CURRENT TECHNOLOGY ASSESSMENT OF STAR TRACKERS

DOC-CR-SP-84-008

ANCON

CURRENT TECHNOLOGY ASSESSMENT OF STAR TRACKERS

DOC-CR-SP-84-008

March 1984

Prepared for : The Communications Research Centre

ANCON Space Technology Corporation

12 Elmbank Road • Thornhill, Ont., Canada L4J 2B7 • Tel. (416) 889-0285

Government of Canada
Gouvernement du Canada

Department of Communications

DOC CONTRACTOR REPORT DOC-CR-SP-84-008

DEPARTMENT OF COMMUNICATIONS - OTTAWA - CANADA

SPACE PROGRAM

TITLE: CURRENT TECHNOLOGY ASSESSMENT OF STAR TRACKERS

AUTHOR(S): Robert W. Armstrong

ISSUED BY CONTRACTOR AS REPORT NO:

PREPARED BY: Armstrong Engineering
Pasadena, California
for
ANCON Space Technology Corporation
12 Elmbank Road, Thornhill, Ontario L4J 2B7

DEPARTMENT OF SUPPLY AND SERVICES CONTRACT NO: 06ST.36001-3-0828

DOC SCIENTIFIC AUTHORITY: Dr. W.S. McMath

CLASSIFICATION: Unclassified

DATE: March, 1984

Current Technology Assessment

of

Star Trackers

Prepared for
ANCON Space Technology Corporation
Toronto, Ontario
Canada

March 28, 1984

Robert W. Armstrong, Ph.D.,P.E.
Armstrong Engineering
Pasadena, California

Introduction

This paper describes the current state of the technology of star trackers designed for use in attitude control systems of free-flying, three-axis-stabilized spacecraft. Specific areas discussed are sensor technology including the current state-of-the-art solid state sensors and techniques of mounting and cooling the sensor, analog image preprocessing electronics performance, and digital processing hardware and software including onboard star cataloging and matching. Requirements specific to three orbits - low earth equitorial, low earth polar, and geosynchronous equitorial - are discussed. The paper is directed to a specific set of pointing requirements for the Canadian Attitude Sensing System (CASS).

This instrument is to be used strictly as a star tracker with no current requirement for planet, moon, or limb tracking. The majority of stars used for attitude stabilization by celestial reference have wavelengths at the blue end of the spectrum so infrared detectors are not considered.

Conventional star trackers have used photomultiplier or image dissector tubes. This technology is still in use for certain applications, particularly where radiation hardness is a primary factor. An example is the Galileo star scanner which uses an EMR ceramic tube (1). It should be noted, however, that the primary Galileo science imaging camera is an 800 X 800 pixel virtual phase charge coupled device by Texas Instruments. Tube type sensors have certain inherent disadvantages when compared to their solid state counterparts. High voltages (>100 volts) must be applied to operate the tubes, adding weight to the spacecraft power generation and distribution system; solid state devices operate from voltages typically less than 28 volts. Scanning is accomplished in tube devices by electromagnetic deflection circuits so pixel size and location are subject to errors or "jitter" in the electronic timing which controls image readout; the size and location of pixels in solid state sensors is an inherent part of the device geometry and remains fixed with respect to the sensor reference point. Magnetic fields must be minimized in the area of the tube type trackers to reduce bias errors which affect accuracy; solid state devices are not subject to magnetic fields. Finally, primarily due to the reasons cited, there is a decreasing availability of flight qualified image dissector tubes. As a result, tube technology is not considered a practical candidate for flight hardware applications into the next decade and is not discussed here.

An example of the state of current solid state star tracker development is presented. The ASTROS tracker developed by the Jet Propulsion Laboratory and under construction at Honeywell is the only known solid state star tracker currently assigned to a flight project. This tracker represents the level of performance acheivable in star tracker designs based on solid state sensors. It also typifies the image processing functions and scan techniques being developed for a range of missions from earth orbital star scanners to outer planetary and interstellar extended target recognition and tracking systems for spacecraft guidance and navigation. The Retroreflector Field Tracker (RFT) by Ball Aerospace and TRW's MADAN are also described. The RFT is a CID point-source tracker scheduled for 1984 shuttle launch of the Solar Array Flight Experiment (SAFE). The MADAN tracker will not be ready for flight for at least three years at present funding levels. Finally, a discussion of solid state line arrays explores the possibilities for one dimensional imagers which offer simplified scan control electronics.

CASS Star Tracker Requirements

The star tracker selected for the Canadian Attitude Sensing System

(CASS) will be an integral part of the spacecraft attitude control system which provides data to correct for gyro drift. Laser gyros which are being developed as the next generation replacement for mechanical gyros will signifigantly reduce these drift errors (2), but prototypes will not be complete until 1986 and first flight hardware production not until after 1990. Even with these high accuracy, low drift gyros the requirement still exists for the star tracker to provide absolute attitude reference not available from the gyro.

The CASS attitude control system with which this star tracker will be used will obtain absolute azimuth and elevation attitude updates from the star tracker at maximum intervals of six minutes. Low earth orbits typically have periods of ninety minutes. There will thus be fifteen tracker updates during each orbit, each view of the celestial sphere being 24 degrees apart resulting in a completely different set of stars being viewed at each update time. This will require a complete star acquisition and identification sequence for each update. This software complexity can be reduced considerably by acquiring star tracker updates continuously. The tracker output rate is a function of star magnitude and would thus be constantly changing. This asynchronous rate is known to the attitude control computer by virtue of the star catalog data and can be accomodated. This concept is a conventional one and formed the basis of the Precision Pointing and Tracking System developed at Jet Propulsion Laboratory.

Geosynchronous orbits with tracker updates at six minute intervals will result in 1.5 degree separation between successive views. This is smaller than the typical field of view of star trackers so continuous star tracking can be used. In either low earth or geosynchronous orbits with star tracker updates at minimum six minute intervals it is possible to operate the tracker in a continuous or free running mode thereby simplifying star tracker and attitude determination system design and implementation.

Reduced system cost and increased reliability can be achived by autonomous star acquisition and position measurement. This eliminates the need for expensive and vulnerable ground data links and improves system bandwidth by eliminating transmission and ground processing time. It does require that a star catalog be stored onboard so the tracker can correctly establish its orientation in relation to the celestial sphere. The size and specific content of this library is dependant on the orbit and the launch date and length of the mission. Typically it can be expected to contain magnitude and position data for 100 to 1000 stars.

The attitude control system transmits coarse attitude data to the tracker at each update time. The tracker acquires an image frame. It then uses the gyro data to call up the appropriate stars from its catalog for the region of sky it expects to see. This data is correlated with the current image to verify the presence of those stars by matching intensity and position for each guide star. The exact position of stars in the current frame is then computed and transmitted to the attitude control system for computing current precision spacecraft attitude/position.

To properly update the gyro data in azimuth, elevation, and roll star trackers are usually required to have on the order of 95% chance of finding at least two stars in the field of view. This criterion is used to establish the tracker field of view (FOV) according to

$$p(x>=n) = 1 - \sum_{k=1}^{n+1} ((N*A)^{k-1} * \exp(N*A))/(k-1)!$$

where N is the number of stars per unit area (from Allen's Astrophysical Quantities), n the number of stars in the FOV, and A is the area of the FOV in square degrees. Star visual magnitudes of -1 to +7 are typical and result in FOV's on the order of two or three degrees corresponding to optical focal lengths of about 200 mm.

The image integration time for any given sensor must be computed to determine the time required to form a star image. This is a combination of the parameters of the optical system and the sensor and the stellar visual magnitude and color. The equation which relates these quantities is of the form

$$N_{e^-} = (1/hc)\sum_{\lambda_i} \lambda_i n(\lambda) f(\lambda) S(m_v) A A_f T_i T \Delta\lambda$$

where $f(\lambda)$ = stellar flux

$n(\lambda)$ = sensor quantum efficiency

A = lens aperture

A_f = area weighting factor

T_i = integration time

T = lens transmittance

h = Planck's constant

c = speed of light

$S(m_v)$= magnitude weighting constant

The accuracy of star trackers is often quoted in milliradians or arcseconds. This is not the most informative unit of measure for accuracy and stability figures. The ultimate limitation to accuracy and stability of any star tracker is the sensor readout noise. Trackers are designed specifically to be noise limited; i.e.,measurement step size is smaller than the noise equivalent angle. The optical system design determines the FOV of the sensor and, therefore, the number of milliradians (or arcseconds) noise equivalent angle. A more informative measure of the ultimate performance limitations of any tracker states the noise equivalent angle, accuracy, and stability in terms of fractions of a pixel.

Accuracy is defined in terms of the Root Sum Square of the deviation from linearity of tracker output as an input source (usually a point source) is scanned over the sensor area. Since solid state trackers have fixed pixel geometries, it is important to establish the uniformity of pixel size in the array. This is accomplished by taking the differences between sucessive sensor outputs as the source is moved across the array in equal increment steps. Constant difference values indicate identical pixel sizes. This data is absolutely essential for sensor calibration in extreme high accuracy systems. Finally, the stability of sensor output is measured in two ways - spatially and temporally. Spatial variance measures the difference in response of pixels in the array. Minor imperfections in the manufacturing process result in such variations, and this can affect sensor output. The temporal variance is a measure of a combination of effects. Readout noise, analog preprocessor noise, and sensor thermal noise are the primary contributors to variations in the response of individual pixels as a function of time. The temporal variance of most solid state devices with well designed amplifiers is usually an order of magnitude less than the spatial or pixel-to-pixel variation.

The amount of drift anticipated in the CASS gyro during the six minutes between star tracker updates is approximately 25 arcseconds. The field of view of two degrees compatible with star detection probability as above is equivalent to 7200 arcseconds. The overall accuracy requirement for the CASS system is given as 10 arcseconds. The star tracker should thus have an accuracy about an order of magnitude less or 1 to 2 arcseconds. Solid state devices currently being used in star trackers have minimum array dimensions of 250 pixels. It is thus possible to establish the requirement for subpixel star position interpolation as

$$i = (1.5 \text{ arcsec}/7200 \text{ arcsec}) \times 250 \text{ pixels}$$

$$= 1/20 \text{ pixel}$$

This degree of pixel interpolation is within the capability of current technology (3).

Radiation requirements are another consideration in design of star trackers. The low earth and geosynchronous equitorial orbits are relatively benign environments. The low earth polar orbit, however, takes the spacecraft through the VanAllen radiation belts. Radiation levels can reach 500 kilorads total absorbed dose and $3(10^{12})\text{cm}^{-2}$ particle fluence. Sheilding of sensitive electronics and use of specially selected optical glasses is necessary to maintain tracker operation. The MADAN tracker uses a radiation hardened CCD sensor. Other trackers must rely on the optics to limit total absorbed dose. In either case, conventional optical glasses have a tendency to turn opaque brown in the presence of high radiation fields so there is a generally applicable requirement for non-sensitive optics.

Current Technological Trends

Three major development areas are currently at the forefront of solid state star tracker research efforts. The first is development of improved image sensors. The thrust of these efforts is enhanced sensitivity and dynamic range, larger array size, expanded spectral response, and increased radiation hardness both to particle fluence and total absorbed dose.

The simplest solid state imaging array is the line array. These devices are cheaper and easier to fabricate than two dimensional imagers and require much less complex clocking electronics to read out the image data. Pixel-to-pixel uniformity is usually superior to large area arrays simply because of the reduction in the number of pixels. As a result, they were the first solid state imaging arrays produced and star tracker designs have been proposed which use only line arrays. In certain applications they are superior to two-dimensional arrays. On spin stabilized spacecraft the rotation of the spacecraft bus can be used to scan a swath of sky. Time Delay Integration (TDI) can be acheived by allowing several complete rotations of the spacecaft before reading out the device. Thus a line array can simulate an area array at greatly reduced cost and complexity. These devices are not without their disadvantages, though. Mounting on a spinning spacecraft must take into account the effects of axial precession which causes the image of a given star to appear at different locations on the array during each revolution. There are similar disadvantages for applications on three-axis stabilized spacecraft. Since they are essentially one-dimensional devices it is necessary to incorporate complex optical designs or accept reduced star detection probability associated with the smaller field of view. Even though individual scanners are cheaper, overall system cost may be increased by the need for multiple devices to obtain azimuth and elevation (Line of Sight and Roll) data. These devices also can place tighter requirements for stability on the attitude control system. This results from the need to maintain the star image over a single line of pixels during the integration time. A two-dimensional imager can allow the image to smear over the sensor area (within limits) and integrate the signal electronically or digitally. A line array must have the image held over a single pixel in at least one dimension long enough to form an image electro-optically.

Charge coupled devices are the most common member of the charge transfer family and represent the bulk of commercially available silicon solid state area array sensors. Manufacturers include RCA, Fairchild, Hughes, and Texas Instruments, although the latter has announced no further device development plans after the imaging science camera to be flown on the Galileo spacecraft.

RCA produces two lines of CCDs, one commercial and one scientific. The scientific device is the only one of interest here and is a three-phase, thinned, back side illuminated, buried channel device. Full well capacity is 500,000 electrons. Experimental results indicate a possible low signal "threshold" for reliable operation of about 2000 electrons. This gives the device a potentially wide dynamic range. The range is adequate to allow a single design to track point source (star) targets and extended source (planet, etc.) targets by changing the electronically controlled integration time. Backside illumination provides increased quantum efficiency (>65%) allowing imaging of low intensity sources. Buried channel design improves the charge transfer efficiency by avoiding interface state trapping effects found in surface channel devices. These characteristics make the device more sensitive to low level targets and allow imaging of stars at shorter integration times. This in turn reduces smear or, conversely, increases the smear limited rate for tracker operation.

The Hughes CCD designed specifically for the MADAN star tacker is a front side illuminated device with approximately 25% quantum efficiency. The advantage to this device structure is that front side illumination places polysiilcon gate structures between the optical input and the photosensitive areas (wells) of the device, contributing signifigantly to its radiation hardness.

Gallium arsenide devices are under development by Rockwell and promise signifigant advantages over silicon devices (4,5). The inherently lower free carrier concentration in gallium arsenide results in thermal noise figures orders of magnitude lower than silicon. These devices can thus deliver noise equivalent angles equal to or less than silicon sensor based trackers while operating essentially at room temperature. This represents an opportunity for signifigant savings in tracker power requirements by not necessitating active cooling. Passive cooling hardware size and weight is also reduced and can represent substantial savings in overall tracker development cost. A further advantage of gallium arsenide devices is the ability to clock data about an order of magnitude faster than silicon devices. This offers the possibility to develop trackers with electronic shuttering times as short as 0.1 millisecond with data readout at 10 to 100 MHz.

Photodiode arrays represented by the Reticon family are widely used in earth-based star scanners because they can be fabricated with enhanced ultraviolet response. Since most stellar sources of interest for navigation and attitude control are concentrated at the blue end of the spectrum (6), this improved response is an important advantage. These devices are available as line and area arrays in commercial and scientific versions. Thermal noise is a major factor in their performance and they are typically operated below -70 C which necessitates mounting in dewars and cooling with liquid hydrogen. The requirement for extreme low temperature operation and their inherent radiation softness make them less desirable for flight hardware than other devices in the charge transfer family. Photodiode arrays are used in "V-slit" trackers by Ball and Perkin-Elmer.

Charge Injection Devices are relatively new to the star tracker field but offer some important potential advantages. The most signifigant of these is the ability to address individual pixels. This advantage is most important in closed-loop star tracker applications where readout time must be minimized to provide updates consistent with system bandwidth requirements. This random pixel access design, however, has one particular inherent disadvantage. In order to access individual pixels at random, polysilicon gate structures must be provided for each pixel. The gates for the pixels at the center of the array become relatively long and have very high capacitance. This reduces maximum acheivable readout clock rate and introduces additional readout noise. Experimental data is not yet available for noise equivalent angles associated with tracking low intensity star targets, but simulations predict performance inferior to CCDs.

The second major area of development work is in image processing hardware and software. The latter is new to the development of star trackers and began in earnest with the STELLAR star tracker designed by Jet Propulsion Laboratory. This was one of the earliest trackers to incorporate a dedicated, onboard microprocessor. This new system element took over many of the functions of hardwired digital and analog circuits and added a new dimension of flexibility to the tracker. It is now possible to reconfigure a tracker for different missions by changing software since the computer controls sensor readout and image processing. The device can be changed from a star tracker to a correlation tracker almost instantly by simply calling up a new software program. The metamorphosis is not as easy as it might at first seem, however. Differences in mission requirements, mounting configurations (spacecraft bus), and availability of "dark sky" viewing for passive cooling usually necessitate changes in tracker optics, sensor cooling and mounting design, and packaging. Nonetheless, standardization of the sensor device, analog and digital electronics, and image processing techniques and algorithms signifigantly reduces the cost of providing a tracker for a specific mission. Much attention has also been given to methods for determining the accuracy of star tracker software and these techniques are now well established (7).

The simplest tracking algorithm is the centroid of brightness. This has been implemented in analog hardware as the standard tracking technique for existing star trackers. The computation of centroids by digital computer involves the processing of many pixels at a time from a track window or an entire frame. As a result, techniques have been sought for reducing the amount of data to be operated on by the computer. Methods have been devised for reducing a two-dimensional imaging array to two or three one-dimensional arrays (8,9) which can be processed rapidly by the computer. This data reduction is based on the theory of projections which is the basis of the medical CAT scanner (10). Reduction of image array dimension has also been implemented optically using solid state line arrays.

Onboard computers have historically been a part of attitude control systems. These computers have also been used to process star imaging data. As the complexity of the control system and the demands for accuracy increase it is becoming evident that there is a need for a dedicated computer for the star tracker (11). Several different computers have been suggested for this application and prototypes built and tested. The Intel 8085 was a prime candidate for a while since it was being developed in CMOS/SOS under a joint RCA and Navy program. This version was to be a low power, radiation hardened (200 krad) device software compatible with the conventional device. This made it possible to develop and debug algorithms using the low cost commercial chip and transport it directly to the flight hardware. Difficulties in fabrication resulted in delays in development and the 8085 was dropped from consideration. Another RCA device, the 1802 was considered, also because of its ability to meet requirements for flight hardware. Throughput capabilities of this device are limited by the internal structure which requires all I/O data to pass through the "D" register. This reduced the processors speed sufficiently to remove it from competition. Other 8-bit microprocessors such as the NSC800 were considered, but all these devices suffered from the limitation of word size. Control system data is typically 24 bits (12). Star tracker data is usually on the order of 12 to 14 bits (3). Using an 8-bit device required double precision operations which limits throughput. As a result newer 16-bit devices were sought. The commercial MOS devices were rejected because they are not radiation hard and are susceptible to hard and soft errors. Two 16-bit machines were identified as realistic candidates - the Texas Instruments SBP9900 and the Itek ATAC-16MS. The Texas Instruments computer offers the attractive advantage of the 8085 of having a commercial counterpart which is software (and to a large extent hardware) compatible. The Integrated Injection Logic (IIL) version proposed for flight hardware is low power and shows high tolerance to radiation in laboratory tests. It has recently been upgraded to the 9989 with smaller geometry for lower probability of particle strikes which cause soft and hard errors.

The ATAC-16MS by Itek has the advantage of being military qualified. It is supported by high level languages (Ada and HAL/S) and is available commercially as opposed to the TI 9989 which would have to be designed and built as a complete computer. The ATAC was originally touted as being radiation hard, but recent test flights on the shuttle indicate a substantial bit flip problem. This is under study at the present time to determine the exact cause and possible solutions.

The third major development area currently being pursued is the technology for mounting and cooling the image sensor. The calibration of the imaging device is directly related to its position in the optical path. Any shift in position can not only cause translation of the sensor origin relative to the tracker mounting feet but can rotate portions of the field of view out of the focal plane. The result is nonuniform geometric response and loss of accuracy. Two types of mounting system have been studied - solid and suspension. The suspension mount is a complex arrangement of supports designed primarily to prevent any movement of the image sensor with changes in temperature such as occur when transitioning from the day side to the night side of an orbit. These mounting schemes lead to expensive designs. The device cooling mechanism is usually a thermally conductive braid or layered strap. Test results have shown that the solid mount is much more efficient thermally as might be expected sincee the device can be mounted on a solid pedestal providing a much lower thermal resistance. This solid mount is also much cheaper to implement than the suspension. However, no test results have been published indicating how much movement accompanies thermal cycling of the solid mount.

Cooling of the solid state device is necessary to reduce thermal noise which contributes to the noise equivalent angle. Active and passive cooling mechanisms have been employed and the spacecraft configuration and mission determine which is required. Earth orbital free flyer spacecraft can usually be arranged so that the star tracker has a constant dark sky view into which to radiate heat permitting use of the simpler, cheaper, passive system. Power requirements are reduced from several watts in active cooling to zero in the passive cooling system. Thermoelectric devices are the most common active coolers and design criteria are well established and verified from previous flight experience (13).

Existing Trackers

There are presently only three known solid state star tracker designs which have been pursued beyond the concept demonstration (breadboard) phase - TRW's MADAN (14,15), the Ball Aerospace Digi-Star (16), and the JPL designed/Honeywell built ASTROS (17,18,19). Of these three, only the ASTROS tracker is currently designated for flight. ASTROS will be flown on a 1986 launched Spacelab mission.

The ASTROS tracker uses an RCA 52501 CCD array of 340 columns by 512 rows divided into two fields of 256 rows each. The field of view is 2.2 x 3.5 degrees making each pixel approximately 30 arcsec square. Analog signal processing (preamplifier and amplifier) noise is limited to less than 1000 electrons by a combination of low-noise electronics design and double-correlated sampling. The analog-to-digital converter is twelve bits in size and the data is processed in floating point format allowing subpixel position interpolation to 0.01 pixel. The tracker thus has a noise equivalent angle of 0.3 arcsec. Uncalibrated accuracy is specified to be 4 arcsec. Calibration reduces this number to 0.8 arcsec. Laboratory testing of the ASTROS tracker on both extended and point source targets showed accuracy or root-sum-square (RSS) deviation from linearity of 0.018 pixel.

ASTROS is capable of tracking three stars simultaneously with visual magnitudes in the range from -0.8 to +8.2. This magnitude range arose from the requirement to detect and track at least three stars in each frame with at least 97% detection probability. Designed for use on the shuttle, the current flight configuration of ASTROS is compatible with Low Earth Equitorial orbits.

ASTROS power consumption is 38 watts and the mass is 28 kg. A major portion of the power consumption is related to the operating environment of the shuttle. Active cooling of the imaging CCD accounts for a large part of the power consumption. It is likely that when reconfigured for a free flyer, passive cooling would be used to reduce that figure. Weight reductions should be possible by reducing the size of optical baffles made necessary in the current design by the nearby reflecting shuttle surfaces.

The TRW MADAN star tracker was developed for the Air Force as a precision strapdown attitude reference device for three axis stabilized earth-orbiting spacecraft. Its image sensor is a composite design much like TEAL Ruby and consists of four 324 x 324 pixel buttable CCD arrays designed and built by Hughes. The imaging area is divided into two sections of 162 rows, each independantly readable. Loss of any one of these sensing areas would reduce two-star detection probability from nominal .997 to .988. The chips have readout arrays and connectors concentrated along two edges allowing them to be mounted as a composite array. A 0.070 inch area in the center of the array where the four subarrays are butted together is used to sense position of a LED fed to the array via a fiber optic cable through the sensor housing. This provides the capability for inflight calibration. it should be noted that, like Texas Instruments, Hughes has no committment to supply CCDs beyond the engineering model phase of the development. Martin Marietta is currently testing the devices and results have shown about 1% yield for 500-chip lots.

The strapdown sensor head assembly is specifically designed for earth orbital applications subject to potentially high radiation doses. The optical system is a folded catadioptric Schmidt design with 142 mm focal length and 80 mm aperture giving the four-CCD array a total field of view of 6.6 degrees square. The optics are defocused to give a 2.5 pixel diameter star image allowing subpixel position interpolation to 1/20 pixel. The CCDs are hard mounted on a thermoelectric cooler and the device is operated at -40 C. The sensor head assembly consists of a focal plane module which is 4" diameter by 3.5" long, an T/E cooler 5" diameter and 1.5" long, and sensor head electronics 5" x 5" x 6". Total weight is 21 kg. Total power consumption including image processing electronics is 29 watts. This includes 6 watts for the T/E cooler.

The image processor is a dedicated TI9900 computer and operates on 12-bit data from the A/D converter. Star position is computed as the mean in azimuth and elevation of pixel magnitueds for star pixels only (track window data). The size and shape of the track window is more complex than that for ASTROS and unlike ASTROS is adaptive. The MADAN star tracker is designed to operate in the MADAN system which consists of three star trackers and one earth sensor supported by an onboard navigation and attitude control computer. This computer carries a star catalog of between 100 and 1000 stars depending on orbital and spacecraft configuration and mission requirements. The navigation computer supplies coarse star position and magnitude data to the tracker for acquisition and the tracker returns star position accurate to 2.7 arcseconds for 5.6 mean star magnitude. MADAN is capable of tracking stars at rates up to 300 arseconds per second. Typical integration time is 0.25 seconds and device readout time is 70 milliseconds with a 750 kHz clock.

Laboratory functional testing of the MADAN star tracker engineering model is scheduled for the summer of 1984. At the present time the Air Force has not defined a flight hardware development plan, but it is estimated that it would require approximately three years to go from engineering model to flight build, depending on the level of funding and availability of CCD devices from Hughes.

The Ball Digi-Star tracker uses a GE ST-256 Charge Injection Device with a 256-pixel square format. Reflective optics are used with intentional aberrations to produce an image of at least 1.4 pixels for subpixel interpolation. Simulation test results indicate that transfer function linearity is 0.003 pixel, and the noise equivalent angle is reported as 2.3 arcseconds for 1 second update and 0.23 arcseconds for 0.5 second update. Empirical test data show standard deviation of position data to be closer to 0.01 pixel. The tracker is designed for an 8 x 8 degree field of view to track stars with magnitudes of 0 to 6 mv at rates up to 1 degree per second. Projected weight of flight hardware is 26.4 kg and power consumption is estimated at 10 watts. The first flight application of the Ball technology is a 1984 shuttle launched Retroreflector Field Tracker (RFT) for the Solar Array Flight Experiment (SAFE). This tracker will detect point sources formed by reflection of laser diode sources from 23 points on a large solar array constructed in the shuttle bay. This position data will have design accuracy of 7 arcseconds (minimum required accuracy 19 arcseconds). Update time is 125 milliseconds. The ST-256 CID array is used with an f/1.8, 13 mm EFL lens having a FOV of 19.3 degrees square. The pixel size of 272 arcseconds indicates that the RFT will be accurate to about 1/40 pixel.

Line array star trackers have been proposed by Marconi and Perkin-Elmer as a simpler, cheaper means of providing star position data. The most common configuration is the V-slit which uses two arrays to detect clock and cone angles by a combination of position of the image within the array and the relative timing of slit crossing. Single array trackers have been proposed which use only the time of detection of star crossing in combination with crossing position. This concept fails to take advantage of one of the major advantages of solid state sensors over tube types - that of spatially fixed (geometrically stable) pixel position. Use of the crossing time to fix position is subject to the same timing jitter and lack of resolution as in tube type trackers. The fundamental limitation is as follows. Star crossing time is measured relative to a base clock signal by detecting a threshold-crossing pixel magnitude. A plot of pixel magnitude as a function of time is used for reference. A low star crossing rate allows sufficient integration time and the curve has high magnitude. This magnitude is quantized to a finite number of bits and the result of a larger magnitude is reduced resolution step size. In addition, the low crossing rate makes crossing time long so the curve of sensor output versus time is not sharply peaked. A small change in intensity (at the limit of resolution step size) thus corresponds to a large "delta t" and crossing time uncertainty is large. This leads to large uncertainty in position in that axis. If the crossing rate is increased to reduce crossing time, signal magnitude is decreased, resolution step size is decreased and some accuracy can be gained subject to the timing jitter in the base clock. For this reason, V-slit and other line array scanners are typically used on spin-stabilized spacecraft only.

Summary

Three solid state star trackers are currently available as viable candidates for the CASS application. Of these three only the JPL ASTROS tracker is currently assigned to a flight project as a star tracker. The Ball Aerospace Retroreflector Field Tracker will be flown on the Solar Array Flight Experiment but will not be used as a star tracker. The TRW MADAN tracker has been delayed in development by lack of funding, but the effort is now underway again and an engineering model will be completed and tested this summer. Performance predictions, weight, size, and optical configurations are quite similar among the three systems. Accuracy is typically 1/20 pixel or better giving each tracker the potential for meeting CASS star tracker requirements of 1-2 arcseconds. The TRW design has the advantage of having a radiation-hardened image sensor capable of operating in the low-earth, polar orbits intended for CASS. The Ball Tracker uses a CID which tends to exhibit greater fixed pattern noise than the CCD sensors overcomes this by using its direct pixel readout capability to rapidly acquire and average multiple readings at rates equivalent to the two other trackers. The JPL design offers the advantage of maturity and will gain first flight experience as a stand alone star tracker. There is no substitute for flight experience in evaluating tracker performance, and this data will soon be available for the JPL ASTROS and Ball RFT. Each of these three trackers is based on its own unique approach and, at the present state of development, each shows potential for meeting the requirements of the Canadian Attitude Sensing System.

Bibliography

1. "A Radiation-Hardened Star Scanner for Spacecraft Guidance and Control", Birnbaum, M.M., Bunker, R.L., Tavolacci, J.T., AIAA Jour. Guid., Control, and Dynamics, vol. 6, #1, February, 1983.

2. "The Mariner Mark II Program", Draper, R.F., AIAA 22nd Aerospace Sciences Meeting, January, 1984.

3. "Ultra-Precise Star Tracking Using Charge-Coupled Devices", Dennison, E.W., Stanton, R.H., Proc. SPIE, vol. 252, July, 1980.

4. "High Performance AlGaAs/GaAs Heterojunction CCDs for Imaging Applications", Harris, J.S., Reitz, L.R., AAS Rocky Mtn. Guid. Contr. Conf., January, 1981.

5. "Integrated Circuits: the case for gallium arsenide", Eden, R.C., et al, IEEE Spectrum, December, 1983, pp.30-37.

6. "Image Processing Techniques Applied to Scanned Radiometric Collections of Stellar Sources", Devich, R.N., et al, Jour. SPIE, vol 95, 1976.

7. "A Model for Testing Centerfinding Algorithms for Automated Optical Navigation", Griffin, M.D., Breckenridge, W.G., Proc. AAS/AIAA Astrodynamics Specialist Conf., Paper #79-124, June, 1979.

8. "A Real-time Structural Tracking Algorithm", Flachs, G.M., et al, NAECON Record, 1976, pp.161-168.

9. "A CCD Tracker for Closed-Loop Instrument Pointing at Halley's Comet", Stanton, R.H., Armstrong, R.W., Proc. AIAA 19th Aerospace Sciences Meeting, January, 1981.

10. "Digital Reconstruction of Multidimensional Signals from Their Projections", Mersereau, R.M., Oppenheim, A.V., Proc. IEEE, vol. 62, pp.1319-1338, October, 1974.

11. "Guidance and Control Concepts for Autonomous Spacecraft", Kawauchi, B.H., Manke, G.M., Williamson, R.K., Proc. AAS Rocky Mtn. Guid. Contr. Conf., AAS 83-045, January, 1983.

12. "One Step Forward - Three Steps Backup: Computing in the U.S. Space Program", Stakem, P., Byte, vol. 6, #9, September, 1981, pp. 112-144.

13. "Estimating Heat Loads on Multistage Thermoelectric Heat Pumps", Marlow, R., Click, P.B., Proc. SPIE, vol. 116, August, 1977.

14. "Multi-Mission Attitude Determination and Autonomous Navigation (MADAN)", Laverty, N.P.,McAloon, K.J., Roberts, J.L., Williams, I.J., Proc. AAS Rocky Mtn Guid. and Contr. Conf., #AAS 80-029, February, 1980.

15. "Design Considerations for Imaging CCD (ICCD) Star Sensors", McAloon, K.J., Proc. SPIE Conf. Shuttle Pointing of Electro-Optical Experiments, vol. 265, #21, February, 1981.

16. "An Advanced Star Tracker Using the Charge Injection Device", Kollodge, J.C., Sand, J.A.

17. "Experimental Verification of CCD-Based Optical Tracking Performance", Armstrong, R.W., Shalom, E., AIAA Guid. Contr. Conf., August, 1982.

18. "CCD Sensors for Interplanetary Spacecraft Navigation and Pointing Control", Armstrong, R.W., Eisenman, A.R., AAS Rocky Mtn. Guid. Contr. Conf., February, 1981.

19. "Image Motion Compensation", Shelton, H., Proc. AAS Rocky Mountain Guidance and Control Conf., AAS 83-006, January, 1983.