High Level Information Fusion (HLIF):
Survey of Models, Issues, and Grand Challenges

Erik P. Blasch
Air Force Research Laboratory
Dale A. Lambert
Defence Science & Tech. Organization
Pierre Valin
Defence R&D Canada - Valcartier
Mieczyslaw "Mitch" M. Kokar
Northeastern University
James Llinas
SUNY – Buffalo
Subrata Das
Machine Analytics
Chee Chong
BAE Systems
&
Elisa Shahbazian
OODA Technologies

SURVEY MOTIVATION

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], as shown in Figure 1.

[1] DFIG members are: Frank White, Otto Kessler, Chris Bowman, James Llinas, Erik Blasch, Gerald Powell, Mike Hinman, Ed Waltz, Dale Walsh, John Salerno, Alan Steinberg, Dave Hall, Ron Mahler, Mitch Kokar, Joe Karakowski, Richard Antony

Author's Current Address:
E.P. Blasch, Air Force Research Laboratory, NY, USA; D.A. Lambert, Defence Science & Tech. Organization, Australia; P. Valin, Defence R&D Canada - Valcartier; M. "Mitch" M. Kokar, Northeastern University, MA, USA; J. Llinas, SUNY – Buffalo, NY, USA; S. Das, Machine Analytics, MA, USA; C. Chong, BAE Systems, CA, USA; and E. Shahbazian, OODA Technologies, Canada.

Manuscxript received February 2; revised March 29, 2012.
Review handled by H. Liu.

While many discussions in HLIF have been coordinated in the past decade at the fusion conferences, 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 Data Fusion* [4], *Human-centered Information Fusion* [5], and *Handbook of Multisensor Data Fusion*, [6, 7].

Organization and Discussion Overview

For this survey, experts were compiled based on various research thrusts:

- ***Modeling:*** *Das, Lambert, Kokar*
- ***Representation:*** *Blasch, Kokar, Valin*
- ***Systems Design:*** *Chong, Das, Lambert*
- ***Decision Support:*** *Blasch, Llinas, Shahbazian*
- ***Evaluation Methods:*** *Blasch, Llinas, Valin*

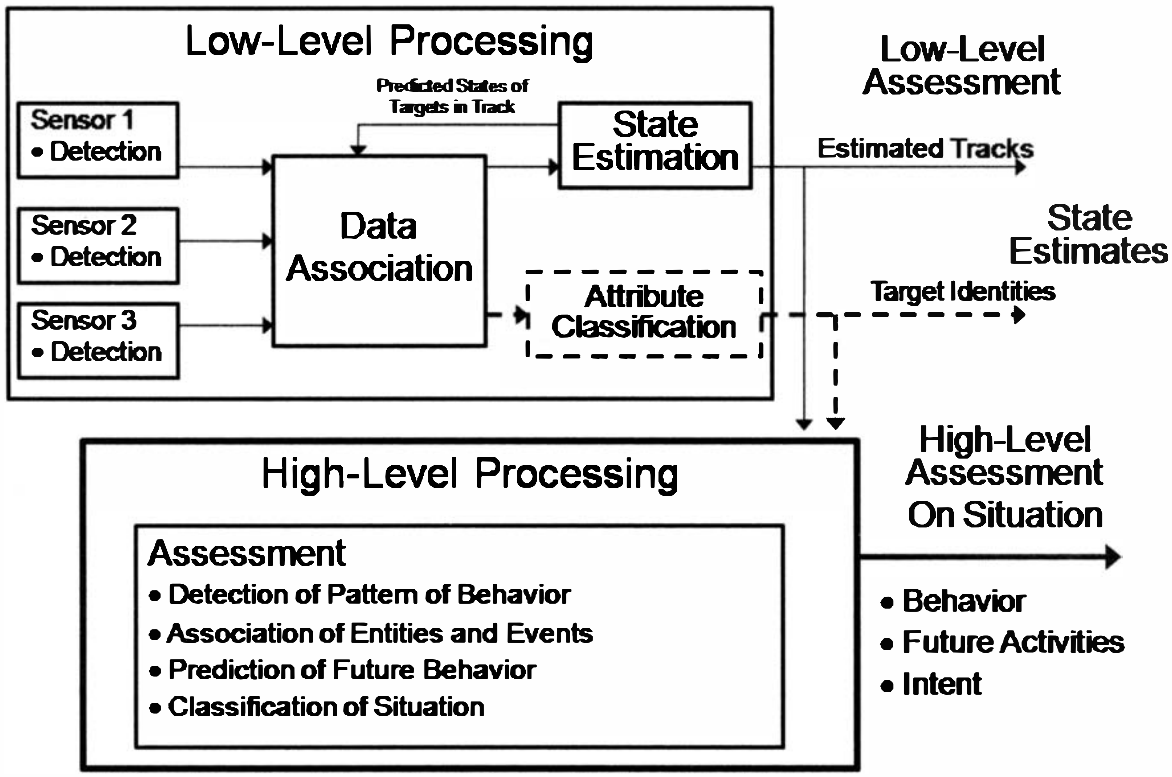

Fig. 1. Elements of a basic data fusion system.
*Adapted from E. Waltz and J. Llinas, **Multisensor Data Fusion,** Artech House, Norwood, MA [1990]*

The HLIF discussion's goal was to survey and highlight the unsolved problems and concerns in order to motivate the information fusion community toward systems-level solutions. The expert perspectives are based on three areas:

- 1) previous panel discussions and summaries,
- 2) an integrated list of HLIF challenges, and
- 3) companion papers presented at each *International Conference on Information Fusion (ICIF)*, of which we will refer to *FusionNN*, where *NN* denotes the year.

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. For this survey, we include a summary of the previous fusion conference panel discussion papers related to HLIF including fusion visions *(Fusion00)* [8], data fusion for level 2-4 *(Fusion01)* [9], challenges in higher-level fusion *(Fusion04)* [10], knowledge representation *(Fusion05)* [11], resource management coordination with situation and threat assessment *(Fusion06)* [12], agent-based design *(Fusion07)* [13], HLIF challenges to the academic community *(Fusion08)* [14], coalition approach to HLIF *(Fusion09)* [15], challenges in HLIF: threat and impact assessment *(Fusion09)* [16], and HLIF developments, issues and challenges *(Fusion10)* [17]. Authors of this survey contributed to many of these previous panel discussions, papers, and presentations.

Common concerns for HLIF include:

- *What HLIF 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?*

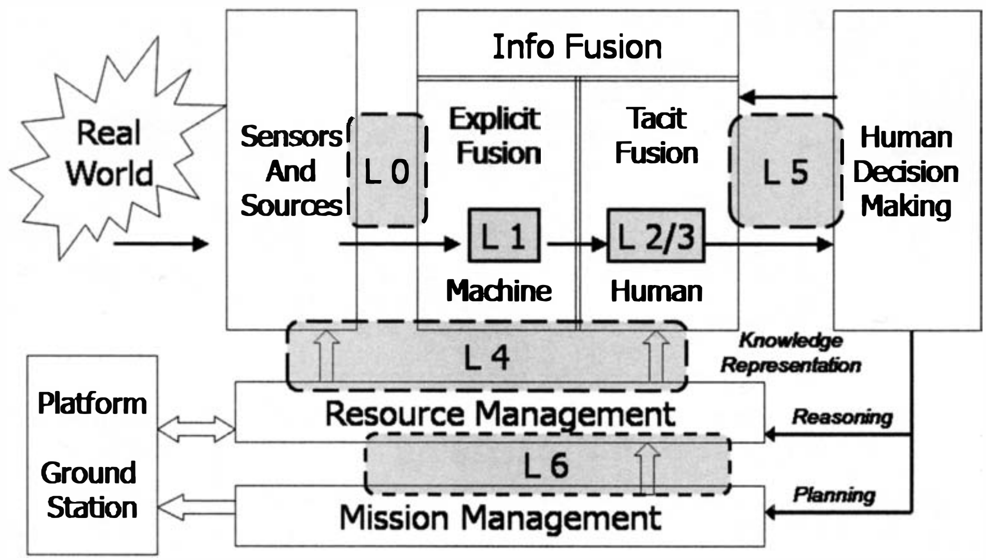

Fig. 2. DFIG Model

- *What constitutes effective system evaluation?*

The rest of this is organized as follows. We introduce the concept of High-Level Information Fusion (HLIF) followed by a discussion of information fusion models. Next, we survey HLIF challenges as posed from panel discussions at the annual *ICIF* over the last decade. To complement the challenges, we survey HLIF issues as evident from the literature review of the proposed tools and design solutions from HLIF papers at *ICIF*. We then highlight the 2010 HLIF panel discussion followed by a table summary of all panel discussions issues in HLIF. We conclude with a summarized list of grand challenges in HLIF.

INTRODUCTION TO HLIF

The distinction between High-Level Fusion (HLIF) and Low-Level Fusion (LLIF) was first made evident by *Waltz* and *Llinas* in the classical text in information fusion (shown in Figure 1) [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).

Following [1], the Joint Directors of Laboratories (JDL) model was proposed [18]. Subsequent revisions [19, 20] were made to the model to incorporate new understandings of the issues involved in developing an information fusion system. In 2004, the JDL model was revised for the proposed Data Fusion Information Group (DFIG) model [11, 12, 21].

DFIG Fusion Model

The DFIG model [11, 12] supports the original JDL goals while highlighting pragmatic design issues by coupling various Resource Management (RM) functions with Information Fusion (IF) estimation needs. The DFIG[1] model supports differing control functions based on the spatial/temporal/spectral 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 DFIG process model, shown in Figure 2, maintains the structure of the JDL model with emphasis on the elements of High Level Information Fusion.

The current DFIG definitions include:

- ***Level 0 – Data Assessment (DA):***
  estimation and prediction of signal/object observable states on the basis of pixel/signal level data association (e.g., information systems collections);

- ***Level 1 – Object Assessment (OA):***
  estimation and prediction of entity states on the basis of data association, continuous state estimation, and discrete state estimation (e.g., data processing);

- ***Level 2 – Situation Assessment (SA):*** *estimation and prediction of relations among entities, to include force structure and force relations, communications, etc., (e.g., information processing);*

- ***Level 3 – Impact Assessment (IA):*** *estimation and prediction of effects on situations of planned or estimated actions by the participants; to include interactions between action plans of multiple players (e.g., assessing threat /intent actions to planned actions and mission requirements, performance evaluation);*

- ***Level 4 – Process Refinement (PR):*** *(an element of Resource Management): adaptive data acquisition and processing to support sensing objectives (e.g., fusion process control and information systems dissemination).*

- ***Level 5 – User Refinement (UR):*** *(an element of Knowledge Management): adaptive determination of who queries information and who has access to information (e.g., information operations) and adaptive data retrieved and displayed to support cognitive decision making and actions (e.g., human systems integration).*

- ***Level 6 – Mission Management (MM):*** *(an element of Platform Management): adaptive determination of spatial-temporal control of assets (e.g., airspace operations) and route planning and goal determination to support team decision making and actions (e.g., theater operations) under social, economic, and political constraints.*

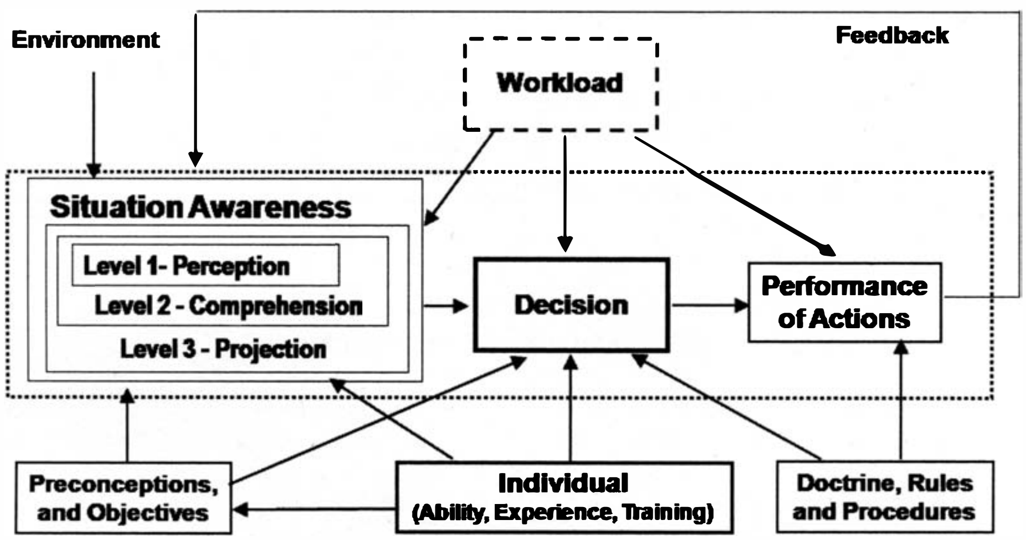

Fig. 3. Endsley's SAW Model

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.

High-Level Information Fusion (as referenced to levels beyond 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,

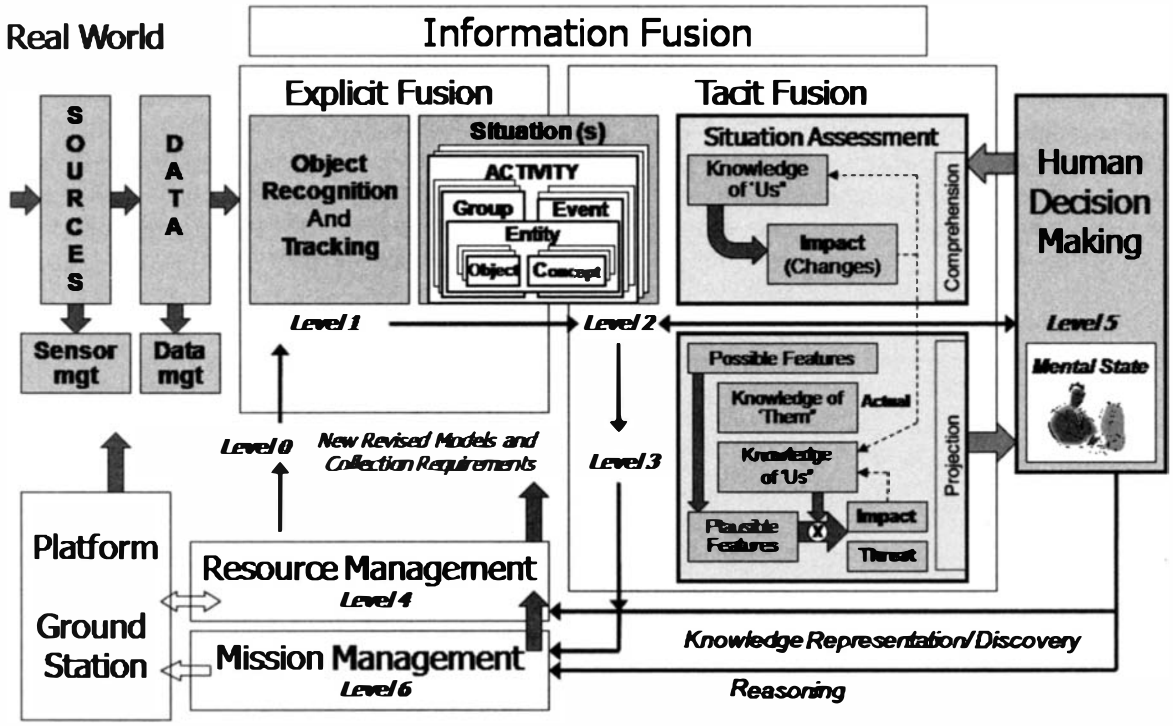

Fig. 4. Information Fusion SA Model

and discern the usefulness and intention of results to meet system-level goals. The Information Fusion community has coined the term *"high-level fusion"* 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). Additionally, there is a need for automated processes that provide functionality in support of user decision processes, particularly at higher levels requiring reasoning and inference.

Situation Assessment/Awareness Fusion Models

One aspect of HLIF is the role of the user [5] in system design, analysis, and man-machine interface. Situation assessment is thought of as a machine function; whereas Situation AWareness (SAW) is a cognitive function. Multiple authors have utilized the model developed by Endsley [22] for human-in-the-loop semi-automated processing for SAW, which builds upon the observe-orient-decide-act (OODA) model [23]. The SAW model, shown in Figure 3, highlights three levels of SAW:

Level 1 SAW –
Perception of environmental elements,

Level 2 SAW –
Comprehension of the current situation, and

Level 3 SAW –
Projection of future states.

Utilizing the elements of SA, SAW, and the DFIG, a combined Information Fusion Situation Assessment Model is shown in Figure 4, which highlights the activities of a situation that a user is concerned with: reasoning (perception), assessing (comprehension), and future state prediction (projection) [24].

State Transition Data Fusion Model

As functional models, variants of the JDL/DFIG models celebrate the differences between the sub-object, object, situation, and impact assessment levels at the expense of highlighting their commonality. In 2006, Lambert [25] introduced the *State Transition Data Fusion (STDF)* model, which rests upon three *unifying* tenets aimed at exposing the essence of data fusion.

1) *Situation awareness is fusion performed by people, while machine fusion is "situation awareness" performed by machines. If "sensation" is added as a level 0 to Endsley's*

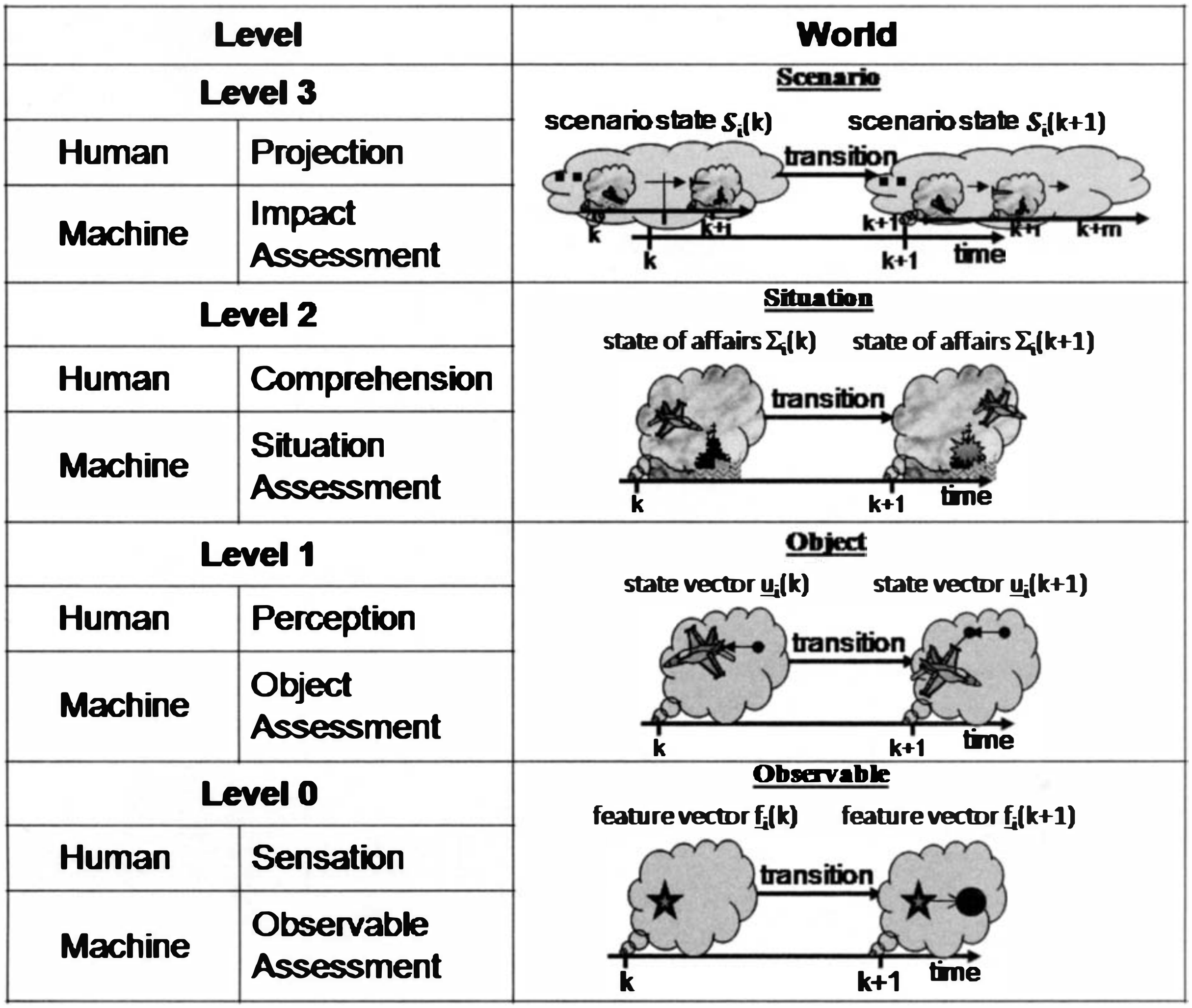

Fig. 5. STDF State Transitions at Each Level

definition of situation awareness, then there is a direct correspondence between levels 0 to 3 of situation awareness and levels 0 to 3 of machine fusion, respectively. The adaptive level 4 can be partitioned across levels 0 to 3. Level 5 then comprises levels 0 to 3 being performed by a human. Fusion at levels 0 to 3 can then be understood as being performed by people, machines, or some combination of the two. The appropriate level of automation for each of these fusion levels should be decided empirically. Some aspects are better handled by people, while others are better performed by machines.

2) *At DFIG levels 0 to 3, the world can be understood in terms of transitions between states. Conceptualizing the world as transitions between states is a common theme for each of the DFIG levels 0 to 3. What differs at each level is the notion of state, which acquires increasing numerical to symbolic complexity across the levels. Figure 5 illustrates the nature of state transitions across levels 0 to 3 and the corresponding human and machine fusion processes associated with them.*

3) *At each DFIG level 0 to 3, a common fusion process applies that aims to explain the world through prediction and observation. The generic fusion process predicts to observe, observes to explain, and explains to predict, as shown in Figure 6. What differs at each level is how the component processes are realized,*

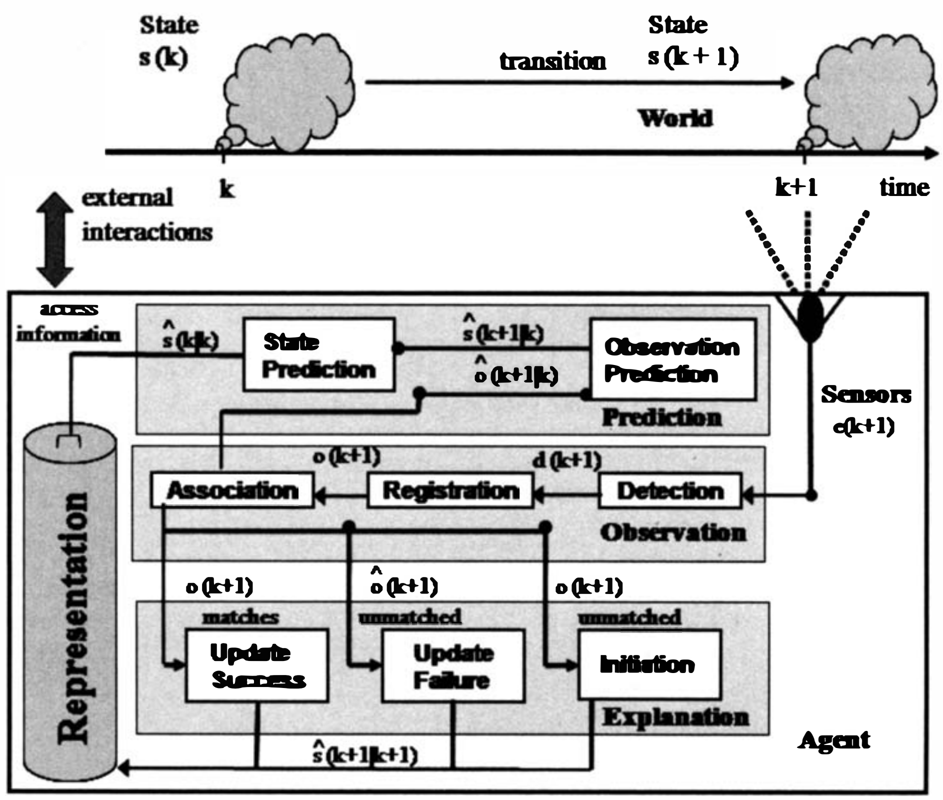

Fig. 6. Generic STDF Fusion Process

Table 1. Issues and Challenges in Level 4 Sensor Management

Current Status	Challenges and Limitations
Robust system for single-sensor system	Incorporation of mission objectives / constraints
Operations research formulation	Environmental context for sensor utilization
Limited approximate reasoning application	Conflicting objectives (e.g., detection vs. accuracy)
Focus on MOP and MOE	Dynamic algorithm selection / modification Diverse sensors

given the nature of states at that level. Some component processes represent the STDF fusion process operating at a different level. When interpreted at level 2, for example, the STDF *model "detection" process is in fact the whole object assessment STDF process of level 1.*

While the various information fusion models and architectures support conceptualizations of fusion process, there are many daunting challenges for delivering an operational system. There have been many guidelines of information fusion challenges that motivate the community for active research.

INFORMATION FUSION CHALLENGES

Early work by Hall and Llinas in 1997 [26] addressed various challenges for high-level information fusion as aligned with the information fusion level notation. For example in Level 4, they list the key techniques of *Measurement Of Effectiveness (MOE), Measures Of Performance (MOP),* and *Utility Theory* as well as attention to mission management with issues and challenges listed in Table 1.

The key challenges expressed were: 1) limited communications bandwidth for data aggregation; 2) context-based approximate reasoning for L3 understanding; and 3) knowledge representation for L2 processing, which were similar issues of the *Fusion05* panel discussion for SA processing [11]. The interplay between RM and the various high-level processes is still evolving as more data becomes available and information fusion techniques are applied to large contextual applications.

Lambert's Grand Challenges

Dale Lambert [27] 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 [21, 28]. Likewise, there are *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 [17]:

Design Challenge:
How should we design information fusion systems formed from combinations of people and machines?

Evaluation Challenge:
How should we evaluate the effectiveness of information fusion systems?

HLIF OVER THE LAST DECADE

This section serves as a retrospective survey of key issues and challenges addressed from the fusion community as per ICIF which is regularly co-sponsored by the *IEEE Aerospace and Electronic Systems Society.* The reader is referred to the individual papers [www.isif.org] for specific detail. One note is that the papers included in the survey specifically address HLIF or *"higher-level fusion,"* although other ICIF papers could have addressed elements of HLIF (L2-L5) without noting the technology as per the research domain of HLIF.

From SA/IA to User Refinement

Initially, researchers were mostly concerned with situation assessment [29]. From 2003 to 2008, there were about 4 papers each year focusing on HLIF. Represented examples are discussed below as space limits a complete survey of all of the papers.

Fusion03 *incorporates differing HLIF issues and solutions to situation assessment and intent estimation. Sycara et. al. [30] focused on user issues including decision-making, semantics, and actionable information and Lee [31] discusses intent estimation. A new theme emerges in ontology representations [32, 33].*

Fusion04 *HLIF research includes situational presentations [34] of context dependent attributes and challenges in situation awareness [10, 35]. Also, the use of category theory to model the space of information fusion systems was introduced [36].*

In 2005, Schubert and Svensson provide the first-of-a-kind literature review of robust high level fusion performance [37]. Also, in the *Fusion05* conference, Lambert [38] expands upon his semantic challenges. Additionally papers are presented on HLIF situation awareness solutions by Kokar [39]. Two approaches to implementing situation assessment programs – *procedural vs. declarative* – were discussed [40] as well as evaluation and user refinement [21].

> ***Fusion06** includes HLIF fusion theories for SA [25] and the importance of decision support [41] as well as game theoretical threat prediction [42] and methods of situational awareness inferencing [43].*

> *Only two papers in **Fusion07** specifically discuss HLIF designs including Laudy et. al. who presented on HLIF conceptual graphs [44] and HLIF design tradeoffs [45] in addition to the panel discussion on agent-based issues [13].*

In 2008, HLIF papers mainly focus on threat assessment evaluation: including Karlsson et. al. for HLIF mission planning based on threat spaces, and credal networks [46] and on formally representing enemy courses of action [47].

HLIF as an Emerging Topic

During 2009, numerous discussions called out the need for HLIF. Solutions were presented for HLIF L2 situation assessment [48, 49], L3 threat assessment and representation of temporal aspects of courses of actions [50]. The scenario issues of context and culture [51] were addressed. Various L5 user refinement decision support techniques were proposed. Finally, system design issues were presented to improve decision-making [52].

> ***Fusion10** included a dedicated session to HLIF that focused on situation and knowledge representations [53, 54], system design [55, 56], decision support [57], and evaluation [58]. Three common themes throughout the Fusion10 papers 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 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.*

Discussion on High-Level Information Fusion

The term *"High-Level Fusion"* is contrasted to *"Low-Level Fusion"* in numerous papers that include image processing, ontology, and robotics. In many cases, the authors dictate a distinction of their own algorithms from data and information aggregation. These papers do not refer to the Information Fusion community levels, but delineate the discussion in their own architectures. For example, in robotics, [59], low-level fusion is defined as direct integration of sensory data, resulting in parameter and state estimates; whereas high-level fusion is used for indirect integration of sensory data through command arbitration of control signals suggested by different hierarchical modules. Many robotics and image processing papers make distinctions between estimation and control, which was the basis of the JDL modifications; however they focus on data versus information fusion.

There are many ideas that the fusion community can leverage in support of HLIF designs. Such conferences on *belief reasoning (BELIEF)*, situation assessment and management *(IEEE Cognitive Methods in Situation Awareness and Decision Support - CogSIMA), Knowledge Discovery and Data Mining (KDD),* and contextual understanding *(Military Operations Research Symposium - MORS)* can provide insights into HLIF designs.

FUSION10 PANEL DISCUSSION

The literature survey overviewed the models and issues of HLIF. From previous participation in panel discussions, research, operational assessment of information fusion systems, and publications provided insights into the current HLIF grand challenges. The order of comments is related to the prioritized summary discussed in the paper conclusions.

> ***Chee Chong** discussed the challenges of situational modeling when moving from Level 1 fusion to higher levels such as increased number of states to estimate, complexity of associations, and expensive computation of inferences. HLIF challenges include: efficient hypothesis evaluation and association such as graphical*

Table 2. Summary of Issues from the Last Decade of Panel Discussions on High-Level Information Fusion

Panel	Category	Summarized Analysis of HLIF Needs
2010 High Level Information Fusion Developments, Issues, and Grand Challenges [17]	Reference Model	**Situation Modeling** (context, environments, and processes) for association management
	Semantics	**HLIF Information Representations** (semantic, knowledge, and complex) for acquisition, relevancy, and processing of information
	User / Agent	**Decision support** processes (reasoning, inference, and explanation of relationships) to support user's needs
	Performance Evaluation	**Standardized Evaluation Metrics** (measures of performance / effectiveness, empirical case studies) to conduct system-level analysis
	Resource Planning	**Systems design techniques** (scenario-based, user-based, and distributed-agent) to provide reasoning capabilities
2009 Issues and Challenges in Higher Level Fusion: Threat/Impact Assessment	Reference Model	**Common reference model** for HLIF processes and analysis
	SA/TA/IA	**Actor state modeling** based on opportunity, capability, capacity, intent and goals for a plausible scenario
	User / Agent	**User support** for analysis rather than filtering through data
	Performance Evaluation	Set of **performance** evaluation metrics and criteria for prioritization
	Scenario	**Evaluation Criteria** to support collection requirements and analysis
2009 A Coalition Approach to Higher-Level Fusion [15]	Reference Model	**Common state estimation** modeling based on social, cognitive, functional, environmental, and metaphysical concepts
	Semantics	**Semantic** registration, observation, estimation, and prediction processing based on data collection, representation, and parsing
	SA/TA/IA	Analysis of **collective behaviors** for intent and target identify
	Social / Behavioral Models	Joint **information fusion testtbed** development with sensors, targets, and environment models
	Scenario	**Common scenario** and vignettes for collaboration and analysis
2008 Higher-Level Information Fusion: Challenges to the Academic Community [14]	Knowledge Representation	**Distribution cognition** design for risk assessment, knowledge representation, and link discovery
	User / Agent	Bring together situation awareness, cognition, consciousness, and **user analysis**
	Social/Behavioral Models	**Utilize methods** from cognitive, social, behavioral, and organizational communities
	Uncertainty	Manage uncertainty **estimation and support** to different agents
	Resource Planning	Bridge the gap between **human-decision models** and large complex data processing of machines

Table 2 continued on next page ⇒

Table 2. Summary of Issues from the Last Decade of Panel Discussions on High-Level Information Fusion ***(continued)***

2007 Agent Based Information Fusion [13]	Reference Model	**Mission Goals** require real-time distributed collaboration methods and service architectures
	Semantics	**Distributed multi-agent fusion** systems need rigorous and integrated modelling and inference methods for system design
	SA/TA/IA	Methods needed for characterizing **agent behaviors** based on action capability, opportunity, and intent
	User / Agent	Complex-adaptive systems require new **HLIF requirements** to assist users
	Joint Theory	Overall **system integration** of components for communication and information dissemination among the different agents
2006 Resource Management Coordination with Level 2/3 Fusion Issues and Challenges [12]	SA/TA/IA	**L 2/3 situation entity** definitons for knowledge discovery, modeling, and information projection
	User / Agent	**Design for users** for resource management
	Performance Evaluation	**Optimizing / evaluating fusion systems over a standard set of metrics** for cost-function optimization
	Resource Planning	Addressing constraints for **resource scheduling and planning** over mission time-horizons
	Joint Theory of Methods	**Joint optimization** of objective functions at all fusion levels
2005 Issues and Challenges of Knowledge Representation and Reasoning Methods in Situation Assessment (Level 2 Fusion) [11]	Reference Model	**Process modeling** for behavioral updates (e.g., Bayes Nets, procedural / logical, perceptual, learning)
	Knowledge Representation	**Process-evidence explanation,** accumulation and contradiction knowledge repreesentation and reasoning
	Semantics	**Semantics and syntax** formallization (formal methods, ontologies)
	SA/TA/IA	**Context-operational situation modeling** (i.e., dependent on the current state-of-the-environment) for projection
	User / Agent	SA process includes **perceptual, interactive, and human control** such as *graphical displays* to facilitate inferential chains, collaborative interactions, and knowledge presentation
	Performance Evaluation	**Standard set of metrics** (e.g., trust, bounds, uncertainty)
	Joint Theory of Methods	Interactive control for corrections and **joint utility asseessment** for knowledge management
2004 Challenges in Higher Level Fusion: Unsolved, Difficult, and Misunderstood Problems / Approaches in Levels 2-4 Fusion Research [10]	Reference Model	**Systems engineering approach** for joint JDL-layer development versus individual layers
	SA/TA/IA	**Situation awareness modeling** in relation to the context through logical reasoning in relation derivation algorithms, relevance of relations, and complexity of derivation algorithms
	Social / Behavioral Models	**Situational modeling** based on *"attributive"* entity states and *"relational"* context-sensitive states
	User / Agent	Develop normal situation models, behavior tactic models from non-normal actors, and HLIF abstractions for appropriate **user task models**
	Scenario	Develop deductive **simulation-based testing** approaches to math inductive HLIF analysis

Table 2 continued on next page ⇒

Table 2. Summary of Issues from the Last Decade of Panel Discussions on High-Level Information Fusion *(continued)*

	Performance Evaluation	**Quality assessment** in formalized performance analysis, methematical/algorithm integrity, and system-level control, resuse, and scalability
	Resource Planning	Develop connection/**communication-resource management options** for distributed sensor fusion
	Joint Theory of Methods	Need a (unification) of **joint statistics** and analysis of all levels of abstraction
2001 Data Fusion for Levels 2, 3, and 4 [9]	**Reference Model**	User as part of a **common reference model**
	SA/TA/IA	Information Fusion needs human-in-the-loop for **SA/TA assessment**
	User / Agent	**Human Refinement** needed for actionable information
	Performance Evaluation	**Information Cells need metrics** for net-centric operations
	Joint Theory of Methods	**Unified framework** needed for information fusion processing
2000 Fusion Vision and Challenges [8]	**SA/TA/IA**	**Reasoning methods** for inferring intent, behaviors, and natural language processing
	User	Support **user reasoning** with multi-modal data uncertainty
	Display	**Man-machine interface** for perceptual coordination and operator display
	Performance Evaluation	Development of models and **metrics** for system analysis
	Resource Planning	**Resource management** for a diverse set of distributed sensors

methods, situation learning and model discovery, and tight coupling between estimation and association.

Pierre Valin *expressed the need for high quality object assessment information that includes both symbolic and numeric information to provide a consistent and comprehensive common distributed picture for the commander. Decision support requires data filtering, presentation of alternatives, and caution from only providing decisions for the operator. To develop a HLIF architecture requires standards and metrics.*

Erik Blasch *highlighted the importance of HLIF MOEs and MOPs that balance the known MOPs from LLIF. Decision support requires standardized design and evaluation methods for system verification and validation.*

Elisa Shahbazian *focused on HLIF challenges of aggregation of information for situational representation, knowledge representation, and system design that incorporates user's needs. HLIF system design requires ontology-based structures, scenario-based instances, and agent-based architectures that incorporate and satisfy user requirements.*

James Llinas *advocated a closed-loop situation management for HLIF system-design architectures that capture current states while proposing plausible future states. Within the architecture, there is a need to balance fusion estimation with reasoning nomination and sensor management for mission effectiveness. Capability spaces are needed to balance exploitation of knowledge and option policies.*

Mitch Kokar *stressed the importance of implementable semantic representations so that an operator can perceive beyond Level 1 spatio-temporal information for relevant context dependent relations. He emphasized a need to use declarative versus imperative programs to capture knowledge for situation-based modeling and planning.*

Table 3. Summary of Topics from the Panel Discussions on HLIF

Panel Topic	2000 Vision	2001 L2-4	2004 HLF	2005 KR-RM	2006 RM	2007 Agent	2008 HLIF	2009 Coalition	2009 TA/IA	2010 HLIF-GC
Reference Model	⊗	⊗	⊗	⊗			⊗	⊗	⊗	⊗
Data / Knowledge Representation				o	o		o	o	o	o
Semantic/ Ontologies				o		o	o	o	o	o
SA/TA/IA Assessment	⊗	⊗	⊗	⊗		⊗		⊗	⊗	⊗
Social/Behavioral Model			⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
User/Agent Coordination	⊗	⊗	⊗	⊗	⊗	⊗		⊗	⊗	⊗
Display (Interactive)	X			X				X		X
Common Scenario			X					X	X	X
Perform-ance Eval./ Metrics	⊕	⊗	⊗	⊗	⊗			⊗	⊗	⊗
Uncer-tainty Analysis	o			o	o		o	o		o
Resource Planning	⊗		⊗	⊗	⊗	⊗	⊗	⊗		⊗
Joint Theory of Methods		X	X		X	X				X

⊗ *Current and Consistent Theme*

o *Key Importance*

X General Importance

Subrata Das highlighted the challenges associated with representations such as linguistics analysis, knowledge acquisition, and reasoning with utility. HLIF is about events such as parsing semantics, determining textual and visual patterns, and providing diagnostic capabilities. Contemporary research that could support the development include: unstructured and social networks content extraction, discriminative versus generative Bayes' net machine learning, and descriptive versus predictive industrial analytics.

SURVEY OF FUSION PANEL DISCUSSIONS ON HLIF CHALLENGES

Over the past decade, the topic of HLIF has become increasingly important and while methods have been presented in the annual *Information Fusion Conferences,* each year a panel discussion is held to bring together contemporary ideas. The numerous panels could be representative of the complexity, challenge, and difficulty HLIF poses to the information fusion community while at the same time demonstrating the real-world, operational, and use-case need for HLIF techniques. Below, we organize a summary of the ideas presented at the various panel discussions to demonstrate the set of common and diverse needs posed from panelists on HLIF directions. Table 2 highlights the issues into a common set of themes.

ANALYSIS OF HLIF TOPICS

It is interesting to look at the common themes of panel discussions at the Fusion Conferences as topics of interest. Table 3 demonstrates the pervasive topics that are of interest to the community over the last decade. The sustained topics represent challenges for the community that are unresolved or need more attention.

Of the many issues in HLIF that have been posed, it would be difficult to say that any have been solved. As technology and information change, so do the systems that are designed to synthesize the data for users. If we capture the issues from the panels of the past decade, we see consistent themes that are important.

1. *We see that the most common discussion was on social/behavioral models which supports situation modeling theory for threat and impact assessment.*

2. *The second most common theme is user and agent (machine) coordination that incorporates decision support.*

3. *The third theme is performance metrics such as uncertainty analysis and common scenarios for standardization evaluation methods.*

4. *An emerging theme for information management is the semantics and ontologies for data models and knowledge representations.*

5. *A common reference model and resource planning are important as system design techniques that facilitate both the operational development and deployment of HLIF systems, respectively.*

While covered in a few panel discussions, we might conclude that the complexity, difficulty, and undefined nature of HLIF limits the ability to fully capture a joint theory across all levels of information fusion, employment of a common scenario of interest to all developers, and research analysis into display technology for the multitude of HLIF designs.

SUMMARY AND HLIF GRAND CHALLENGES

High-Level Information Fusion (Situation and Threat Assessment, Process and User Refinement) requires novel solutions for the operational transition of information fusion designs. Low-level (signal processing, object state estimation and characterization) is well-vetted in the community as compared to High-Level Information Fusion (control and relationships to the environment). Specific areas of interest include *modeling* (situations, environments), *representations* (semantic, knowledge, and complex), *information management* (ontologies, protocols) *systems design* (scenario-based, user-based, distributed-agent) and *evaluation* (measures of performance/effectiveness, and empirical case studies).

There are numerous ongoing challenges that the fusion community can discuss toward a common understanding and coordination. The authors highlight these five grand challenges for HLIF in order of prioritization of issues from the last decade:

1) ***Situation modeling theory*** *(context, environments, and processes) for association management,*

2) ***Decision support processes*** *(reasoning, inference, and explanation of relationships) to support user's needs,*

3) ***Standardized evaluation methods*** *(measures of performance / effectiveness, and empirical case studies) to conduct system-level evaluation,*

4) ***Systems design techniques*** *(scenario-based, user-based, and distributed-agent) to provide reasoning capabilities, and*

5) ***Representations of HLIF information*** *(semantic, knowledge, and complex) for acquisition, relevancy, management, and processing of data and information.*

Discussions and analysis of these grand challenges are presented in the text: *High-Level Information Fusion Management and Systems Design* [60].

REFERENCES

[1] E. Waltz and J. Llinas,
Multisensor Data Fusion,
Artech House, Norwood, MA, 1990.

[2] D.L. Hall and S.A. McMullen,
Mathematical Techniques in Multisensor Data Fusion,
Artech House, Norwood, MA, 2004.

[3] E. Bossé, J. Roy and S. Wark,
Concepts, Models, and Tools for Information Fusion,
Artech House, Norwood, MA, 2007.

[4] S. Das,
High-Level Data Fusion,
Artech House, Norwood, MA, 2008.

[5] D.L. Hall and J.M. Jordan,
Human-centered Information Fusion,
Artech House, Norwood, MA, 2010.

[6] D.L. Hall and J. Llinas,
Handbook of Multisensor Data Fusion,
CRC Press, 2001.

[7] M.E. Liggins, D.L. Hall and J. Llinas
Handbook of Multisensor Data Fusion: Theory and Practice,
CRC Press, 2008.

[8] I. Kadar, C. Chong, G. Ruget, S. Serpico. F.E. White, B. Wyne, W.D. Blair and J-P. Le Cadre,
Fusion, Vision and Challenges,
Int. Conf. on Information Fusion, 2000.
(materials available at: < http://www.onera.fr/fusion2000/panel.html>.

[9] E. Blasch, M. Hinman, J. Llinas, E. Shahbazian, P. Valin, A. Waxman and F. White,
Data Fusion for Levels 2, 3, and 4,
Int. Conf. on Information Fusion, 2001,
(papers and slides in proceedings,
<http://www.isif.org/content/isif-plenary-talks>).

[10] I. Kadar and P. Svensson,
Challenges in higher level fusion: unsolved, difficult, and misunderstood problems/approaches in levels 2-4 fusion research,
Int. Conf. on Information Fusion, 2004.

[11] E. Blasch, I. Kadar, J. Salerno, M. Kokar, S. Das, G. Powell, D. Corkill and E. Ruspini,
Issues and Challenges in Situation Assessment (Level 2) fusion,
Journal of Advances in Information Fusion,
Vol. 1, No. 2, pp. 122 - 139, December 2006.

[12] E. Blasch, I. Kadar, K. Hintz, J. Biermann, C. Chong, and S. Das,
Resource Management Coordination with Level 2/3 Fusion Issues and Challenges,
IEEE AES Magazine, Vol. 23, No. 3, pp. 32-46, March 2008.

[13] S. Das, J. Llinas, G. Pavlin, D. Snyder, A. Steinberg and K. Sycara,
Agent Based Information Fusion: Panel Discussion,
Int. Conf. on Info. Fusion, 2007.

[14] G. Toth, M.M. Kokar, K. Wallenius, K.B. Laskey, M. Sudit, M. Hultner and O. Kessler,
Higher-level Information Fusion: Challenges to the Academic Community: Panel Discussion,
Int. Conf. on Info. Fusion, 2008.

[15] D.A Lambert, M.L. Hinman, É. Bossé and C.P. Blackman,
A Coalition Approach to Higher-Level Fusion,
Accessed at: <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA506230>.

[16] J.J. Salerno, M. Sudit, S.J. Yang, G.P. Tadda, I. Kadar and J. Holsopple,
Issues and challenges in higher level fusion: Threat/impact assessment and intent modeling (a panel summary),
Int. Conf. on Info. Fusion, 2010.

[17] E. Blasch, J. Llinas, D. Lambert, P. Valin, S. Das, C-Y. Chong, M.M. Kokar and E. Shahbazian,
High Level Information Fusion Developments, Issues, and Grand Challenges – Fusion10 Panel Discussion,
Int. Conf. on Info. Fusion, 2010.

[18] O. Kessler, et. al.,
Functional Description of the Data Fusion Process, technical report for the Office of Naval Technology Data Fusion Development Strategy,
Naval Air Development Center,
Warminster, PA, November 1991.

[19] A.N. Steinberg, C.L. Bowman, and F.E. White,
Revisions to the JDL model
Joint NATO/IRIS Conf., 1998.

[20] J. Llinas, C. Bowman, G. Rogova, A. Steinberg, E. Waltz and F. White,
Revisiting the JDL Data Fusion Model II,
Int. Conf. on Information Fusion, 2004.

[21] E. Blasch and S. Plano,
DFIG Level 5 (User Refinement) issues supporting Situational Assessment Reasoning,
Int. Conf. on Info Fusion, 2005.

[22] M.R. Endsley,
Toward a Theory of Situation Awareness in Dynamic Systems,
Human Factors Journal, 37(1), 32-64, 1995.

[23] D.S. Fadok, J. Boyd and J. Warden,
Air Power's Quest for Strategic Paralysis,

Maxwell Air Force Base AL: *Air University Press,* (AD–A291621), 1995.

[24] E. Blasch, J.J. Salerno and G. Tadda, Measuring the Worthiness of Situation Assessment, *IEEE Nat. Aerospace Electronics Conf.,* 2011.

[25] D.A. Lambert, Unification of Sensor and Higher-Level Fusion, *Int. Conf. on Info. Fusion,* 2006.

[26] D.L. Hall and J. Llinas, Introduction to Multisensor Data Fusion, *Proc. of IEEE,* Vol. 85, No. 1, pp. 6 – 23, January 1997.

[27] D.A. Lambert, Grand Challenges of Information Fusion, *Int. Conf. on Info. Fusion,* 2003.

[28] E. Blasch, Assembling a distributed fused Information-based Human-Computer Cognitive Decision Making Tool, *IEEE AES Magazine,* Vol. 15, No. 5, 11-17, 2000.

[29] D.A. Lambert, Situations for situation awareness, *Int. Conf. on Info. Fusion,* 2001.

[30] K. Sycara, M. Paolucci and M. Lewis, Information Discovery and Fusion: Semantics on the Battlefield, *Int. Conf. on Info. Fusion,* 2003.

[31] K. Lee and J. Llinas, Hybrid Model for Intent Estimation, *Int. Conf. on Info. Fusion,* 2003.

[32] A-C. Boury-Brisset, Ontology-based Approach for Information Fusion, *Int. Conf. on Info. Fusion,* 2003.

[33] C.J. Matheus, M.M. Kokar and K. Baclawski, A Core Ontology for Situation Awareness, *Int. Conf. on Info. Fusion,* 2003.

[34] J. Salerno, M. Hinman and D. Boulware, Building a Framework for Situational Awareness, *Int. Conf. on Info. Fusion,* 2004.

[35] J. Schubert and P. Svensson, Methodology for guaranteed and robust high level fusion performance: a literature study, *FOI-D-0216-SE,* May 2005.

[36] M.M. Kokar. Situation awareness: issues and challenges. *Int. Conf. on Info. Fusion,* 2004.

[37] M.M. Kokar, J.A. Tomasik and J. Weyman, Formalizing classes of information fusion systems, *Information Fusion: An International Journal on Multi-Sensor, Multi-Source Information Fusion,* 5,3:189-202, 2004.

[38] C. Nowak and D.A. Lambert, The Semantic Challenge for Situation Assessments, *Int. Conf. on Info. Fusion,* 2005.

[39] C.J. Matheus and M.M. Kokar, et. al,. Lessons learned from developing SAWA: A situation awareness assistant, *Int. Conf. on Info. Fusion,* 2005.

[40] M.M. Kokar, Situation assessment: Procedural vs. logical, *Int. Conf. on Info. Fusion,* 2005.

[41] E. Blasch, Sensor, User, Mission (SUM) Resource Management and Their interaction with Level 2/3 Fusion, *Int. Conf. on Info. Fusion,* 2006.

[42] G. Chen, D. Shen, C. Kwan, J. Cruz, M. Kruger and E. Blasch, Game Theoretic Approach to Threat Prediction and Situation Awareness, *J. of Adv. in Information Fusion,* Vol. 2, No. 1, 1-14, 2007.

[43] M. Sudit, M. Holender, A. Stotz, T. Rickard and R. Yager, INFERD and Entropy for Situational Awareness *J. of Adv. in Information Fusion,* Vol. 2, No. 1, 2007.

[44] C. Laudy, J-G. Ganascia and C. Sedogbo, High-Level Fusion based on Conceptual Graphs, *Int. Conf. on Info. Fusion,* 2007.

[45] D.A. Lambert, Tradeoffs in the Design of Higher-level Fusion Systems, *Int. Conf. on Info. Fusion,* 2007.

[46] A. Karlsson, R. Johansson and S.F. Andler, An Empirical Comparison of Bayesian and Credal Networks for Dependable High-Level Information Fusion, *Int. Conf. on Info. Fusion,* 2008.

[47] B. Ulicny, C.J. Matheus, M.M. Kokar and G.M. Powell. Problems and prospects for formally representing and reasoning about enemy courses of action. *Int. Conf. on Info. Fusion,* 2008.

[48] A. Stotz, R. Nagi and M. Sudit, Incremental Graph Matching for Situation Awareness, *Int. Conf. on Info. Fusion,* 2009.

[49] P.C.G. Costa, K-C. Chang, K.B. Laskey and R.N. Carvalho, A Multi-Disciplinary Approach to High Level Fusion in Predictive Situational Awareness, *Int. Conf. on Info. Fusion,* 2009.

[50] B. Matheus, C.J. Ulicny, M.M. Kokar and G.M. Powell. Towards the formal representation of temporal aspects of courses of action, *Int. Conf. on Info. Fusion,* 2009.

[51] E. Blasch, P. Valin, E. Bossé, M. Nilsson, J. Van Laere and E. Shahbazian, Implication of Culture: User Roles in Information Fusion for Enhanced Situational Understanding, *Int. Conf. on Info. Fusion,* 2009.

[52] P. Hilletofth, S. Ujvari and R. Johansson, Agent-Based Simulation Fusion for Improved Decision Making for Service Operations, *Int. Conf. on Info. Fusion,* 2009.

[53] T. Schuck and E. Blasch,
Description of the Choquet Integral for Tactical Knowledge Representation,
Int. Conf. on Info. Fusion, 2010.

[54] E. Blasch, E. Dorion, P. Valin, E. Bossé and J. Roy,
Ontology Alignment in Geographical Hard-Soft Information Fusion Systems,
Int. Conf. on Info. Fusion, 2010.

[55] J. Gomez-Romero, J. Garcia, M.A. Patricio, J.M. Molin, J. Llinas, S.C. Shapiro, M. Kandefer and M. Prentice,
Strategies and Techniques for Use and Exploitation of Contextual Information for High-Level Fusion Architectures,
Int. Conf. on Info. Fusion, 2010.

[56] P. Valin, E. Bossé, A. Guitouni, H. Wehn and J. Happe,
Testbed for Distributed High-Level Information Fusion and Dynamic Resource Management,
Int. Conf. on Info. Fusion, 2010.

[57] B. Ulicny, C.J. Matheus, G. Powell and M.M. Kokar,
Current Approaches to automated Evaluation and their Applicability to Priority Intelligence Requirement Answering,
Int. Conf. on Info. Fusion, 2010.

[58] E. Blasch, P. Valin and E. Bossé,
Measures of Effectiveness for High-Level Fusion,
Int. Conf. on Info. Fusion, 2010.

[59] M. Kam, X. Zhu and P. Kalata,
Sensor Fusion for Mobile Robot Navigation,
Proc. IEEE, Vol. 85, No. 1, January 1997.

[60] E.P. Blasch, E. Bossé and D.A. Lambert.
High-Level Information Fusion Management and Systems Design,
Artech House, Norwood, MA, 2012.