Top Ten Trends in High-Level Information Fusion

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Abstract – High-Level Information Fusion (HLIF) is a relatively new exploration of methods in the last decade. The discussion will address the issues between low-level (signal processing and object state estimation and characterization) and high-level information fusion (control, situational understanding, and relationships to the environment). From a series of efforts in identifying the main research focuses for the next decade, we have addressed the main issues from fusion conference papers and panel discussions, towards a comprehensive analysis. With the advent of the key grand challenges, many of the issues were analyzed over the last decade. In this paper, we highlight the main themes and a discussion of the attributes of the top ten issues. Since IF is to reduce uncertainty, a focus of this paper for the Evaluation of Techniques for Uncertainty Representation (ETUR) working group is to posit the issues of uncertainty for HLIF. Specific trends include data/knowledge representations, situation/threat/impact assessment, systems design, evaluation, and information management. The paper concludes with an topic of limited analysis of an uncertainty ontology for the ETURWG.

Keywords: Fusion, Situational/Impact Assessment, Resource/Sensor Management, User Refinement

1 Introduction

High-level Information Fusion (HLIF) has been of considerable interest to the fusion community ever since the development of the fusion process models. The low-level versus high-level distinction was made evident in the seminal text on the subject by Waltz and Llinas, *Multisensor Data Fusion*. [1] While many discussions in HLIF have been coordinated in the past decade at the fusion conferences, including other panel discussions, there is a need to gather contemporary insights into the ongoing challenges. Recent HLIF texts include: *Mathematical Techniques in Multisensor Data Fusion* [2], *Concepts, Models, and Tools for Information Fusion* [3], *High-Level Fusion* [4], *Handbook of Multisensor Data Fusion*, [5-6], *Brain-mind Machinery* [7], *High-Level Information Fusion Management and Systems Design* [8].

Many panel sessions at the *International Conference on Information Fusion (ICIF)* have focused on HLIF of which we sought to canvass [9] and organize the discussions on HLIF. HLIF typically includes situation/threat/impact (SA/TA/IA) assessment and resource management. For the general problem areas, we further analyzed the results from which ten themes emerge categorized below:

Figure 1. Situation Uncertainty

To derive the top trends in HLIF, numerous efforts were conducted to bring together the new ideas in HLIF over the last decade as well as the featured problem/challenge/issue discussions.

1.1 Lambert’s Grand Challenges

Dale Lambert [10] posed some grand challenges for the Information community in 2003 to include:
**Semantic Challenge:** What symbols should be used and how do those symbols acquire meaning?

**Epistemic Challenge:** What information should we represent and how should it be represented and processed within the machine?

**Paradigm Challenge:** How should the interdependency between the sensor fusion and information fusion paradigms be managed?

**Interface Challenge:** How do we interface people to complex symbolic information stored within machines?

**System Challenge:** How should we manage data fusion systems formed from combinations of people and machines?

The grand challenges relate to the need to incorporate the human in the decision process (i.e. Level 5, “User Refinement” [11]). Likewise, there were representation, design, and decision support challenges. The implied modeling challenges pose the need for syntactic, semantic, and pragmatic solutions. What is added to the original grand challenge list are evaluation challenges and systems design challenges [8].

### 1.2 HLIF Grand Challenges

From the discussion, five areas of interest that pose grand challenges for the information fusion community include: [9]

1. How to model (e.g. formal theories) and control a situation using a systems-level fusion context?
2. What constitutes situational, semantic, belief and knowledge representations?
3. How to design distributed systems and incorporate scenario-based design approaches?
4. When and where are user-system interactions coordinated in the fusion system’s decision support?, and
5. What are the metrics and visualizations needed for effective evaluation of HLIF systems?

Note that the discussion of higher-level fusion architectures have not specifically addressed who are the users for the various systems; whether it be an operator, commander, or design engineer.

For completeness of the analysis, we list again certain aspects of the analysis that were used to derive the current thinking. Here we focus on the current issues (while referring the reader to the companion paper in Fusion10 [9]).

The rest of this paper includes an overview of high-information level fusion in Section 2. Section 3 provides previous statements of information fusion challenges and Section 4 review the literature from past fusion conferences on HLIF. The literature review provides a basis that motivates the panel discussion from which conclusions are drawn in Section 5.

### 2 Introduction to HLIF

The distinction between high-level fusion (HLIF) and low-level fusion (LLIF) was first made evident by Waltz and Linas in the classical text in information fusion (shown in Figure 2) [1]. The low-level functional processes support target classification, identification, and tracking, while high-level functional processes support situation, impact, and fusion process refinement. LLIF concerns numerical data (e.g., locations, kinematics, and attribute target types). HLIF concerns abstract symbolic information (e.g., threat, intent, and goals). One model that captures the LLIF-HLIF distinctions is the Data Fusion Information Group (DFIG) Model.

![DFIG Fusion Model](image)

**Figure 2.** LLIF-HLIF Distinctions.

### 2.1 DFIG Fusion Model

The DFIG model [12] supports systems design issues by coupling various resource management (RM) functions with information fusion (IF) estimation needs. The DFIG model supports differing control functions based on the spatial/temporal/ spectrum differences. The spectral needs drive sensor selection. The temporal needs are based on the user’s need for timely information to afford action. Finally, the spatial needs are based on the mission goals.

The current team diagrammed the current process model, shown in Figure 3, while maintaining the structure of the JDL model. The current DFIG definitions include:

- Level 0 – Data Assessment
- Level 1 – Object Assessment
- Level 2 – Situation Assessment
- Level 3 – Impact Assessment
- Level 4 – Process Refinement
- Level 5 – User Refinement
- Level 6 – Mission Management

In the DFIG model, the goal was to separate the IF and RM functions. RM is divided into sensor control, platform placement, and user selection to meet mission objectives.

L2 (SA) includes tacit functions which are inferred from L1 explicit representations of object assessment. Since the unobserved aspects of the SA problem cannot be processed by a computer, user knowledge and reasoning is necessary. L3 (IA) sense-making of impacts (threats, course of actions, game-theoretic decisions, intent, etc.)
helps refine the SA estimation and information needs for different actions.

**Figure 3.** Data Fusion Information Group (DFIG) model.

High-level information fusion [8] (as referenced to levels beyond the DFIG Model Level 1) is the ability of a fusion system, through knowledge, expertise, and understanding, to capture awareness and complex relations, reason over past and future events, utilize direct sensing exploitations and tacit reports, and discern the usefulness and intention of results to meet system-level goals. The Information Fusion community has coined the term “high-level fusion” [13] however this implies that there is a low-level / high-level distinction when in reality they are coupled. Designs of real-world Information Fusion Systems imply distributed information source coordination (network), organizational concepts (command), and environmental understanding (context). There is a need for automated processes that provide functionality in support of user reasoning and inference, coupling to sensor machine processing [14], and scenario-based applications [15, 8]. Next we overview the panel discussions from the last decade in HLIF as a basis to determine the trends reported in the ICIF.

## 3 Current Trends

Previous panel discussions focused on a variety of areas such as modeling, representation, systems design, decision support; and evaluation methods as applied to SA/TA/IA, sensor, user, and mission (SUM) management [16].

### 3.1 Previous Related Panel Discussions

Panel discussions provide a valuable resource to the community to overview the current techniques and provide areas of concern for future research. Previous Fusion The ICIF panel discussion papers began in 2000 [17] discussing the visions for the community in presentation formats. Here we refer to the ICIF as FusionXX. Fusion01 [18] included presentations and supporting papers. Fusion04 [19] information was organized into a collective summary. Other panels related to HLIF include knowledge representation (Fusion05) [20], resource management coordination with situation and threat assessment (Fusion06) [21, 22], agent-based design (Fusion07) [23], and HLIF challenges (Fusion08) [24]. Three panel discussions were conducted at Fusion09 without papers [25, 26], with a summary report of SA/TA/IA at Fusion10 [27]. At Fusion10 [9] experts were compiled to focus on HLIF and current issues. In the Fusion10 paper, we highlight the aspects of many of the panels; however, here we organize the information in a common framework to determine the current trends and then match the under-researched/under-reported areas that are related to the ETURWG.

For ease of analysis, we grouped the discussion topics and then organized based on the 10 areas of importance. In Table 1, we list the topic area on the left with the discussion from the panel on the right. The table lists the most recent first.

<table>
<thead>
<tr>
<th>Category</th>
<th>Summarized Analysis of HLIF Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 ETUR Panel: Developments and Issues in Uncertainty Representation</td>
<td></td>
</tr>
<tr>
<td>Performance Eval</td>
<td>Standardized evaluation with use cases, data, and uncertainty metrics</td>
</tr>
<tr>
<td>2010 High Level Information Fusion Developments, Issues, and Grand Challenges [X]</td>
<td></td>
</tr>
<tr>
<td>Reference Model Semantics</td>
<td>Situation Modeling (context, environments, and processes) for association management</td>
</tr>
<tr>
<td>HLIF Information Representations (semantic, knowledge, and complex) for acquisition, relevancy, and processing of information</td>
<td></td>
</tr>
<tr>
<td>User/Agent Performance Eval</td>
<td>Decision support processes (reasoning, inference, and explanation of relationships) to support user’s needs</td>
</tr>
<tr>
<td>Standardized evaluation metrics (measures of performance/ effectiveness, empirical case studies) to conduct system-level analysis</td>
<td></td>
</tr>
<tr>
<td>Resource Planning</td>
<td>Systems design techniques (scenario-based, user-based, and distributed-agent) to provide reasoning capabilities</td>
</tr>
<tr>
<td>2009 Issues and Challenges in Higher Level Fusion: Threat/Impact Assessment [X]</td>
<td></td>
</tr>
<tr>
<td>Reference Model SA/TA/IA</td>
<td>Common reference model for HLIF processes and analysis</td>
</tr>
<tr>
<td>Actor state modeling based on opportunity, capability, capacity, intent and goals for a plausible scenario</td>
<td></td>
</tr>
<tr>
<td>User/Agent Performance Eval Scenario</td>
<td>User support for analysis rather than filtering through data</td>
</tr>
<tr>
<td>Set of performance evaluation metrics and criteria for prioritization</td>
<td></td>
</tr>
<tr>
<td>Evaluation criteria to support collection requirements and analysts</td>
<td></td>
</tr>
<tr>
<td>2009 A Coalition Approach to Higher-Level Fusion [X]</td>
<td></td>
</tr>
<tr>
<td>Reference Model Semantics SA/TA/IA</td>
<td>Common state estimation modeling based on social, cognitive, functional, environmental, and metaphysical concepts</td>
</tr>
<tr>
<td>Semantic registration, observation, estimation, and prediction processing based on data collection, representation, and parsing</td>
<td></td>
</tr>
<tr>
<td>Analysis of collective behaviors for intent and target identity</td>
<td></td>
</tr>
</tbody>
</table>
### 2008 Higher-level Information Fusion: Challenges to the Academic Community [X]

<table>
<thead>
<tr>
<th>Knowledge Representation</th>
<th>Representation cognition design for risk assessment, knowledge representation, and link discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>User/Agent</td>
<td>Bring together situation awareness, cognition, consciousness, and user analysis</td>
</tr>
<tr>
<td>Social/Behavioral Models</td>
<td>Utilize methods from cognitive, social, behavioral, and organizational communities</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Manage uncertainty estimation and support to different agents</td>
</tr>
<tr>
<td>Resource Planning</td>
<td>Bridge the gap between human-decision models and large complex data processing of machines</td>
</tr>
</tbody>
</table>

### 2007 Agent Based Information Fusion [X]

<table>
<thead>
<tr>
<th>Reference Model</th>
<th>Mission goals require real-time distributed collaboration methods and service architectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semantics</td>
<td>Distributed multi-agent fusion systems need rigorous and integrated modeling and inference methods for system design</td>
</tr>
<tr>
<td>SA/TA/IA Methods</td>
<td>Methods needed for characterizing agent behaviors based on action capability, opportunity, and intent</td>
</tr>
<tr>
<td>User/Agent</td>
<td>Complex-adaptive systems require new HLIF requirements to assist users</td>
</tr>
<tr>
<td>Joint Theory of methods</td>
<td>Overall system integration of components for communication and information dissemination among the different agents</td>
</tr>
</tbody>
</table>

### 2006 Resource Management Coordination with Level 2/3 Fusion Issues and Challenges [X]

<table>
<thead>
<tr>
<th>SA/TA/IA</th>
<th>L 2/3 situation entity definitions for knowledge discovery, modeling, and information projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>User/Agent Performance</td>
<td>Design for users for resource management</td>
</tr>
<tr>
<td>Eval</td>
<td>Optimizing/evaluating fusion systems over a standard set of metrics for cost-function optimization</td>
</tr>
<tr>
<td>Resource Planning</td>
<td>Addressing constraints for resource scheduling and planning over mission time-horizons</td>
</tr>
<tr>
<td>Joint Theory of methods</td>
<td>Joint optimization of objective functions at all fusion levels</td>
</tr>
</tbody>
</table>

### 2005 Issues and Challenges of Knowledge Representation and Reasoning Methods in Situation Assessment (Level 2 Fusion) [X]

<table>
<thead>
<tr>
<th>Reference Model</th>
<th>Process modeling for behavioral updates (e.g. Bayes Nets, procedural/logical, perceptual, learning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge Representation</td>
<td>Process–evidence explanation, accumulation, and contradiction in knowledge representation and reasoning</td>
</tr>
<tr>
<td>Semantics</td>
<td>Semantics and syntax formalization (formal methods, ontologies)</td>
</tr>
<tr>
<td>SA/TA/IA</td>
<td>Context–operational situation modeling (i.e., dependent on the current state of the environment) for projection</td>
</tr>
<tr>
<td>User/Agent</td>
<td>SA process includes perceptual, interactive, and human control such as graphical displays to facilitate inferential chains, collaborative interaction, and knowledge presentation</td>
</tr>
</tbody>
</table>

3.2 Contemporary Trends

The concern for the community is a various instantiation of these thrusts [9] such as:

- What techniques and procedures are most applicable?
- What are the tacit implications for HLIF?
- What is needed in HLIF to support control?
- What is the impact of HLIF to decision support?
What constitutes effective system evaluation?

Key areas of research directions emerged in these areas:
- Formal theories for HLIF SA modeling [28, 29].
- Situation and Knowledge IF [30, 31].
- HLIF system design [32].
- HLIF for decision support [33].
- HLIF evaluation [34].

Common trends discussed include:
(A) Information fusion designs support situational awareness. Advanced techniques in design (e.g., agent-based) and formal theories are needed to support contextual understanding and information management. Common prototypes and testbeds are needed for comparative evaluation of techniques.
(B) The fusion process has a requirement for a layered set of adaptive process control loops of various types (i.e., between fusion processes and within a level, inter-level control, and sensor/information management). Distributed control issues are a critical key element of design and implementation of any fusion process yet receives little attention in the community.
(C) Understanding feasible solutions and the role of human intelligence. Today, we are facing complex, dynamic problem environments and new input modalities (text/language) that impute entirely new challenges. We need to understand what aspects of these problems can be addressed with automated machine-processing methods and where and to what extent we need human intelligence inserted. There is little to no calibration of what levels of complexity and dimensionality a HLIF system can support users via automated operations. A successful HLIF system should combine machine computing power with human cognition/intuition.

From the discussions, the areas are (1) theoretical coordination between low-level (signal processing, object state estimation and characterization) and high-level fusion (control and relationships to the environment), (2) information management methods including modeling (situations, environments), representations (semantic, knowledge, and complex), and (3) Systems design (scenario-based, user-based, distributed-agent) and evaluation (measures of performance/effectiveness, and empirical case studies). Further analysis of these areas are evident from an organization of listed panel discussions.

Grouping the key attributes of Table 1, (left side) we then determined which of these areas were highlighted in the panel discussion as shown in Table 2. Table 2 provides a highlight of each topic with the knowledge that the discussion typically was supported with a companion paper at ICIF. From the list, we see that the trends include (1) data/knowledge representation, (2) SA/TA/IA assessment, (3) systems design, (4) evaluation, and (5) information management.

Further analysis of these areas is evident from an organization of listed panel discussions. Two areas of importance to the ETURWG is uncertainty analysis and ontologies that support uncertainty representation. Both of these topics are current trends in information fusion. To instantiate the issues of uncertainty analysis and ontologies, we next overview the basic issues and then provide a use-case for a LLIF-HLIF interaction of target tracking and identification.

### 4 Uncertainty Analysis

Uncertainty analysis is needed for the man-machine interface to coordinate human-systems integration (HSI) [35]. Both the human and machine have a notion of uncertainty [36], but there is a need to bring these ideas together in a common ontology and formulation which includes the quantitative and qualitative aspects for measures of effectiveness [34]. For example, uncertainty by the DFIG levels:

- Level 0 – Skew, Rotation registration error

<table>
<thead>
<tr>
<th>Table 2. Summary of Key Topics from the Panel Discussions on HLIF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Model</td>
</tr>
<tr>
<td>Data/Knowledge</td>
</tr>
<tr>
<td>Representation</td>
</tr>
<tr>
<td>Semantics/Ontologies</td>
</tr>
<tr>
<td>SA/TA/IA Assessment</td>
</tr>
<tr>
<td>Social/Behavioral Model</td>
</tr>
<tr>
<td>User/Agent Coordination</td>
</tr>
<tr>
<td>Display (Interactive)</td>
</tr>
<tr>
<td>Common Scenario</td>
</tr>
<tr>
<td>Performance Eval/Metrics</td>
</tr>
<tr>
<td>Uncertainty Analysis</td>
</tr>
<tr>
<td>Resource Planning</td>
</tr>
<tr>
<td>Joint Theory of Methods</td>
</tr>
</tbody>
</table>
Level 1 – Prob. Detection, False Alarm
  Root Mean Square Error (RMSE)
Level 2 – Number of objects, association error
Level 3 – Threat, Risk
Level 4 – Assignment error
Level 5 – Ignorance, time delay, sensor cost
Level 6 – Completeness, throughput

If we use the notion of uncertainty from the taxonomy of ignorance, [37] we can develop the notions of uncertainty as shown in Figure 4. For the human-decision making, we have ignorance as subdivided into error and irrelevance. Uncertainty is then a form of incompleteness. To coordinate the HIS, the user needs to determine the irrelevance and the incompleteness from which to query or control the machine.

Figure 4. Taxonomy of Uncertainty from Ignorance.

To determine ignorance, we Uncertainty analysis covers both precision and accuracy [34]. Figure 5 presents the accuracy analysis from a Gaussian distribution.

Figure 5. Uncertainty Analysis of Sensor Track Accuracy.

If we analyze the information from Figure 5, then we can demonstrate information uncertainty reduction. Let’s say we have two systems with uncertainty $\sigma_1 = 1$ and $\sigma_2 = 2$. Assuming that we model the information fusion reduction, $\sigma_F$, we have:

$$\frac{1}{\sigma_F^2} = \frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} \quad \text{where:} \quad \sigma_F^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

From the example,

$$\sigma_F^2 = \frac{(1)(4)}{(1)+(4)} = \frac{4}{5}$$

where 0.8 is less than 1 of 2. The uncertainty reduction is developed from information fusion. This method is used for target tracking, but we can also do for object assessment as developed in the community using either a Bayesian or evidential reasoning strategy [38] where an aggregate measure of uncertainty is desired [39] for decision support [40].

For object recognition, classification, or identification, there is a note of ignorance. Ignorance is the uncertainty between the believability and the plausibility. Beliefs are what you know and non-plausible is the information that you can rule out as irrelevance. Furthermore, one proposed method [41] is to use a Gaussian distribution for the ignorance as an interval of uncertainty and a sum of Gaussians for the regions of believability and non-plausibility.

Figure 6. Uncertainty Analysis of Sensor Identification.

Using the above paradigm as an example, we bring together the uncertainty from LLIF for object tracking and ID. Next we need to coordinate the uncertainty analysis of LLIF with a HLIF ontology.

5 Semantics/Ontologies

In previous discussions, semantics were developed in the ontology framework of knowledge, epistemologies, and taxonomies. [42] Here, for the example, we need and ontology framework for uncertainty analysis [43] such as that of activity based intelligence (ABI) [44] which characterizes the objects, their movements, and their intent for situation awareness for the user. Current trends include using a social network analysis [45], probabilistic ontologies [28], and HLIF ontologies [46] across the DFIG levels [47]. In [8], for HLIF information management and sharing, semantics are described with Resource Description Framework (RDF) [48] and/or Ontology Web Language (OWL) [49] in conjunction with the Business Processing Execution Language (BPEL) [50] and variants for workflow analysis. For example, in a target tracking and ID scenario, we need to utilize the sensor markup language (Sensor ML) as well as a variant of the BPEL using the Human Behavior ML (HBML) for assessment of the actors in the environment as shown in the taxonomy of ontologies in Figure 7.
Current needs are a comprehensive ontology with such attributes as a linking between LLIF to HLIF, uncertainty analysis and ontologies for such attributes as a threat assessment.

6 Example

Figure 8 shows the 2 UAVs approaching a target and fused result of target ID PDF. The use-case is an EO sensor in which the resolution gets better as the sensor approaches the target. Uncertainty is captured in the accuracy, ID, number of targets from which an aggregate assessment of threat analysis is determined.

Using a Rayleigh distribution for threat uncertainty, Figure 9 shows a 3D representation of threat space of a target on the ground as aggregated from the fused information from the sensors.

The information from the quantitative analysis can support a mark-up language description for an ontology representation of uncertainty. Further analysis can utilize the ontology representations discussed in the work of previous panelists in probabilistic ontologies (Costa/Laskey) and target identification ontologies (Kokar).

As part of the ETURWG, there is a need to bring together the LLIF (quantitative) and HLIF (qualitative) ontological representations of uncertainties for such applications as sensor management using covariance and information filtering approaches [51].

7 Summary of Trends

High-level information fusion (Situation and Threat Assessment, Process and User Refinement) requires further analysis from the ISIF community. Form the analysis, the trends listed below where the two under-represented areas for the ETURWG are ontologies and uncertainty analysis.

Area A. Data/Knowledge Representation
- Reference Model
- Taxonomy of notations, symbols, and meanings

Area B. SA/TA/IA Assessment
- Semantics/ontologies
- Social/Behavioral Models

Area C. Systems Design
- User/agent coordination
- Display (interactive)

Area D. Evaluation
- Common Scenario, Performance Comparison
- Metrics / Uncertainty analysis

Area E. Information Management
- Resource planning and information analysis
- Joint theory of methods integration

Acknowledgements: previous panel discussions and analysis with contributions from Kokar.

8 References


PANELS


FUSION10


UNCERTAINTY


ONTOLOGY


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OTHER

