Reference Data (Navigation) in Fusion and Information Operations

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Abstract

The author feels the growing need to build the bridge (dialogue and collaboration) between the *Reference (Navigation)* and *Information Fusion* Communities in support of the current increasing interest in Information Operations.

Department of Defense (DoD) and Military Services are leading a revolution in future warfare, building on lessons of Operation Desert Storm and technology revolutions. Joint Vision 2010 (JV2010) [2] identifies theater-wide information superiority as the foundation for this revolution. The Advanced Battlespace Information Management System (ABIS) [3] Task Force reports:

> *… a federation of systems that forms an underlying grid of flexible, shared, and assured information services and provides advanced capabilities in support of new command and control and force employment concepts.*

Former Chief of Staff of the Air Force (CSAF) Gen Ronald Fogleman had begun a revolutionary (in this author's opinion) rebuilding of the US Air Force. Gen Michael Ryan, current CSAF, continues this transformation from a *Cold War* Air Force to the expeditionary Aerospace Force (eAF) of the 21st Century. The USAF Vision: *Global Engagement: A Vision of the 21st Century Air Force* documents the goals and the course that the Air Force has set to achieve such. One of the first key steps is the rebuilding the fragmented USAF Command and Control (C2) infrastructure into an flexible, rapidly adaptable, stateside-based core with minimum C2 projected forward to the fight. Overarching theme under the eAF C2 is: ***move information, not people*** to the fight.

Each of these, and numerous other Air Force and DoD, studies and initiatives identifies information superiority as a key enabler of revolutionary warfare. An overwhelming amount of information is available to the warfighter. Information fusion technology (focus of the Information Fusion Community) integrated with operational concepts, enables transformation of collected data into warfighters' mission capability. Precise space/time (geometric) reference, the focus of the Navigation Community, is the foundation of information fusion [4]. A similar information and fusion framework and perspective is suggested for the exploding commercial information products and services.

Introduction

History of warfare records that up to the time of air and space vehicles, the terrain high ground provided the commander the required view of the battlespace. This view, combined with reconnaissance patrols and other intelligence, provided the situational awareness necessary for the commander to employ his forces. Today,

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situational awareness is generated from data and information objects provided by air, space, maritime, and ground sensors, data bases, as well as human sources. These elements are created and stored in various formats including images, communication and direction/ranging signals, radar reports, human observations, and others.

Various command levels, such as theater, strike force, or an aircraft commander (in the Air Force mission structure) require different views of the same battlespace. These *near-real-time*, *near-perfect* views of the battlespace can be constructed from various information objects. The construction process for these battlespace views is defined as data/information fusion to provide the commanders the required situational awareness.

Rapid advances in sensor and information technologies provide the richness and abundance of data and information for various applications. Today a theater-wide battlespace system perspective is essential to absorb the rapidly advancing information technologies and to integrate these with the traditional disciplines, such as navigation, into warfighter mission systems.

The prominent role of information superiority in the military mission suggests a similar framework for commercial infrastructure to better deliver the various information products and services which are rapidly permeating our society. Such a global view of commercial information systems helps to identify common infrastructure requirements and the focusing of system level technology developments. Both DoD and commercial integrated information systems share the requirement for a global space-time geometric reference infrastructure enabled by reference systems such as GPS. An example of such evolving global civil infrastructure is in application of GPS to the air traffic control.

Joint Vision 2010

The Chairman, Joint Chiefs of Staff (CJCS), General John Shalikashvili, has presented his framework for future military capability in the Joint Vision 2010.

> *It is a conceptual template for how America's Armed Forces will … achieve new levels of effectiveness in joint warfighting. Focused on achieving dominance across the range of military operations through the applications of new operational concepts, this template provides a common direction for our Services in developing their unique capabilities within a joint framework of doctrine and programs as they prepare to meet an uncertain and challenging future. … develop four operational concepts: Dominant maneuver, precision engagement, full dimension protection, and focused logistics.*

These four new operational concepts become the basis for new operational capabilities listed on the left of Figure 1. The Joint Vision 2010 applies to all of the military functions across the various DoD services and departments. It recognizes the unique roles and contributions of the individual services, as well as the opportunity for collaboration and commonality of battlespace-wide information resources.

The Lens of Information Superiority
Integrates and Amplifies Four new Operational Concepts:

Enables New Operational Capabilities:

- **Self-Synchronizing Forces**
- **Increased Speed of Command**
- **C4ISR Matched to Combat Power**
- **Decentralized Empowerment**
- **Enable Alternative Command Structures and Procedures**
- **Self Adapting and Learning Organizations**

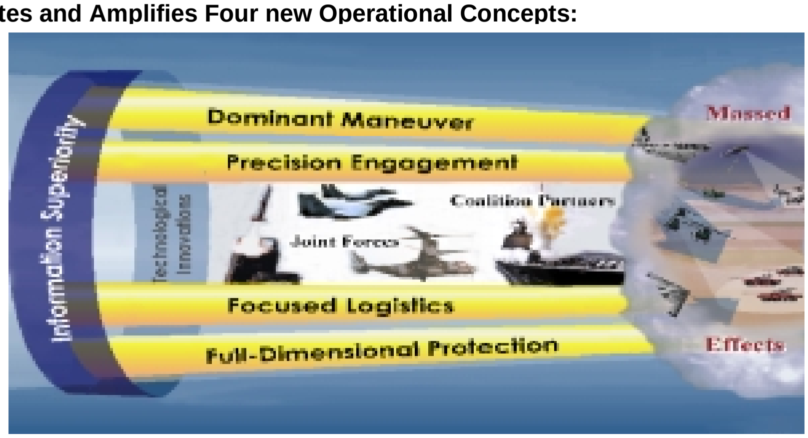


Figure 1. Joint Vision 2010

Advanced Battlespace Information Management [3]

The Director of Defense Research and Development (DDR&E) Dr. Anita K. Jones and the Director for Command, Control, Communications, and Computer Systems (DC^4S) Vice Admiral USN Arthur Cebrowski have commissioned the ABIS Task Force. Its charter:

… is to explore how emerging information technologies could be used to provide the warfighter with significant new capabilities as articulated by the Chairman, Joint Chiefs of Staff (CJCS) in his recently published Joint Vision 2010.

The ABIS report identifies information superiority applied at various levels of C2 of theater forces. The study was organized in an Executive Steering Committee and three Working Groups: Battle Management, Sensor-to-Shooter, and Grid Capabilities. It laid out a dynamic battle management concept consisting of two loops. The outer loop reflects theater-wide battle management conducted on the time scale of minutes to hours and an inner sensor-to-shooter loop operating on a time scale of seconds to minutes. This short time scale is required to prosecute time-critical-targets (TCTs).

The ABIS framework, center region of Figure 2, shows the overall *Grid* providing for collection and distribution of the required information to the required location at the required time. The *Precision Sensors* reflects collection of all the information sources within the Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C^4ISR) infrastructure. The *Precision Forces* provides for the precise deployment, employment, and redeployment of forces. It includes weapon systems necessary to hold the enemy forces at risk, precise and timely delivery of supplies and reinforcements, and precisely coordinated combined operations.

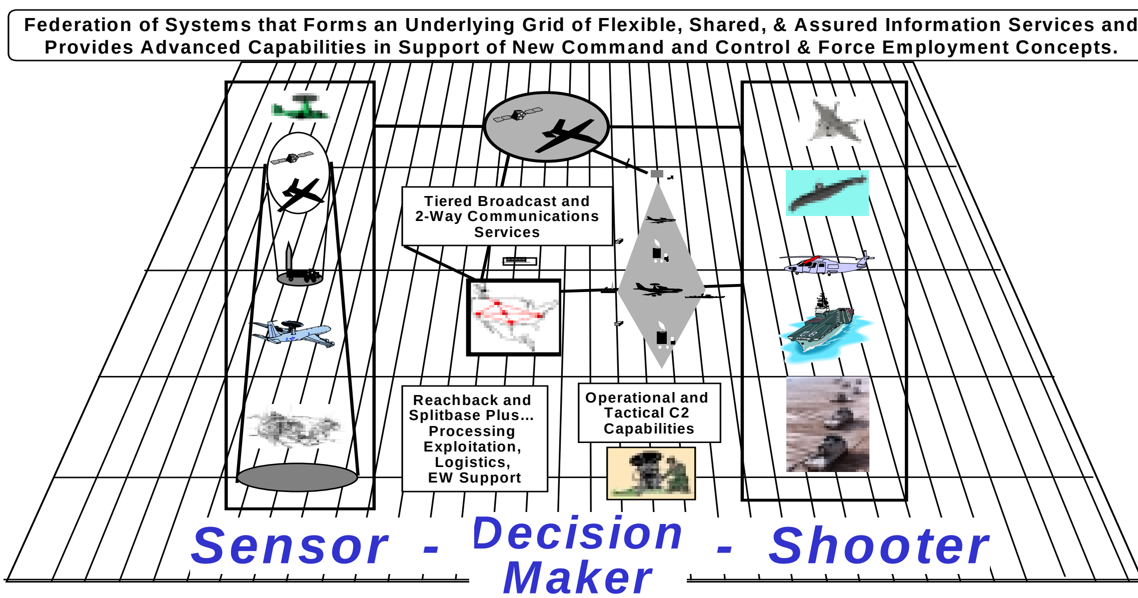


Figure 2. Advanced Battlespace Information Management (ABIS)

The ABIS study identified several key technologies required to achieve the JV 2010 objectives. Prominent among those are precise geolocation and fusion of information at various levels of information collection, distribution, and application for the warfighter.

Global Engagement: Vision of the 21st Century Air Force

According to Gen Fogleman and Honorable Sheila Widnall, former Secretary of the Air Force:

Global Engagement: A Vision for the 21st Century Air Force flows from the National Security Strategy and is our continuing commitment to provide America the air and space capabilities required to deter, fight and win. This vision is *grounded in the Chairman of the Joint Chiefs of Staff concept of how we will fight in the early 21st Century - Joint Vision 2010. Moreover, it embodies our belief that in the 21st Century, the strategic instrument of choice will be air and space power. …*

After extensive study and discussion, the Air Force senior leadership began to build this Air Force vision for the 21st Century. It was shaped by Joint Vision 2010, the new guidance published by the Chairman of the Joint Chiefs of Staff. Air Force leaders understood that their new strategic vision must meet the national security needs of the nation, and a national military strategy that has as its focus an increasingly U.S.-based contingency force. ***The Air Force also recognizes the emerging reality that in the 21st Century it will be possible to find, fix or track and target anything that on the surface of the earth.***

The "find, fix, track, target, engage, and assess" (F2T2EA) has become one of the six operational thrusts that the US Air Force is building to. The F2T2EA requires an integrated infrastructure to collect, process, and disseminate the ***right*** information, to the ***right*** person, at the ***right*** time. The US Air Force has begun to build such infrastructure - it is an undertaking of immense proportions! Transforming collected data from the variety of sensor and intelligence sources into the ***right information*** requires a variety of information processing tools and systems, including information fusion.

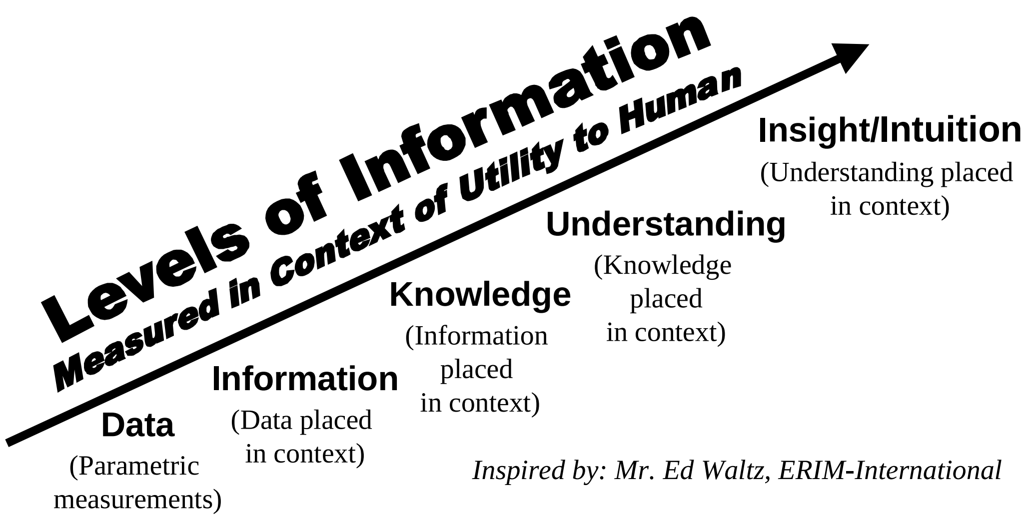


Figure 3. Information Fusion - Transform data into mission capability.

Data, Information, and Fusion

In the context of this paper, data is defined as a representation of an observation in some symbolic form. Examples of data are the raw detector analog output of an infra-red (IR) imaging sensor, digital output of a staring array, phase history of a synthetic aperture radar, or the output of the GPS receiver phase-lock loop. Without processing, this data offers no useful information.

In this paper, information is defined as an observation which has meaning in the context of the instrument or (sensor) application. It can be an image from any of the three examples cited in the previous paragraph, or it could be the aggregation of various information objects. Clear distinctions between data and information do not exist. At best, one could define the boundaries between data and information within narrowly defined applications. We often find that information to one is data to another. Debate continues, in the research and development community, about the definitions of, and distinctions between, data and information. For the purposes of this paper data and information are treated interchangeably and defined as information objects. Data and/or information in any form is merely an intermediate step toward the required warfighter, or civil/commercial, mission capability function/tools.

An additional debate rages about the definition of fusion. In the broad sense, information fusion frames the numerous information engineering activities, disciplines, and applications. The fusion concept, combining information from various sources, is advancing rapidly in numerous communities. Within the Department of Defense, the JDL1 Fusion Model2 serves as a useful framework for information fusion concepts and activities. The JDL Fusion Model was developed by a diverse set of C2 and other information communities to provide a common framework for the various information fusion activities. This Fusion Model is described in a later section.

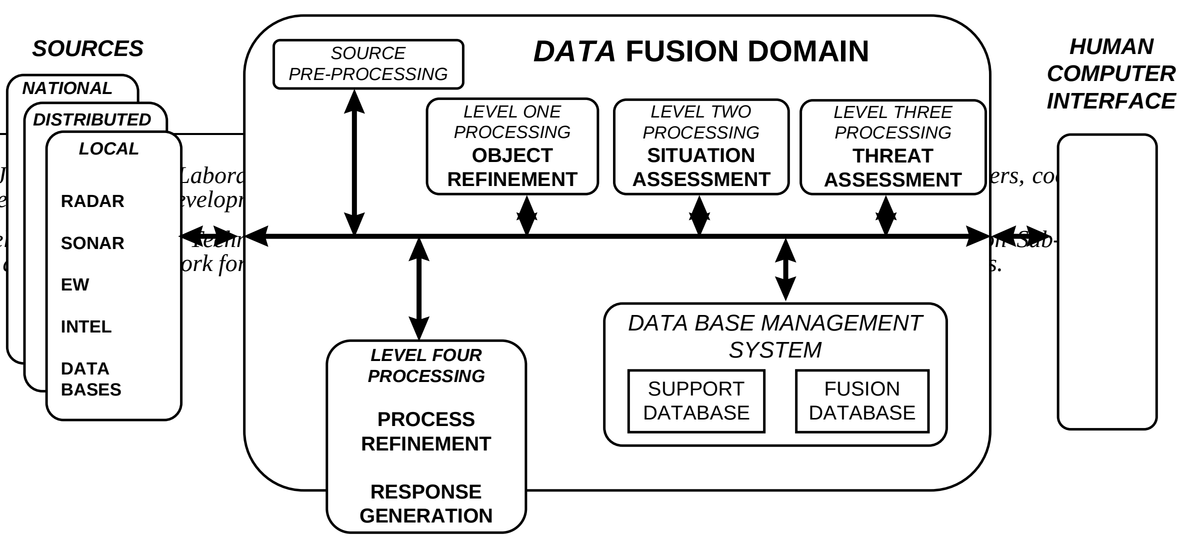
Information fusion is an engineering process which has demonstrated a capability to profoundly increase mission capability, and potentially reduce cost, through integrated leveraging of relevant information available from sensors and sources on- and off-board weapon systems. It is a process which, in general terms, operates on more than one information source to create a capability which is greater that the sum of individual parts. At the core of the process is the likely presence of spatial, spectral, and temporal cross-correlations that are often present between the two or more data sources. If such cross-correlations exist, and they are observable in the sensor/source outputs, then a potential exists that the fused information will provide a benefit greater than the independent sum of the individual outputs.

Information fusion is a framework of tools and processes necessary to transform available information into required mission capability. Generally, the goal is to select that subset of information which satisfies the required mission task at minimum cost. An additional step could consider an entire set of required operational weapon system mission capability tasks. Optimizing over the global set of information to minimize the cost for the entire set of required mission tasks is an added benefit In a commercial example, various industry groups are examining the benefits of fusing data and/or information from cellular, GPS, terrain data base, and other data sources to provide an integrated multi-function information system.

The decision at which signal level to fuse depends on several factors, such as the specific sensors considered, mission application, and practical constraints, e.g. available signal processing and information transmission resources. Of significance is the fact that fusion can be performed at various levels of signal processing. As a technology, information fusion is the integration and application of many traditional disciplines and new areas of engineering [5,6,7].

Information fusion has several different perspectives and interpretations. Toward the goal of providing a common basis of fusion tools and strategies, the Joint Director of Laboratories (JDL) Fusion Panel has developed a four-level Fusion Model used by various DoD information fusion communities (Figure 3).

The left side of Figure 3 identifies the various layers of information sources which could be considered for fusion. The Data Fusion Domain, the large block in center of Figure 3, includes source pre-processing, the four fusion levels, and the necessary data base management system consisting of the fusion and supporting databases. The right side of Figure 3 illustrates the fusion process result feeding the human decision process or another computation, perhaps a higher level of fusion. The four levels of fusion are hierarchical in nature and are briefly described[5,6,7]



[1] The J… Labora… ers, co… Service… evelopm…

[2] Devel… Techn… on Sub-… create … ork for… s.

Figure 4. JDL Fusion Model

A distinction between fusing of cooperative and noncooperative information sources is useful. Fusion of information from cooperative sources offers the advantage of degree of information management control. In cooperative fusion the weapon systems and the concepts of operation dictate who, when, where, how emits signals to achieve the required result. For example, fusing of the Identification, Friend or Foe (IFF) function combined with a Joint Tactical Information Data System (JTIDS) is relatively easy to achieve because both signals can be provided on demand. Fusion of information from non-cooperative sources is much more difficult, especially if the owner attempts to conceal the signatures of the information emitters. The latter case would likely include elaborate sensing and fusion schemes to *uncover information degrees of freedom* optimized for cost effective detection, location, and identification of such signals and signatures.

The first fusion level in the JDL Fusion Model is the ***Level One*** processing identified in Figure 3. Antony [5] describes JDL ***Level One*** fusion, in the context of object refinement, as:

1. Object detection;
2. Association of new detections with known objects (observed previously by either the same or different sensor);
3. Refinement of object attributes (such as position, velocity, and status);
4. Object typing, classification, and identification.

Antony also states that ***Level One*** fusion benefits from:

1. The use of heterogeneous sensors that provide at least partially independent sensor-derived information;
2. The employment of spatially distributed sensors to enhance the coverage, perspective, and reliability of the measurements;
3. The application of non-sensor-derived domain knowledge that can provide important problem-solving constraints.

His definitions and observations apply to a generic information fusion process. When the operational mission context is specified, these definitions and observations take on focused meanings and attributes.

Thus, ***Level One*** fusion consists of information object detection, location (geometric fusion), classification, identification, and attribute determination. The definition of detection includes classical detection in communications, image processing, and other domains. All information objects to be fused must be located—spatially and temporally cross-referenced— within a battlespace. Conceptually, every information object, be it an observed vehicle, an image, a pixel, or a measured electromagnetic pulse, requires referencing within this battlespace. Pixels within an image, or between images, require a relative reference in the space-time battlespace framework. The information object location, or space-time registration, includes the classical reference (navigation) function, both relative and absolute.

The next action in ***Level One*** fusion is the object classification and/or identification. This applies to all information objects, whether these are pulse outputs of a radar warning receiver, *globs* in a synthetic aperture radar (SAR) image, or molecular concentration in a chemical detector. The available information is operated on with various algorithms to increase the probability of correct identification or classification, while decreasing the false identification probabilities.

For some applications, ***Level One*** information fusion processing is sufficient. For example, the process of detecting, locating, and identifying an electromagnetic emission is sufficient for the offensive sensor-to-shooter mission. In other applications, such as self protection (defensive electronic warfare), information fusion at higher levels is required.

Level Two processing involves situation abstraction and assessment of hostile behavioral patterns and capabilities. It generally requires that ***Level One*** fusion of information objects be accomplished prior to, or simultaneously with, ***Level Two*** fusion. Numerous information objects are aggregated in the constraining context of the specific mission, its requirements, and a-priori knowledge of the characteristics and behaviors of such objects. The ***Level Two*** fusion goal, see respective block in Figure 3, is typically situational assessment. ***Level Two*** fusion could be applied to the vicinity of a particular manned aircraft, ship, or tank, or it could be applied to a theater-wide situational assessment. The higher the force level for which fusion is attempted, the fuzzier are the expected results due to the cumulative effects of statistical uncertainties in sensed information and the larger number of information objects.

At ***Level Three***, fusion processing quantifies the threat's capability and predicts the intent of hostile forces. Figure 3 labels this block as ***Threat Assessment***. It could be the assessment of a battlespace-wide threat, or it could be the threat in the vicinity of the aircraft, ship, or tank. The potential adverse consequences are the real motivators for accurate and reliable ***Level Three*** fusion results.

Level Four provides a closed loop feedback to manage the sensor resources as dictated by the results of fusion at levels one, two, and three. Figure 3 labels this block as ***Processing Refinement***. It includes the assessment of the process by measuring the quality of the results and adjusting the four level fusion process to improve those results. This includes the sensor retasking function, which simply could mean allocation of more timely and/or higher quality sensor resources necessary to complete the required mission task.

The entire four-level process can be adapted to nearly any or all fusion tasks. It is applied to the fusion of pixels within images. Or, in the other extreme, it is applied to battlespace-wide aggregation of various fusion engine outputs to generate high-level force structure assessments necessary to support all of the services operating within the battlespace.

Increased Mission Capability Through Fusion

Numerous examples exist of mission capability increases at lower cost through information fusion. The Joint Strike Fighter (JSF) [8] is a relevant example of information fusion driving down the cost of an entire weapon system:

> *… Information fusion, leveraging the off-board and on-board information sources will result in a minimum cost avionics system that satisfies the JSF mission requirements.*

Commercial applications increasingly fuse multiple sources information to provide mission capability that would not have been thought possible just a few years ago. A cornerstone of such integration *fusion* is the globally available reference - a key element of ***Level One*** fusion as defined in the JDL Fusion Model.

Geometric Reference - Geometric Fusion Foundation

Geometric fusion includes the *"refinement of object attributes (such as position, velocity ...)"* defined by Antony and discussed earlier in this paper. To the navigation community, this means geolocation or georegistration as a function of time. At the foundation of geometric fusion is the geometric reference, either absolute or relative. Absolute reference is defined as that which is invariant with respect to all the objects being considered. In this physical world, an absolute geometric reference does not exist. However, for engineering applications, a reference can be chosen that satisfies the absolute reference requirement. For example, for intra-solar space operations the solar-centered absolute reference might be chosen. For earth based operations, earth centered reference is most useful. Before the advent of the GPS, many "absolute" references were developed for various applications. There exist dozens of various reference frames, including body, earth, tangent plane, and many others. The GPS has offered a global perspective and a global reference capability that can cross-reference any and all systems and operations that can benefit from a global reference frame— some circles call this the global grid. A natural choice for a common, globally absolute, reference is the earth-centered, earth-fixed (ECEF) frame. The World Geodetic Survey of 1984, (WGS-84) is the most current and accurate geoid model which has been specified as the DoD standard for most geo-referenced applications - and it is ECEF referenced.

Of greatest significance is the fact that all share fundamental characteristics. Each object, sensor, or information source in general, occupies a point (or region) in space and time, and may possess additional spatial attributes, such as attitude. These spatial attributes can be assigned with respect to some absolute reference, such as ECEF, or relative to another sensor or object. This is useful because many of the mission capability problems deal with otherwise sufficiently accurate locations of objects, both friendly and hostile, in absolute and relative time-space references. Ideally, if one could geometrically register (locate) with sufficient accuracy each object in a combat theater of operations, one would possess a near perfect geometric view of the battlefield. Of course, this would not be the complete picture, because each located object must be classified, identified, and characterized with an increasingly higher level of information content through information fusion. One must not underestimate the imperative of geometric fusion. No other target attribute is useful without the space-time registration. Thus, the geometric (time-space) registration, in the absolute and/or relative reference, is an absolutely essential step toward information generation, fusion, or application.

Toward the goal of geometric registration within the geometric battlespace, it is useful to define a concept - called the geometric vector which accounts for the position, velocity, attitude, and time [4]. In three-dimensional space, the position, velocity, and attitude each require three degrees of freedom (vector elements) for geometric definition. Together with the degree of freedom of time, this makes up a ten-element array. It is useful to call this array of ten elements the geometric vector3.

The geometric vector is useful in several ways. First, it can be used to define the geometric state of any object with respect to an absolute reference frame. Thus, the entire battlespace can be expressed with a set of geometric vectors at any instant of time. Further, the time and space relationships between any pair of objects are formally and unambiguously expressed as a difference between the two respective geometric vectors. The difference in the positional subvector produces the relative position vector which consists of the line-of-sight between the two objects and the distance between them. Similarly, the difference in the velocity subvector produces the relative velocity vector. The difference in the attitude subvectors results in a relative attitude measure. Of course the difference, if any, in the time elements of the two vectors, provides the time difference between two events associated with the two objects. The geometric vector concept is not new; however, there is utility in its definition and its application. As just illustrated, the combining of the geometric attributes of an object/target, provides a notational efficiency needed in system integration and information fusion. Such a notation facilitates system level aggregation so essential to multi-sensor, multi-platform, multi-target modeling, simulation, and analysis, and certainly to fusion itself. For more detailed discussion of the geometric vector concept and its application, the reader is referred to [4].

The geometric vector represents the maximum geometric information content in any information source. Some information sources provide limited geometric information content— a subset of the ten vector elements. For example, the GPS sensor provides a measure of the range and time from the GPS receiver antenna to a particular satellite. This range measure is related to the magnitude of relative vector formed from the difference of the two geometric vectors position subvectors. An imaging sensor points its image center into the three dimensional space along a line-of-sight (LOS). A line-of-sight is the three dimensional representation of the angle of the relative vector between two points in that space; it is called a unit vector. Any electromagnetic signal that is emitted and received and that has an identifying signal structure contains geometric information. It is also useful to classify the geometric measurements, coming from a number of sensors, according the fundamental quantities that they measure - position, range, line of sight, and time difference. The INS is an example of a position sensor. Imaging sensors measure a line-of-sight, such as a forward looking infra-red (FLIR), or azimuth-range, such as the SAR. A laser detection and ranging (LADAR) sensor combines an imaging sensor with a ranging pulse to provide a measure of range and LOS. GPS and JTIDS are examples of ranging sensors. This discussion suggests the following concepts:

1. All data objects contain geometric attributes;

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[3] *Caution is required in the use of this vector quantity. The three-element attitude subvector does not satisfy, in general, the linear algebra definition of a vector - that is the attitude subvector does not satisfy the commutation properties for large angles. It does satisfy, to first order, commutations properties for small angle assumptions.*

2. All of the information generated within a battle space is geometrically cross-correlated by the fundamental fact that it occupies the same space;
3. All information sensors include geometric errors in their measurement domain. The geometric errors often are characterized by biases as the dominant error sources in geometric applications. Geometric sensor errors, in most cases are also cross-correlated with information in other-than-geometric domain, such as image quality; and
4. Performance of fusion above the geometric level fusion requires as a necessary condition the geometric fusion, as a baseline, often to a high degree of accuracy.

In establishing a geometric reference, the digital terrain elevation data (DTED) database must be included as another sensor. The DTED provides exceptionally useful information in satisfying the reference requirements. The earth's surface is a rigid, predictable, widely available, and stable reference information source. In some regions it lacks horizontally distinguishable features, such as desert and water, however it always contains elevation information. In many regions it provides useful horizontal information present in the vertical gradients created by natural and man-made features. Use of such features had been demonstrated in various reference applications, most noteworthy of which is terrain map matching. Numerous applications of information fusion have demonstrated the value added in fusing DTED form of geoid model with other information. Photogrammetry is an example of fusion of DTED with other sensor data in the commercial sector.

GPS Revolution

The Navigation community clearly understands the GPS revolution and its impact on the navigation and reference technologies. Every year we are exposed to numerous additions to the collection of innovations and ingenious application of GPS and related technologies. The thoughts reflected in this paper suggest that the impact of the GPS revolution might be far greater. Perhaps a recent casual comment made by someone that "GPS might make a greater impact on our society than the computer chip" could become a fact. The global geometric (space-time) reference infrastructure that the GPS enables will grow in its impact on the information systems and technologies.

Conclusion

DoD is recognizing information superiority as the foundation for revolutionary changes in the conduct of warfare. Several recent activities, including the CJCS JV 2010, the DDR&E ABIS study, and the CSAF and SECAF NWV study, point to numerous technologies as enablers. Information fusion is a robust framework which facilitates the fusion of not only specific information elements, but more significantly, it provides a framework for the interactions of various information technologies toward the information superiority goal.

The advent of global reference capabilities enabled by GPS, in combination with other reference sensor information, provides an unprecedented foundation for commercial and DoD global information fusion applications. Geometric reference is the foundation of the ***Level One*** information fusion process, and the sole fusion process for those applications where the information objects are detected and identified unambiguously. The GPS revolution, and its global impact on numerous systems and activities, both defense and commercial, has just begun.

Both the DoD and commercial information application domains include the same basic requirement for geometric fusion of information, not only as a particular goal, but also as the foundation for all other levels and elements of the fusion process as defined by the JDL Fusion Model.

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