Solar Standards, to deal with engineering and thermal applications, is held by Australia. The Secretariat of TC85-SC1 Terminology, Definitions, Units, and Symbols in Nuclear Science is held by ANSI. New issues of ISO documents on measurement and control include:

*2972-1979 Symbols for Numerical Control of Machines; Draft 2806.2 Vocabulary
*3530-1979 Vacuum Technology—Mass-Spectromer-Type Leak-Detector Calibration
*4373-1979 Measurement of Liquid Flow in Open Channels-Water Level Measurement
*1438/1-1980 Water Flow in Open Channels—Thin-Plate Weirs
*4882-1979 Data Processing Equipment—Line Spacings and Character Spacings
*Guide 2, ed.3 General Terms and Definitions on Standardization and Certification
*Publ. 1539-1980 Programming Languages—FORTRAN
*Draft Prqd. 7189—Programming Languages—PASCAL
*DP 7179—Modified report on ALGOL 60
*DP 7205—Gauges Incorporating Radio-Elements
*DIS 5085—Mechanical Vibration & Shock Affecting Man
*DIS 4414—Pneumatic Fluid Power—Application to Transmission and Control Systems
*TC20—Aircraft and Space Vehicles—Terms and Symbols for Flight Dynamics
*5167-1980 Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-Section Conduits Running Full
Directory of International Standardizing Bodies—1979

NBS

National Bureau of Standards
Washington, DC 20234

In October 1979 NBS and ANSI hosted a Symposium on International Standards Information and ISONET (NBS SP 579—1980). ISONET is an information network sponsored by ISO/INFCO which links with the Geneva office the information centers of ISO members. National data bases were described by representatives from Deutsches Institut für Normung, British Standards Institution, Standards Council of Canada, Norges Strandiseringsforbund, Association Francaise de Normalization, and Polski Komitet Normalizacji. ANSI has designated the NBS Standards Information Service (Room B162, Bldg. 225, Gaithersburg) as its ISONET link. SIS has on file over 240,000 documents—voluntary standards, specifications, test methods, codes, recommended practices from 400 USA organizations—as well as standards and technical rules drawn up by ISO, IEC, COMECON, CENELEC, IAEC and various national commissions. In promotion of international trade, Symposium speakers discussed the Department of Commerce Industry and Trade Administration, the US implementation of the GATT Standards Code, the BSI Technical Help to Exporters, and the NATO objectives for standards harmonization. NBS GCR 79-171 titled Regulatory Use of Standards: Implications for Standards Writers discusses both points of view.

A workshop on Robot Interfaces convened at Gaithersburg June 4-6, 1980 under the joint sponsorship of the USAF program on Intergrated Computer Aided Manufacturing and the Robot Institute of America. NBS/NEL has prepared a Draft Glossary of Terms of Robotics. Informed reviewers are invited to comment to Bradford M. Smith, B-322 Metrology Bldg. Some 350 terms indexed alphabetically are grouped with their definitions as Types of Manipulators, General Terms, Related Technical Areas, Manufacturing Systems, Mechanical Hardware, Performance Measures, Statics and Kinematics, Dynamics and Control, Sensory Feedback, Computer and Control Hardware, Software, Operator Interfaces, Communications, Economic Analysis.

Federal Information Processing Standard 63 Operational Specifications for Rotating Mass Storage Subsystems will govern the federal use of magnetic disc and peripheral equipment connection, together with FIPS 60 I/O Channel Interface and FIPS 61 Channel Level Power Control Interface.

Computerized control and instrumentation techniques for combustion systems will be studied by the Center for Mechanical Engineering and Process Technology. The new laboratory is built around a slot forging furnace rated at one million Btu/hr with an air preheater for 850C. It will be used to study automatic control systems that could improve the combustion efficiency of furnaces; to examine the combustion characteristics of synthetic fuels; and to evaluate diagnostic test methods.

SAE

Society of Automotive Engineers
400 Commonwealth Drive, Warrendale PA 15096

Standards development has been one of the principal activities of SAE, currently celebrating its 75th anniversary. The designation ANSI/SAE precedes the serial number of the following recent issuances:

*AS 1290 Graphical Symbols for Aircraft Hydraulic and Pneumatic Systems
*AS 1355 Performance Parameters for Aerospace Transducers
*AS 8007 Minimum Safe Performance of Aerospace Overspeed Warning Instruments
*AS 8016 Vertical Velocity Aerospace Instruments
*ARP 147C Nomenclature for Aircraft Air Conditioning Equipment
*ARP 490D Electrohydraulic Servovalves for Flow Control
*ARP 1383 Impulse Testing of Fluid Systems Components for Aerospace
*J 184a Qualifying a Sound Data Acquisition System; also J986b, J1008, J1174
*J 1074 Engine Sound Level Measurement Procedure
*J 551d Measurement of Electromagnetic Radiation from a Motor Vehicle
*J 1145a Emissions Terminology and Nomenclature
*J 1124 Glossary of Filters and Filter Testing of Central Hydraulic Fluid Systems
*J 1135 Measurement and Reporting of Internal Leakage of Hydraulic Power Valves

UL

Underwriters Laboratories
333 Pfingsten Road,
Northbrook, IL 60611

The ANSI Board of Review is considering comment on:

*UL 698 Safety Standard for Industrial Control Equipment for Use in Hazardous Locations, Class I Groups A,B, C, and D and Class II E, F, and G—Revised ANSI C33.30-1973 in accord with ANSI/NFPA 70-1978
*UL873 Safety Standard for Temperature Indicating and Regulating Equipment. The following Safety Standards have been recently approved by ANSI:
*UL 347-1978 High Voltage Industrial Control Equipment
*UL 478-1979 Electronic Data Processing Equipment □

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Government
of Canada

Regional Industrial
Expansion

Gouvernement
du Canada

Expansion industrielle
régionale