Data Fusion "Cube": A Multi-Dimensional Perspective

By Dr. Paul W. Phister, Jr. and Igor Plonisch

Abstract

In the classical sense, data fusion can be viewed as a one-dimensional entity having five distinct levels. However, this view does not convey the multi-dimensional aspect of data fusion. This paper argues that data fusion is not one-dimensional, but rather a three-dimensional entity. These three attributes are sensor fusion, system fusion and information fusion. Sensor fusion can be thought of as taking the raw sensor data and fusing it together so it seems to have come from a single sensor. System fusion can be thought of as combining the output of various heterogeneous systems together into a single fused output. Information fusion can be thought of as taking information gathered from various sources and fusing it into a single output. This paper provides an overview and discussion of this three-dimensional perspective of data fusion in order to illustrate its multi-faceted capabilities and applications. For each of the three dimensions, a definition and possible application, along with a discussion and comparison to the classical Level-0 to Level-4 levels of data fusion, is presented. Finally, this new data fusion "cube" is offered for consideration in which each axis (Sensor, System, Information) has a corresponding relationship to the classical aspects of data fusion.

Introduction

The importance of fusion is quite evident. The Commander wants an all-source picture of the battlespace to provide real-time situational awareness. However, today all the Commander gets is an extremely large number of uncorrelated reports that further contribute to what has become known as "the fog of war". Fusion is a methodology to merge all available information to provide all-source consistent actionable information or knowledge throughout the battlespace to the Commander so that rapid, intelligent decisions can be made. To the Commander, this merging of information and data sources, as well as refinement of information, appears to come from one source.

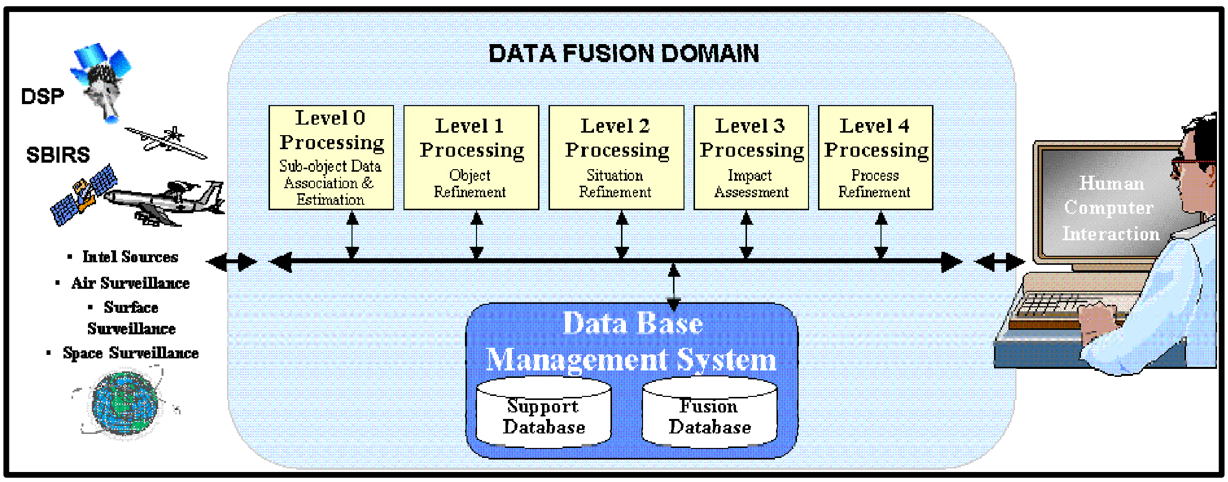
Historically, the US military has spent enormous amounts of resources in building aerospace platforms, (probably because more information is "better" information) but, little has been spent dealing with the corresponding use of the data to be gathered; e.g., fusion, decision making and ultimately Command and Control (C2). A prime example is hyperspectral sensors. A significant amount of resources have gone into the design of the space segment; however, little has gone into the Tasking-Processing-Exploitation-Dissemination (TPED) portion. For a 3500-band hyperspectral sensor, it is unrealistic to think that all the processing will be accomplished on the ground. Some amount of processing, fusion and exploitation must be accomplished on-board the space vehicle.

Recently, however, there has been a turnaround and there have been significant resources allocated to developing technology to support data fusion to allow the rapid use of extremely large amounts of information from diverse sources. For example, the Air Force Research Laboratory's Information Directorate has an Advanced Technology Development initiative known as "Adaptive Sensor Fusion - ASF". The ASF Program is building an open, standards-based architecture for information fusion. The philosophy of the open, plug and play fusion architecture is to provide a system that provides standard data and application interfaces to maximize interoperability among different fusion approaches and systems. The fusion architecture includes an adaptive fusion manager that optimizes the performance of the selected confederation of fusion engines. The objectives are the optimization and control of the fusion process to foster an effective and complete use of all available sensor data. The Adaptive Sensor Fusion System will have the ability to use different fusion parameters, models and configurations, optimized according to specified user needs, changes in the situation, and available fusion engines. This is a one-dimensional approach to fusion.

"One-dimensional" Data Fusion Overview

Figure 1 below represents the classical (or one-dimensional) model of fusion breaking it down into five levels.

Figure 1: Data Fusion Levels



The five levels can be defined as follows:

a) Level 0 — **Sub-Object Data Association & Estimation:** pixel/signal level data association and characterization;
b) Level 1 — **Object Refinement:** observation-to-track association, continuous state estimation (e.g. kinematics) and discrete state estimation (e.g. target type and ID) and prediction;
c) Level 2 — **Situation Refinement:** object clustering and relational analysis, to include force structure and cross force relations, communications, physical context, etc.;
d) Level 3 — **Impact Assessment:** includes threat refinement, threat intent estimation, event prediction, consequence prediction, susceptibility and vulnerability assessment, and;
e) Level 4: **Process Refinement:** adaptive search and processing (an element of resource management)

This is the classical approach to the topology of fusion. It promotes a data ontology technology that will result in a plug-and-play architecture that can provide a standard for fusion. However, this view can be expanded.

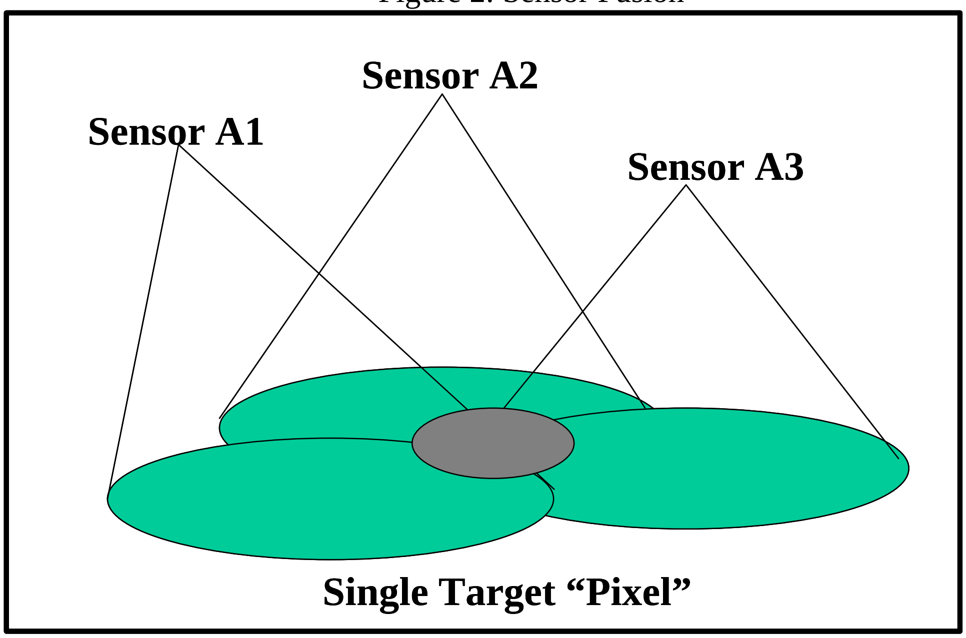
"Three-dimensional" Data Fusion: Proposed Perspective

Fusion takes on different attributes depending on what type of fusion is being performed. Fusion can be thought of in three-dimensions: sensor, system and information. They are briefly discussed as:

a) Dimension 1: Sensor Fusion

Senor fusion can be thought of as fusing raw data from a multitude of sensors together to create a single sensor output. This is like making each sensor a mode or component of a larger integrated sensor. Figure 2 portrays a cluster of three microsats. Each microsat would have a sensor. Integrating the three sensors together from the three microsats into a single "sensor" creating a single target pixel would be an example of sensor fusion.

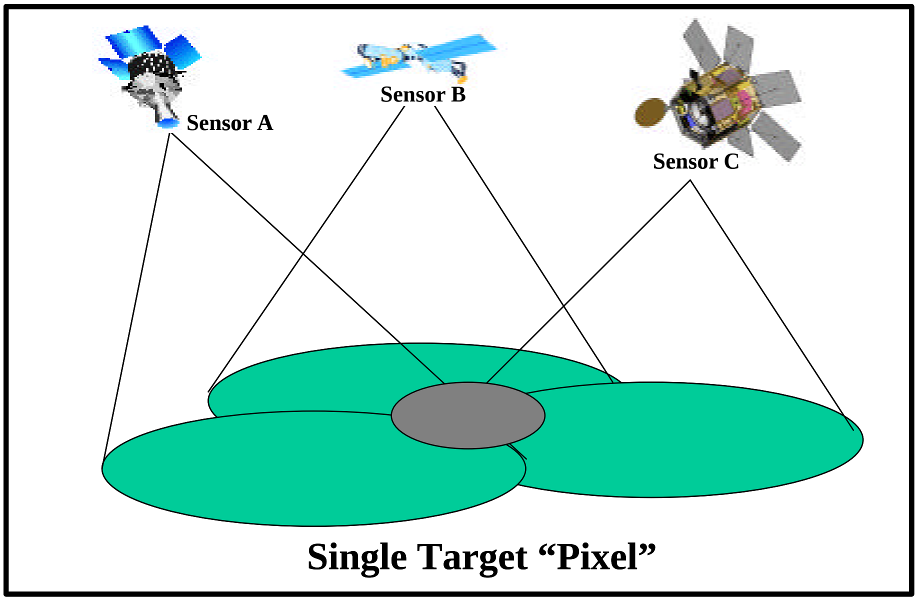
Figure 2: Sensor Fusion



b) Dimension 2: System Fusion

The second dimension of fusion can be thought of as fusing two different sensors located on two different systems (e.g., EO-EO, SAR-SAR, IR-IR, EO-SAR, etc.) to create a single integrated output. Figure 3 illustrates the fusion of three different systems to create a single target pixel. Note that this is not just an overlay of three ellipses, but also a true fusion of the outputs of the three systems. The resultant error ellipse for fusion would be smaller than the overlays of the three ellipses.

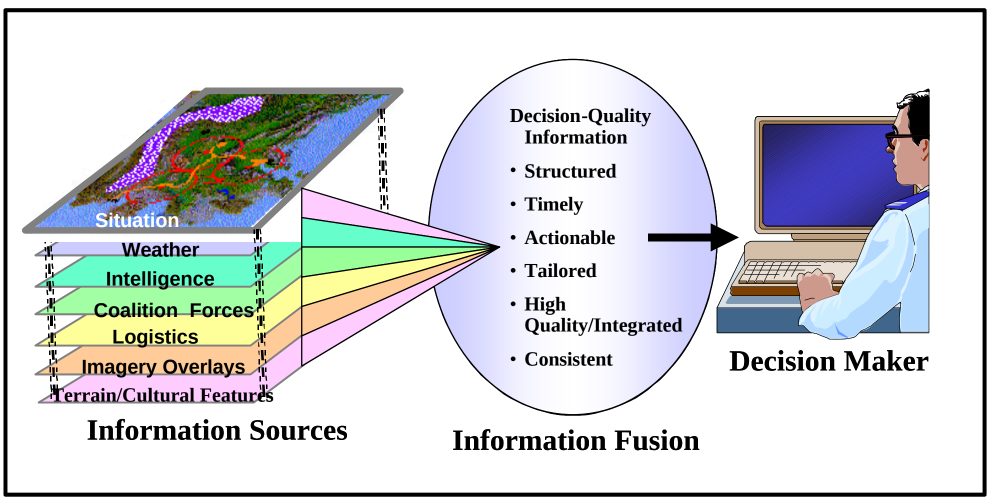
Figure 3: System Fusion



c) Dimension 3: Information Fusion

The third dimension of fusion is information fusion. This is the fusion of information that is gathered from a particular system; e.g., human intelligence (HUMINT), imagery intelligence (IMINT) or signals intelligence (SIGINT) and converted into some general knowledge. Figure 4 illustrates some of the sources for information fusion, and the resultant attribute of decision quality information.

Figure 4: Information Fusion



Fusion Dimension Levels

Combining the three dimensions of fusion (sensor, system and information) makes up the overall data fusion cube. However, each of the levels means different things regarding the three dimensions. For example:

a) Sensor Fusion Dimension/Levels

Sensor fusion deals primarily with the first two levels of the classical model, namely Level-0 and Level-1 (as shown in Figure 1. These two levels technologically relatively mature. However, the difficulty lies in trying to track targets in a dense target environment with highly maneuverable targets. The sensor fusion technologies applicable to Level-0 and Level-1 are locating sensors on multi-platforms and providing precision tracking of those targets.

b) System Fusion Dimension/Levels

System fusion covers not only Level-0 and Level-1, but since this also incorporates other system's sensors (e.g., EO, SAR, IR) located on additional platforms, it also incorporates Level-2. Although Level's 0 and 1 are relatively mature, Level-2 is immature from a technology perspective.
There is a lack of automated reasoning techniques, cognitive models and the doctrinal foundation is not well defined. The system fusion technologies applicable to Level-2 must provide robust techniques to solve situation/threat refinement along with providing predictive analysis methodologies.

c) Information Fusion Dimension/Levels

Information fusion deals primarily with the upper three levels of the classical fusion hierarchy, namely Levels-2 through 4. It is in these three levels that decision support technologies play a major part, especially with the prediction and assessment in Level-3. Levels-3 and 4 are very immature from a technology perspective. The technology areas deal with generic architecture and techniques for fusion process control, predictive battlespace awareness, plug-N-play fusion algorithms, adaptive fusion management and situation refinement.

From a technology maturity point-of-view, the state-of-the-art in data fusion is at Level-0-1-2. Additional research needs to be done in the areas of:

a) Assessment of the overall information fusion space with statistical and learning techniques to identify weak points within the overall fusion space.

b) Investigate and evaluate use of local fusion models embodied in dynamically created, distributed intelligent agents,

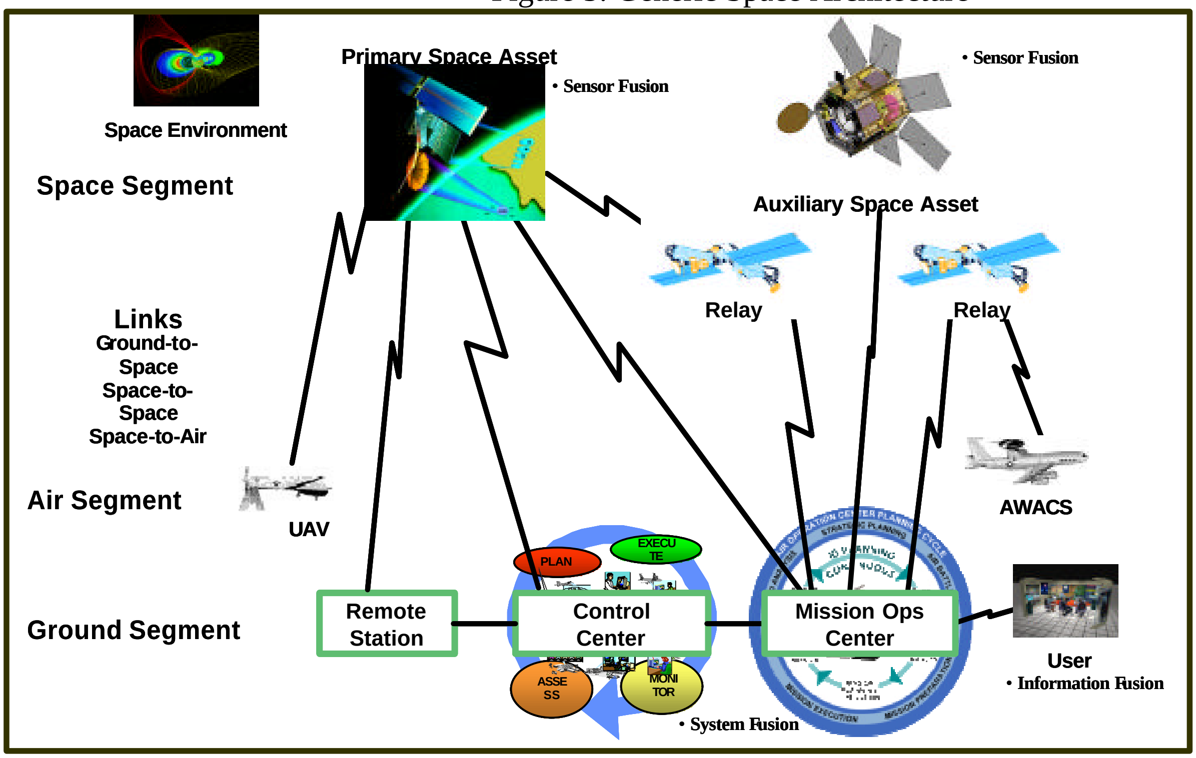
c) Investigate operational plan recognition and plan inference, based on multi-level fused data; and,

d) Development of measures of performance/measures of effectiveness (MOP/MOE) to be able to evaluate the upper three levels of fusion.

Space Application

The three dimensions of fusion occur naturally at three different levels within the total system architecture. Figure 5 illustrates the placement of the three-dimension of fusion in a generic space system. Each of the three dimensions (Sensor, System, Information) is represented.

Figure 5: Generic Space Architecture



Sensor fusion can be thought of as occurring at the closest point to the intended target as possible. In Figure 5, this is on-board either the space or air vehicle.

System fusion typically occurs within the Control Center, since this is where the raw data processing normally occurs. Naturally, taking advantage of advanced technologies, this processing could be performed on-board the vehicle. If system fusion is to occur, then a communications path needs to be established between the two systems so that the fusion process can take place.

Information fusion naturally occurs at the user point since this is where processed information comes together. As discussed above, this can be accomplished on-board the vehicles, but then the appropriate fusion algorithms must be located on-board each of the vehicles, so that a complete process can be performed.

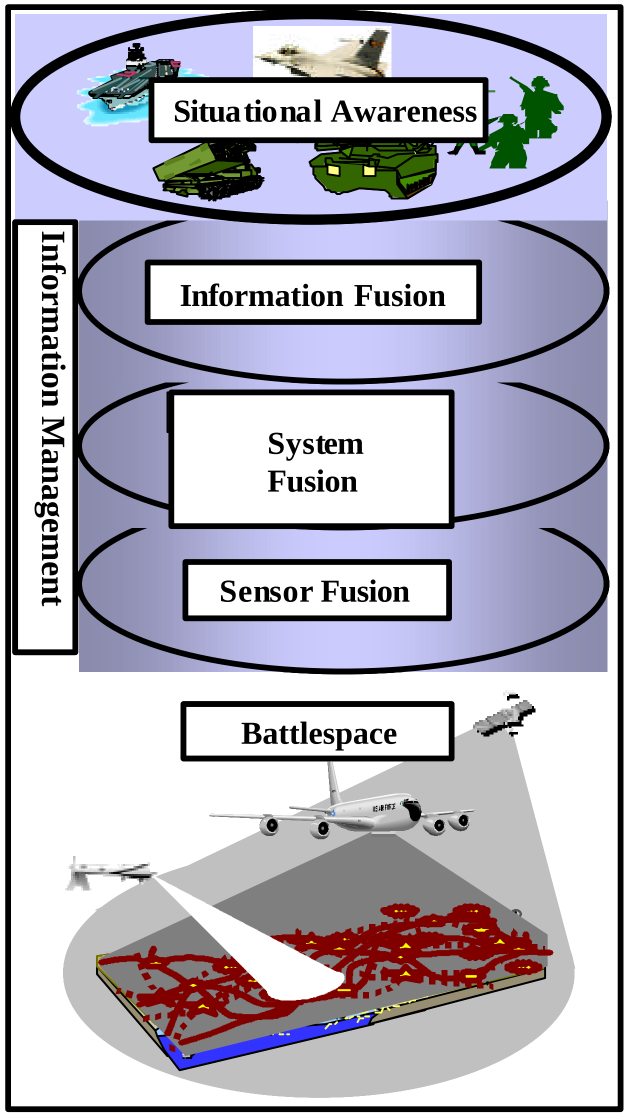
Summary

This paper illustrated that data fusion can be thought of as a three-dimension "cube". Each dimension (senor, system and information) has unique properties and provides something different to each of the five levels of fusion.
Figure 6 illustrates the multi-dimensional data fusion "cube".

This paper also proposes that this Cube" topology be used when approaching the fusion problem.

Figure 6 illustrates the relationships of the fusion "cube" as it fits into the Situational Awareness of the Battlespace.

Figure 6: Multi-dimensional Data Fusion Cube



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