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Visualization to augment comprehension models of a complex phenomenon - IMAGE VI exploration module

Marielle Mokhtari; Éric Boivin, Frédéric Drolet
DRDC Valcartier

Defence Research and Development Canada – Valcartier

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Abstract

In a wide range of scientific and technological domains (e.g. economics, climate and seismic modeling, melting modeling, astronomy, neuroscience and archaeology), experts need to make sense of and extract useful information and/or knowledge from (large) datasets composed of various types of data. To achieve these goals, experts require tools combining advanced analysis and visualization, and rich user interactions to guide them to incrementally and interactively explore datasets, to organize data, to process information, and to go through and understand these datasets. The *Exploration* concept (developed for the *IMAGE* project) consists in making datasets clear in explanatory and tailored (visualization) views, which can be exploited by experts to augment their individual or collective comprehension models of a complex phenomenon.

Résumé

Dans un large éventail de domaines scientifiques et technologiques (par exemple l'économie, le climat et la modélisation sismique, la modélisation de la fonte des glaces, l'astronomie, les neurosciences et l'archéologie), les experts ont besoin de donner une signification aux données et d'extraire de l'information et/ou de la connaissance utiles de (grands) ensembles de données composées de divers types de données. Pour atteindre ces objectifs, les experts exigent des outils combinant une analyse et une visualisation avancées, et des interactions riches pour les guider à une découverte progressive et interactive des jeux de données, pour organiser les données, pour traiter l'information, et pour naviguer au travers de ces ensembles de données et pour les comprendre. Le concept d'*Exploration* développé pour le projet *IMAGE* consiste à donner un sens aux ensembles de données à travers des vues (visualisations) explicatives et adaptées, qui peuvent être exploitées par des experts afin d'augmenter leurs modèles individuels ou collectifs de compréhension d'un phénomène complexe.

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Executive summary

Visualization to Augment Comprehension Models of a Complex Phenomenon: IMAGE V1 Exploration Module

Mokhtari, M.; Boivin, É.; Drolet, F.; DRDC Valcartier TM 2013-482; Defence R&D Canada – Valcartier; December 2013.

Complexity has always existed in natural and biological realms. However, with the advances in Sciences and Technology, humanity is now capable of building artefacts whose complexity approaches those of life itself. There is a need for using new methods to tackle this *new complexity* including such artefacts. To address the new defence and national security challenges of dealing with an ever increasing range of elements, some natural but many human-made, DRDC scientists propose through the IMAGE project (part of the Technological Investment Funds) a toolset concept targeting the collaboration of experts from different disciplines trying to reach a shared understanding of a complex situation (CS).

The concept IMAGE: The proposed concept aims at disentangling CSs more quickly, specifically targeting the collaboration of experts from different disciplines trying to reach a shared comprehension model of a CS. The goal of the concept is two-fold: increasing understanding of a CS and enabling individuals to share their comprehension (through a common comprehension model). The concept elaboration was mainly guided by three principles or assumptions: (1) iterative understanding: a common understanding is reached through revision and sharing of successive representations of the situation; (2) human-driven toolset: the common understanding is above all a human task involving team members using tools their own way; and (3) synergy of technologies: the common understanding is better served by the synergy of technologies than a single one. IMAGE researchers have identified four complementary modules to achieve this synergy: *Representation*, *Scenarisation*, *Simulation* and *Exploration*. The *Representation* module (I-REP) consists in rendering a mental model explicit in a comprehension model. From this comprehension model, the *Scenarisation* module (I-SCE) generates an executable model to be used by the *Simulation* module (I-SIM) that provides interactivity enabling investigation of the space of variables. Finally the *Exploration* module (I-EXP) provides powerful tools allowing experts to invent views that bring a significant meaning to (large) datasets generated by the I-SIM module.

Scenario: The selected scenario is inspired by logistic convoy attack situations experienced by the Department of National Defence and the Canadian Armed Forces (CAF) deployed in Afghanistan. The convoy-insurgents coevolution idea was implemented in two parts: the first one at a lower level of complexity named *Tactical* (a mission corresponds to only one simulation) and another one at a higher level of complexity named *Standard Operating Procedure*, or *SOP* (a mission corresponds to one hundred *Tactical* missions). Both levels were made deterministic to reduce variability in the experimental data.

Exploration (I-EXP) concept: The I-EXP concept aims to produce, individually or collectively, explanatory and tailored views in ways that words cannot communicate clearly. These views, in order to bring a meaning to data, have to generate, stimulate, increase or accelerate the understanding effort. The concept is supported by tools, which implement visualization and interaction techniques and/or mechanisms by, taking advantage of the potential of different

platforms in terms of technology and in terms of exploitation of human sensory information (mainly *perception* and *action*). The I-EXP concept has been developed through the I-EXP V1 prototype composed of I-EXP V1 *Tactical* and I-EXP V1 *SOP*. I-EXP V1 was part of the IMAGE V1 cognitive experiment focussing on individual comprehension. Hardware components composing the platforms supporting the I-EXP tools span from a traditional hardware setup composed of LCD screen - keyboard - mouse to a more high-tech platform exploiting immersive technologies leading to the user's immersion in a virtual environment. In fact, the I-EXP module puts emphasis on the proper use of technologies in order to fulfill the user's exploration needs.

Exploration (I-EXP) toolset: In the spirit of the *Visualization* domain, the main task of which is to allow *information* to be derived from *data*, the I-EXP V1 toolset has been thought to assist experts / users understand and interpret datasets, by exploiting different graphical renderings (e.g. graphs, diagrams, charts, etc.) which are visual artefacts representing data, illustrating relationships and patterns among data, presenting *information* (appropriate conversion of *data*), and also allowing analysis and comparisons between graphical representation of datasets. In addition, the I-EXP V1 toolset addresses the dynamic display of trends in the data and human interaction with the displayed data. Consequently the toolset has been designed to: (1) explore and compare datasets; (2) extract information / knowledge; (3) discover unexpected trends in the data or find patterns; and, finally, (4) understand specific non-intuitive aspects of CSs. To achieve these goals, the I-EXP module exploits different techniques such as (1) filtering (for focusing on relevant subsets of data) and data brushing (that supports visual linking of various data and addresses the visual fragmentation problem of multivariate data representations), (2) datasets comparison, (3) multi-level datasets exploration (at *Tactical* and *SOP* levels), and (4) real-time and stereoscopic rendering (for the immersive version).

Users: The targeted users of IMAGE, when ultimately deployed, are people (individuals or teams) that are involved in taking critical decisions. Three categories of users are targeted: (1) people involved in *planning mode*; (2) people involved in *support mode*; and (3) people involved in *training mode*. Under IMAGE, users are expected to develop a less-linear mindset capable of sustaining a more holistic approach.

Readers: The targeted readers are potential users but are also people interested in novelty in Visualization and in immersive virtual environments.

Potential Applications: There are many contexts into which the I-EXP concept (through the IMAGE concept) has potential. Here are two different examples both about circumstances where there is a need to disentangle CSs more quickly: a comprehensive approach and a cyber-threat. The first one is operational while the second one has more a technological flavour, although it may have important operational impacts. CAF recognises the importance of a comprehensive approach considering all dimensions of a situation, more than the military power alone. The various issues (ethnics, religious, ideological and material), the various power and influence (diplomatic, economic, informational ...) as well as the national and international public opinion and Medias are examples of the variety and diversity of the dimensions. A comprehensive approach is required to elaborate plans but moreover, a whole-of-government approach is required to achieve the strategic national objectives. Cyber is a quite new and complex challenge. Actually, CAF created the new environment Cyber, distinct from Land, Air and Sea, to face it. Risk analysis identifying critical components, investigating attack vectors and study impacts of successful attacks is needed to face cyber-threats impacting freedom of CAF manoeuvre. Such analysis requires explanatory and tailored visualizations, and an efficient collaboration between experts of friendly plans, enemy intents, computer networks and software applications.

Sommaire

Visualization to Augment Comprehension Models of a Complex Phenomenon: IMAGE V1 Exploration Module

Mokhtari, M.; Boivin, É.; Drolet, F.; DRDC Valcartier TM 2013-482 ; R & D pour la défense Canada – Valcartier; décembre 2013.

La complexité a toujours existé dans les mondes naturels et biologiques. Cependant, avec les progrès en sciences et technologie, l'homme est désormais capable de construire des objets dont la complexité se rapproche de celle de la vie elle-même. De nouvelles méthodes sont nécessaires pour s'attaquer à cette nouvelle complexité incluant de tels objets. Pour aborder les nouveaux défis de sécurité nationale et de défense devant traiter un éventail toujours croissant d'éléments, certains naturels, mais beaucoup fabriqués par l'homme, les scientifiques de RDDC proposent, à travers le projet IMAGE (partie intégrante du programme de Fonds d'investissement technologique), un concept de boîte à outils visant la collaboration d'experts œuvrant dans différentes disciplines qui tentent de parvenir à une compréhension commune d'une situation complexe (SC).

Le concept IMAGE : Le concept proposé vise à déchiffrer les SCs plus rapidement, ciblant spécifiquement la collaboration d'experts de différentes disciplines qui tentent de parvenir à une compréhension commune d'une SC. L'objectif du concept IMAGE est double: accroître la compréhension d'une SC et permettre aux individus de partager leur compréhension. L'élaboration du concept a principalement été guidée par trois principes ou hypothèses: (1) la compréhension itérative: une compréhension commune est atteinte grâce à la révision et au partage de représentations successives de la situation, (2) le contrôle des outils par l'homme: la compréhension commune est avant tout une tâche réalisée par l'homme et qui implique des membres de l'équipe utilisant les outils à leur manière, et (3) la synergie des technologies: la compréhension commune est mieux servie par la synergie de technologies que par une seule. Les chercheurs œuvrant sur le projet IMAGE ont identifié quatre modules complémentaires pour atteindre cette synergie: *Représentation*, *Scénarisation*, *Simulation* et *Exploration*. Le module de *Représentation* (I-REP) consiste à expliciter un modèle mental en un modèle de compréhension. À partir de ce modèle de compréhension, le module de *Scénarisation* (I-SCE) génère un modèle exécutable utilisé par le module de *Simulation* (I-SIM) qui apporte un niveau élevé d'interactivité permettant une investigation de l'espace des variables. Enfin, le module d'*Exploration* (I-EXP) fournit des outils puissants permettant aux experts d'inventer des vues qui apportent une signification importante aux grands ensembles de données générés par le module I-SIM.

Scénario: Le scénario retenu s'inspire des situations d'attaque de convois logistiques rencontrées par le ministère de la Défense nationale et les Forces armées canadiennes (FAC) déployées en Afghanistan. L'idée d'un scénario mettant de l'avant la coévolution entre un convoi et des insurgés a été mise en œuvre en deux parties: la première à un niveau inférieur de complexité nommé *Tactique* (une mission correspond à une simulation unique) et l'autre à un niveau supérieur de complexité nommé *Standard Operating Procedure*, ou *SOP* (une mission correspond à une centaine de missions *Tactiques*). Les deux niveaux ont été rendus déterministes pour réduire la variabilité des données expérimentales.

Le concept Exploration (I-EXP): Le concept I-EXP vise à produire, de manière individuelle ou collective, des vues (nommées aussi *visualisations*) explicatives et adaptées que seuls des mots ne peuvent communiquer clairement. Ces vues, dont le but est d'apporter un sens aux données, doivent générer, stimuler, accroître ou accélérer l'effort de compréhension. Le concept s'appuie sur des outils qui mettent en œuvre des techniques et/ou des mécanismes de visualisation et d'interaction, qui profitent du potentiel de différentes plates-formes en termes de technologie et d'exploitation de l'information sensorielle humaine (principalement *perception* et *action*). Le concept I-EXP a été développé à travers le prototype I-EXP Version 1 (V1) composé de I-EXP V1 *Tactique* et I-EXP V1 *SOP*. I-EXP V1 a fait partie de l'expérience cognitive IMAGE V1 axée sur la compréhension individuelle. Les composants matériels qui composent les plates-formes supportant les outils I-EXP s'étendent de la configuration traditionnelle composée de l'écran LCD / clavier / souris à une plate-forme de plus haute technologie exploitant les technologies immersives menant à l'immersion de l'utilisateur dans un environnement virtuel. En fait, le module I-EXP met l'accent sur la bonne utilisation des technologies afin de répondre aux besoins d'exploration de l'utilisateur.

Les outils d'Exploration (I-EXP): Dans l'esprit du domaine de la *Visualisation*, domaine dont la tâche principale est de permettre à l'information d'être extraite / dérivée des données, les outils I-EXP V1 ont été pensés pour aider les experts et/ou utilisateurs à comprendre et interpréter les ensembles de données en exploitant les différents types de rendu graphique (par exemple, graphiques, diagrammes, *charts*, etc.) qui sont des artefacts visuels représentant les données, illustrant les relations et les tendances entre les données, présentant de l'information (selon une conversion appropriée des données), et permettant également l'analyse et les comparaisons entre les représentations graphiques d'ensembles de données. Les outils I-EXP V1 abordent également l'affichage dynamique des tendances dans les données et l'interaction avec les données affichées. Par conséquent, la boîte à outils a été conçue pour : (1) explorer et comparer des ensembles de données, (2) extraire de l'information / la connaissance; (3) découvrir des tendances inattendues dans les données ou trouver des modèles, et, enfin, (4) comprendre les aspects non intuitifs spécifiques des SCs. Pour atteindre ces objectifs, le module I-EXP exploite différentes techniques telles que (1) le filtrage (pour se concentrer sur des sous-ensembles de données pertinentes) et le *brossage* de données (qui supporte la liaison visuelle des diverses données et résout le problème de la fragmentation visuelle des représentations de données multi variées), (2) la comparaison d'ensembles de données, (3) l'exploration des ensembles de données multi-niveaux (par exemple, aux niveaux *Tactique* et *SOP*), et (4) le rendu stéréoscopique en temps réel (pour la version immersive).

Les utilisateurs: Les utilisateurs (potentiels) ciblés de IMAGE, lorsque finalisé et déployé, sont des personnes (individus ou équipes) qui sont impliquées dans la prise de décision critique. Trois catégories d'usagers sont visés: (1) les personnes impliquées dans le *mode de planification*; (2) les personnes impliquées dans le *mode de soutien*; et (3) les personnes impliquées dans le *mode de formation*. Avec IMAGE, les utilisateurs sont appelés à développer un état d'esprit moins linéaire capable de soutenir une approche plus holistique.

Public cible: Les lecteurs ciblés sont des utilisateurs potentiels, mais aussi des personnes qui s'intéressent à la nouveauté dans le domaine de la visualisation et des environnements virtuels immersifs.

Applications potentielles: Il existe de nombreux contextes pour lesquels le concept I-EXP (à travers le concept IMAGE) a un potentiel. Voici deux exemples où il est nécessaire de déchiffrer plus rapidement les SCs: une approche globale et une menace cybernétique. Le premier est un exemple opérationnel tandis que le second est un exemple à saveur plus technologique, même s'il peut avoir d'importantes répercussions opérationnelles. Les FAC reconnaissent l'importance d'une approche globale tenant compte de toutes les dimensions d'une situation, plus que la puissance militaire seule. Les diverses questions (d'ordre ethnique, religieuse, idéologique et matérielle), la puissance et l'influence (d'ordre diplomatique, économique, informationnel ...) ainsi que les opinions publiques nationale et internationale et les médias sont des exemples de la variété et de la diversité de dimensions. Une approche globale est nécessaire pour élaborer des plans mais une approche pangouvernementale est plus que nécessaire pour atteindre les objectifs nationaux stratégiques. La cybernétique est un défi tout à fait nouveau et complexe. En fait, les FAC ont créé le nouvel environnement Cyber, distinct de Terre, Air et Mer, pour y faire face. L'analyse de risques identifiant les composants critiques, investiguant les vecteurs d'attaque et les impacts de l'étude des attaques réussies est nécessaire pour faire face aux menaces cybernétiques ayant une incidence sur la liberté de manœuvre des FAC. Une telle analyse nécessite une collaboration efficace entre les experts de la planification côté ami, ceux des intentions ennemies, ainsi que les experts des réseaux informatiques et des applications logicielles.

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1 Introduction

Complexity has always existed in natural and biological realms. However, with the advances in Sciences and Technology, humanity is now capable of building artefacts whose complexity approaches those of life itself. There is a need for using new approaches to tackle this *new complexity* including such artefacts. To address the new defence and national security challenges of dealing with an ever increasing range of elements, some natural but many human-made, DRDC scientists propose, through the IMAGE project, a toolset concept targeting the collaboration of experts from different disciplines trying to reach a shared comprehension of a complex situation (CS) (Lizotte, Bernier, Mokhtari, & Boivin, 2012). The IMAGE project was part of the Technological Investment Funds (TIF) program. Researchers from various research fields and organizations contributed to the effort: software, computer and electrical engineering at DRDC Valcartier and Université Laval (Computer Vision and Systems Laboratory); cognitive psychology at Université Laval (Cognition Distribution Organisation Technologies Laboratory); and operational research at DRDC Centre for Operational Research and Analysis.

Figure 1 depicts the IMAGE concept through a wheel. The centre of the wheel illustrates that the CS understanding effort is fully driven by human (experts, decision makers … – in an individual way and/or in a team). The wheel contour identifies the various technologies available while the in-between spiral represents, through different modules, the iterative and incremental development of a comprehension from individual perspectives evolving to a common comprehension of the CS. IMAGE researchers have identified capabilities that each of the four modules can bring:

- Knowledge Representation (I-REP): assists experts in recording any piece of information they wish to include, and asserting any type of links between them as well as inferring conclusions from this set of beliefs. Each expert should be able to create an *individual comprehension model* and share it with other experts. After some collaborative work, the I-REP team efforts result in a *common comprehension model* i.e. a set of conceptual graphs representing the CS ((Lizotte et al., 2012), Chapter 4);
- Scenarization or Scenario Scripting (I-SCE): supports agent-based modelling of the CS. Starting from the common comprehension model (I-REP), I-SCE assists experts in working out an *executable model*. Comprehension model items relevant for a simulation are isolated and standardised using a predefined scenario scripting vocabulary. Required details, such as properties and behaviour implementations are added to produce an executable model ((Lizotte et al., 2012), Chapter 5);
- Simulation (I-SIM): necessitates a high level of interactivity enabling investigation of the space of variables in order to test hypotheses about the CS. I-SIM uses as input the I-SCE executable model and enables experts to initiate and control *parallel simulations* by changing parameter values and allowing comparison from what-if bifurcation points ((Lizotte et al., 2012), Chapter 6); and
- Exploration (I-EXP): (focus of this document) allows experts to invent *views* as the comprehension progresses. In particular, I-EXP aims at extracting useful information / knowledge from datasets generated by I-SIM. It combines visualization and rich user interactions allowing experts to explore such datasets. The resulting views are inputs to enhance comprehension models worked out by I-REP.

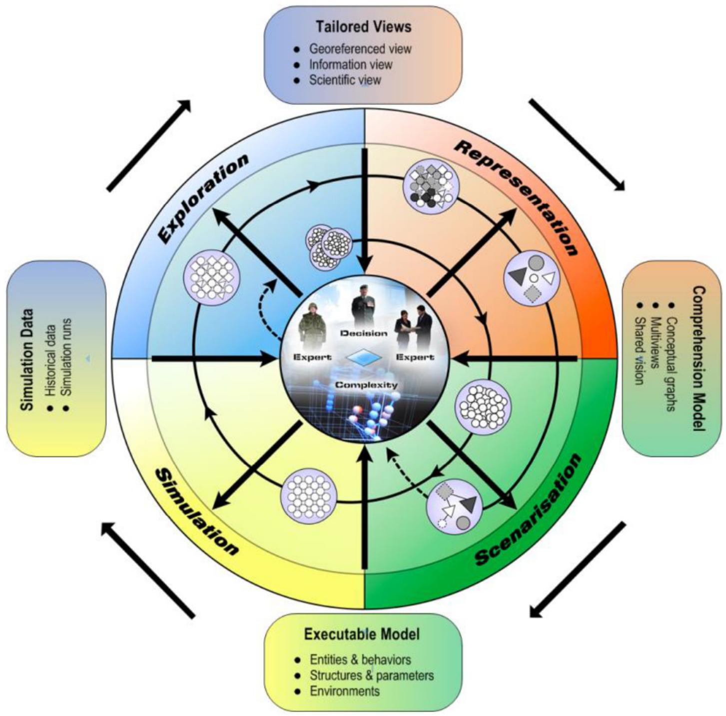


Figure 1: The IMAGE wheel

Figure 2 illustrates the I-EXP concept which aims to produce, individually or collectively, explanatory and tailored (static and/or dynamic) views in ways that words cannot communicate clearly. These views, in order to bring a meaning to (raw and/or processed) data, have to generate, stimulate, increase or accelerate the understanding effort leading to the CS comprehension. The concept is supported by the I-EXP tools, which implement visualization and interaction techniques and/or mechanisms by, taking advantage of the potential of different platforms in terms of technology and in terms of exploitation of human sensory information (mainly *perception* and *action*). The I-EXP concept has been developed through two main prototypes: the I-EXP Version 1 (V1) (specific focus of this document) composed of I-EXP V1 Tactical (at a *low level* of complexity) and I-EXP V1 SOP (at a *high level*[1] of complexity), and the I-EXP Version 2 (V2). I-EXP V1 was part of the IMAGE V1 cognitive experiment focussing on individual comprehension ((Lizotte et al., 2012), Chapter 8) while I-EXP V2 was part of the IMAGE V2 feasibility effort and focused on immersive virtual exploration and collaboration aspects (Mokhtari, Boivin, & Drolet, 2013).

As represented in Figure 2, hardware components composing the platforms supporting the I-EXP tools span from a traditional hardware setup composed of LCD screen / keyboard / mouse to a more high-tech platform exploiting immersive technologies leading to the user's immersion in a virtual environment (VE). In fact, the I-EXP module puts emphasis on the proper use of technologies in order to fulfill the user's exploration needs: from (1) conventional non-immersive systems (no immersion, limited or traditional interaction), to (2) hybrid systems combining the adequate use of non-immersive systems and immersive interactive systems (in terms of head-centered interaction, access to traditional interaction tools augmented by virtual gadgets) up to (3) high-end fully

[1] The meaning of "low level" and "high level" is given in section 3.1.

immersive systems (in terms of large displays, large field of view, head- / hands-centered interaction, more natural interactions). Immersion can be achieved to varying degrees by using advanced human machine interfaces (involving sensory modalities – visual, auditory, tactile, olfactory – and body tracking, etc.), and by exploiting more natural interaction with the immersive VE (IVE). Immersion may lead to a sense of presence which is a psychological emergent property of an immersive system (Sadowski & Stanney, 2002). This property refers to the user's sense of "being there" which means that the user feels he is part of the environment because he forgets that his perceptions are mediated by technologies. Immersion is a *necessary* rather than a *sufficient* condition for presence (Youngblut, 2006).

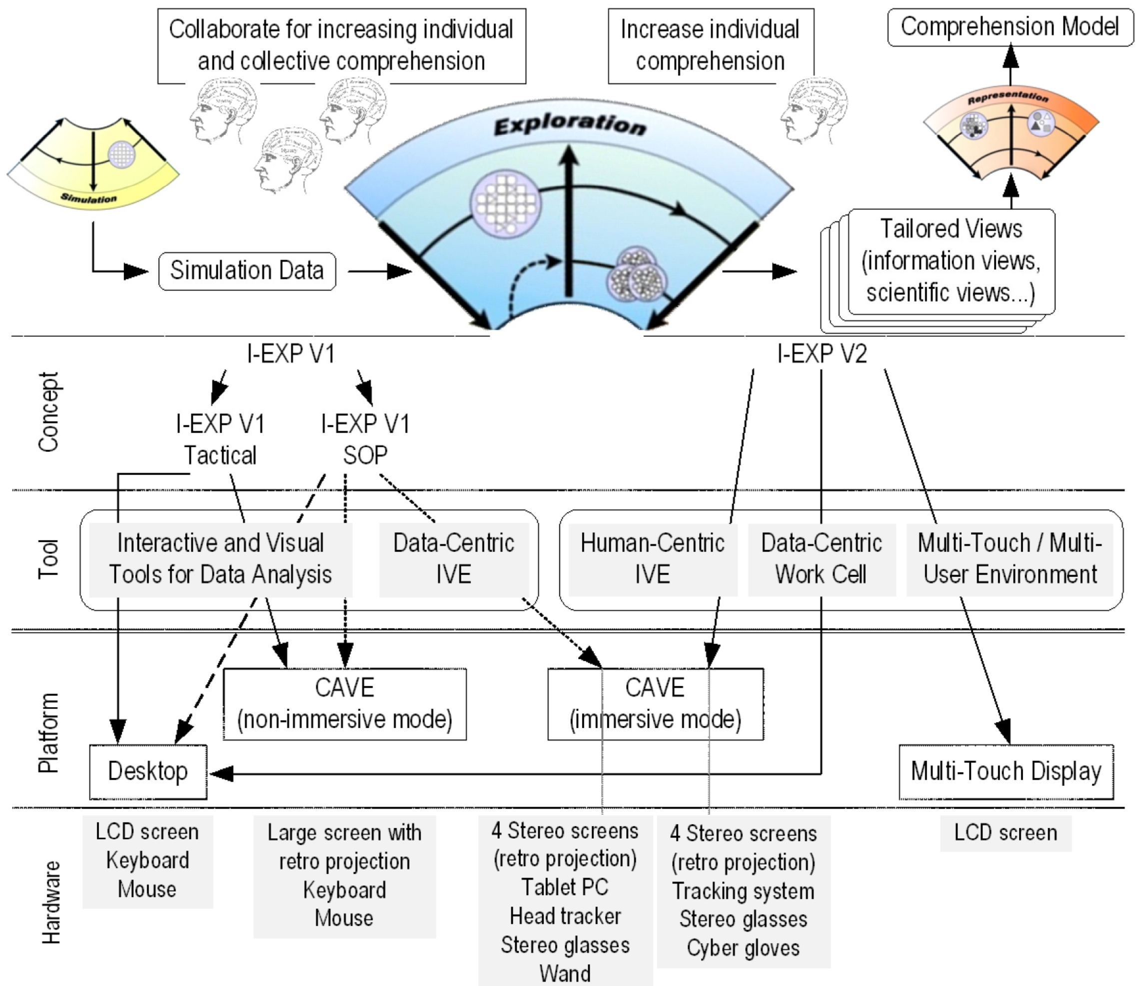


Figure 2: The I-EXP module at a glance

The current document focusses on the I-EXP V1 module and is built as follows. Chapter 2 introduces requirements – defined by the IMAGE team – that guide the I-EXP module building, and also familiarizes readers to exploration aspects exploited in the module. Chapter 3 describes the case studies that are used as well for the cognitive experiments as to draw the tools themselves. Chapter 4 presents the architecture behind the I-EXP V1 toolset as well at the desktop level as at the CAVE level. Finally, the document concludes by summarizing the main findings and proposing potential applications for the I-EXP concept.

This document is accompanied by a set of videos that show I-EXP tools in action and their relation with other tools (from other modules such as the I-SIM module), exemplify different aspects of the tools and help readers to better understand the tools themselves and what they look like. (See Annex B, available on request).

2 Exploration module in IMAGE

The core objective of the I-EXP module is to develop a high-level understanding of the data produced by the I-SIM module and to externalize this understanding in *explanatory* and *tailored views* (such as scientific, geospatial…). At this point, the reader has to keep in mind that the I-EXP module aims to externalize *a view of the world* while the I-REP module focusses on externalizing *a view of the mind*.[2] Internal (or even mental) visualization is a means of instantiating the mental model corresponding to phenomenon understanding. IMAGE seeks to *externalize* that model through a set of capabilities implemented in a *visualization* framework. *Externalize* means making phenomenon understanding *explicit* and *sharable*. In fact, IMAGE *packages* a mental model of understanding in a form that can be *exported*. And the I-REP module products that package that could take a variety of forms. IMAGE has selected the *visualization* as its main communication channel. Visualization is a means to achieve effective human communication (e.g. as quality printing contributes to effective distribution of text). *Interactive visualization*[3] is a good way to explore a CS because this technique is conducive to incrementally building a mental assessment of the CS. Visualization is exploited as a support to the exploration process (I-EXP) and as a vehicle for (explicit) representation (I-REP). These are two distinct modes and this report addresses only the first one. *Playing* with "what if's" (I-SIM) during exploration (I-EXP) *is not representation* (I-REP) but a key component of the process leading to it. Visualization is everywhere in IMAGE and it must strongly adhere to usability principles that are essential for human – machine synergy. But its two modes call for somewhat different usability emphasis, i.e. the I-EXP module promotes exploration as a highly dynamic activity (because rapid interactiveness is key); and the I-REP module relates to higher abstraction levels (e.g. navigating among various knowledge domains, tracking through asserted linkages). The I-EXP module does not work on the *final visualization* of the understanding representation but conducts to its building.

Data exploration[4] allows users to reduce the amount of data so that they can focus on the key aspects of relevant data before analysis can be achieved. Thus, *data exploration* is considered as a methodology using *manual techniques* in order for users to find their way through data sets and bring important and relevant data to be focused and utilized for analysis. Though such a methodology can be applied to data sets of any size or type, its *manual* nature makes it more reasonable for smaller data sets, especially those in which the data has been carefully gathered and constructed (such as the I-SIM module). *Data exploration* is performed by using *data visualization techniques* (any technique "for creating images, diagrams, or animations to communicate a

---

[2] This distinction has often been expressed by Dr. Denis Poussart in these terms and the rest of the paragraph is aligned with some of his reflections accompanying this distinction.
[3] *Interactive visualization* "is a branch of graphic visualization in computer science that involves studying how humans interact with computers to create graphic illustrations of information and how this process can be made more efficient". (http://en.wikipedia.org/wiki/Interactive_visualization)
[4] In most cases, narrowing an information search may cause problems because one may lost important perspectives of the relevant data among the unrelated data. There are generally two methodologies users can have to get relevant data from huge datasets: *manual* and *automatic*. They are more commonly known as *data exploration* for manual and *data mining* for automatic. Although they are categorized as such, these terms are not really well defined in the real information technology sense. But in line of these definitions, IMAGE is more interested in *data exploration* than in *data mining*.

message"[5]) and also by applying *human – computer interaction (HCI) techniques* (any technique for improving interactions between users and data/information / computers). "*Interaction techniques* essentially involve *data entry* and *manipulation*, and thus place greater *emphasis on input* than output. *Output* is merely used to convey affordances and provide *user feedback*. The use of the term input technique further reinforces the central role of input. Conversely, techniques that mainly involve *data exploration* and thus place greater *emphasis on output* are called *visualization techniques*".[6]

This chapter firstly recaps the I-EXP requirements as well in terms of project objectives as in terms of user and architecture. It also reviews the *Visualization* requirements that are closely intertwined with the I-EXP requirements but expressed differently. Then, the chapter pursues with an overview of literature in the field of *Visualization* and its related issues. This overview was realized, covering particularly the following topics: geospatial, scientific, information and knowledge visualization, and the use of visualization in IVEs. Documents, work and relevant tools were selected and mentioned and/or summarized along the text.

2.1 I-EXP requirements (generic)

This section presents the I-EXP requirements as expressed during a workshop which took place in July 2008 (2th and 3th July) at DRDC (Valcartier) and gathering all collaborators. The I-EXP requirements are integral part of the IMAGE requirements categories defined earlier in the project (formerly known as 1- *expressing and sharing understanding*, 2- *looking for something*, 3- *handling concepts and relationships*, 4- *interacting with IMAGE*, 5- *analyzing the situation*, 6- *testing hypotheses*, 7- *supporting users*, 8- *supporting experimentation*, and 9- *miscellaneous*). In addition, IMAGE requirements were prioritized for each category (see 0 for more details).

During the workshop, the I-EXP requirements were subdivided in three main groups (in the following, each one is related – → – to its label in 0 and also to the (sub-) sections describing the (part of) tool(s) developed for the I-EXP V1 module and addressing the issue of the requirement):

1. Requirements in terms of *project objectives* such as I-EXP must provide
    a. visualization paradigms that fit with the *scenario intent*. For that purpose, the three well-known visualization paradigms – geospatial, scientific and information visualizations – were suggested (exploiting both 2D and 3D aspects – including immersive aspect);

        → P1-4.2 (see sections 3.3.1 and 3.3.2), P1-4.4 and P1-5.1, see sections 3.2 and 3.3 describing the I-EXP V1 toolset

[5] http://en.wikipedia.org/wiki/Visualization_(computer_graphics)
[6] http://en.wikipedia.org/wiki/Interaction_techniques

b. visualization that fit the *user cognitive capabilities*[7];

→ closely related to point a. but taken in charge by the Cognitive Psychology Research Group

c. visualization that fit with the *(cognitive) experiment* (i.e. measure user actions);

→ P1-8.1, see point g.

2. Requirements in terms of *architecture* such as I-EXP

d. must provide visualization capabilities in IVEs[8];

→ P1-4.1 and P3-4.2, see section 3.3.3

e. must manipulate data sets coming from the I-SIM module (different data formats could be exploited – e.g. *xml*, *excel* files, open source databases such as *mysql*…);

→ P1-4.2, P1-4.3, and P1-6.1, see sections 3.3.4 and 4.1

f. must be supported by help tools;

→ P1-7.1 (implemented at the beginning of the experimental procedure, not directly inside the tools – e.g. supported by callouts)

g. must log user actions[9] (for cognitive experiment purpose);

→ P1-8.1, for the sake of the data analysis, I-EXP V1 recorded a log entry for each significant tool (application) event e.g. the user activates the spatial simulations distribution display, selects MoP to display (for comparison) or activate the immersion aspect. Chapter 8 in (Lizotte et al., 2012) presents the most interesting findings from the various data collected in this huge log.

h. could integrate different types of visualization tools;

→ P2-5.2, see sections 3.2.4, 4.2 and 4.3 (*Tableau Software*[10], and end-user application and *Eye-Sys*[11], an API, were integrated)

3. Requirements in terms of *user* such as

a. user must be able to explore, brush, compare, combine views;

→ P1-2.3, P1-4.2, P2-2.1 and P3-4.2, see sections 3.3.1 and 3.3.2 (more [externalized / useful] in the analysis tools developed at the SOP level)

---

[7] In terms of apprehension and intuition (structure and content of the *visualization* must be readily and accurately perceived and comprehended), congruence (structure and content of the *visualization* must correspond to the structure and content of the *mental representation* to be instilled), and respect of HCI principles.
[8] Reminder: a CAVE (CAVE Automatic Virtual Environment) is an example of an IVE.
[9] This requirement is a problem for a majority of end-user application.
[10] See section 4.2.
[11] See section 4.3.

b. user must be able to refine views;

→ P1-4.3 and P2-2.1, see sections 3.2 and 3.3

c. user actions (I-EXP) could highlight / set focus on elements in other views (I-SIM, I-EXP, I-REP);

→ P2-4.1, according to the synchronization between the I-SIM and I-EXP modules (both at Tactical and SOP levels), only user actions in the I-SIM module can highlight / set focus on elements in the I-EXP module, see section 3.3.4

d. user must be able to create and delete views "on demand" (by exploiting almost as possible an "in time" view generation method able to translate user needs);

→ P2-5.2, see sections 3.2.5, 3.2.6, 3.3.1.2 and 3.3.2

e. user could create or use view templates (could be useful for IMAGE experiment);

→ P2-5.1, see sections 3.2.2, 3.2.3, 3.2.5 and 3.3.1.1 for proposed view templates

f. user must be able to archive views;

→ P2-5.2 (not implemented at this time)

g. user must be able to attach notes on views;

→ P2-5.3 (not implemented at this time)

h. user must be able to take snapshots of views;

→ P2-5.4 (currently available by the way of the traditional *Print Screen* button – desktop version)

i. user actions could be for observation purposes (I-EXP) as well as modification purposes (I-SIM);

→ Pna-8.1

A part of the workshop was also dedicated to define characteristics necessary to implement the set of I-EXP requirements as well for the whole project (in terms of *architecture*, *data*, *usability* and *rendering*) as for the scenario intent (in terms of *view paradigms*). The correlation between requirements and characteristics is given by the description of functional properties expressed as a matrix shown on Figure 3.

X = Required, L = Low, M = Medium, H = High.

	Characteristics / Needs	IMAGE: 1. Architecture: 1a. Plug-in capabilities	1b. GMS (Global Messaging System)	1c. ULS (User Logging System)	2. Data: 2a. Compatibility (XML, ODBC, ...)	2b. Selection and filtering	2c. Real time feeding	3. Usability: 3a. View control (navigation, POV, zoom, ...)	3b. View enhancement (color, scaling, notes, ...)	3c. View manipulation (view selection, ...)	3d. Saving capabilities	3e. Help tools	4. Rendering: 4a. Real time	4b. Multi-views	4c. Multi-screens	4d. Stereoscopy	Convoy Scenario: View Paradigms: GeoViz view	SciViz view	InfoViz view	Functionality level targeted: V1	V2
Objectives	A. I-EXP must provide visualization paradigms that fit with the **scenario intent**						X	X	X	X			X	X			M	H	L	M-H	H
	B. I-EXP must provide visualization that fit with the **user cognitive capabilities**						X	X	X	X			X	X	X	X	L	H	?	M	L-M
	C. I-EXP must provide visualization that fit with the **experiment**		X	X				X	X	X	X	X	X	X	X	X	M	H	L	M	L-M
Architecture needs	D. I-EXP must provide CAVE visualization capabilities							M							M	H				M	M-H
	E. I-EXP must manipulate data sets coming from the I-SIM module	M			H	M	M													H	H
	F. I-EXP could integrate different types of Visualization tools (API, End-user app., ...)	H			H															L-M	L-H
	G. I-EXP must be supported by help tools											X								L	L-M
	H. I-EXP must log user actions		M	H																L	L-M
User needs	I. User must be able to create and delete views "on demand"	H		L	H	M	M	M	M	M			M	H						L-M	M
	J User could create or use view templates	H		L				M	M	M	M			L			L	H	L	L-M	M-H
	K. User must be able to refine views			L				H	H	H										L-M	M
	L. User must be able to explore, brush, compare, combine views			L				M		H			L	M						L-M	M
	M. User must be able to attach notes on views			L					H	M										L	M-H
	N. User must be able to archive views			L							H									L-M	M-H
	O. User must be able to take snapshots of views			L							H							H		M	M-H
	P. User actions could be for observation purposes (I-EXP) as well as modification purposes (I-SIM)		H	L						H				H						L	L-M
	Q. User actions (I-EXP) could highlight / set focus on elements in other views (I-SIM, I-EXP, I-REP)		H	L						H				H						L	L-M

Figure 3: Description of functional properties of the I-EXP module – Mapping of requirements and functionalities in terms of both IMAGE and scenario intents

The three targeted visualization paradigms were also thought as required by the project and were correlated to functionalities needed to implement them (see Figure 4).

	Characteristics / Requirements	4. Rendering: 4a. Real time	4b. Multi-views	4c. Multi-screens	4d. Stereoscopy	5. Specific functionalities: 5a. Realism / Quality	5b. Augmented Information	5c. Exploratiion technics	5d. Multi-dimentional	5e. Comparaison technics	Functionality level targeted: V1	V2
Views	GeoViz view	H	L	H	H	M	H	L	L	M	M-H	M-H
	SciViz view	M	H	H	H	H	M	H	H	H	M-H	M-H
	InfoViz view	?	?	?	?	M	H				L	L-M

Figure 4: Description of functional properties of the visualization paradigms in terms of rendering functionalities and specific functionalities for the prototypes to develop during the two phases of IMAGE project

2.2 Visualization requirements (specific)

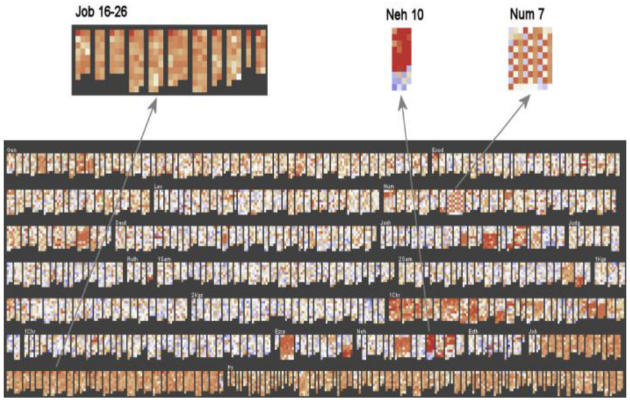
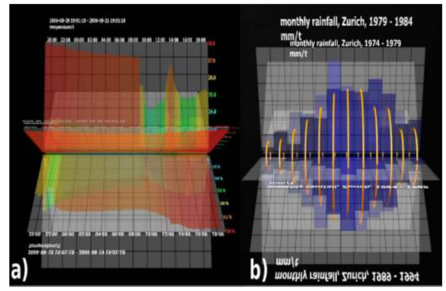
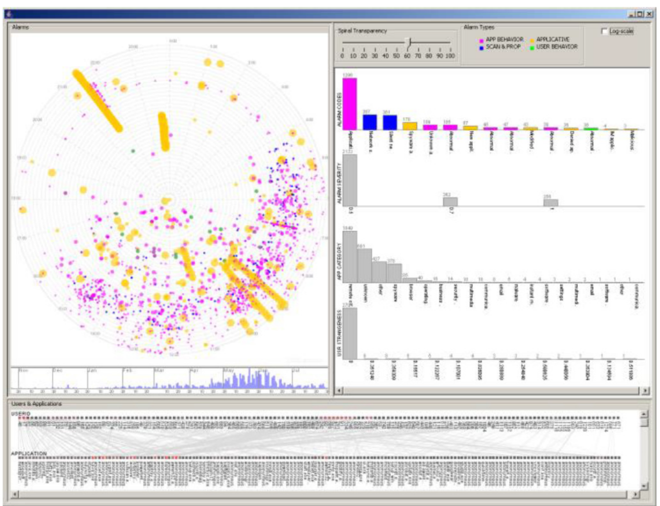
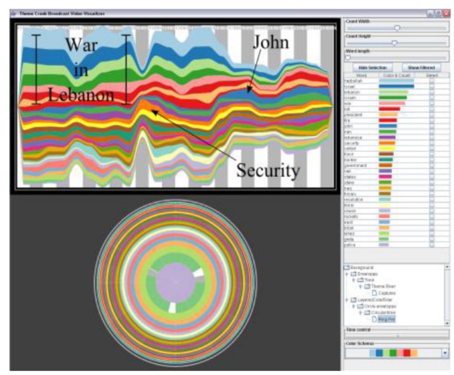
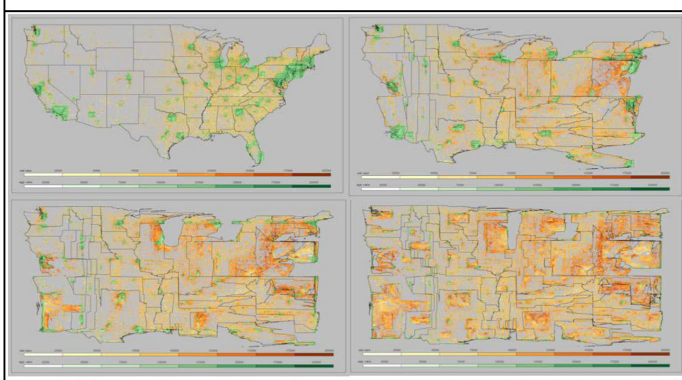
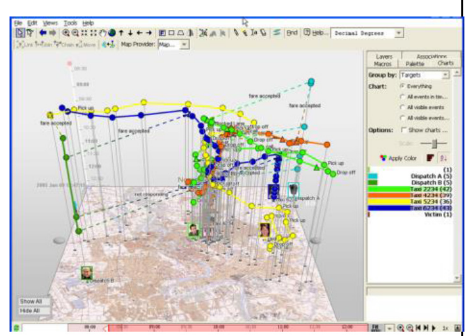
Four main requirements in *Visualization* (techniques, approaches…) were also expressed during the workshop: (1) understanding situations / discovering patterns, (2) on-demand visualization, (3) coordinated views, and (4) integrated software solution. Statements associated to these visualization requirements are presented in the next subsections.

2.2.1 Requirement 1 – Understand / discover

This first statement (more related to requirements in terms of project objectives) has to create or exploit existing innovative view paradigms to understand (part of) data and also to discover the unexpected in data12. This statement is partially solved by using (a combination of) view paradigms exploiting geospatial, scientific and information visualizations. Table 1 shows different examples of research done in this trend.

[12] The *Visual Analytics* community is related to this statement, and consequently all activities connecting this community (e.g. IEEE VAST conferences, IEEE Information Visualization Journal…).

Table 1: Examples of views answering the requirement 1

<table>
<tr>
<td>Literature fingerprinting of the Bible (blue pixel means long sentence and brown pixel means short sentence) (Keim & Oelke, 2007)</td>
<td>Rotary diagrams (Einsfeld, Ebert, & Wolle, 2007)</td>
</tr>
<tr>
<td>Visual correlation of network resources with evolution of alarms (Bertini, Hertzog, & Lalanne, 2007)</td>
<td>River metaphor – News broadcast analysis (Ghoniem, Luo, Yang, & Ribarsky, 2007)</td>
</tr>
<tr>
<td>Scalable pixel-based visual interface (Sips, Schneidewind, Keim, & Schumann, 2006)</td>
<td>GeoTime – Geo temporal patterns detection (Eccles, Kapler, Harper, & Wright, 2008)</td>
</tr>
</table>

2.2.2 Requirement 2 – On-demand visualization

The second statement (more related to requirements in terms of *user*) has to exploit a flexible method to generate views in real time in order to interact with views by tailoring them at any time during the IMAGE process. An interesting example is Tableau Software[13], an end-user application[14] that exploits a flexible method to generate views in real time, allows interaction with views by customizing them at any time, but analyses only 2D data (see Figure 5). This visual analytics tool was included in the I-EXP V1 toolset to explore 2D data in a different but complementary way in opposite to in-house tools.

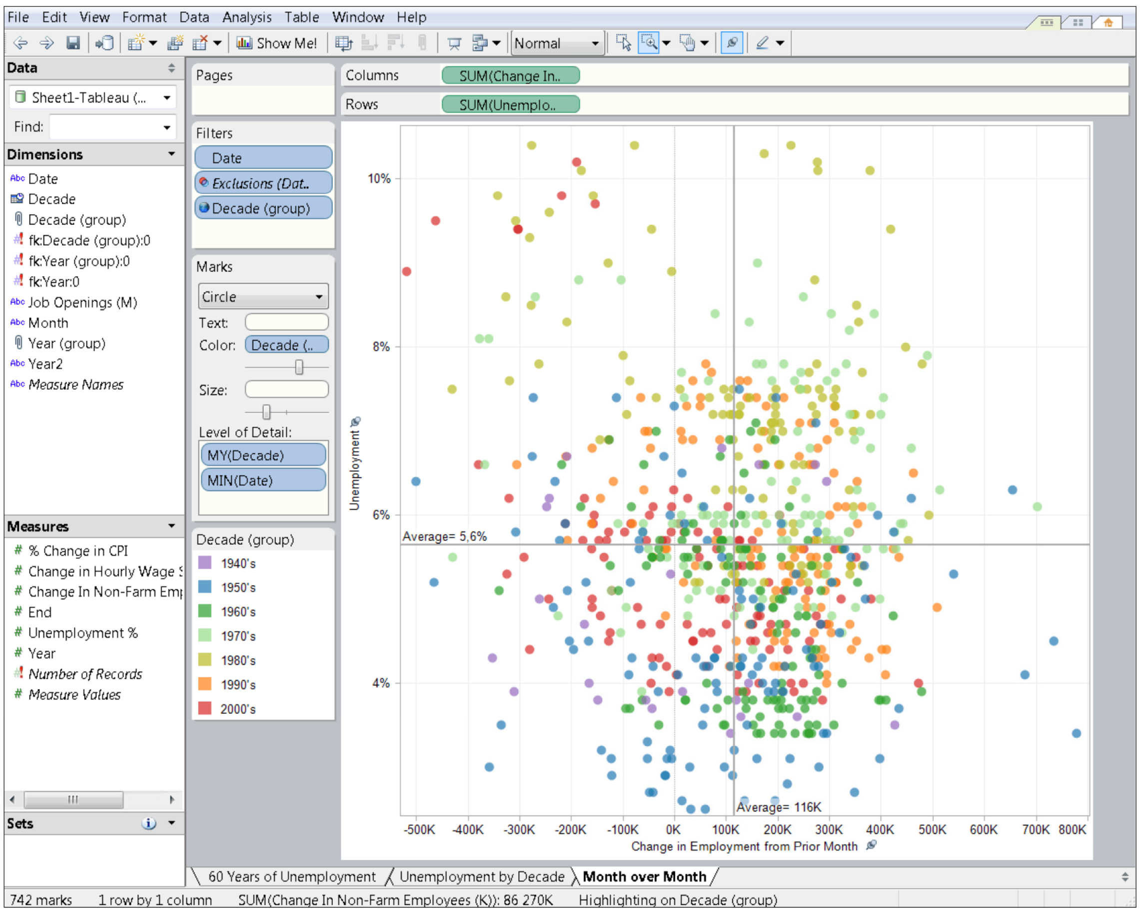


Figure 5: Snapshot of Tableau Software in action

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[13] http://www.tableausoftware.com/

[14] Note that the requirement "I-EXP must log user actions", stated in section 2.1, is a problem for a majority of end-user application such as Tableau Software.

2.2.3 Requirement 3 – Coordinate views

The third statement (more related to requirements in terms of *user*) has to product coordinated views because data subset could have more than one representation and linking these representations is of interest for the understanding process. An interesting example is given by the JIGSAW tool[15] shown on Figure 6. Another interesting aspect is the data brushing[16] approach that supports visual linking of various data and addresses the visual fragmentation problem of multivariate data representations) (Becker & Cleveland, 1987). Data brushing can be used for highlighting data interrelationships (Figure 7). It can be used as the first step for further data filtering, walking through hierarchies of numeric or categorical data…

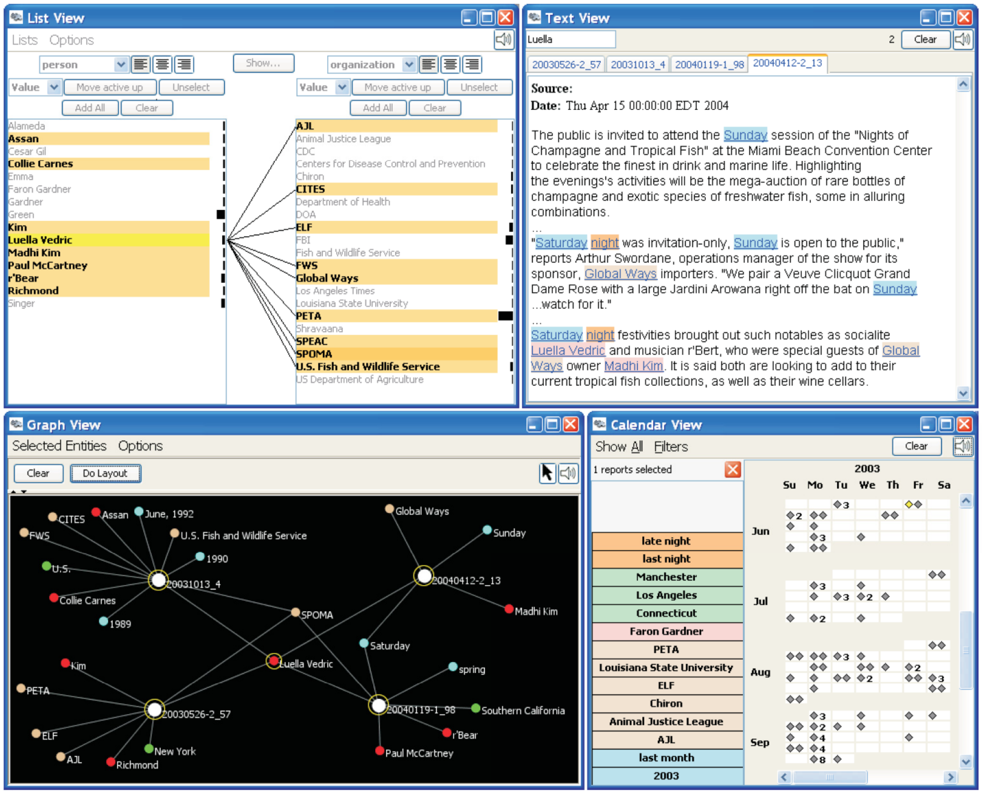


Figure 6: JIGSAW – Visual analytics for exploring and understanding document collections

[15] http://www.cc.gatech.edu/gvu/ii/jigsaw/

[16] Brushing is the process of interactively selecting data items from a visual representation. The original intention of brushing is to highlight brushed data items in different views of a *visualization*.

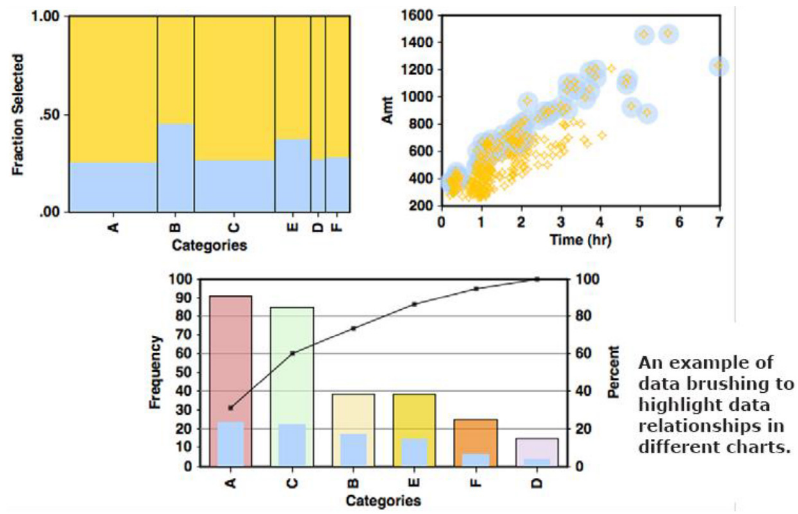


Figure 7: Example of data brushing

2.2.4 Requirement 4 – Integrated software solution

The last statement (more related to requirements in terms of *architecture*) has to exploit an open architecture or an architecture having SDK capabilities in order to (a) implement visualization paradigms, (b) develop a generic interface layer between the I-SIM and I-EXP modules, and (c) integrate interaction devices for exploring data. Eye-Sys Software[17] is the selected technology that is a data-driven real time visualization system (tool snapshot visible on Figure 8, deeper / thorough explanation is given in section 4.3).

[17] http://www.eye-sys.com/

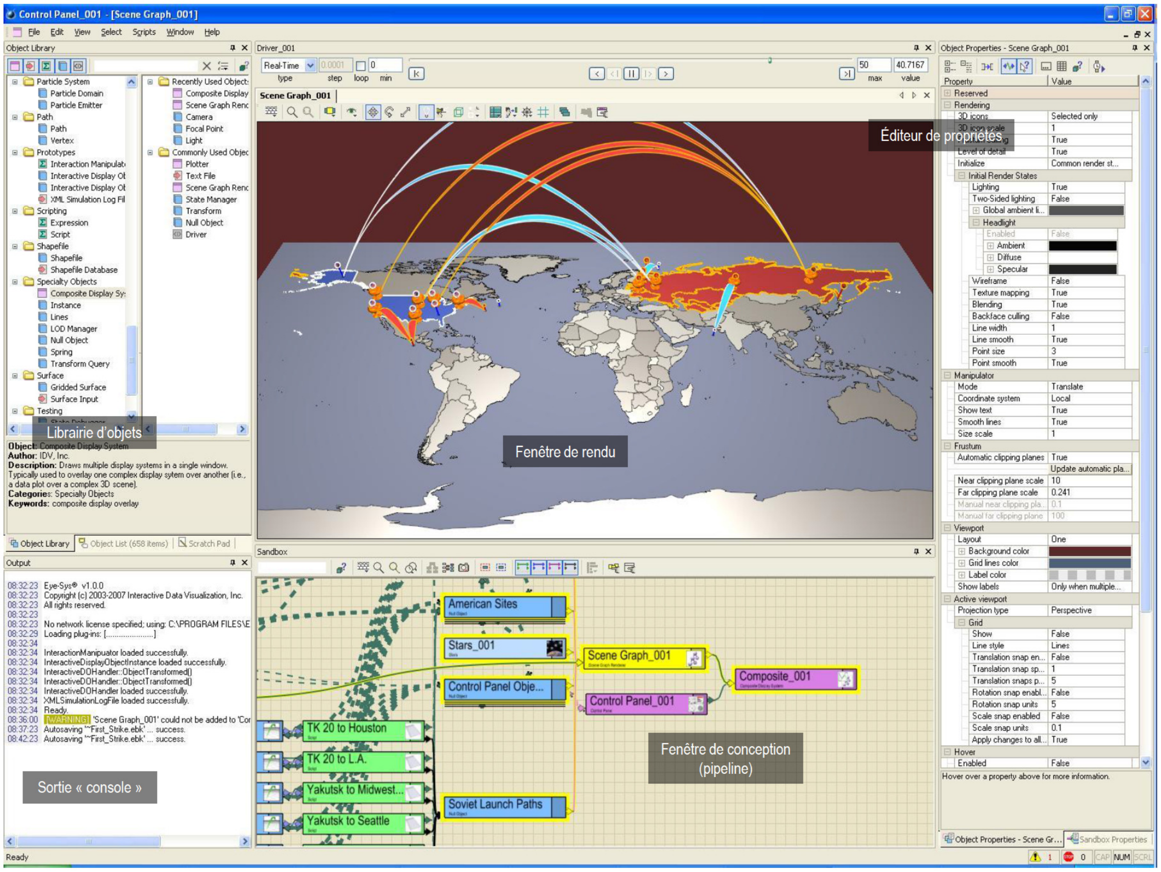


Figure 8: A snapshot of Eye-Sys Software in action

2.3 Visualization paradigms

By definition, *visualization* is "the act or process of interpreting in visual terms or of putting into visible form"[18]. *Data visualization* is simply the study of the visual representation of *data*. In other words, a *visualization view* – or *view* or *visualization* – is defined as a graphical representation of concepts or *data*, which is either an internal construct of the mind or an external artifact supporting decision making and/or action. Visualization views may range from simple to complex, but no matter the level of complexity and the type of data, a visualization view is intended to help interpret data in a meaningful way. *Data* can be defined as the raw of facts, doesn't really have a meaning at all on its own. When data has been processed, data become *information* which has a valuable meaning for human who visualizes it. And *knowledge* corresponds to a transformation of information triggering people to decide and act. The presentation of the relationships among data, information, and knowledge in a hierarchical arrangement has been part of the language of *information science* for many years[19]. In the IMAGE project, *knowledge* aspect is taken in charge by the I-REP module. Visualization domain was historically categorized into two major areas:

[18] http://www.merriam-webster.com/dictionary/visualization
[19] http://en.wikipedia.org/wiki/DIKW_Pyramid

information visualization and *scientific visualization*. And *data visualization* is a slightly narrower domain and just an umbrella expression under which the different categories can be grouped.

Visualizing.org (a community of people making sense of complex issues through data and design) has been working on a taxonomy of *data visualization*[20]. This taxonomy is composed of eight categories that "are meant to describe a visualization's primary method of comparing data" and depicted by Figure 9.

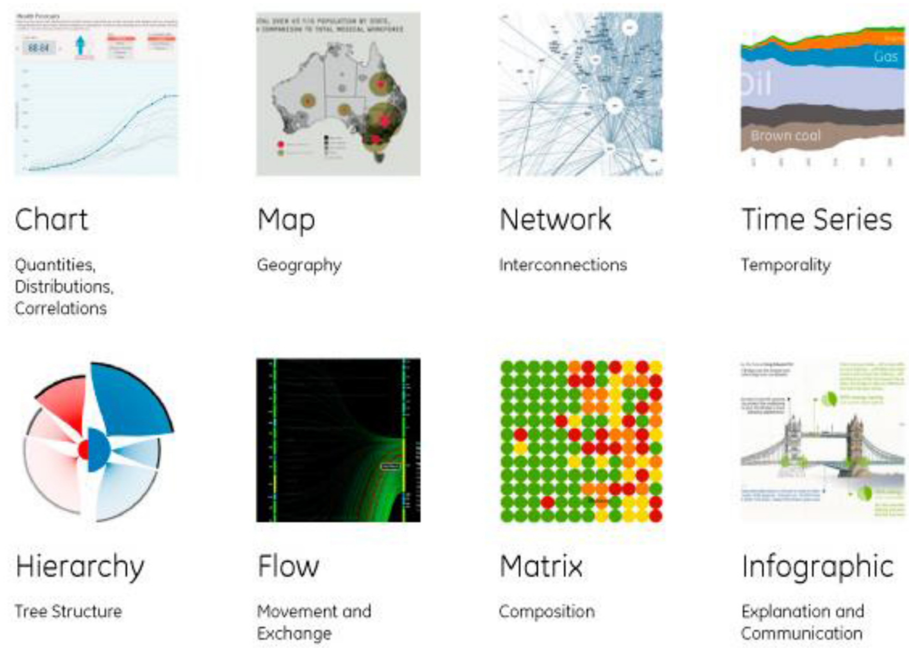


Figure 9: Taxonomy of data visualization (http://visualizing.org/)

Visual-Literacy.org[21] has developed a periodic table of visualization methods that corresponds to an interactive chart displaying various *data visualization* methods (Lengler & Eppler, 2007). This chart (shown on Figure 10) displays around 100 diagram types (with examples) and a multi-faceted classification by:

- simple to complex;
- data / information / concept / strategy / metaphor / compound (methods);
- process / structure;
- detail / overview; and
- divergence / convergence.

[20] http://visualizing.org/stories/taxonomy-data-visualization
[21] http://www.visual-literacy.org/index.html

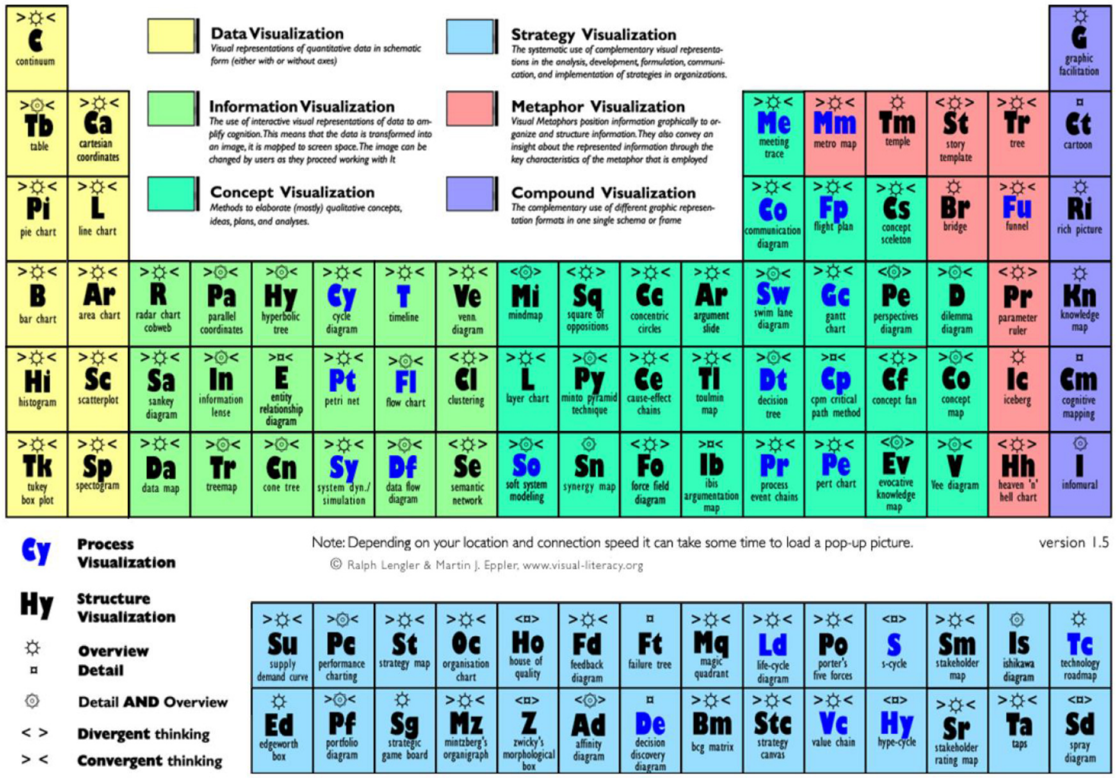


Figure 10: Periodic table of visualization methods[22]

According to the scenario intent and the inherent data (explained in section 3.1), *scientific visualization* was considered as a high priority (mainly because of data nature), *geospatial visualization* as a medium to high priority (because of the scenario intent itself), and *information visualization* as a low priority (abstract data are not considered in the scenario so far). The next subsections explain what these paradigms represent and give samples of their instantiation in different contexts. These subsections do not be considered as an exhaustive state-of-the-art in the visualization domain but a high level overview of what it is possible to do when exploiting these visualization paradigms.

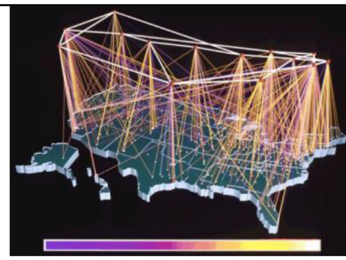
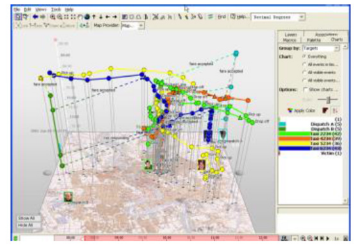
2.3.1 Geospatial visualization leading to *geospatial views*

Geospatial visualization "refers to a set of tools and techniques supporting geospatial data analysis through the use of *interactive visualization*. Like the related fields of *scientific* and *information visualizations*, *geospatial visualization* emphasizes knowledge construction over knowledge storage or information transmission. To do this, *geospatial visualization* communicates geospatial information in ways that, when combined with human understanding, allow for data exploration and decision-making processes."[23] Table 2 shows different usages of the geospatial information: on the left, real geospatial data are directly exploited by a commercial product to create virtual world populated with dynamic virtual objects; and in the center and on the right, geospatial data

[22] http://www.visual-literacy.org/periodic_table/periodic_table.html
[23] http://en.wikipedia.org/wiki/Geovisualization

are exploited by researchers to reinforce part of their data analysis or to position geographically their data to stimulate comprehension.

Table 2: Examples of geospatial views

		
Eye Sys (http://www.eye-sys.com)	Network traffic visualization by Donna Cox and Robert Patterson (http://avl.ncsa.illinois.edu/project-archive/visualizing-the-early-internet)	Geotime – Analysis of events in time and space (Eccles et al., 2008)

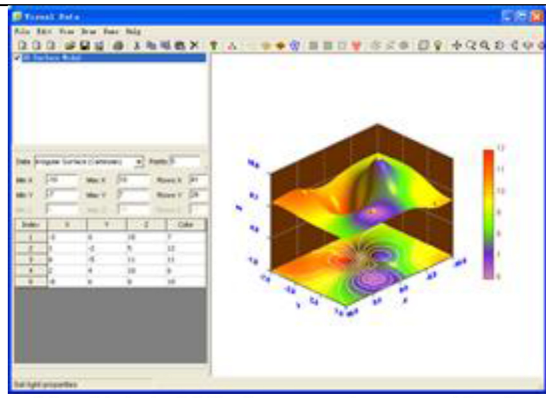
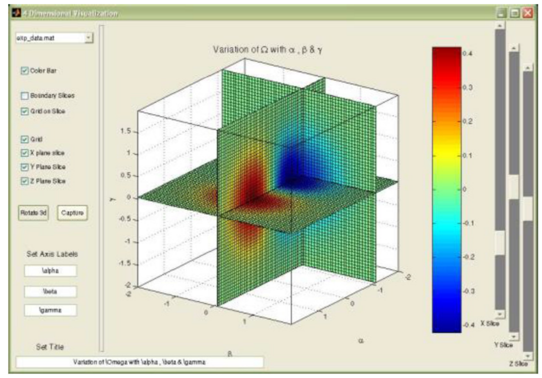
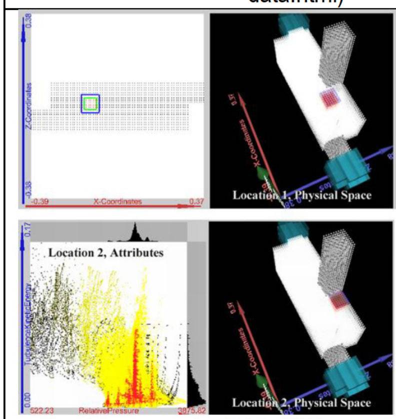
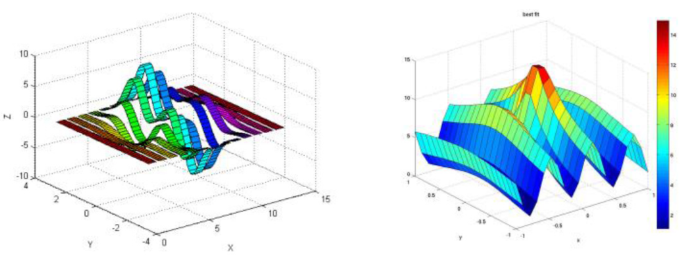
2.3.2 Scientific visualization leading to *scientific views*

As mentioned at the beginning of this chapter, the main goal of the I-EXP module is to develop a high-level understanding of the datasets produced by the I-SIM module and/or *a priori* datasets [included / inserted] in the understanding process but not produced by any modules.

Scientific visualization "is an interdisciplinary branch of science primarily concerned with the visualization of three-dimensional phenomena […] where the emphasis is on realistic renderings of volumes, surfaces […], perhaps with a dynamic (time) component. […] The purpose of *scientific visualization* is to graphically illustrate scientific data to enable users to understand, illustrate, and glean insight from data"[24]. Tools such as *Statistica (StatSoft)*[25], *Matlab (MathWorks)*[26], *VTK – the Visualization toolkit*[27] , and *Visualizer (NovoSpark)*[28] are included in this category. Table 3 illustrates by examples what scientific views look like.

[24] http://en.wikipedia.org/wiki/Scientific_visualization
[25] http://www.statsoft.com/Products/STATISTICA-Features/Version-10/
[26] http://www.mathworks.com/products/matlab/
[27] http://www.vtk.org/
[28] http://www.novospark.com/

Table 3: Examples of scientific views

 VisualData tool (http://www.graphnow.com/visual-data.html)	 Matlab – Plot Matrix
 Brushing aspect – VrVis (Piringer, Kosara, & Hauser, 2004)	 Matlab - Area / Ribbon / Band Chart

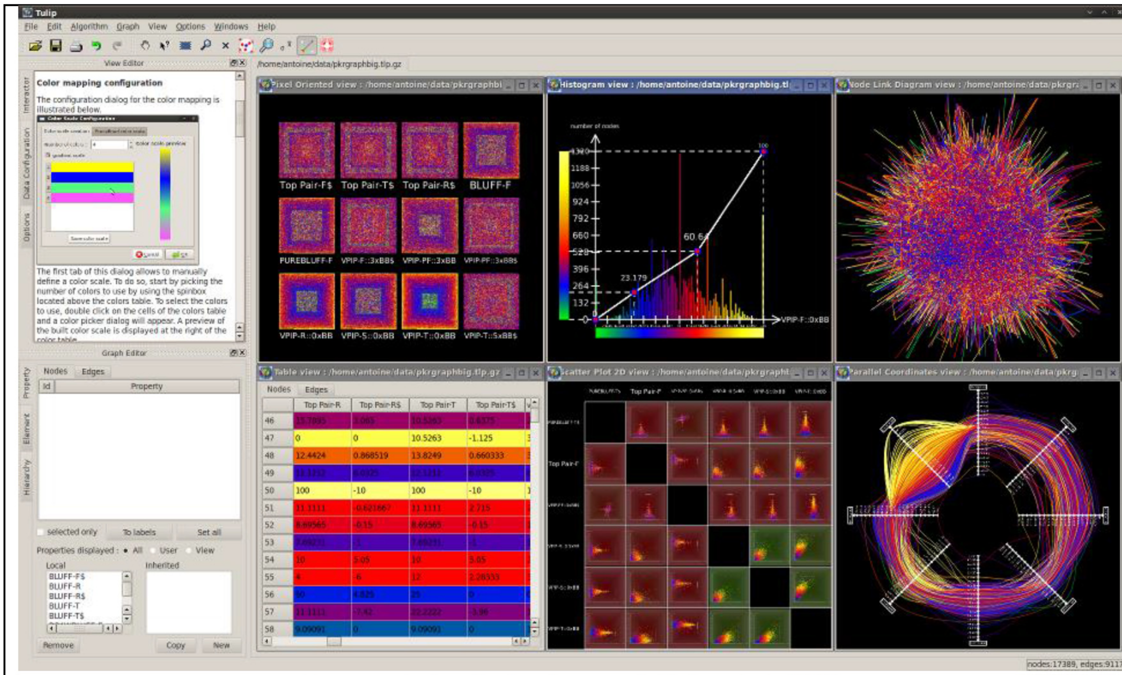
2.3.3 Information visualization leading to *information views*

Information visualization (visual data analysis) "is the study of (interactive) visual representations of abstract data[29] to reinforce human cognition. […] However, *information visualization* differs from *scientific visualization*: "it's *infovis* [information visualization] when the spatial representation is chosen, and it's *scivis* [scientific visualization] when the spatial representation is given" (Munzner, 2008). […] *Information visualization* is the most reliant on the cognitive skills of human analysts, and allows the discovery of unstructured actionable insights that are limited only by human imagination and creativity. The analyst does not have to learn any sophisticated methods to be able to interpret the visualizations of the data. *Information visualization* is also a hypothesis generation scheme, which can be, and is typically followed by more analytical or formal analysis, such as statistical hypothesis testing"[30].

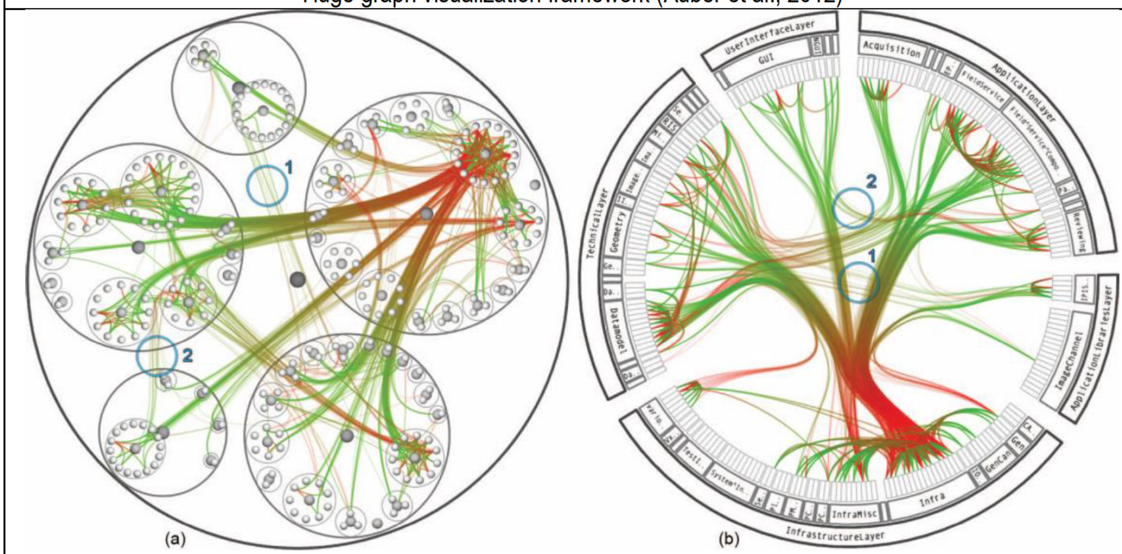
[29] The abstract data include both numerical and non-numerical data, such as text and geographic information.
[30] http://en.wikipedia.org/wiki/Information_visualization

Table 4 gives diverse examples of what information visualization looks like and means according to the specific application (the context) exploiting it.

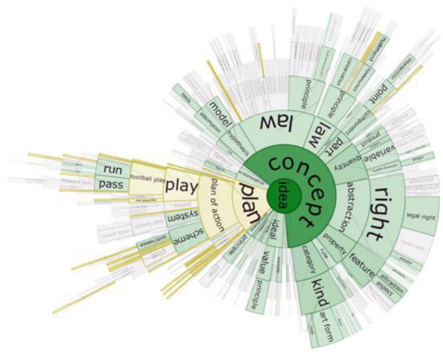
Table 4: Examples of information views



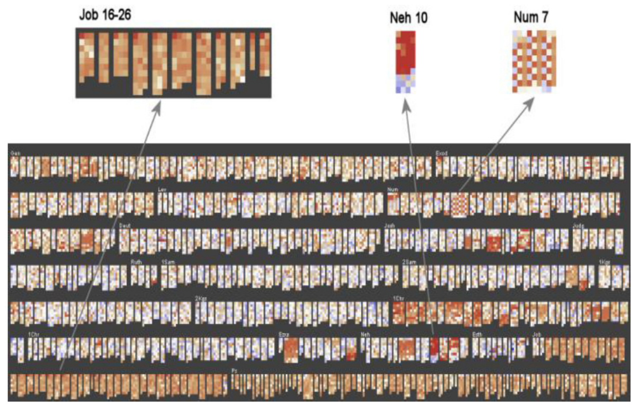
Huge graph visualization framework (Auber et al., 2012)



Hierarchical Edge Bundles (Holten, 2006)



DocuBurst: Visualizing document content using language structure (Collins, Carpendale, & Penn, 2009)



Literature fingerprinting of the Bible (blue pixel means long sentence and brown pixel means short sentence) (Keim & Oelke, 2007)

2.3.4 Visualization and immersive virtual environment

Multi-dimensional visualization in an immersive context would allow users to better understand relation between data as showed in previous studies (Arms, Cook, & Cruz-Neira, 1999; Raja, Bowman, Lucas, & North, 2004; Van Dam, Forsberg, Laidlaw, LaViola Jr, & Simpson, 2000). Although traditional techniques of data visualization remain conceptually interesting and viable when the user faces a (very) large amount of data to be processed, some techniques become more difficult to implement on a traditional desktop screen. Virtual reality (VR) allows for the ability to simultaneously analyze a large amount of data as well as for a more intuitive exploration in IVEs. The VR gives the impression to the user that he interacts and manipulates data directly and not just its graphical representation (Bryson, 1996). Desktop tools and parts of desktop tools have been adapted with this in mind so that users can visualize and explore data as being "in-the-box / inside looking out" rather than as being "out-of-the-box / outside looking in" (desktop version). The quality of a VR application depends on a multitude of factors, mainly the realism of the 3D environment, the fluidity of the graphics display, the sensory feedback and intuitiveness of navigation (Sherman & Craig, 2003)[31].

IVEs provide many benefits for understanding complex systems (Knight & Munro, 1999), namely the visualization of immersive 3D graphics and different immersion paradigms offering intuitive navigation to explore and analyze data. Besides, IVEs facilitate the learning process (Dalgarno & Lee, 2010) by, among other factors, promoting the spatial representation of knowledge and augmenting both user's motivation and commitment.

VR is a technology that immerses one or more users in a VE representing a real or fictive world that allows users to become agents capable of changing the properties of the environment and interact with its entities (Burdea & Coiffet, 2003). Since the advent of VR technology, researchers were particularly interested in the 3D interaction which can be regarded as the driving component behind any interactive system. Indeed, interaction gives a better feeling of immersion and plays a crucial role in the determination of presence. IVEs, such as CAVE (Creagh, 2003; Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992) support, among other things, the ability to analyze and

[31] To understand concepts related to VR, the reader can refer to (Drolet, 2008), chapter 1.

interpret a large amount of data faster and to explore data in a more intuitive way through interactions with visually rendered data. The CAVE (from Mechdyne[32]) used in IMAGE is a multi-screen projection-based VR system with three walls and a floor that are arranged in a cube for total immersion. One of the major advantages of the CAVE is that it makes (collaborative) exploration of large-scale content possible through manipulation and navigation within an IVE. The user navigates the virtual content by naturally moving around inside the cube, while his field of view is filled with 3D representations of components of the environment. The CAVE is viewed as a spatially immersive display because it enables simultaneous access to a huge amount of data more directly than any other display devices and helps escaping the conventional bias towards 2D computing by organizing content more effectively in 3D. To achieve realistic interactions with immersive displays, the tracking system (IS-900 system from Intersense[33]) implements fast refresh rates, low latency and smooth tracking. Consequently, it provides smooth and precise estimates of the position and orientation (6-DOF) of the user's head / user's hands while not interfering with the user's immersive experience. The tracking system offers ergonomically designed devices: (1) a head tracker attached to stereo glasses (CrystalEyes®3 from StereoGraphics Corp.[34]); (2) trackers attached to Cybergloves[35] (from Immersion Inc.[36]) which are composed of 22 flexible sensors that can accurately measure the position and movement of the fingers and wrist; and (3) a tracked wand (from InterSense) which includes buttons (four on one side and a trigger on the other side) and a joystick for interacting with the virtual content. Stereoscopic rendering based on active goggles provides the user with depth perception of the virtual content.

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[32] http://www.mechdyne.com/
[33] http://www.intersense.com
[34] http://www.reald.com
[35] Only used in I-EXP V2 (Mokhtari, Boivin, & Drolet, 2013).
[36] http://www.cyberglovesystems.com

3 Analysis toolset

First of all, this chapter introduces a scenario – aka CS – about land convoys facing insurgents. This scenario constitutes the case study utilized to develop IMAGE modules, experiment and test the feasibility of advanced functionalities. The chapter pursues by presenting interactive and informative simulation analysis tools implemented for this version. The toolset allows exploring different aspects of the scenario, but is, at the same time, constrained by the cognition-driven evaluation strategy. The tools mainly offer the user rapid prototyping of views, as well as tailored views and focus on the "best view" concept rather than the "perfect view" concept. Furthermore, to address as much as possible exploration needs with respect to diversity and richness, the toolset proposed is a combination of turn-key and commercial off-the-shelf (COTS) tools.

In the spirit of the *Visualization* domain, the main task of which is to allow *information* to be derived from *data*, the I-EXP V1 toolset has been thought to assist experts / users understand and interpret (large and rich) datasets, by exploiting information rendered graphically (e.g. graphs, diagrams, charts, etc.) which are visual artefacts representing data, illustrating relationships and patterns among data, presenting *information* (appropriate conversion of *data*), and also allowing analysis and comparisons between graphical representation of datasets. In addition, the I-EXP V1 toolset also addresses the dynamic display of trends in the data and human interaction with the displayed data. Consequently the toolset has been designed to: (1) explore and compare (large) datasets; (2) extract (hidden) information / knowledge; (3) discover unexpected trends in the data or find patterns; and, finally, (4) understand specific non-intuitive aspects of CSs. To achieve these goals, the I-EXP module [exploits / uses] different techniques such as (1) filtering[37] (for focusing on relevant subsets of data) and data brushing[38] (Becker & Cleveland, 1987), (2) datasets comparison, (3) multi-level datasets exploration (at Tactical and SOP levels), and (4) real-time and stereoscopic rendering (for the CAVE version).

3.1 The case study: Land convoy facing insurgents

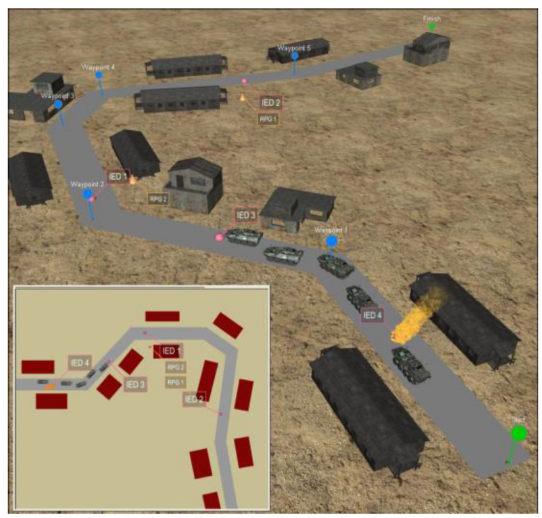
The selected scenario is inspired by logistic convoy attack situations experienced by the Department of National Defence and the Canadian Armed Forces deployed in Afghanistan (Bernier & Rioux, 2010). The convoy-insurgents coevolution concept was implemented in two parts: the first one at a lower level of complexity named Tactical and another one at a higher level of complexity named Standard Operating Procedure, or SOP. Both levels were made deterministic to reduce variability in the experimental data.

[37] Filtering is one of the basic interaction techniques often used in *data or information visualization* to limit the amount of displayed information through filter criteria.
[38] By definition, data brushing supports visual linking of various data and addresses the visual fragmentation problem of multivariate data representations. Brushing is the process of interactively selecting data items from a visual representation. The original intention of brushing is to highlight brushed data items in different views of a *visualization*.

3.1.1 Tactical level

A Blue Forces (BF) convoy composed of *n* Light Armoured Vehicles (LAV) travels from A to B through a predetermined road crossing a small town with the objective of carrying cargo to destination i.e. to provide troops with fresh supplies. Each vehicle is protected by customizable Lateral and Underneath Armour Thicknesses (respectively LAT and UAT). It is equipped with (i) sensors for the detection of Improvised Explosives Devices (IEDs) and insurgents using Rocket Propelled Grenades (RPGs), (ii) an IED disarming system, and (iii) weapons for firing back at insurgents. Alongside the road, Red Forces (RF), characterized by *m* IEDs and *p* insurgents with RPGs, attack the convoy which reacts accordingly, e.g. by decreasing cruise speed to fight insurgents or to disarm IEDs. Increasing vehicle protection (i.e. armour thickness) is a counter-measure adopted by BF to prevent casualties. At the end of each tactical simulation (i.e. when the convoy has completed its mission), a set of Measures of Performance (MoP) is computed: amount of cargo arriving at destination (cargo), convoy remaining life (integrity) and mission duration (timeliness). Mission success is assessed by MoP representative of the mission goals. Only the values assigned to LAT, UAT, IED and RPG parameters are allowed to be changed by users and are considered as BF and RF resources allocated prior the execution of the mission. Figure 12 summarizes the analysis process at the Tactical level for which the number of mission outcomes is limited to 726 by restricting the resource allocation (in this case 121 for the – light and underneath - armour thickness and six for the distribution of IEDs and RPGs, explanation are given in (Bernier & Rioux, 2010), Chapter 2).

Context and agents of the scenario



Instance of the simulated scenario (snapshot and orthographic view)

Figure 11: Explained scenario at a predetermined time and for predetermined BF and RF resource allocation – Convoy road in the small town + location of IEDs and RPG launchers on the road are predefined

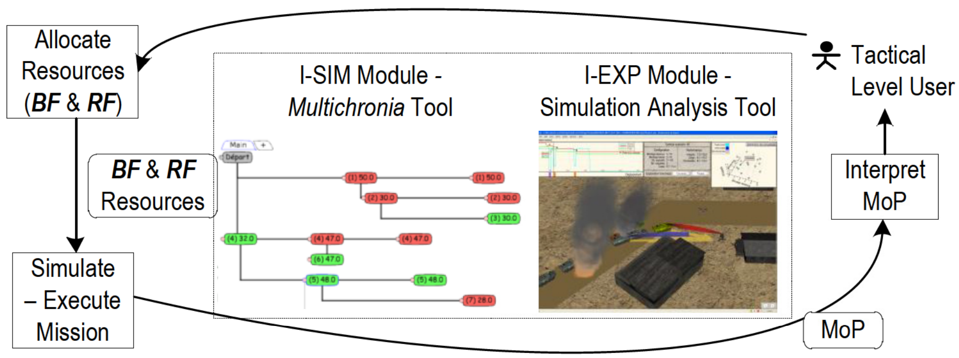


Figure 12: Tactical level – Analysis process

3.1.2 SOP level

The SOP level of the scenario encompasses the Tactical level. Here, an iterative co-evolution of BF and RF is implemented. The objective of the scenario (whole mission) is to carry cargo from A to B with minimum of loss (in terms of cargo or convoy integrity) i.e. to provide troops with building material for the construction of a school. The scenario is composed of 100 successive tactical simulations with a co-evolution step between each during which BF and RF are allowed to evolve separately as follows. After each simulation, an algorithm reallocates the BF and RF resources in order to maximize their chances of reaching their own objectives at the next simulation (i.e. MoP for BF are cargo, integrity and timeliness). When applied repeatedly, this reallocation results in a co-evolution similar to the one observed in real enduring conflicts. Besides the concepts defined at the Tactical level, the SOP level introduces new concepts that can be exploited in order to influence the evolution: population allegiance, cargo offered to the population and intelligence. Evolution of the RF cannot be modified by the user, who, in the meantime, can control the BF by allocating a portion of the carried cargo to increase population allegiance which facilitates intelligence gathering (that will hopefully influence BF evolution positively). Figure 14 summarizes the analysis process at the SOP level and combined with Figure 13 show the links between the SOP and Tactical levels.

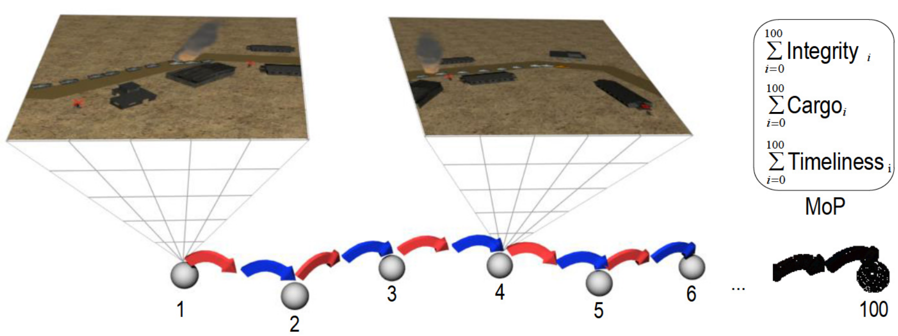


Figure 13: SOP level – Coevolution process showing the embedded Tactical level (red arrows indicate RF evolution while blue arrows designate BF evolution)

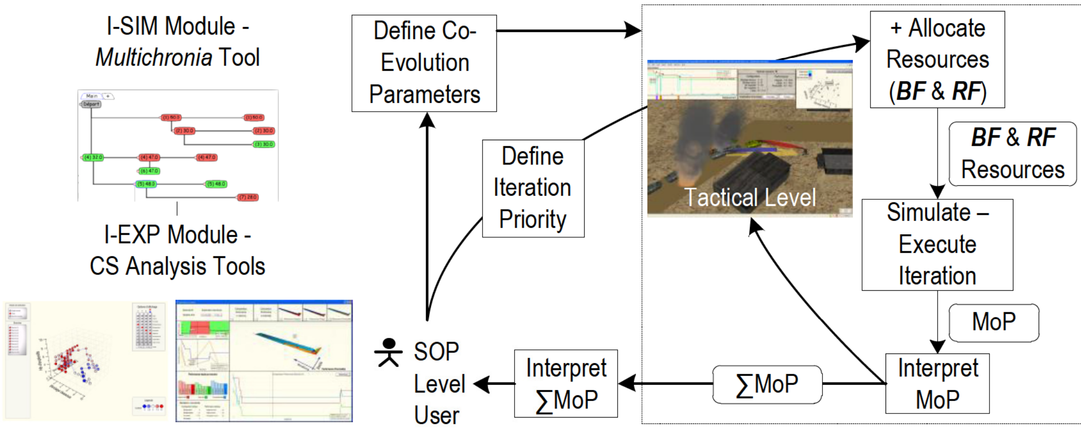


Figure 14: SOP level – Analysis process

3.2 Analysis tool at the Tactical level[39]

A simulation analysis tool has been designed at this level (one mission corresponds to one simulation). On one hand, it allows users to visualize, analyze and explore (input and output) simulation data but also how / in what way the set of parameters evolves during the simulation. On the other hand, it localises / cartographies in the space the simulations created by the user through the 726 combinations of variables. The tool interface is visible on Figure 15 and is mainly built around five displays or boards of information (zones A to E) in which users can visualize or interact with the simulation parameters. These five displays or boards are explained in the next subsections.

Videos associated to the Tactical level are grouped under the directory named *Tactical*. Four videos are listed: *Scenario* illustrates an instantiation of the Tactical level scenario as expressed in 3.1.1; *Desktop – Tactical View 02* and *Desktop – Tactical View 08* summarize the simulation analysis tool through two scenario instances. (A part of) functionalities expressed in following subsections (3.2.1 to 3.2.6 except 3.2.4) are included in videos; finally, *I-EXP and I-SIM (joint view)* gives an opportunity to the reader to observe the I-SIM tool (Multichronia, (Rioux, Bernier, & Laurendeau, 2008; Rioux, 2008)) and the I-EXP tool (simulation analysis tool) in action in their intertwined functioning.

[39] A more detailed description can be found in (Tye-Gingras, 2011).

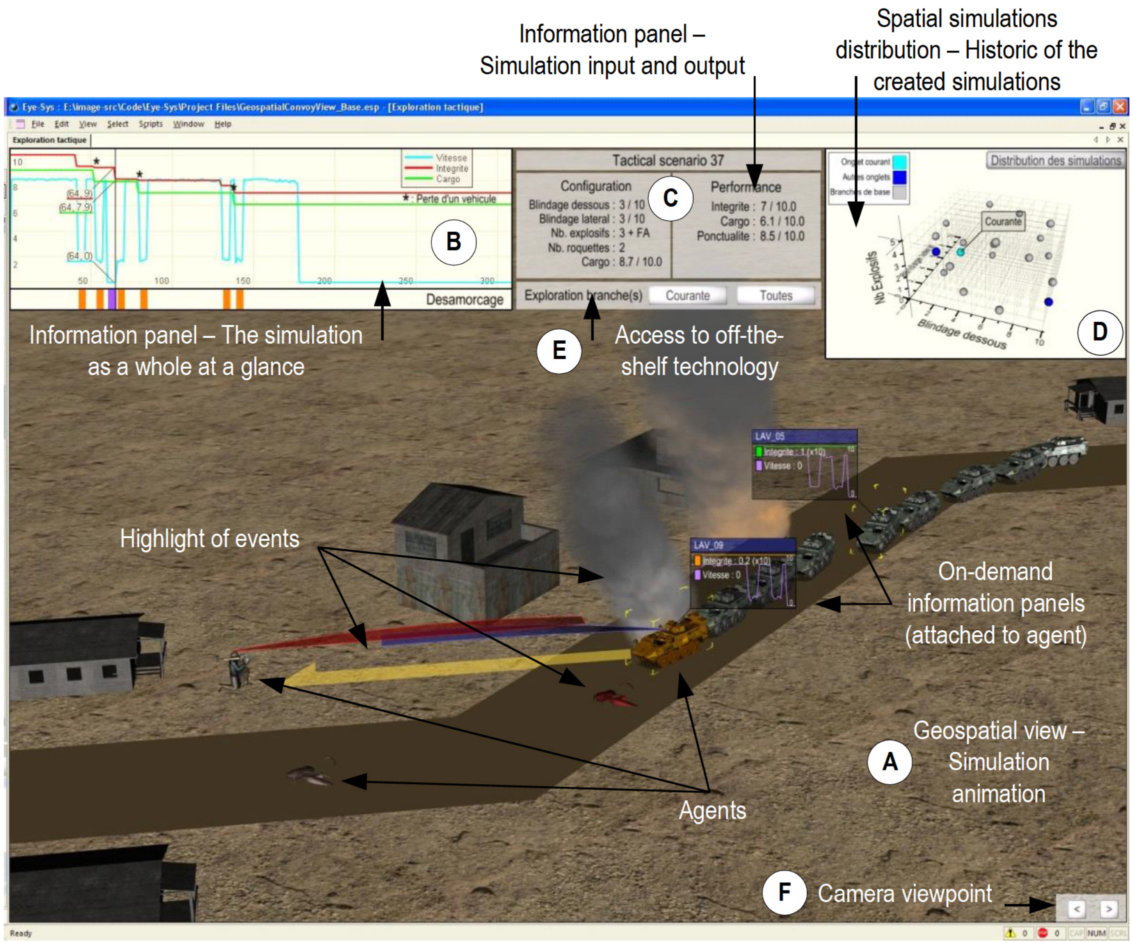


Figure 15: I-EXP V1 - Simulation analysis interface at the Tactical level

3.2.1 Simulation animation

The main display (zone A, Figure 15) of the interface is a geospatial view in which simulation animation is performed, important events are highlighted, and information panels linked / associated / attached to each simulation agent (LAV, IED and RPG) are visible on-demand.

3.2.1.1 Simulation agents

Three agents (shown in Figure 16) evolve in the scenario. BF is characterized by the LAVs composing the convoy and their potential states (`moving`, `disarming`, `damaged`...). RF is characterized by two elements: (1) RPG launchers and their three potential states (`searching` for target, `attacking` - when a target is found - and `eliminated`) represented by specific icons; and (2) IEDs and their four potential states (`armed`, `disarming`, `disarmed` and `exploded`) represented by specific colors and/or explosion artefacts.

Figure 16: Agent 3D models evolving in the tactical simulation

3.2.1.2 Animation

Users can change the camera viewpoint (zone F, Figure 15). Two modes are available: (1) in the *free navigation* mode, users can at any time zoom-in, zoom-out, translate, tilt, pan and swing the display to observe the scene from any vantage point; or (2) in the *fixed view point* mode, users can follow the moving of the convoy along the road from a preconfigured camera. An instantiation of these two modes are visible on Figure 17.

Figure 17: Camera viewpoints: free camera (left) and preconfigured camera (right)

3.2.1.2.1 LAV animation

The LAV agent can take six different states but two states can also be combined to become the LAV's state at a specific time of the simulation. An instantiation (at a simulation step) of each one of these states are explained in Table 5 and succinctly presented as follow:

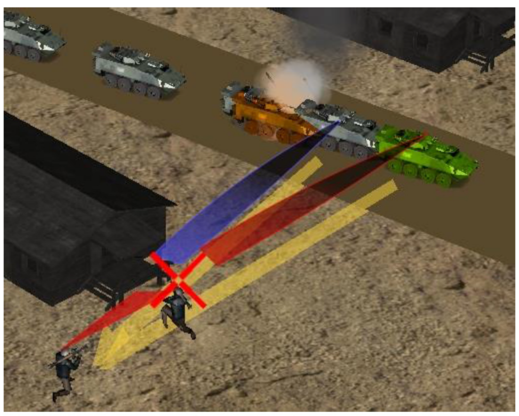
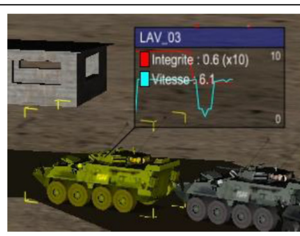
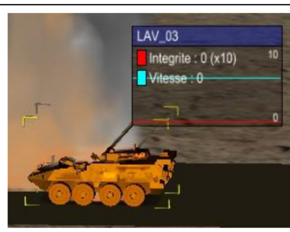
- `moving`: a LAV moves at its maximum speed unless it decelerates and stops for disarming an IED or it slows down for attacking a detected enemy;
- `disarming`: the first LAV of the convoy continuously scans for IEDs and once one is detected, the convoy decelerates, stops, and the first LAV can disarm the IED;
- `enemy detection`: LAVs continuously scan for detecting enemy's presence – still `moving` (example of combination of two states);
- `attacking` – still `moving` – the convoy has decelerated and slows down;

- `damaged` – still `moving`; and
- `eliminated`.

The LAVs can detect enemy's presence. When a RPG launcher enters the field of view of a LAV, the launcher is targeted. This `enemy detection` state is represented by a yellow arrow pointing to the enemy and remains visible until the enemy is eliminated. The detection is influenced by the distance which separates the LAV of the enemy and the potential obstruction caused by the buildings (or other). A LAV can attack and eliminate the enemy after the convoy decelerates and slows down. This `attacking` state is represented by a full blue ribbon. Even if several LAVs can detect the same enemy, only one can attack. The scenario is defined such that the LAVs always have 100% shot efficiency.

LAVs can be damaged by the RF. When this `damaged` state occurs, color changes according to a gradation starting from *green* to *yellow* and ending with *orange*, according to their integrity (or quantity of remaining life). The LAV stops moving when integrity drops to 0 and it is then in the `eliminated` state. This situation is illustrated by a plume of smoke effect.

Table 5: Some potential states of the LAV agent

<table>
<tr><td></td><td>A RPG launcher is entered the field of view of two LAVs (the first two ones in the convoy); consequently two distinct yellow arrows are pointing to the detected enemy and the two LAVs are in an <code>enemy detection</code> state. After detection, one of the two LAVs attacks the enemy; this <code>attacking</code> state is represented by a blue ribbon - in deployment on the snapshot extracted from a Tactical simulation. At the same time, the first LAV of the convoy is attacked by the RPG launcher - represented by a red ribbon on the snapshot - while the third LAV has been eliminated (note: before being eliminated, it was the first LAV of the convoy).</td></tr>
<tr><td>
</td><td><code>Damaged</code> and <code>moving</code> states – After being attacked and if the attack was not fatal (then before reaching the <code>eliminated</code> state), the LAV integrity drops from 100% to X% but it continues to move. The LAV color changes - green in the snapshot extracted from a Tactical simulation.</td></tr>
<tr><td>
</td><td><code>Eliminated</code> state - The LAV stops moving and integrity drops to 0. The LAV color becomes orange.</td></tr>
</table>

3.2.1.2.2 RPG animation

The RPG launchers attack as soon one LAV enters their line of sight. Detection and attack are not differentiated and a full red ribbon is used. Being always eliminated in one shot, they don't need an integrity scale. Thus, they can take three different states:

- `targeting`: continuously as long as a target is detected. A target is detected where it is in line of sight and at a predefined distance;
- `attacking`: once a target is detected, an attack is immediately launched. The launcher fires repeatedly on the target until it is killed or when the RPG launcher himself is killed; and
- `eliminated`: when attacked by BF, RPG launchers are eliminated in one shot.

While the attack is shown by the presence of the red ribbon, the two other states are indicated with 2D icons added on the 3D model. During the animation, the RPG launcher's pose is such that it always faces the convoy.

Figure 18: Potential states of the RPG launcher agent – (left) `targeting` *state (searching for a target), (middle) target detected and* `attacking` *state (represented by a full red ribbon), and (right)* `eliminated` *state*

3.2.1.2.3 IED animation

The IEDs can take different states depending on the circumstances:

- `armed`: represented with the normal color of the model;
- `disarming`: in twinkling red;
- `disarmed`: in green;
- `exploded`: by an effect of explosion with smoke.

Figure 19: Potential states of the IED agent – (left) `disarming` (twinkle), (middle) `disarmed`, (right) `exploded`

3.2.2 Evolution of BF behaviours and parameters

Users can see in a glance on one graphic the evolution of each simulation parameter (zone B, Figure 15, Figure 20). This graphic is divided in two parts. In the upper part, users can observe simultaneously the evolution of the convoy parameters: (average) speed in *cyan*, carried cargo amount in *green*, integrity in *red*, and loss of vehicle(s) expressed by a *black* star. This latter has a direct impact on carried cargo amount and integrity of the convoy. In the lower part, users can rapidly observe the status of the convoy on the simulation timeline: moving (no color), IED disarming in *mauve*, fighting in *orange*. Furthermore, the status period in simulation steps is given. A "black cursor line" is visible and evolves according to the I-SIM module (synchronization between the I-SIM and I-EXP modules). Finally, at each simulation step, users are informed of the speed, carried cargo and integrity (information associated to the "black cursor line").

Figure 20: Tactical simulation as a whole

3.2.3 Input and output board

Zone C (Figure 15, Figure 21) gives information on the value of simulation input data (i.e. the value of initial resources), and also the value of simulation output data (i.e. the set of MoPs). The simulation input data board displays the resources allocated prior the execution of the mission: the BF resources (UAT, LAT); the RF resources (number of IEDs and RPGs); and the cargo amount carried by the BF convoy. And the simulation output data board displays the value of each MoP (integrity, cargo and timeliness). These three values allow the evaluation of the mission success.

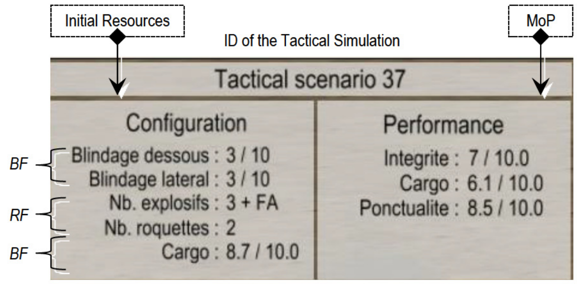


Figure 21: Configuration panel summarizing input (resource allocation) and output (MoP) data

3.2.4 Links with visual analytics tools

The simulation analysis tool allows the study of only one tactical simulation at a time, the analysis and/or comparison of a set of simulation data is performed by Tableau Software[40] (access to by zone E, Figure 15). Users can use Tableau Software, if required, to analyze the current simulation or all existing simulations (Figure 22).

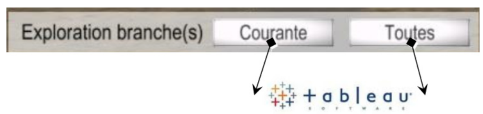


Figure 22: Access to Visual Analytics tool(s)

3.2.5 Spatial simulations distribution – Link with the I-SIM module

The 3D graphic exhibiting the spatial distribution of simulations (zone D, Figure 15, Figure 23) according to the – BF and RF – resource allocation (LAT, UAT and IEDs/RPGs) is available and updated at each creation and deletion of one simulation. Users always know which subspace of simulations space is being observed and can direct their analysis towards the subspace they want to investigate. Currently, three colors are used: *cyan* for the current simulation (tagged by a callout); *grey* for the set of simulations defined at the beginning of the analysis[41]; and *blue* for the others simulation tabs. Users can hide this graphic at will. They can also at any time zoom-in, zoom-out, tilt, pan and swing the view.

[40] http://www.tableausoftware.com/

[41] For the experimental validation, refer to Chapter 8, (Lizotte, Bernier, Mokhtari, & Boivin, 2012).

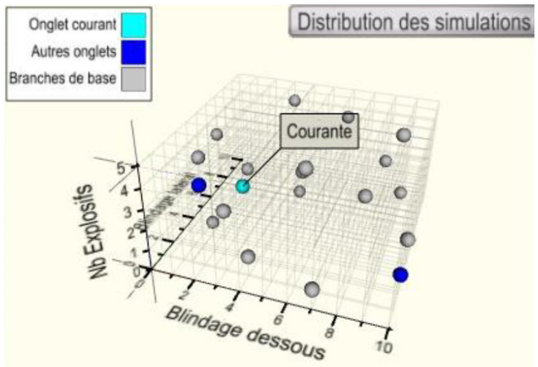
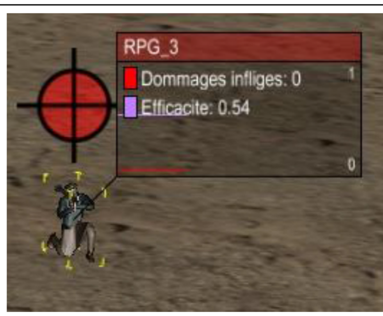


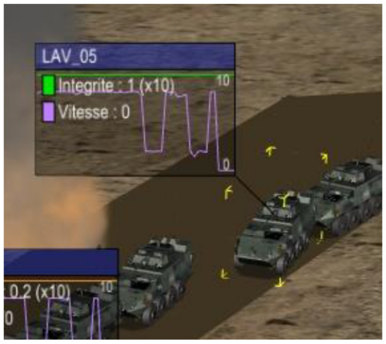
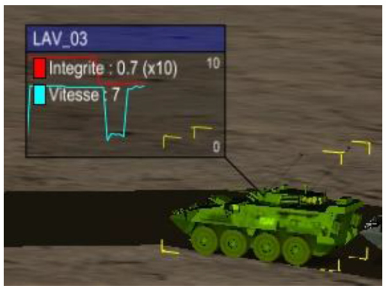
Figure 23: Spatial simulations distribution

3.2.6 On-demand information panel

At any time during the simulation, users can access information about simulation agents. For that purpose, users have "to pause" the simulation and, in the main display just click on the simulation agent they need to know information. Each information panel displays (1) textual information that represents variable value at the current simulation step, and (2) graphics in background that shows the historic of the last 50 values. Table 6 gives explained examples of information panels associated to different simulation agents.

Table 6: Examples of information panels

	IED agent and its information panel showing information about damages (variable value in *red*) inflicted. Damages inflicted by this IED agent are nil because the IED is in the `armed` state.
	RPG launcher agent and its information panel showing information about damages (variable value in *red*) inflicted by the launcher et his efficiency in fighting (variable value in *mauve*).

	LAV agent and its information panel showing information about its integrity (graphics in *green*): 100% (as shown in the next example, the color associated to the convoy integrity can change if the LAV is damaged by the enemy); and its speed (graphics in *mauve*): 0, the convoy is stopped because the first LAV of the convoy is disarming an IED.
	LAV agent and its information panel showing information about its integrity (graphics in *red*): 70% meaning that the LAV has been damaged by the enemy prior this snapshot; and its speed (graphics in *cyan*): 7, the convoy moves along the road. The color characterizing the convoy integrity has been modified because the LAV agent is in the `damaged` state.
	LAV agent and its information panel showing information about its integrity (graphics in *red*): 0%, the LAV has been damaged by the enemy prior this snapshot and is in the `eliminated` state; and its speed (graphics in cyan): 0, the LAV has stopped but the convoy (the remaining LAVs) continues to move along the road.

3.3 Analysis toolset at the SOP level[42]

Two complementary mission analysis tools have been designed at this level (one mission corresponds to 100 tactical simulations): the mission data analysis tool itself, and the parameters and MoPs analysis tool. These two tools are explained in more detail in the next subsections.

[42] More details can be found in (Girardin, 2012; Mokhtari, Boivin, Laurendeau, & Girardin, 2010).

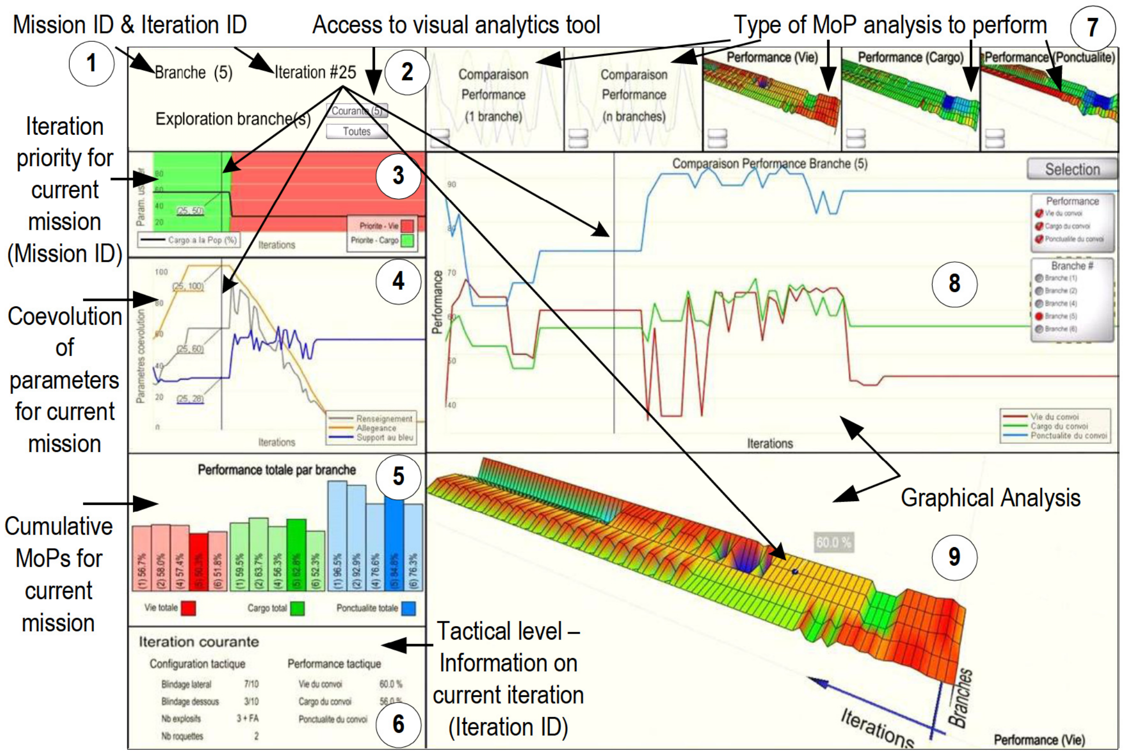


Figure 24: I-EXP V1 – Mission analysis data interface at the SOP level

3.3.1 Mission data analysis interface

The mission data analysis tool interface (visible on Figure 24) is divided into two distinct zones: the information zone and the interaction zone with data.

3.3.1.1 Information zone

The information zone, composed of zones 1 to 6 (on the left of the interface), gives to users a (limited) restrictive access to data:

Zone 1 – *MissionID* corresponds to the identification number of the current mission (mission focused by the user) and *IterationID*, the identification number of the current iteration (corresponding to a tactical simulation as defined at the Tactical level) which is one of the 100 iterations composing the mission;

Zone 2 – At any time, users can access a visual analytics tool (e.g. Tableau Software) to analyze the current mission data or a set of mission data;

Zones 3 to 6 correspond to information panels.

- Zone 3 (iteration priority, Figure 25) illustrates input data for each iteration of the whole current mission: priority given by the BF evolutionary algorithm in terms of optimizing integrity or cargo (*color* aspect – *red* for integrity and *green* for cargo) and the percentage of cargo given / offered to the population (*line* aspect – thicker black line);

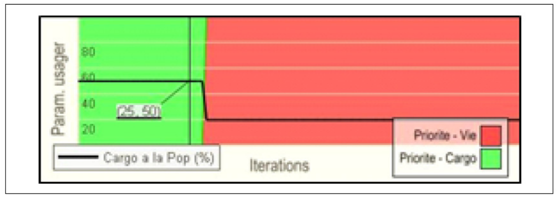


Figure 25: Mission analysis interface – Iteration priority

- Zone 4 (mission co-evolution parameters, Figure 26) displays, for the current mission, the coevolution parameter performance, i.e. population allegiance in *orange*, intelligence gathering in *grey*, and support to BF in *blue* (*line* aspect);

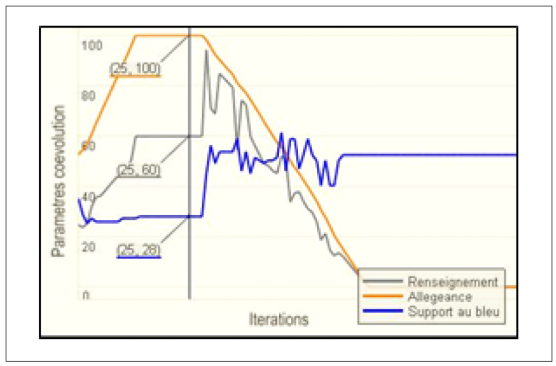


Figure 26: Mission analysis interface – Mission co-evolution parameters

- Zone 5 (mission MoP, Figure 27) presents, for all the missions created by users, mission MoPs that correspond to the cumulative iteration MoPs (integrity, cargo and timeliness). Users can select the MoP to display: integrity, cargo and/or timeliness – each one is characterized by a specific color and each instantiation is tagged by its number (mission ID). The current mission (on which the focus is) is highlighted. Each MoP is represented as a histogram (*bar* aspect). Users have then the possibility to compare the different values per MoP. The content of this panel adapts to the number of missions to be displayed. When this number is too large, only one MoP is shown and the width of the histogram bars decreases so only the last ones are shown.

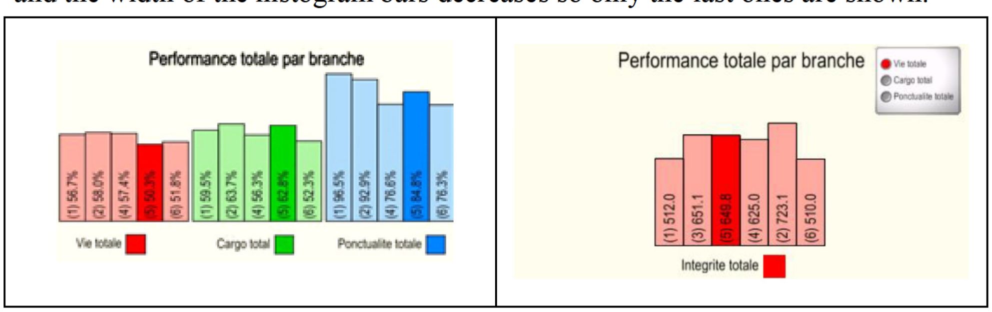


Figure 27: Mission analysis interface – Mission MoP

- Zone 6 (information on current iteration) gives input and output data for the current tactical simulation (i.e. the simulation tagged *IterationID*). This information panel is a remake of an information panel available at the Tactical level (Figure 15, zone C)[43].

3.3.1.2 Interaction zone

Interaction zone, composed of zones 7 to 9 (on the right of the interface), corresponds to interactive panels exhibiting detailed and tailored display modules.

MoP to analyse – Zone 7 (Figure 28) allows choosing what data to display and how displaying these data. Users can compare / analyze (1) only one MoP for a set of existing missions or for all missions or (2) several MoPs for one mission. He can also select the type of graphics, (2D or 2D½), and in which visualization panel (top / bottom – zones 8 and 9) it has to appears.

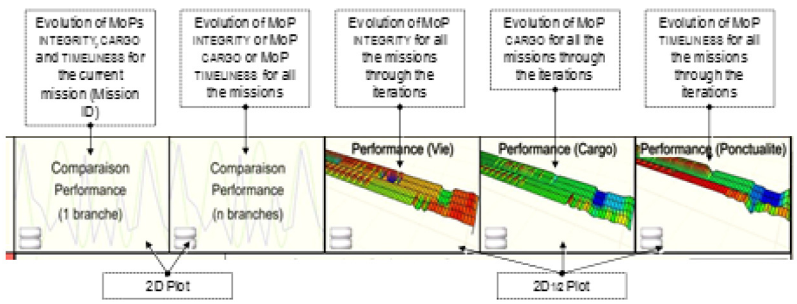


Figure 28: Mission analysis interface – MoP to analyse

Main display – Zones 8 and 9 (Figure 29) exhibit 2D or 3D graphics. These display boards allow users to visualize information by:

- line graphs: show / compare information for one or several MoP associated to one mission. Users have to select what mission(s) and/or MoP to investigate;
- surface graphs: compare information on only one MoP but for all existing missions in order to understand the differences, similarities and relations between MoP. At any time, users can zoom-in, zoom-out, tilt, pan and swing the surface graph.

[43] In an earlier version of the tool, this zone was directly linked to the Simulation analysis tool as presented at section 3.2.

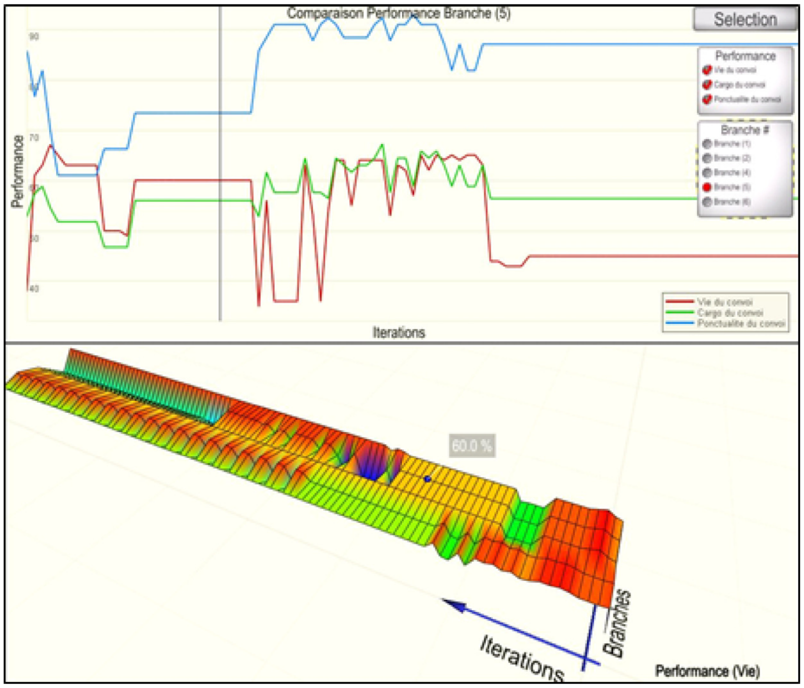


Figure 29: Mission data analysis interface – Main displays exhibiting line (2D) and surface (3D) graphs

3.3.2 Parameters and MoP analysis interface

The mission parameters analysis tool (its interface is visible on Figure 30) allows users to create tailored views to understand correlation between parameters. The main display (zone D) exhibits / shows, on-demand, all available combinations of parameters: input data (BF resources – LAT and UAT; RF resources – RPGs and IEDs), MoPs (cargo, integrity and timeliness), co-evolution parameters (population allegiance, intelligence gathering, BF support, the cargo offered to the population), and the iteration priority (integrity or cargo) (*form* or *colour* aspect can be used for this parameter). Users can choose (via zone A) what mission or set of missions to explore. Each mission, composed of 100 iterations, is displayed as a chain of *coloured* and *sized* spheres (representing one or several iterations). Depending on the parameters selected, all 100 iterations are not represented each by a sphere, some being lumped in a common sphere. The graphics is updated automatically to adapt to changes of parameter values. Three to five dimensions are always available to users (zone B) – three dimensions refer to traditional XYZ axes and the fourth and fifth dimensions necessitate usage of *color* and *form*. The displays are updated dynamically each time a new mission is created / an existing mission is deleted in the I-SIM module (synchronization between the I-SIM and I-EXP modules), and when user focus changes (current mission). The current mission is highlighted by a thicker chain, the current iteration is highlighted by a cross and an information panel is attached to it (zone E). The *color*, *form* and *size* codes are given by the corresponding legend (zones B and C). A set of four legends is available: (a) no legend (if XYZ); (b) defining the meaning of *color* and *size* associated to the fourth selected parameter; (c) defining, if iteration priority is chosen, the meaning of *color* or *form*; and (d) defining, if iteration priority is chosen, the meaning of *color* and *form*. Finally, users can also at any time zoom-in, zoom-out, tilt, pan and swing the view.

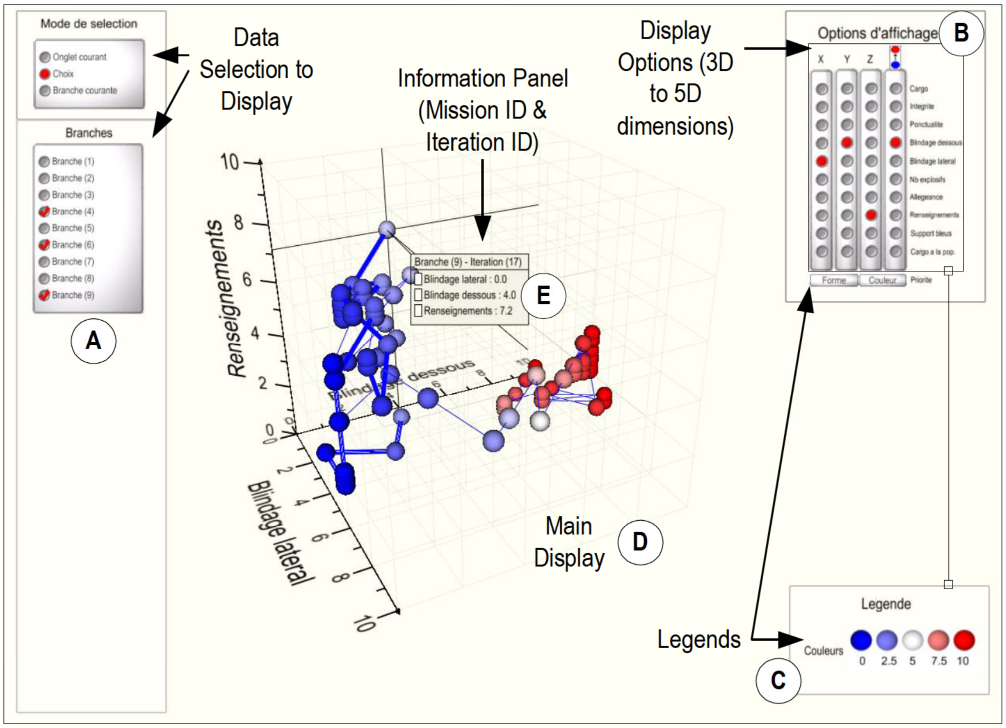


Figure 30: I-EXP V1 – Parameters and MoP analysis interface at the SOP level

Videos associated to the SOP level are grouped under the directory named *SOP*. Two videos are listed: *Desktop – SOP View* summarizes the mission data analysis tool. Parts of the video figure out the synchronization of the I-SIM and I-EXP modules; *Desktop – SOP View (CUBE)* illustrates (a part of) functionalities available in the parameters and MoP analysis tool.

Furthermore, as depicted on Figure 2, the I-EXP V1 toolset can be used as well on a traditional desktop as on a larger screen, thus video titled *Non-immersive* under the directory *CAVE* is an illustration of what the tools look like when tools developed for desktop are transposed on a larger screen.

3.3.3 CAVE adaptation – A data-centric virtual environment

Two data-centric IVEs have been developed; the mission parameters and MoPs analysis tool has been adapted to become the *Cube View* tool and the analysis and comparison graphics of missions in terms of MoPs have been adjusted to become the *Ribbon View* tool (Mokhtari, Boivin, & Laurendeau, 2013). The Cube View (on the left of Figure 39) allows users to visualize datasets and manipulate up to five parameters at a time (the three axes and two aspects to choose between color, form and size) with the same approach as the one defined for the desktop version. The Ribbon View (on the right of Figure 39) supports simultaneously visualization of the three MoPs throughout the 100 iterations of the SOP mission, and for all simulated missions. A tablet PC is used to switch between immersive and non-immersive modes, and also to select parameters and data to configure and display. The user can navigate inside the 3D virtual content at will. He uses the wand to manipulate (translate, rotate, and resize) the 3D graphics. Data selection is not needed because any manipulation involves the whole view (see videos titled *I-EXPV1 HCII2013* and *Immersive* under directory *CAVE*). Figure 39 shows a user manipulating datasets with the wand and visualising them with the stereo glasses. The data-centric IVEs are supported by a custom open architecture, mainly based on openGL[44] and the 3D graphics toolkit OpenSceneGraph[45] (OSG), a 3D graphics rendering engine, frequently used to develop applications in scientific visualization, VR and modeling.

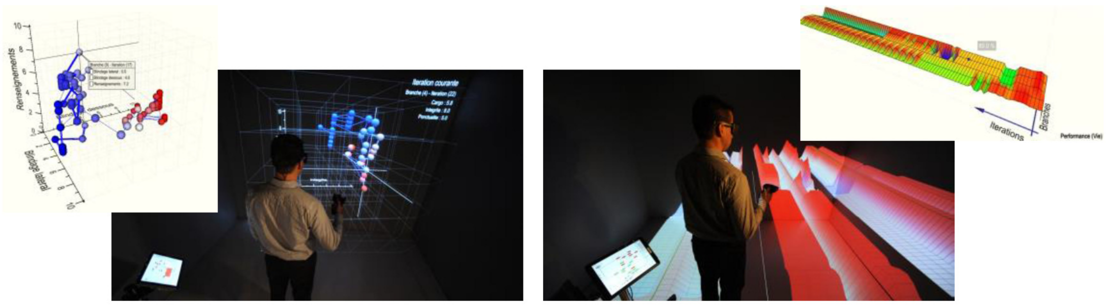


Figure 31: I-EXP V1 – Immersive tools at the SOP level (adaptation of desktop tools)

3.3.4 Synchronization between I-SIM and I-EXP modules

A key aspect to consider is the synchronization between the I-SIM and I-EXP modules. Select a simulation in the I-SIM module must be reflected in the *exploration* or *visualization views* according to a visual paradigm that highlights focused data. All interactions relative to the control of the simulations are executed in the *Multichronia*[46] interface (I-SIM, visible on Figure 32). However, actions such as creation, destruction, selection and temporal control of the simulation must be forwarded to the I-EXP analysis interfaces. The actions are reflected as follow:

- creation must activate the database request process as well as object instantiation;
- destruction must of course destroy object instantiation and also update the database;
- selection must activate the database request process, start the animation in the visualization display(s) as well as update information panels and others;
- the temporal control of a simulation (play, rewind…), either executed manually by the user or automatically by the simulator, must move and position the simulation agents at the selected simulation step; and
- data brushing is implemented by showing where the current simulation is located as selected and manipulated directly in the I-SIM module.

[44] http://www.opengl.org
[45] http://www.openscenegraph.org/
[46] *Multichronia*, the I-SIM tool, is a visual interactive simulation framework (Rioux, Bernier, & Laurendeau, 2008; Rioux, 2008).

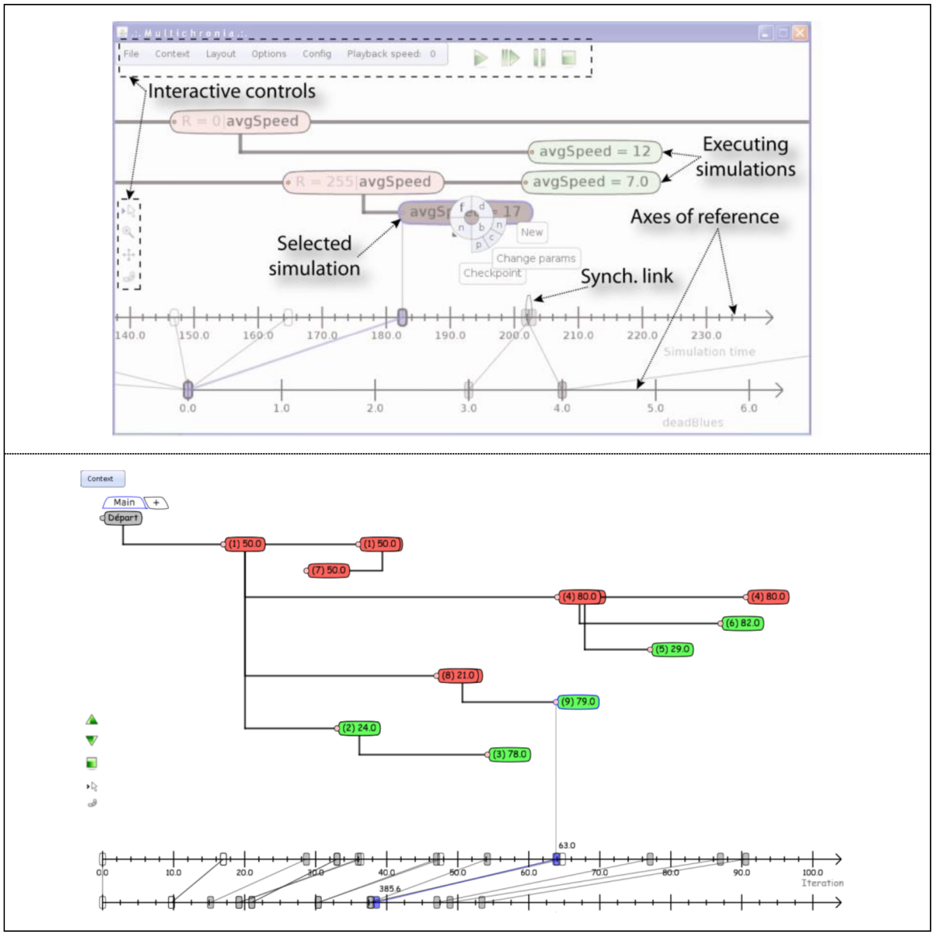


Figure 32: I-SIM tool (Multichronia) – (top) Graphical user interface, and (down) version used for the cognitive experiment

3.4 Experimental setup

The I-EXP V1 tools can be used on a traditional desktop and on a large screen (see Figure 33, left and middle) as well as on a display wall and in a CAVE, both providing active stereoscopic visualization (see Figure 33, right). Two hardware set-ups were used for the experiment. Baseline and IMAGE-Desktop shared the same computer platform: a BOXX 7400 workstation (2x Opteron 275 @ 2.2 GHz, 4 GB RAM, 250 GB HD, 2x NVIDIA Quadro FX 4500, Windows XP) with three 22-inch flat screens with a resolution of 1600×1200. IMAGE-CAVE used two BOXX 7500 (2x Opteron 2222 @ 3 GHz, 4 GB RAM, 146 GB HD, 2x NVIDIA Quadro FX 5600G, Windows XP) and a Safari Tablet PC connected to a CAVE. The CAVE consisted of a three-wall one-floor stereoscopic immersion environment called the Flex (http://www.mechdyne.com). Four Digital Projection (http://www.digitalprojection.com) Highlite 8000Dsx+ digital light processing projectors displayed images at 8000 ANSI lumens and a native resolution of 1400×1050@96 Hz on the 10’8”×8’ screens. Participants wore RealD Crystal Eyes 3 (http://www.reald.com) shuttle glasses. An Intersense IS-900 VET motion tracking system (http://www.intersense.com) tracked the Wand device and the participant's position for correcting the image perspective when in immersion mode.

Figure 33: I-EXP V1: desktop (left), CAVE in a non-immersive configuration (middle) and CAVE in an immersive configuration (right)

4 Architecture

The exploitation of complementary exploration tools is at the core of the I-EXP module, increasing the number of analysis opportunities available to users. COTS technologies were also included in the I-EXP module. The next subsections describe, (1) briefly, the data communication channel between the I-SIM and I-EXP modules, and Tableau software, a COTS tool used to analyse multidimensional data, and (2) in more details, Eye-Sys software, another COTS tool which allows users to create interactive visualizations, complex and dynamic 3D visual scenes and interaction widgets using a relatively user-friendly interface that minimizes the need for programming and scripting. Another subsection is dedicated to the CORE3D – Complete Off-axis Rendering Engine in 3D – library, developed at DRDC Valcartier, that was adapted to meet the functional requirements for the CAVE experimental setup. The generic features added to the library to adapt Eye-Sys to the CAVE are also described in this subsection. The chapter concludes with some unresolved problems and issues handled in IMAGE V2.

Figure 34 summarizes the main structure of the proposed architecture.

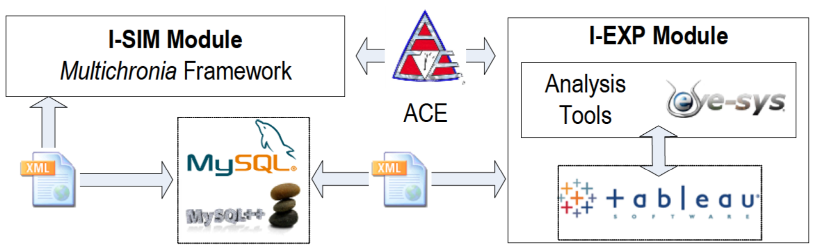


Figure 34: Software architecture of the I-EXP module for IMAGE V1

4.1 Data exchange between I-SIM and I-EXP modules

The data exchange between the I-SIM and I-EXP modules is a difficult problem to address because of multiple XML data streams that need to be transferred in parallel from the I-SIM module to the I-EXP module. The usage of a database[47] (DB) to create data persistence and centralisation has been adopted. To avoid the I-EXP module to consult the DB too frequently, the I-SIM module notifies the I-EXP module of changes occurring in real-time such as creation, deletion or selection of one simulation. For that purpose, a synchronization application (communication channel) has been created between the I-SIM and I-EXP modules. Managing multiple connections and executing data processing in parallel are performed by using the ACE framework[48].

[47] The DB is a MySQL database (http://www.mysql.com/) managed with MySQL++ (http://tangentsoft.net/mysql++/) which is a library of C++ classes.
[48] http://www.cs.wustl.edu/~schmidt/ACE.html

4.2 Tableau software

The Tableau software package[49], a visual analytics tool, was included in the I-EXP V1 toolset to explore data in a different but complementary way. Its strengths are mainly its user-friendly interface and the ease of learning and use. It exhibits several powerful functionalities, i.e. a “drag and drop” technique that is very intuitive and accessible to almost all interface elements and a support for (small to large) data sets in a wide variety of formats. These latter ones are handled automatically, quickly displayed in one or more dimensions, and represented using visual techniques such as color, shape, or size of the dots. Techniques such as zooming and filtering, combination of parameters, summation, and averaging complement Tableau’s analysis capabilities.

4.3 Eye-Sys software

The analysis toolset (both at Tactical and SOP levels) has been developed with the Eye-Sys software package[50], which is a commercial visualization application. It gathers data from various sources adopting different formats, manipulates them in real-time, and uses them to drive interactive and real-time visualizations. Mathematical operations can be applied to specific parameters, 2D and 3D representations of datasets can be displayed easily, 3D models can be arranged in different views using a scene graph approach, all visuals and graphics can be combined in a single view, user interface can be developed to control the flow of information, etc. Scripting and C++ programming through a software development kit (SDK) to develop custom functionalities is also possible to create advanced features.

Eye-Sys uses a sandbox concept where users must create a set of boxes with different behaviours linked together to produce the visual environment. The interface is relatively easy to use and the production of a flexible visual scene can be done in no time with minimal programming needs. A sample of the Eye-Sys sandbox with its outputs is presented in Figure 35. In this case, there are two displays: one is a 3D representation of a geographic area with moving landmarks; the other is a simple 2D plot. Note that these outputs are actually in separate windows in the Eye-Sys interface.

[49] http://www.tableausoftware.com/
[50] http://www.eye-sys.com/

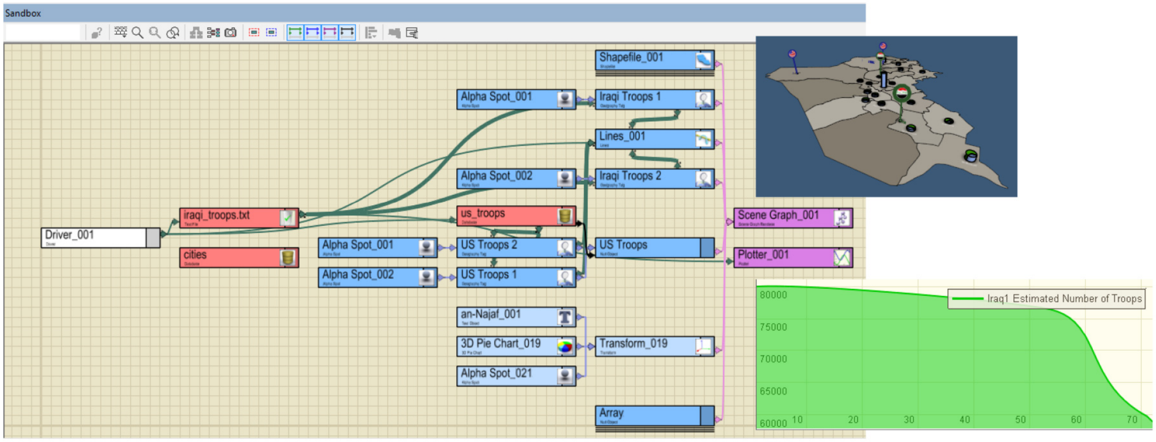


Figure 35: Eye-sys v2.0.0 Sandbox sample

There are a lot of object types in Eye-Sys depending on the behaviour one is looking for. Here's a few that had been used in the IMAGE project:

- Input objects (*orange* boxes) can import data of any kind in Eye-Sys: text file, database, socket, etc. The Eye-Sys SDK can be used to create new types of input objects.
- Manipulator objects (*green* boxes) are used to apply mathematical operation on the data or a unit conversion. Custom modification to the data can also be applied using scripts. The Eye-Sys scripting language is similar to C++. Again, custom manipulators can be developed using the SDK.
- Display objects (*blue* boxes) are used to create or influence the display. There are many types of specialized display objects depending on the desired display feature: simple 2D and 3D shapes (e.g. box, plane or sphere) can be created, 3D models can be loaded, transform matrix can be applied to move objects in the scene, pie charts, axis and plots can be displayed. Linked together, a complex visual system can be generated in no time.
- Display system objects (*pink* boxes) are responsible for managing the rendering of data and display objects and processing user input. Display system objects always have a window associated with them in the Eye-Sys interface.
- Driver objects (*white* boxes) are used to traverse or animate a set of data by providing an index, a percent or a time reference to access and display a specific value.

To create new simulations, control the flow of data and select specific parameters to display on the graph axis, *Multichronia* (I-SIM tool for IMAGE) is available as a remote interface through a TabletPC (in the CAVE). This interface is connected to a custom tool launched by the Eye-Sys host. Then specific events generated from *Multichronia* are sent to Eye-Sys to update the displayed information dynamically. The *Multichronia* interface also determines which analysis view is displayed during the SOP phase of the experiment: the 2D tools, the 3D *Cube View* or the *Ribbon View*.

Finally, to make sure a display system object is updated in real-time at a specific FPS, another custom script was added to the scene. Otherwise, the display updates only when the user interacts with the window using the mouse.

To interact with Eye-Sys in the CAVE, the wand from the Intersense IS-900 tracking system has been integrated as a custom input objects using the Eye-Sys SDK. It is a tracked device with joysticks and buttons. It has been used to rotate, move and scale the displayed models or reset the scene to default values. The head tracker is handled by the wrapper to handle the off-axis stereoscopic effect as presented in the next section. Both devices are presented in Figure 36.

Figure 36: Head tracker and wand from the Intersense IS-900 system

4.4 Wrapping Eye-Sys using CORE3D

The CORE3D library allows adapting almost any 3D applications providing a relatively open SDK to an immersive virtual environment such as the CAVE. The fundamental functionality of CORE3D is to intercept any call to the rendering engine by creating a mimic library of the original one called a “wrapper”. In fact, the wrapper encapsulates and reroutes the functionalities of the original display library by redefining every exported function. When the application starts, the CORE3D library is loaded instead of the original one then any rendering call will be overridden allowing the introduction of any behavior before forwarding the operation (with potentially modified parameters) to the actual engine DLL. The generic concept of this process is depicted in Figure 37. This mechanism also provides the ability to link high-level functions such as user interfaces or network capabilities.

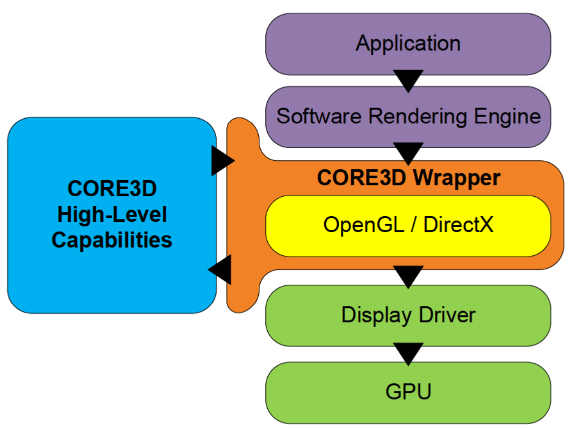


Figure 37: CORE3D wrapper concept

Eye-Sys meets the CORE3D prerequisites for off-axis stereo rendering. To integrate the CORE3D functionalities into Eye-Sys, four display system objects are created and linked to the same scene graph. To simplify, it’s possible to disable the culling in the display system object properties to make sure the whole scene is drawn on every frame despite the field of view of the camera. This feature makes sure the wrapper can modify the camera position and orientation without missing geometries or visual artefacts on the display.

The CORE3D wrapper has been used for only one commercial application before the IMAGE project: Unreal Tournament 2004 (UT2004), its mods and derived games. UT2004 offers a great SDK that goes beyond the prerequisites for off-axis rendering. It offers many possibilities such as scripting, world edition, AI capabilities, network communication, and new kinds of interactions and so on. However, this application uses only one window and the SDK doesn’t give the possibility to create more than one by instance. In addition, the performance would certainly be greatly affected. So we need to connect multiple instances on the network together to create an immersive experience in the CAVE on four different machines. The situation was different for the IMAGE project. The available machines had to be used for different software tools during the experiment and the chosen OpenGL application could not be easily linked on the network using multiple instances. However, multiple windows could be created in a single instance so this was a great opportunity to make the CORE3D wrapper more generic using a totally different type of applications.

Indeed, for both versions of the IMAGE project, a single machine is required to create the immersive representation of the simulation. Even so, in both cases multiple hosts are required to hold the set of tools developed to support the experiments.

Adapting CORE3D to Eye-Sys was an opportunity to make the wrapper more generic. Indeed, the applications used so far didn’t offer multiple display rendering and the camera management was assumed by the application SDK. The following subsections explain how the CORE3D wrapper handles the creation of multiple windows and OpenGL contexts on a single application and the multiple ways the camera can be managed at the wrapper level. Then, subsequent subsections will describe in details the additional features implemented into the CORE3D wrapper for OpenGL to enable off-axis stereo rendering on four screens simultaneously using a single computer.

4.4.1 Creation of multiple windows

Some modifications had to be done to the CORE3D wrapper to work with multiple windows. With UT2004, the application creates a single full-screen window and applies an OpenGL context to it for rendering so the wrapper simply needs to modify drawing calls. However since most applications like Eye-Sys don’t handle multiple displays in full-screen, the windows and the OpenGL contexts need to be taken care of by CORE3D. Fortunately, Eye-Sys allows the creation of four windows with four simultaneous OpenGL contexts and the deactivation of the culling which fulfill the prerequisites for an immersive off-axis stereo experience in the CAVE.

The OpenGL contexts creation calls are intercepted using the wrapper and full screen quad buffered OpenGL contexts are created in parallel and used instead. When the application sets the current context to one of the originals, this call is also intercepted and the corresponding stereo context is set as current instead. Then, drawing calls will be rendered in the new full screen window. This process is illustrated in Figure 38.

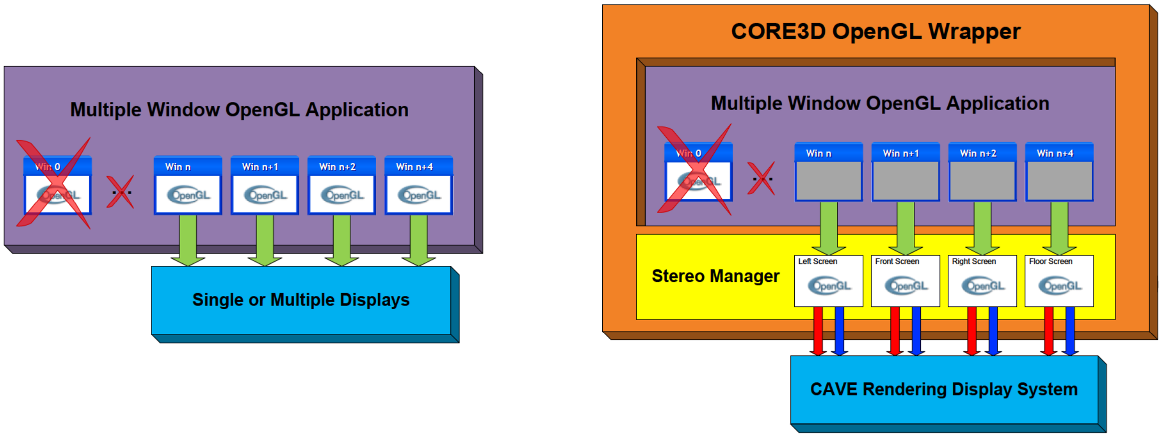


Figure 38: Using CORE3D to intercept OpenGL rendering contexts

When the application starts, multiple OpenGL contexts can be created and destroyed for logos or introduction videos. Since the amount of temporary contexts and the order of creation of the display windows can vary for each application, a new set of parameters has been added to the CORE3D application profile to specify which OpenGL context is associated to which screen in the CAVE system.

To define if an application needs its OpenGL context to be intercepted and expanded in full screen, another parameter called `ImmersionMode` has been added to the application profile. It's used to choose between three options to handle the application windows:

- Directly from application (`app`), where no OpenGL context interception is done and no external windows are created. The application handles the rendering by itself and only the view and projection transforms are modified by the CORE3D wrapper. This was the implied mode used before IMAGE;
- Debug mode (`debug`), where four small windows are created on a single display to be able to debug the application without having to deploy in the CAVE. OpenGL contexts are intercepted and forwarded to the small windows created by the wrapper;
- Full immersive mode (`full`), where four full screen windows are created using a computer with four video outputs. OpenGL contexts are intercepted and forwarded to the windows created by the wrapper.

In all three cases, users can choose between a static and a dynamic screen configuration through the parameter `UseDynamicScreenConfig` in the profile. The dynamic configuration allows to change the immersion mode and other parameters in real-time during the execution without having to restart. However, a little more resources and a user interface to use keyboard shortcuts are necessary.

4.4.2 Virtual camera management

The management of the camera is different for Eye-Sys due to the use of multiple displays. In UT2004, the SDK provides the ability to move the camera in-game directly by inputting the head tracker coordinates into the application. In this case the CORE3D wrapper simply handles the stereo offset and the off-axis projection matrix.

In Eye-Sys, the introduction of tracking coordinates in real-time didn't give good results so the camera is fixed to a specific location and the CORE3D wrapper is adding a translation offset to the camera according to the tracking coordinates. The wrapper must also take care of the camera orientation depending on the screen it's associated to since all Eye-Sys windows share the same camera object.

Each application will offer different possibilities through its SDK for the management of the camera. Applications without a SDK can be adapted at some point but with serious limitations. To make the CORE3D wrapper as generic as possible, four different ways to handle the camera, referred as camera modes, are suggested to the user: the "direct", "origin", "offset" and "rotated" camera modes. The resulting stereo offset matrix applied to the view matrix will be a bit different depending on the selected mode.

4.4.2.1 Directly-from-application mode

The direct mode is used by UT2004 and should be used with applications offering a SDK which gives partial or full control over the camera. The camera position is assumed to be taken care of directly in the application. Consequently, the view matrix won't be modified by the wrapper except for the stereo offset which is applied using the rotation of the tracker if stereo is enabled. Since the application is already taking care of the rotation of the camera to face each screen of the CAVE, the view offset matrix needs to use another matrix to

$$\boldsymbol{M}_{offset} = {}^{cam}M_{CAVE} \cdot {}^{CAVE_{rot}}M_{CAVE_{front}} \cdot M_{offset_{scale}} \cdot \boldsymbol{M}_{offset_{stereo}} \cdot M^{-1}_{offset_{scale}} \cdot {}^{CAVE_{front}}M_{CAVE_{rot}} \cdot {}^{CAVE}M_{cam}$$

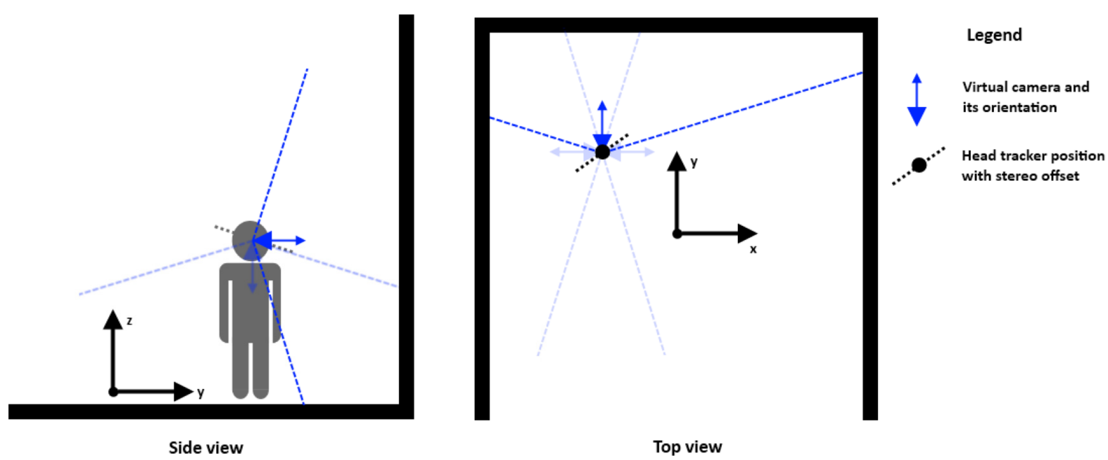


Figure 39: "Direct" camera mode

To use this mode, the application SDK must also provide the ability to input tracker data directly into the simulation to affect the camera position before the OpenGL calls. The field of view must also be enlarged enough to cover the whole screen or the culling has to be disabled to make sure there are no gaps in the display. Note that the camera orientation must always be perpendicular to the screen surface to apply the perspective projection. That means only the tracker's position is used to affect the camera in the application. This mode is depictured in Figure 39.

4.4.2.2 Camera-at-origin mode

This is the mode used with Eye-Sys. The camera locations received from the application are assumed to be located at the CAVE origin facing the front screen with no offset. In the wrapper, the tracker position and stereo effect are directly applied to the view matrix after the camera rotation. That means ${}_{CAVE_{front}}M_{CAVE_{rot}}$ is left out of the equation since the camera is not originally rotated on the application side. The $M_{offset_{cam}}$ matrix is also an identity matrix since there is no camera offset:

$$\boldsymbol{M_{offset}} = {}_{cam}M_{CAVE} \cdot {}_{CAVE_{rot}}M_{CAVE_{front}} \cdot M_{offset_{scale}} \cdot \boldsymbol{M_{offset_{stereo}}} \cdot \boldsymbol{M_{offset_{pos}}} \cdot M_{offset_{scale}}^{-1} \cdot {}_{CAVE}M_{cam}$$

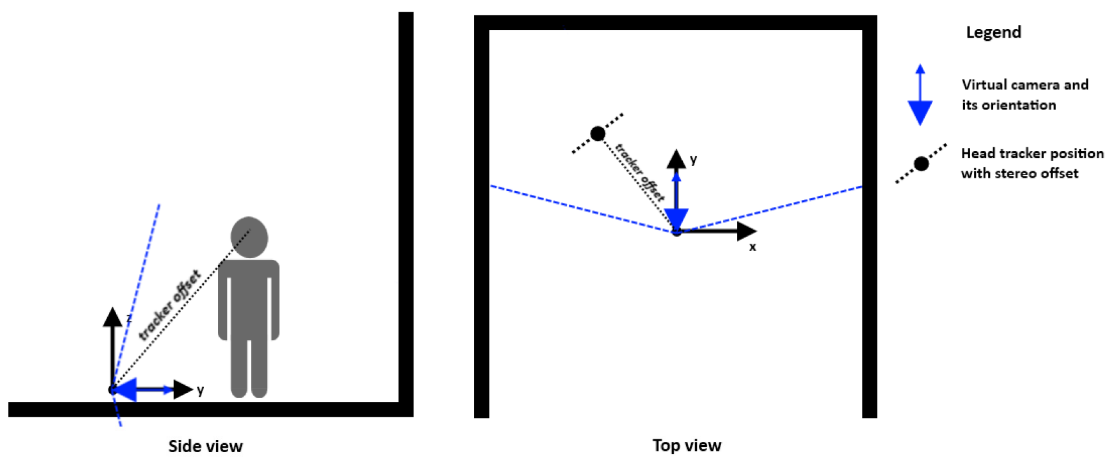


Figure 40: "Origin" camera mode

This is by far the easiest mode to apply to any application since it requires almost no modifications on the application side. However, the culling must be deactivated to avoid clipping on the side screens since the whole field of view of the cameras won't cover the whole scene. At least, the field of the view of the cameras has to be enlarged as must as possible to cover a larger part of the scene. This mode is used for simulations without avatars since the height relative to the ground doesn't really matter. Using this mode for a first person simulation would give the impression to actually be in third person, above the character. Figure 40 illustrates this mode.

4.4.2.3 Offset camera mode

Very similar to the "camera-at-origin" mode, this one assumes all the camera locations provided by the application to be located at a specific height offset above the virtual ground. This information is then used to make the correspondence with the CAVE origin. As presented in Figure 41, this mode can be used to compensate for the avatar's height in a first person simulation. Knowing this information, the camera height can be adjusted in the wrapper so that the user feels the virtual floor is actually under its feet. It's also the best mode to use to adapt an application with a limited or no SDK. The offset matrix is computed the same way as the "camera-at-origin" mode but the camera height coming from the application has to be compensated in the $M_{offset_{cam}}$ matrix before applying the tracker and stereo offsets:

$$M_{offset_{cam}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -cam_{height\_offset} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{M_{offset}} = {}_{cam}M_{CAVE} \cdot {}_{CAVE_{rot}}M_{CAVE_{front}} \cdot M_{offset_{scale}} \cdot \boldsymbol{M_{offset_{stereo}}} \cdot \boldsymbol{M_{offset_{pos}}} \cdot \boldsymbol{M_{offset_{cam}}} \cdot M_{offset_{scale}}^{-1} \cdot {}_{CAVE}M_{cam}$$

Since the height can change depending on the application, this parameter needs to be kept in the application profile. However, assuming a fixed height for the avatar is not always right: for instance, if the avatar can crouch or prone, the camera height above the ground will be adjusted in consequence and the compensation in the wrapper won't be right anymore. Using high-level CORE3D features, it's possible to overcome this limitation by using a socket that modifies the height offset in real-time according to the avatar state. Of course, the application SDK must be versatile enough to provide such functionalities. Again, the FOV must be enlarged or the culling deactivated to avoid clipping on the side screens.

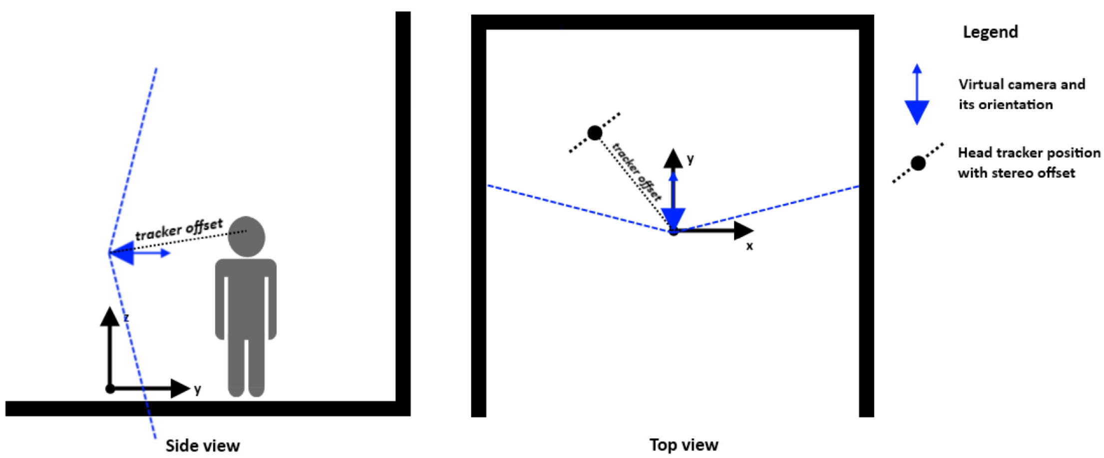


Figure 41: "Offset" camera mode

4.4.2.4 Rotated camera mode

This mode is a first approach to overcome the culling limitations of the previous modes. In addition to the height above the CAVE origin introduced in the "offset" camera mode, this mode assumes that the application rotates the cameras to face each screen plane perpendicularly and that the field of view is large enough to cross each other and fill the whole screens as illustrated in Figure 42. For most situations, the culling can remain activated this time which will enhance performance.

This time, the initial camera rotation needs to be compensated in ${}_{CAVE_{front}}M_{CAVE_{rot}}$ before applying the actual offset resulting in the complete stereo view offset matrix equation:

$$\boldsymbol{M}_{offset} = {}_{cam}M_{CAVE} \cdot {}_{CAVE_{rot}}M_{CAVE_{front}} \cdot M_{offset_{scale}} \cdot \boldsymbol{M}_{offset_{stereo}} \cdot \boldsymbol{M}_{offset_{pos}} \cdot \boldsymbol{M}_{offset_{cam}} \cdot M^{-1}_{offset_{scale}} \cdot {}_{CAVE_{front}}M_{CAVE_{rot}} \cdot {}_{CAVE}M_{cam}$$

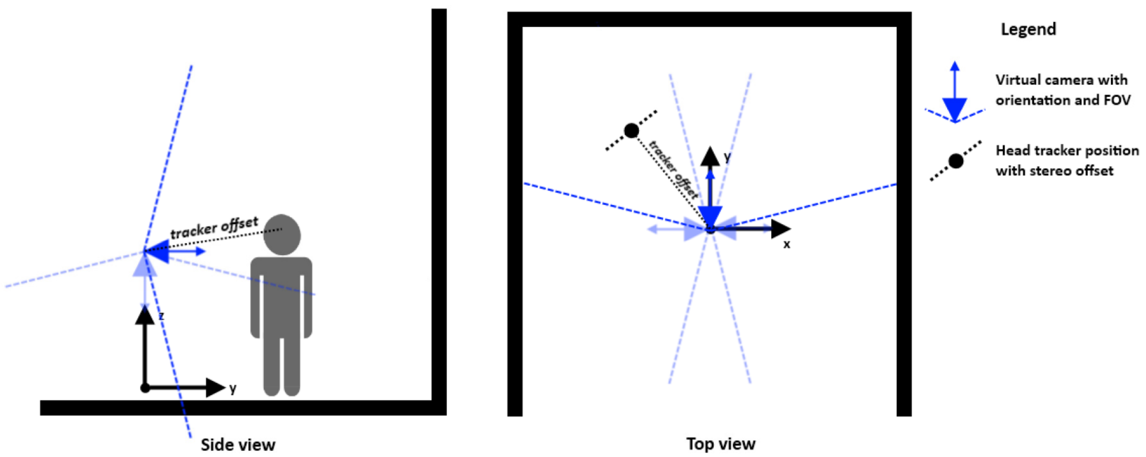


Figure 42: "Rotated" camera mode

Except the direct mode used with an application SDK allowing full control over the position and field of view of the camera, none of the created modes at this point can maximize performance and avoid visual artifacts at the same time. Even with the "rotated camera" mode, the user can observe strange culling behaviors such as objects being partially or completely invisible especially for those located inside the CAVE area depending on their relative position to the user.

Indeed, as depictured in Figure 43, when culling is activated the fields of view of the cameras define areas where objects are drawn or discarded for each screen. If there is a difference between the locations of the cameras in the CORE3D wrapper and the ones in the application, there will be some locations in the CAVE where the user will observe visual artifacts, especially at the edges of the screen. This is due to the fact that the user can move and look outside the area covered by the cameras so some polygons might be culled out when an object switches from one screen to another.

The Figure 43a shows a closer look at the area covered by two cameras in the "rotated camera" mode. Assuming the fields of view are large enough to overlap each other, it defines four areas:

- The green area, where every object inside is rendered regardless of the user's position in the CAVE (visible from both screen cameras);
- The red area, where every object is discarded by both cameras due to culling;
- Both orange areas, where objects can be culled out by either one of the cameras depending on the user's position.

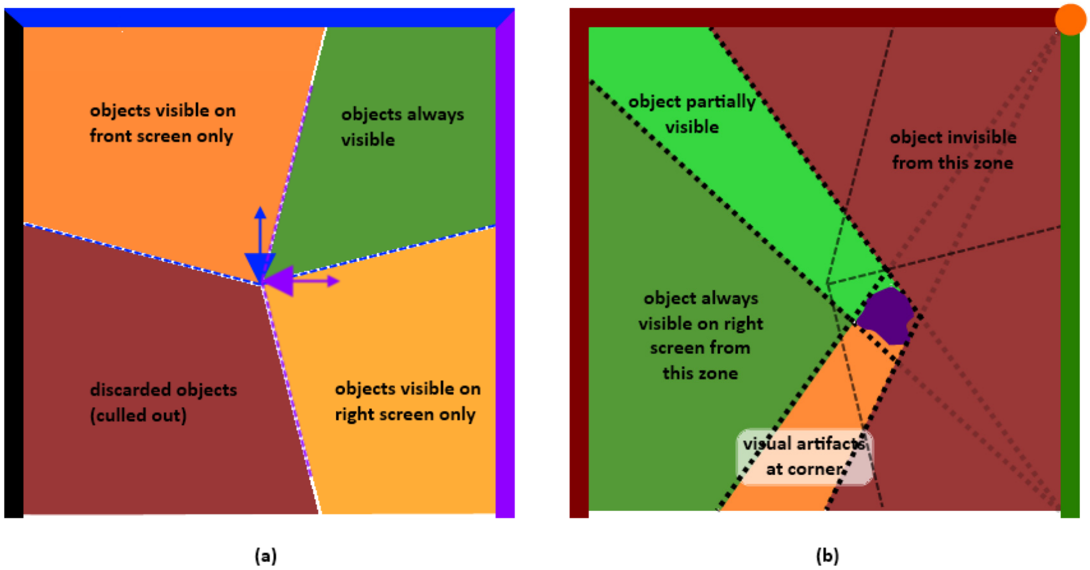


Figure 43: Potential visual artifacts caused by culling

Figure 43b shows an example with an object in the orange zone covered by the right screen camera. Drawing a line from the screen edge to the center of the object defines three areas for the user's position:

- The area left to the line is the zone where the user will always be able to observe the object on the right screen;
- The area to the right is where the object is culled out by the front screen camera so it's not visible to the user;
- The area along the dashed lines is where the user will perceive visual artifacts on the edge of the screen (partially visible polygons or object rapidly appearing and disappearing).

At this point, the "rotated camera" mode was the best mode developed but since the user would observe visual artifacts when looking at virtual objects inside the CAVE area at specific angles, the culling was disabled for IMAGE V1 and the "camera-at-origin" mode was chosen as a matter of simplicity. For other applications it would be a costly choice but this was acceptable for Eye-Sys since the scenes could be simplified to optimize the frame rate.

4.4.3 Extending Eye-Sys functionalities using C++ plugins

A great feature of Eye-Sys is the extensibility of its basic functionalities using scripts and C++ plugins. Indeed, the software allows the addition of specialized high-level behaviors to the scene by creating scripts with custom inputs and outputs. For even more flexibility or to add a third party library, custom C++ plugins can also be loaded as the application starts.

Eye-Sys defines five types of objects with different types of behaviors:

- Input objects: load or generate data to be linked to the properties of other objects in order to control some aspect of their behavior;
- Manipulators: modify data already in Eye-Sys;
- Display objects: render individual visualization components (or control some aspect of the rendering process). Many display objects are typically used to create visualization systems;
- Display systems: make up the "windows" in Eye-Sys. These objects process user input and control the manner in which data and display objects are rendered;
- Driver: act as the "engines" inside Eye-Sys. They control when, how fast, and in what direction data is traversed during animations.

Many specialized objects falling in those five categories are included with Eye-Sys forming the basic functionalities of the software. These objects are represented by boxes linked together in the sandbox edition area, as presented in Figure 35, to create a visualization system with custom behaviors. The creation of a C++ plugin will generate new specialized objects to extend the visualization system functionalities.

For instance, to interact with the scene using a tracked device the easiest way was to embed the Intersense tracking library developed at the VIF into a C++ plugin as described in the following.

4.4.4 Interacting with the 3D scene using a tracked devices

To interact with a 3D scene on a desktop computer, mouse and keyboard will generally be sufficient for most applications. On the other hand, interacting with an immersive virtual environment where the user is generally standing up requires totally different devices. For IMAGE V1, only the Intersense IS-900 wand was necessary as the main interaction device since the navigation and manipulation tasks are relatively simple: move, zoom and rotate views mostly.

To integrate the wand in the system, the C++ library already available to obtain tracking data was simply encapsulated in an Eye-Sys plugin named "WandInput". The wand is represented by an input object holding axis data and button states which are then available to any other object in the sandbox. Using this data, it's easy to create high-level behavior in the 3D scene.

Since the immersive view was used only for SOP analysis, the wand interactions had to be configured for two 3D scenes: the Ribbon View and the 3D Cube View. A similar interaction approach could be used for both views with some variation according to the context:

- Joystick left/right: Rotation of the 3D graph or translation left/right in the Ribbon View;
- Joystick up/down: Translation front/back in both views;
- Red button : Scale up the 3D graph or expand the ribbon;
- Yellow button : Scale down the 3D graph or shrink the ribbon;
- Blue button : Translation up in both views;
- Green button : Translation down in both views;
- Trigger: Reset the scene to default view parameters.

4.4.5 Other Eye-Sys plugins developed for IMAGE

Table 7 corresponds to a brief description of the other Eye-Sys plugins developed for the project.

Table 7: Eye-Sys Plugins

Name of the plugin	Description
`DisplaySystemRefresh`	Manipulator that periodically refreshes linked display systems at a specified frequency.
`DriverRegulator`	Input object used to control the movements of vehicles in the tactical view.
`Graph3DCustom`	Display object holding all the primitives to construct the cube view described earlier.
`HistoryConcatenator`	Concatenates the histories of multiple input sources into one, mainly for gridded surface rendering.
`MySqlDatabase`	Customized connection object for MySQL databases. Keeps a persistent connection to the MySQL server.
`PropertyMultiplexor`	Allow a better management of properties with multiple objects
`ScriptAutoRefresh`	Update a list of scripts at a specified refresh rate
`ScriptHelper`	Facilitates development of scripts by importing code from an external JavaScript file and automatically linking its contents to a specific Script object. Also supports automatic property creation with special commenting in source code.
`SelectableObject`	Renders a selectable display object to interact with the mouse.
`SelectionState`	Observes a group of objects periodically and indicates if any of them is selected through a Boolean output property.

4.5 Encountered problems

Despite the fact that the CORE3D wrapper was made more generic for the use with Eye-Sys, some compatibility issues remained with some specialized rendering functionalities using OpenGL extensions. Also, many performance issues were still unresolved at that point.

4.5.1 Compatibility issues with OpenGL extensions

Since the CORE3D wrapper intercepts and redirects OpenGL calls, any unexpected call to an OpenGL extension method or a future version would result in a crash of the application or an unexpected result if the call is ignored.

Unfortunately, it has been found during the development that Eye-Sys uses the GLEW extensions to manage textures with some display objects and other specialized OpenGL features. Of course, this caused problems with the wrapper intercepting only basic OpenGL calls. Since most tactical views are using such objects, the wrapper could not be used to produce an immersive display without causing visual artifacts. Instead, the 2D tools were simply rendered on the CAVE screens during the tactical analysis and standard interaction tools were used.

Some efforts have been done to intercept GLEW calls and redirect them to a local version of the DLL but the approach didn't work in time so it was decided to restrict the immersive mode to the SOP views. This constraint hadn't been an issue in IMAGE V2 because the rendering engine is open source. Consequently, no additional efforts have been put to make the wrapper more generic using OpenGL extensions.

4.5.2 Performance issues

During the first tests in the CAVE there was still a performance issue in Eye-Sys using the 3D graph view with large datasets. Indeed, because the culling is disabled, all four OpenGL contexts need to render the whole scene even if all primitives are not visible. Since the original dataset contained a lot of redundant entries, a lot of OpenGL primitives could be merged to enhance performance to an acceptable level for the experimentation. This problem was resolved in IMAVE V2 using field of view optimization.

5 Conclusion

The IMAGE project aims at disentangling complex situations more quickly, specifically targeting the collaboration of experts from different disciplines trying to reach a shared understanding of a situation. The goal of the IMAGE concept is two-fold: increasing understanding of a situation and enabling individuals to share their comprehension. The elaboration of the IMAGE concept was mainly guided by three principles or assumptions: (1) iterative understanding: a common understanding is reached through revision and sharing of successive representations of the situation; (2) human-driven toolset: the common understanding is above all a human task involving team members using tools their own way; and (3) synergy of technologies: the common understanding is better served by the synergy of technologies than a single one. IMAGE researchers have identified four complementary modules to achieve this synergy: *Representation*, *Scenarisation*, *Simulation* and *Exploration*. The *Representation* module (I-REP) consists in rendering a mental model explicit in a comprehension model. From this comprehension model, the *Scenarisation* module (I-SCE) generates an executable model to be used by the *Simulation* module (I-SIM) that provides a high level of interactivity enabling investigation of the space of variables.

This document has presented the last module, the *Exploration* (I-EXP) module (and its underlying architecture) that provides powerful tools allowing experts / users to invent views that bring a significant meaning to large datasets generated by the I-SIM module. These (explanatory and personalized) views have to generate, stimulate, increase or accelerate the complex situation understanding, and consequently augment individual or collective comprehension models. The I-EXP module puts emphasis on the proper use of technologies in order to fulfill the individual's exploration needs. The I-EXP tools implement visualization and interaction techniques and/or mechanisms by, taking advantage of the potential of different platforms in terms of technology and in terms of exploitation of human sensory information. The developed tools mainly offer the user rapid prototyping of views and focus on the "best view" concept rather than the "perfect view" concept. Furthermore, to address as much as possible exploration needs with respect to diversity and richness, the toolset includes, if necessary, a combination of turn-key and COTS tools.

Many CAF contexts could potentially benefit from such tools accelerating understanding. A whole-of-government team working out a situation involving security, development and political issues is an obvious one but facing a cyber-threat is another one requiring an efficient collaboration between experts of friendly plans, enemy intents, computer networks and software applications. The first one is operational while the second one has more a technological flavour, although it may have important operational impacts.

CAF recognises the importance of a comprehensive approach considering all dimensions of a situation, more than the military power alone. The various issues (ethnics, religious, ideological and material), the various power and influence (diplomatic, economic, informational ...) as well as the national and international public opinion and Medias are examples of the variety and diversity of the dimensions. A comprehensive approach is required to elaborate plans but moreover, a whole-of-government approach is required to achieve the strategic national objectives.

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Annex A IMAGE Requirements

A.1 IMAGE requirements – Priority 1

1. Expressing and sharing understanding:

P1-1.1. Using a graphical formalism to represent comprehension by displaying "animated concepts ("things, variables...")" and links between them;

2. Looking for something:

P1-2.1. Browsing through all concepts;

P1-2.2. Searching through all concepts;

P1-2.3. Allowing multiple synchronized views (perspectives) over a set of concepts;

3. Handling concepts and relationships:

P1-3.1. Creating concepts and relationships;

4. Interacting with IMAGE:

P1-4.1. Using CAVE visualization screen capabilities to interact with the user;

P1-4.2. Using visualization paradigms enabling comparison of data sets (I-SIM);

P1-4.3. Feeding views in real-time;

P1-4.4. Providing visualization paradigm focused on quantitative data;

5. Analyzing the situation:

P1-5.1. Fitting visualization features with the scenario intent;

6. Testing hypotheses:

P1-6.1. Running many simulations on a short period of time (seconds or minutes);

P1-6.2. Modifying simulation parameters / variables / inputs;

P1-6.3. Controlling simulation execution and playback;

7. Supporting users:

P1-7.1. Providing mentoring;

8. Supporting experimentation:

P1-8.1. Logging user actions to allow cognitive analysis studies;

9. Miscellaneous:

P1-9.1. Scenario must have quantitative data;

P1-9.2. Providing users with appropriate scenario background material defining the context, the objectives and the available models;

P1-9.3. Defining a terminology which matches established standards favouring SME users' confidence in the software and its outcomes;

A.2 IMAGE requirements – Priority 2

1. Expressing and sharing understanding:

P2-1.1. Supporting multiple users;

P2-1.2. Handling user ownership of comprehension models;

P2-1.3. Allowing users to access comprehension models owned by others;

2. Looking for something:

P2-2.1. Filtering a view according to some criteria;

P2-2.2. Identifying differences between concepts;

3. Handling concepts and relationships:

P2-3.1. Creating clusters of concepts and relationships;

P2-3.2. Merging concepts;

P2-3.3. Splitting concepts;

P2-3.4. Duplicating concepts;

4. Interacting with IMAGE:

P2-4.1. Triggering other IMAGE tools from the Representation views;

P2-4.2. Meeting common user-friendliness criteria;

P2-4.3. Keeping responsiveness even when lots of processing are taking place in the background;

5. Analyzing the situation:

P2-5.1. Creating view templates for accelerating view instantiations;

P2-5.2. Creating, deleting and archiving views;

P2-5.3. Attaching notes to views;

P2-5.4. Taking pictures (snapshots) of views;

6. Testing hypotheses:

P2-6.1. Probing simulation variables;

P2-6.2. Injecting events into the simulation;

P2-6.3. Supporting "What-if" simulation;

P2-6.4. Supporting stochastic models and providing appropriate tools such as data farming and statistical analysis tools;

7. Supporting users:

8. Supporting experimentation:

9. Miscellaneous:

P2-9.1. Scenario must integrate sensor models;

A.3 IMAGE requirements – Priority 3

1. Expressing and sharing understanding:

P3-1.1. Using a visualization structure and content corresponding to the desire structure and content of the mental representation to be instilled;

2. Looking for something:

P3-2.1. Recognizing a set of concepts matching a pattern of concept properties and relationships;

3. Handling concepts and relationships:

4. Interacting with the tools:

P3-4.1. Reorganizing layout according to the importance of "concepts" (iconography, layers...);

P3-4.2. Switching from one view paradigm to another (e.g. 3D to 2D);

5. Analyzing the situation:

P3-5.1. Prioritizing key concepts and relationships;

P3-5.2. Keeping comprehension history;

P3-5.3. Handling confidence levels;

P3-5.4. Supporting validation mechanisms;

P3-5.5. Assessing effects through time: short, medium and long terms;

6. Testing hypotheses:

7. Supporting users:

P3-7.1. Providing on-line task support;

8. Supporting experimentation:

9. Miscellaneous:

P3-9.1. Searching into a database to confirm observation and find similar situations;

P3-9.2. Providing network analysis tools;

P3-9.3. Providing dynamic updates of the available tools;

P3-9.4. Providing performance evaluation tools;

A.4 IMAGE requirements – N/A

1. Expressing and sharing understanding:

2. Looking for something:

3. Handling concepts and relationships:

4. Interacting with the tools:

Pna-4.1. Take care of the workload of these tools;

5. Analyzing the situation:

6. Testing hypotheses:

7. Supporting users:

8. Supporting experimentation:

Pna-8.1. User actions could be for observation purposes (I-EXP) as well as modification purposes (I-SIM);

9. Miscellaneous:

Annex B Videos

This document is accompanied by a set of videos (available on request) that show I-EXP tools in action and their relation with other tools (from other modules such as the I-SIM module), exemplify different aspects of the tools and help readers to better understand the tools themselves and what they look like. The videos are grouped under the directory *Videos* and are named as follows:

- Sub-directory *Tactical*: *Desktop – Tactical View02*, *Desktop – Tactical View02*, *I-EXP and I-SIM (joint view)*, and *Scenario*;
- Sub-directory *SOP*: *Desktop – SOP View* and *Desktop – SOP View*;
- Sub-directory *CAVE*: *Non-Immersive*, *Immersive* and *I-EXPV1HCII2013* (video presented to HCII 2013 – (Mokhtari, Boivin, & Laurendeau, 2013) – that summarizes work done for the immersive part of I-EXP V1).

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List of symbols/abbreviations/acronyms/initialisms

ACE	Adaptive communication environment
CAVE	CAVE automatic virtual environment
CAF	Canadian Armed Forces
COTS	Commercial off-the-shelf
CS	Complex situation
DND	Department of National Defence
DRDC	Defence Research & Development Canada
I-EXP	IMAGE Exploration
I-REP	IMAGE Representation
I-SCE	IMAGE Scenarisation
I-SIM	IMAGE Simulation
IED	Improvised explosive device
LAV	Light armoured vehicle
NIED	Number of improvised explosive devices
NRPG	Number of rocket-propelled grenades
R&D	Research & Development
RPG	Rocket-propelled grenades
SAT	Side armour vehicle
SDK	Software development kit
SOP	Standard operating procedure
XML	Extensible Markup Language

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In a wide range of scientific and technological domains (e.g. economics, climate and seismic modeling, melting modeling, astronomy, neuroscience and archaeology), experts need to make sense of and extract useful information and/or knowledge from (large) datasets composed of various types of data. To achieve these goals, experts require tools combining advanced analysis and visualization, and rich user interactions to guide them to incrementally and interactively explore datasets, to organize data, to process information, and to go through and understand these datasets. The *Exploration* concept (developed for the *IMAGE* project) consists in making datasets clear in explanatory and tailored (visualization) views, which can be exploited by experts to augment their individual or collective comprehension models of a complex phenomenon.

Dans un large éventail de domaines scientifiques et technologiques (par exemple l'économie, le climat et la modélisation sismique, la modélisation de la fonte des glaces, l'astronomie, les neurosciences et l'archéologie), les experts ont besoin de donner une signification aux données et d'extraire de l'information et/ou de la connaissance utiles de (grands) ensembles de données composées de divers types de données. Pour atteindre ces objectifs, les experts exigent des outils combinant une analyse et une visualisation avancées, et des interactions riches pour les guider à une découverte progressive et interactive des jeux de données, pour organiser les données, pour traiter l'information, et pour naviguer au travers de ces ensembles de données et pour les comprendre. Le concept d'*Exploration* développé pour le projet *IMAGE* consiste à donner un sens aux ensembles de données à travers des vues (visualisations) explicatives et adaptées, qui peuvent être exploitées par des experts afin d'augmenter leurs modèles individuels ou collectifs de compréhension d'un phénomène complexe.

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data visualization; scientific visualization; virtual reality; CAVE; complexity

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