Plan-Driven Fusion: Shaping the Situation Awareness Process using Empirical Plan Data

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Abstract - Historically, in a tactical C4ISR environment, information fusion processing and plan understanding and execution monitoring have been performed without regard to one another. In particular, plan execution monitoring assumes that an accurate "world state" is available, while information fusion processing assumes that "operational context" is available. Because operational context allows information fusion to develop an accurate representation of world state, and world state is the basis from which plan execution monitoring assesses the status of plans, a loose coupling between information fusion and plan understanding and execution monitoring results in less-than-optimal situational awareness for a commander. Leveraging plan understanding and Levels 1-4 information fusion techniques, Lockheed Martin Advanced Technology Laboratories (LM ATL) has developed a concept design and prototype, plan-driven fusion, which enables iterative, closed-loop cooperation between planning and fusion components within a C4ISR environment.

Keywords: Situation Awareness, Information Requirements, Information Fusion, Plan Execution Monitoring

1. Introduction

Information fusion systems operating in tactical C4ISR environments depend entirely on the data produced by sensors and other information sources. These fusion systems, using the given data, develop and provide situational awareness to decision-aiding systems or human operators who act upon it. The results of these information fusion systems are only appreciated if the situational awareness they provide is relevant to the decision maker's information needs and operational context. Therefore, in programs that require monitoring a maneuver or logistics plan against current world state is often assumed to be appropriate and relevant to the plan's context. This assumption may not be accurate and leads to two common problems in the development of situational awareness. In some cases, the generated world state is insufficient in meeting the needs of the decision makers. Sensors and information gathering assets may not provide enough relevant data pertinent to the plan. Numerous reasons contribute to this situation. The sensors providing the data may not be covering the complete geographic area pertinent to the mission. Sensor data may also not be of an appropriate level of fidelity to support decision making, including accuracy in kinematics, classification, and identification. In other cases, the opposite problem occurs. Too much data and information can overwhelm fusion processing, causing it to expend its computational resources on irrelevant or appropriate data to the plan. In such cases, overall system performance can degrade to an unacceptable level. To guide our information fusion processing for the needs of decision makers, we have adopted the "plan" to represent what the decision maker is engaged in. Plans, therefore, provide the operational context needed to drive the information fusion process. The resultant concept design is subsequently referred to as plan-driven fusion. This paper describes a proposed system design that can realize the plan-driven fusion concept by forming a closed-loop between plan execution monitoring and information fusion processing.

2. Requirements

The primary requirement of a plan-driven fusion system is the ability to derive the information needs (i.e., information requirements) of the decision maker and, consequently, the information fusion system. These information needs are the basis for the fusion processing, allowing the fusion system to be proactive in collecting, filtering, and processing the required information, rather than relying on sensors and information sources to "push" potentially irrelevant or inadequate data to the fusion processing.

The second requirement of the system is to ensure that the derived information needs are continually prioritized based on the tactical significance of that information need. In any operational environment, significance of information requirements varies due to unit position, unit vulnerabilities, spatio-temporal proximity to threats or resources, the current phase of the mission (plan), or current performance of the sensors and information sources (i.e., how well the sensors are providing the required data). Because these attributes of tactical significance are
continually changing, the resultant priority of information needs must also continually change to reflect these attributes. By having the information needs prioritized, information fusion processing, specifically Level-4 (fusion process refinement), can leverage these priorities to optimize the computational workload. In cases of processing or data overload, these priorities can also facilitate the graceful degradation of the system by allowing the system to have knowledge of the criticality (significance) of each information requirement. The priorities assigned to information needs, however, cannot rely solely upon this tactical significance. Priorities must also reflect the temporal criticality of the information requirement as well as the current (actual) performance of the sensors and information sources ability to satisfy the information requirement.

To facilitate the processing of Level-4 information fusion, specifically sensor and resource tasking, it is not sufficient to simply develop and provide the raw information requirements needed to form the situational awareness. The operational context of that information need must also be provided, which is the third requirement of the plan-driven fusion system. This operational context includes the enumeration of any resources, sensors, or platforms (and their associated constraints) that are used to provide information and/or support the mission’s tasks; the context is extracted from the aggregated set of operations and collections plans ingested by the system.

The fourth requirement of Plan-Driven Fusion is that it must be able to operate in any C4ISR domain (e.g., U.S. Air Force Air Operations Center). Each domain has its own set of information needs and requirements, prioritization schemes, plan resources and actors (with their specific characteristics and vulnerabilities), threats, and sensors. The system must provide a common approach that will satisfy the information needs of these varied environments.

### 3. Plan-Driven Fusion Approach

Because we intend to apply the Plan-Driven Fusion approach in numerous domains, the proposed system design uses the Core Plan Representation (CPR) ontology as the basis for plan modeling and instantiation [1]. The CPR ontology expresses information common to many plan, process, and activity models. Building upon previous work in plan ontologies [2], the CPR identifies and extends the minimal concepts necessary to represent a plan and builds an object model of the entities, and their relationships, common to all plans. The initial task of the Plan-Driven Fusion approach is ingesting, maintaining, and understanding C4ISR plans, including tactical (maneuver), logistics, and collection plans, as represented in CPR. Developing information needs necessitates understanding of the objectives, actions, actors, resources, and spatio-temporal constraints contained in these plans. The action is the basic unit of knowledge in the plan, representing a task accomplished by one or more plan actors. The spatial specifications and time specifications of actions are used heavily in the Plan-Driven Fusion approach to develop the information needs. To develop the operational context for the information needs, the dependencies among cross-domain (e.g., logistics, maneuver, collection) plans must be inferred. For example, a collection plan may specify that a JSTARS aircraft provide ground moving target indicator (GMTI) sensor coverage in support of a convoy mission. Unfortunately, these interdependencies are often not specified in the various plans because they are developed by different plan generators. Using our Plan Understanding capabilities [3], we infer these inter-plan relationships such as: Action-A supports Action-B, Action-B depends on Action-A, Sensor-A is a resource to Action-C. These relationships, in conjunction with intra-plan constraints and resources, are used to develop operational context. This context can be used by information fusion for potential tasking and refinement of both computational and sensor resources. Information Needs Assessment (INA) derives and prioritizes information requirements on behalf of the decision maker for information fusion processing. These requirements are prioritized based on their tactical and temporal relevance with respect to the current mission plan. The process of deriving and evaluating information needs is discussed in Section 7. Information needs are produced from resource tasking objects (RTOs) and situational awareness regions. An RTO can be defined as any entity in the battle space requiring a system resource (e.g., sensors, fusion algorithms, information-gathering mobile agents) in support of the development of situational awareness using information fusion processing. Specific examples of RTOs are search volumes—regions in which sensors will dwell—and tracks—digital representations of entities in the battle space. A situational awareness (SA) region encapsulates plan-specific spatial information defined in the Performance objective table (see Table 1). Sections 4 and 6 provide a more detailed discussion of RTOs and SA regions, respectively.

<table>
<thead>
<tr>
<th>#</th>
<th>RTO Criterion Description</th>
<th>Criterion Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Is the RTO considered hostile?</td>
<td>Known Hostility</td>
</tr>
<tr>
<td>2</td>
<td>Is the RTO near the mission actors?</td>
<td>Near</td>
</tr>
<tr>
<td>3</td>
<td>Will the RTO affect the mission soon?</td>
<td>Soon</td>
</tr>
<tr>
<td>4</td>
<td>Is the Track-Type RTO approaching the mission’s actors?</td>
<td>Approaching</td>
</tr>
<tr>
<td>5</td>
<td>Are our mission actors stronger than the Track-Type RTO?</td>
<td>Force Ratio</td>
</tr>
</tbody>
</table>

### 4. Resource Tasking Object Maintenance

A Resource Tasking Object (RTO) represents any entity in the battle space upon which sensor or computational
resources (e.g., information fusion algorithms) are required to be expended (or tasked) in order to support the development of situational awareness. RTOs are classified into one of two categories: tracks and search volumes. Track RTOs are created and maintained with respect to physical tracks in the battle space, regardless of its affiliation or classification. However, if a track RTO is associated with an actor (i.e., a friendly entity specified in the plan that executes one or more actions in the mission), it is further specialized as an actor RTO. As entities in the battle space are detected, track RTOs are created and updated (i.e., kinematics, classification, affiliation) based on the data provided by sensors and information fusion algorithms. Search volume RTOs are created based on spatial specifications identified in the mission plan that delineates the regions on which sensors must focus for gathering and processing information as well as the areas specified in the plan where a mission’s actors will be operating. The search volume RTOs, therefore, denote areas of interest where situational awareness may be required by the system or its operators. As mission plans are modified, search volume RTOs may be deleted, changed, or added to meet the needs of the new plan instance.

RTOs are also instantiated dynamically when an entity such as a track is detected in the battle space. Track RTOs are also updated with the perceived current information by the information fusion processing component; RTOs are continually prioritized based on tactical significance supporting the second requirement for Plan-Driven Fusion. This is not necessarily the priority of information needs, but rather the priority of the RTO, a key element in determining the priority of any resulting information needs.

Determining RTO priority is a domain-specific function that requires mission and subject matter expertise. There may be numerous criterions for determining the overall priority for an RTO, and capturing the criteria is challenging from both a knowledge acquisition and a data modeling standpoint. The relative significance of each criterion must be identified in order to determine the overall prioritization of each RTO. Simply ranking all criterions will not produce a valid weighting mechanism for the development of an RTO priority. Instead, it is necessary to have a subject matter expert determine the relative importance between each possible pairing of criterions (e.g., the “nearness” of a track to an actor is three times more significant than whether the track is approaching the actor). This approach is used to simplify the knowledge acquisition process with the domain’s subject matter experts (SME).

The expert is asked to generate a list of the relevant attributes of tactical significance for the domain or mission (see Table 1). Then the expert should determine the relative importance between these attributes and not be concerned with generating a complete ranking among all attributes (see Table 2). Using the subject matter expert’s relationship table, we then employ a Hasse Diagram [4] to model these relationships to ultimately generate a criteria graph. Each vector in the diagram, therefore, represents the subject matter expert’s assessment of relative importance between any two criterions (see Figure 1). This diagram is modeled in software as a criteria matrix, which is then transformed into a numerical belief vector. The Plan-Driven Fusion system will evaluate each criterion node (resulting in a numerical score between 0 and 1) for each RTO. Once all scores have been evaluated for each node, these scores are entered into the belief vector to compute an overall priority score for the RTO.

### Table 2. Sample Relative Importance between Criteria

<table>
<thead>
<tr>
<th>Criterion A</th>
<th>Criterion B</th>
<th>Relative Importance of Criterion A vs. B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known Hostility</td>
<td>Near</td>
<td>1.5x</td>
</tr>
<tr>
<td>Known Hostility</td>
<td>Soon</td>
<td>2.5x</td>
</tr>
<tr>
<td>Known Hostility</td>
<td>Approaching</td>
<td>4.0x</td>
</tr>
<tr>
<td>Known Hostility</td>
<td>Force Ratio</td>
<td>6.0x</td>
</tr>
<tr>
<td>Near</td>
<td>Soon</td>
<td>1.5x</td>
</tr>
<tr>
<td>Near</td>
<td>Approaching</td>
<td>3.0x</td>
</tr>
<tr>
<td>Near</td>
<td>Force Ratio</td>
<td>5.0x</td>
</tr>
<tr>
<td>Soon</td>
<td>Approaching</td>
<td>2.0x</td>
</tr>
<tr>
<td>Soon</td>
<td>Force Ratio</td>
<td>2.0x</td>
</tr>
<tr>
<td>Approaching</td>
<td>Force Ratio</td>
<td>4.0x</td>
</tr>
</tbody>
</table>

Lockheed Martin ATL developed the virtual battle space, a multi-dimensional repository [5]. This data store provides capabilities to track the history of RTOs and the entities to which they correspond (actors, actions, search volumes). Furthermore, the data store provides an interface that can be exploited by other components in the system to gain access to the RTOs it stores.

### 5. Performance Objectives

Plan-dependent information is presented through a domain-specific adaptation supplied to the system at run-time. This adaptation data supplies the specification of SA Regions (see Section 6) and a performance objective table tailored to each type of RTO that may be encountered in the battle space specific to the domain. An example of such a document is presented below.

As shown in Table 3, the information performance objectives for each RTO type are presented with varying levels of fidelity. For example, the performance objectives for all RTOs of track type include Positional Accuracy, Hostility Known, Hostility Near, Hostility Approaching, Soon, Near, Force Ratio, Approaching, and Force Comparison. Each of these performance objectives requires varying levels of fidelity for the Survivability and

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1 Some plans specify where to concentrate sensor attention, while others would delegate the responsibility of inferring those specifications to our Plan-Driven Fusion system.
Table 3. Performance Objectives

<table>
<thead>
<tr>
<th>Track RTO Type</th>
<th>Survivability Region</th>
<th>Plan Impact Region</th>
<th>Threat Awareness Region</th>
<th>Detection Region</th>
<th>Mission Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Rate Accuracy</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Positional Accuracy</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
</tr>
<tr>
<td>Classification Confidence</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>N/A</td>
</tr>
<tr>
<td>Force Comparison</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

the Detection Regions. Performance objectives are modeled as fuzzy sets where the quality of information is expressed as fuzzy linguistic variables. In modeling the quality of information as fuzzy linguistic variables, the system is able to better adapt to complex situations where the exact diagnosis is not always clear. Consider an example scenario where a series of sensors are deployed as part of the information fusion processing component. These sensors can potentially satisfy information requests made by the RTO in the battle space. An information need is produced and requires information on the actual location of a particular track. The information need furthermore requires that the quality of the information is "good". Although multiple sensors may be available as part of the information fusion processing component, not all may be qualified to satisfy such a request. Although some sensors can sense information about a particular track, they may provide the wrong type of information, while others may provide the right type of information but with insufficient fidelity. Sensor fidelity may be affected by the limitations of the sensor itself or environmental factors such as the position of the sensor with respect to the track or current weather conditions. Lastly, it is important to note that the perceived (actual) quality of information that is being supplied with the information and stored in the data store, allowing for more effective information need prioritization.

6. Situational Awareness Region Maintenance

Situational awareness (SA) regions encapsulate the spatial information contained in the performance objective table with respect to the plan (see Table 3). Each SA region either describes a spatial region around a particular RTO associated with an actor in the plan referred to as an actor-centric spatial region, or a set of plan spatial specifications, referred to as a plan-centric spatial region. The exact geometry of the regions is highly dependent on the context, domain, and the planned mission parameters. For example, if the domain of a given plan is Air Force Operations, then the region’s geometrical properties such as shape and size around an F-15 aircraft will be significantly larger than if the domain of operations was a dismounted marine unit. The architecture presented in this paper was designed to abstract the geometrical specifications of the SA regions by relying on a "plug-in" architecture where software extensions can be developed to specify domain-specific geometries. Lastly, for each plan action, one SA region is instantiated for each column in

![Figure 1. RTO Prioritization: Criteria Graph and Resulting Criteria Matrix](image-url)
the performance objective table to models the information needs and their corresponding level of fidelity.

Consider an example illustrating how SA regions are used in the architecture presented in this paper. Specifically an RTO that represents an actor in a maneuver plan. The actor’s track (see Figure 2) has one spatial region associated with it to which the plan associates four more regions. The smallest region associated with the track is called the Survivability Region2, and the largest region is the Mission Region. Although not always the case, in this example the Mission Region encompasses all of the other four regions. Furthermore, the track has two information needs: range rate accuracy and positional accuracy. The fidelity of the information that is required by these needs changes with each region. Typically, the fidelity of the information is higher in the smaller regions spatially closer to the plan itself and degrades as the regions become larger and further removed from the plan. The fidelity of information required by the information need depends on the specific region the RTO intersects. Therefore, domain subject matter experts can tailor the information needs and their target fidelity in order to meet the objectives of the mission.

![Figure 2. Situational Awareness Regions](image)

**7. Information Needs Assessment**

The system described in this paper consists of five major components (Figure 3): Plan Execution and Understanding System (PLEXUS), Plan Execution Monitoring, Information Needs Assessment (INA), and Information Fusion Processing. When integrated, these components provide the Plan-Driven Fusion capability. PLEXUS maintains the state and structure of the cross-domain plans and infers inter-plan relationships as described in Section 3. It then provides this information to the INA component. INA is responsible for the development and prioritization of all information needs, using the algorithm illustrated in Figure 4. Once the plan(s) are ingested by PLEXUS, INA performs two high level tasks: SA region maintenance and RTO maintenance. Using the plan and the performance objective table, INA creates a set of SA regions that specify the information objectives and their associated fidelity, as described in Section 5. INA also uses the operational context of the plan(s) and current world state (as represented by the data store) to develop the RTOs, those objects in the battle space for which information fusion processing will expend sensor and computational resources in order to form its situational awareness. Once the RTOs are generated, they are prioritized based on their tactical significance, a key factor in the overall priority of resulting information needs.

Using the set of SA regions and RTOs, INA determines their spatio-temporal intersections. If an RTO intersects an SA region in both space and time. INA gathers the set of information objectives (and their associated fidelity objectives) from the column of the performance objective table that is associated with the intersecting SA region. These resulting information objectives are refined into information needs by applying temporal constraints to the information objectives using the time specifications contained in the plans. Before supplying these information needs to information fusion, they must be prioritized based on: the priority of the RTO spawning the information need, the temporal constraints assigned to the information need, and the current (actual) performance of the need as compared to its target performance. As information fusion forms its situation awareness to supply to the data store, the algorithm will continue to iterate, maintaining the instantiations and details of RTOs, spatio-temporal attributes of the SA regions based on the current world state and sensor performance provided by information fusion, as well as the current plan state as provided by plan execution monitoring.

**8. Conclusions**

LM ATL has developed the concept of Plan-Driven Fusion, which enables the closed-loop cooperation between planning and information fusion components within a C4ISR environment. This proposed design for a Plan-Driven Fusion system provides a framework for the development of information needs and operational context by defining a domain-independent approach, yet still leverages domain-specific knowledge and subject matter expertise. This framework requires that any domain employing it implement a set of "plug-ins" (i.e., domain-specific software extensions) to supply that domain knowledge. This includes translation of domain-specific plans into the Core Plan Representation model, Situation Assessment Region Maintenance (SARM), RTO prioritization, and the definition of the performance objective table. The resulting system provides the decision maker with a situational awareness that is both relevant and appropriate to the mission objectives.

In December 2005, LM ATL successfully demonstrated a prototype of the Plan-Driven Fusion design. The concepts were tested within the context of a convoy-based resupply mission in Iraq. This scenario employed multiple stationary (e.g., unattended ground sensors) and platform-centric sensors (e.g., JSTARS platform) providing data on numerous simulated entities and threats throughout the test. This scenario demonstrated the ability to incorporate domain-specific extensions into the proposed domain-independent framework, while meeting each of the

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2 The Survivability Region (shown in the Actor-Centric view of Figure 2) is the closest to the track and requires the greatest fidelity of information given its proximity.
requirements outlined in Section 2. This prototype demonstrated that the Plan-Driven Fusion concept is conceptually feasible and can provide the ability to significantly improve situational awareness for a decision-maker.

References


