Knowledge-Intensive Fusion for Situational Awareness

Requirements for Knowledge-Filtered Awareness

Paul Smart

School of Electronics and Computer Science
University of Southampton
Southampton
SO17 1BJ
United Kingdom

15th August 2005
Knowledge-Intensive Fusion for Situational Awareness

This report aims to outline the requirements for knowledge-filtered awareness in the context of the DIF DTC ‘Knowledge-Based Information Fusion for Improved Situation Awareness’ project. Relevant literature relating to both information fusion and situation awareness is reviewed, with a particular focus on how fusion-related processes may be used to enhance situation awareness and operational effectiveness. The critical role of background knowledge as a mechanism for improving both current and future approaches to information fusion is discussed, and the role of extant Semantic Web technologies is highlighted both with respect to fusion-related processes and issues of situation awareness. Knowledge-filtered awareness is presented as the ability to constrain or filter incoming information with respect to dimensions of contextual relevance and a generic mechanism for such knowledge filtration, or information triage, is presented. We argue that a combination of ontologies and Semantic Web query languages, such as RDQL and SPARQL, are essential ingredients to knowledge-based information fusion and situation awareness respectively. In particular, we argue that queries exploiting the semantic infrastructure of an application domain can be cast as ‘goals’ for situation awareness. Such goals support ‘contextual relevance reasoning’ regarding the extent to which particular information items need to be monitored by operators engaged in a situation analysis task. We discuss the range of technologies to be exploited in the context of the current initiative and describe how these technologies are to be used in the development of the AKTiveSA TDS (Technical Demonstrator System). This report therefore reviews the requirements and constraints to be considered in respect of initiatives geared towards the development of knowledge-based information fusion systems that aim to increase situation awareness. It simultaneously presents our vision as to the technological realization of these processes in the context of a real world technology demonstrator against which empirical assessments of MOEs and situation awareness can be made.
Acknowledgements

This work was undertaken as part of the Data and Information Fusion Defence Technology Centre (DIF DTC), a consortium of academic and industrial partners headed by General Dynamics UK Ltd. The DIF DTC was established by the UK Ministry of Defence (MoD) to undertake leading-edge research in the area of data and information fusion (http://www.difdtc.com).
Abstract

This report aims to outline the requirements for knowledge-filtered awareness in the context of the DIF DTC ‘Knowledge-Based Information Fusion for Improved Situation Awareness’ project. Relevant literature relating to both information fusion and situation awareness is reviewed, with a particular focus on how fusion-related processes may be used to enhance situation awareness and operational effectiveness. The critical role of background knowledge as a mechanism for improving both current and future approaches to information fusion is discussed, and the role of extant Semantic Web technologies is highlighted both with respect to fusion-related processes and issues of situation awareness. Knowledge-filtered awareness is presented as the ability to constrain or filter incoming information with respect to dimensions of contextual relevance and a generic mechanism for such knowledge filtration, or information triage, is presented. We argue that a combination of ontologies and Semantic Web query languages, such as RDQL and SPARQL, are essential ingredients to knowledge-based information fusion and situation awareness respectively. In particular, we argue that queries exploiting the semantic infrastructure of an application domain can be cast as ‘goals’ for situation awareness. Such goals support ‘contextual relevance reasoning’ regarding the extent to which particular information items need to be monitored by operators engaged in a situation analysis task. We discuss the range of technologies to be exploited in the context of the current initiative and describe how these technologies are to be used in the development of the AKTiveSA TDS (Technical Demonstrator System). This report therefore reviews the requirements and constraints to be considered in respect of initiatives geared towards the development of knowledge-based information fusion systems that aim to increase situation awareness. It simultaneously presents our vision as to the technological realization of these processes in the context of a real world technology demonstrator against which empirical assessments of MOEs and situation awareness can be made.
Contents

1 INTRODUCTION ............................................................................................................. 1

1.1 PROJECT BACKGROUND ....................................................................................... 1
1.2 DOCUMENT PURPOSE ......................................................................................... 1
1.3 DOCUMENT SCOPE ............................................................................................... 2
1.4 DOCUMENT BASIS .............................................................................................. 2
1.5 DOCUMENT STRUCTURE ...................................................................................... 2

2 KEY CONCEPTS ........................................................................................................... 4

2.1 SITUATION AWARENESS ..................................................................................... 4
2.1.1 DEFINITION ...................................................................................................... 4
2.1.2 MODELS OF SITUATION AWARENESS ......................................................... 6
2.1.3 MEASUREMENT AND OPERATIONALIZATION OF SITUATION AWARENESS .. 10
2.1.4 MEASUREMENT TECHNIQUES ....................................................................... 11
2.2 INFORMATION FUSION ...................................................................................... 15
2.2.1 IMPORTANCE OF DATA FUSION .................................................................. 15
2.2.2 DATA FUSION MODEL .................................................................................. 17
2.2.3 KNOWLEDGE-BASED INFORMATION FUSION ........................................... 20
2.2.4 INFORMATION FUSION & SITUATION AWARENESS ................................ 27
2.3 SUMMARY ........................................................................................................... 29

3 COGNITIVE PROCESSES IN SITUATION AWARENESS ............................................ 30

3.1 PERCEPTION ........................................................................................................ 31
3.2 COGNITION ......................................................................................................... 31
3.2.1 ATTENTION .................................................................................................... 31
3.2.2 WORKING MEMORY ..................................................................................... 37
3.2.3 LONG TERM MEMORY, MENTAL MODELS AND SCHEMATAS ..................... 38
3.2.4 AUTOMATIC PROCESSING ............................................................................ 43
3.3 ACTION ................................................................................................................ 44
3.4 SUMMARY ........................................................................................................... 45

4 REQUIREMENTS ANALYSIS ...................................................................................... 47

5 APPLICATION TO SEMANTIC WEB TECHNOLOGIES ................................................. 59

5.1 EXISTING SYSTEMS ............................................................................................ 59
5.2 ONTOLOGIES ...................................................................................................... 63
5.3 KNOWLEDGE REPOSITORY ............................................................................... 64
5.4 SEMANTIC QUERY CAPABILITIES ..................................................................... 64
# Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Model of Situation Awareness</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Recognition-Primed Decision Model (Klein, 1997)</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>JDL Data Fusion Model (Steinberg &amp; Bowman, 2004)</td>
<td>17</td>
</tr>
<tr>
<td>3.1</td>
<td>Mechanisms and Processes Involved in Situation Awareness</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>Role of Mental Models in Situation Awareness (Endsley, 2000)</td>
<td>39</td>
</tr>
<tr>
<td>3.3</td>
<td>The Perception-Action Cycle</td>
<td>45</td>
</tr>
<tr>
<td>5.1</td>
<td>SAW Ontology (from Matheus et al., 2005)</td>
<td>59</td>
</tr>
<tr>
<td>5.2</td>
<td>Source Concept Hierarchy</td>
<td>72</td>
</tr>
<tr>
<td>5.3</td>
<td>Datum Concept Hierarchy</td>
<td>74</td>
</tr>
<tr>
<td>5.4</td>
<td>Representation of Data Latency Information</td>
<td>75</td>
</tr>
<tr>
<td>6.1</td>
<td>AKTiveSA TDS Architecture</td>
<td>78</td>
</tr>
<tr>
<td>6.2</td>
<td>FOAEW Mk7 DSS Mission System Interface</td>
<td>81</td>
</tr>
<tr>
<td>6.3</td>
<td>OpenMap Demo Applet</td>
<td>82</td>
</tr>
<tr>
<td>6.4</td>
<td>Concept Ladder Tab – AKTiveSA Prototype</td>
<td>83</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Project Background

This project (project no: 8.14) addresses the development of a Technical Demonstrator System (TDS) to showcase the ability of knowledge technologies to improve situation awareness via intelligent information fusion. The work is being undertaken by the University of Southampton\(^1\) as part of the MOD’s DIF DTC initiative\(^2\), which represents a formal collaborative agreement between industry and academic experts to generate and enhance the defensive capabilities of UK military forces.

This project is an extension to an earlier initiative, called FloodSim\(^3\), which demonstrated how semantically-enriched information, interpreted against the backdrop of formal ontologies, could be used to improve situation awareness with respect to humanitarian relief operations. The current project has a similar objective in that it aims to improve operational effectiveness in the planning, coordination and delivery of humanitarian relief operations by enhancing the situation awareness of executive decision makers. At the heart of the current project is the need to receive, and in some cases actively acquire, information that can be subsequently assimilated (fused) into a coherent representation of the current operational environment. The operational environment provides a framework within which information can be disseminated to executive agencies in a manner that befits their specific epistemic and representational requirements. It also provides a basis for reasoning activities aimed at improving the operational effectiveness of decision processes undertaken in regard to humanitarian initiatives, e.g. alerting operatives to information that may have been overlooked, advising as to the best course of action, selectively presenting information of immediate strategic relevance (thereby avoiding the notorious problem of information overload), etc. In general, there are 4 main objectives for the current project:

1. to leverage increased operational effectiveness from improved situation awareness in the planning, coordination and delivery of humanitarian relief efforts
2. to demonstrate the effective use and exploitation of ontological characterizations of the target domain in the interpretation, integration and presentation of semantically-enriched information
3. to exploit knowledge-rich contingencies supporting competent performance in the target domain in order to yield operationally effective decision outcomes that are strategically aligned with the goals and objectives of humanitarian agencies or those involved in relief efforts
4. to exploit the technologies and methods developed in the context of the AKT (Advanced Knowledge Technologies) initiative\(^4\) as a means of highlighting the general applicability of these techniques for a variety of knowledge-intensive applications

1.2 Document Purpose

The aim of the current document is to outline the key requirements of the proposed TDS with respect to improved situation awareness in coalition MOOTW scenarios. As such we aim to outline

\(1\) http://www.ecs.soton.ac.uk/
\(2\) http://www.difdtc.com/
\(3\) http://www.aktors.org/technologies/floodsim/
\(4\) http://www.aktors.org/akt/
what we mean by ‘situation awareness’ and highlight how the knowledge infrastructure of the prospective system can be harnessed to facilitate increased situation awareness in operationally-useful ways. Knowledge-filtered awareness, we argue, represents an awareness of the temporal unfolding of events as they occur in an operational context in a manner that augments problem-solving competency and propitiates the successful execution of response outcomes strategically aligned with operational objectives. As we will see, a consideration of the requirements for knowledge-filtered awareness impacts on a number of architectural design and technology issues, which will be discussed in the context of the current document.

1.3 Document Scope

The scope of this document is limited to a discussion of the requirements for improved situation awareness in coalition military and MOOTW contexts. The document attempts to highlight how the knowledge and technological infrastructure of the proposed system can be used to improve situation awareness and operational effectiveness in such contexts. The scope of the document is limited in the sense that we focus specifically on the exploitation of one particular set of technologies, namely those made available by the Semantic Web initiative (Berners-Lee et al., 2001), and discuss how such technologies may be used in a limited range of scenario contexts. Nevertheless, we see no reason why the general principles alluded to in the current document should not have more widespread applicability, subsuming scenario contexts as diverse as emergency response, eHealth, homeland security, and coalition offensive operations. The general applicability of Semantic Web technologies with respect to such domain areas is already the focus of a number of ongoing projects and applications, e.g. (Shadbolt et al., 2004).

1.4 Document Basis

This document represents a formal deliverable for the DIF DTC 8.14 project. The document forms part of WorkPackage 200, i.e. the knowledge engineering component of the aforementioned project. Further details about the delivery schedule for the current project can be found in the Project Plan document.

1.5 Document Structure

The structure of the current document reflects the document aims alluded to in Section 1.2. Section 2 attempts to provide operational definitions for the various concepts used throughout the remainder of the report. In particular we attempt to provide definitions for such terms as situation awareness, information fusion and knowledge-filtered awareness and propose some guidelines as to how these notions may be operationalized in an empirical context. Section 3 discusses issues arising from a review of the cognitive psychology literature as it relates to issues of situation awareness. Since we argue that improved situation awareness is predicated on the ability to monitor filtered information streams, it is important to review factors that might underpin or undermine selective attention to subsets of task-relevant information. Section 4 presents the results of a requirements analysis geared towards the development of knowledge-based systems that aim to improve situation awareness in information fusion contexts. We discuss these requirements against the backdrop of the information presented in Sections 2 and 3. Section 5 provides an overview of how mechanisms for selective attention and monitoring of filtered information streams can be

---

5 document reference: DTC/WP530/ProjectPlan
accomplished using a variety of Semantic Web technologies. We discuss the relative advantages and
disadvantages of these technologies and propose a general mechanism by which the functionality
afforded by such technologies may be harnessed to provide effective solutions to the problems
posed by information fusion and situation awareness. Finally, Section 6 provides an architectural
perspective of the prospective system. In this section we provide an architectural blueprint for the
AKTiveSA TDS and discuss some of the implementation issues arising from the effort to deliver
systems for knowledge-based information fusion and enhanced situation awareness. The discussion
on architectural design issues is constrained by the results of the requirements analysis detailed in
Section 4 and aims to discharge our responsibilities in respect of these requirements at the
implementation level.

As a description of a knowledge-rich application domain, namely the domain of military operations
and humanitarian relief efforts, this document uses a number of acronyms and abbreviations. These
are detailed in Appendix A.
2 Key Concepts

This section describes some of the key concepts used in the context of our project. In particular we attempt to review relevant literature related to the definition and formalization of notions such as ‘situation awareness’ and ‘information fusion’.

2.1 Situation Awareness

2.1.1 Definition

A variety of definitions of situation awareness exist in the information fusion and human factors literature. A formal definition of situation awareness is complicated by the ambiguity surrounding both the terms ‘situation’ and ‘awareness’. For instance, does awareness necessarily involve conscious awareness, and if so then how should conscious awareness be defined? The earliest formal notion of situation (although not situation awareness) was introduced by Barwise (1981) as a means of providing a more realistic formal semantics for speech acts than was theretofore available. Barwise argued that a situation corresponds to the limited parts of reality we perceive, reason about and live in and is contrasted with the world environment, which determines the value of every proposition. Being limited to subsets of information, a situation will therefore determine answers in some cases, but not all cases.

The term ‘situation awareness’ is most commonly used in the HCI community where the emphasis is on the design of user interfaces to promote awareness of system states in a manner that ensures appropriate response and decision outcomes. Endsley (1988) thus defines situation awareness as:

“...the perception of the elements in the environment within a volume of space and time, the comprehension of their meaning and the projection of their status in the near future.”

The notion of situation awareness is also used extensively in the information fusion literature, where it forms an intrinsic part of the JDL Data Fusion Model (Llinas et al., 2004; Steinberg & Bowman, 2004; Steinberg et al., 1999; Steinberg et al., 1998). The model posits a number of levels for fusion-related processes in which situation awareness is deemed to reflect the outcome of Level 2 fusion processes (see Section 2.1.2). The JDL defines situation awareness to be the estimation and prediction of relations among entities, which includes notions such as force composition and structure, cross force relations, high-level fusion-dependent concepts and so forth. Level 2 processing is thus considered to typically involve the association of:

“...tracks (hypothesized entities) into aggregations. The state of the aggregate is represented as a network of relations among its elements. We admit any variety of relations to be considered – physical, organizational, information, perceptual as appropriate to the given need” (Steinberg et al., 1999)

Such definitions have served as the basis for a number of studies aimed at investigating the role of ontologies in information fusion, (e.g. Matheus, 2005; Matheus et al., 2005; Matheus et al., 2005). Matheus (2005) therefore argues that:
“In our view, situation awareness primarily comes down to identifying higher-order relations that come into being within a situation and that have particular relevance to the problem at hand as defined by the user’s goals or objectives. By higher-order relations we mean relations involving multiple objects; OWL ObjectProperties represent the simplest of such relations involving two objects, but situation awareness is often interested in more complex relations involving several objects. We contrast these high-order relations with those that merely define characteristics of an individual object; DataProperties fall into this category.”

In general, the notions of situation awareness used throughout the literature emphasize the perception and processing of subsets of environmental information, in particular those information subsets that are relevant to ongoing needs and concerns and which promote the selection of response outcomes strategically aligned with operational goals and objectives. Inherent to such definitions is the notion of what is important. Operators are often confronted with a dazzling array of data that must be perceived, comprehended and interpreted, and often such information is highly dynamic and complicated by issues of uncertainty. In order to avoid information overload, operators must filter information input by selectively attending to those sources of perceptual input of greatest relative importance to their ongoing problem-solving needs and task commitments. Mechanisms of selective attention are therefore a critical component of situation awareness (see Section 3.2.1). The task confronting the operator is to filter information in a manner that avoids information overload and promotes the selective focus of available cognitive resources to those aspects of the incoming information stream that are of greatest relevance to their monitoring and decision-making responsibilities. The criteria used for assessing contextual relevance in this case includes current task commitments, problem-solving goals, operational roles, the relative perceptual salience of incoming information and so on. In this sense the notion of situation awareness is analogous to the notion of an animal’s ‘Umwelt’ (Von Uexkull, 1934/1957). Jacob Von Uexkull (1934/1957) defines an animal’s Umwelt as the set of environmental parameters to which it is sensitised to respond to. It subsumes those features of the environment which an organism is predisposed to process with high priority because of their respective survival requirements. Animals thus inhabit different ‘effective’ environments in which perception is skewed towards those features of the world that matter to an organism in terms of its ecological niche-specific needs and concerns.

We argue that situation awareness is predicated on the ability to assess the significance of incoming information in semantically-significant ways. While it is perhaps obvious that selective attention is based on a variety of contextual relevance criteria, we also suggest that the ‘meaning’ assigned to information is critical in terms of guiding and maintaining focalized attentional processes. As Flach (1995) points out:

“...the construct of situation awareness demands that the problem of meaning be addressed head-on. Meaning must be considered both in the sense of subjective interpretation (awareness) and in the sense of objective significance or importance (situation).” (pg. 3)

Much as the interactionist approach in Sociology provides the basis for understanding actions in terms of the meaning actors assign to various events (Haralambos & Holborn, 1990), so we argue
that the way in which events are interpreted, in terms of the meanings assigned to them, underpins their merit for inclusion as central elements in situation awareness. Knowledge and reasoning are therefore essential ingredients in this process. An evaluation of the meaning assigned to particular events in terms of their implications and predictive relevance to the occurrence of other events establishes the basis for ‘contextual relevance reasoning’. Such reasoning rides on the knowledge-rich contingencies that inhere in a particular problem domain and serve to alert the operator to future events and information states that impact on operational processes and goals.

Issues of meaning are inherent in some of the existing definitions of situation awareness. Endsley’s (1988) definition of situation awareness thus encompasses the notion of spatio-temporal aspects of the perceived information. A critical part of situation awareness, he argues, is understanding how much time is available until some event occurs or some action must be taken. The ‘within a volume of space and time’ phrase in Endsley’s definition is intended to reflect the fact that operators constrain the parts of the world (or situation) that are of interest to them based not only on space (how far away an element is), but also how soon that element will have an impact on the operator’s goals and tasks. Such abilities depend on understanding the meaning and implications of events as they relate to operational objectives, and in this sense knowledge becomes an inherent feature of the situation assessment/analysis process. To make informed decisions, the operator must be cognizant of all the relevant elements of the environment, what these elements mean, and how those elements will affect the operational environment over time.

As a limited view of the world, situation awareness provides a means of avoiding information overload given limited cognitive resources. It also has a number of implications for modelling and systems engineering approaches that attempt to deal with the notion of situation awareness. Since situations provide only partial knowledge of the world, in which the value of only some propositions can be determined (Barwise, 1981), the notion of situation awareness can be argued to endorse an open world assumption. Accordingly, the monotonic logic used by ontology representation languages such as OWL is more appropriate for systems dealing with situation awareness than representational approaches committed to closed world assumptions, e.g. the UML.

2.1.2 Models of Situation Awareness
Endsley (2000) presents a model of situation awareness that highlights a number of issues relevant to the understanding and measurement of situation awareness. The model includes a consideration of the role of limited attention and working memory, mental models and schemas, pattern matching and critical cues, ties between situation awareness and automatic action selection, categorization, data-driven and goal-driven processes, expectations and dynamic goal selection (see Figure 2.1).
Endsley’s model defines situation awareness in terms of three levels:

- **Level 1 – Perception:** Perception of environmental cues is fundamental to situation awareness. Without basic perception of important information, the odds of forming an incorrect picture of the situation increase dramatically.

- **Level 2 – Comprehension:** The notion of situation awareness also encompasses how people combine, interpret, store and retain information. Thus, it includes more than just perceiving or attending to information; it also involves the integration (fusion) of multiple pieces of information and a determination of their relevance to the persons goals and objectives.

- **Level 3 – Projection:** At the highest level of situation awareness, the ability to forecast future situation events and dynamics is apparent. This ability to project from current events and dynamics to anticipate future events (and their implications) constitutes the basis for operationally-useful decision making, e.g. knowing that a threat aircraft is currently offensive and is in a certain location allows fighter pilots or military commanders to project that the aircraft is likely to attack in a given manner.

According to Endsley’s model, situation awareness involves far more that simply perceiving information in the environment. It includes the importance of comprehending the **meaning** of the information in an integrated form, especially in terms of being able to understand the implications of the current situation in terms of future projected states. Such an understanding is arguably of critical significance in making operationally and strategically-effective decisions.

The critical role of understanding a situation is also apparent in the context of naturalistic decision making (Zsambok & Klein, 1997). Naturalistic decision making (NDM) is a field of research aimed at investigating the way people make decisions in realistic problem-solving contexts. Decision-making
in these settings tends to differ significantly from the analytic style derived from structured laboratory tasks that constitutes the basis for traditional decision theory research. The central tenet of NDM is that under realistic conditions, experts make decisions using an holistic process involving pattern matching to memory structures in order to make rapid decisions (Dreyfus, 1981; Klein, 1989; Klein, 1997). Within this framework, a person’s situation awareness, an internal conceptualisation of the situation, becomes the driving factor in the decision making process. Klein’s RPD model emphasizes the role played by situation recognition in the selection of appropriate response output. In contrast to conventional models of problem-solving behaviour in which decision-making is based around the generation and evaluation of alternative response outcomes, the RPD model emphasizes the importance of recognizing a situation in terms of its typicality to previously experienced situations and the execution of scripted response sequences that are associated with that situation. Evidence for the RPD model has been put forward in the case of decision making in operational Naval warfare incidents involving AEGIS cruisers (Kempf et al., 1992). In 78% of cases the decision maker adopted a course of action without any deliberate evaluation of the various response alternatives, and in 18% of the cases the evaluation was accomplished using mental simulation methods. In only 4% of the cases was there any introspective evidence for comparisons of the various strengths and weaknesses of different response options.

![Figure 2.2: Recognition-Primed Decision Model (Klein, 1997)](image)

The RPD model is defined in terms of three types of decision making strategy (see Figure 2.2):

- **Simple Matching:** This is represented as the straightforward case in which a decision maker identifies a situation (which means that the goals are obvious, the critical cues are
being attended to, expectations about future states are formed, and a typical course of action is recognized) and reacts accordingly

- **Option Evaluation:** In this case the course of action is deliberately assessed by conducting a mental simulation to see if the course of action runs into any difficulties and whether these can be remedied, or whether a new course of action is required.

- **Situation Diagnosis:** In situation diagnosis a decision maker attempts to link observed events to causal factors in order to derive an explanation of current events. Diagnosis is important for the RPD model because an understanding of the nature of the situation can largely determine the course of action adopted. Often decision makers will spend more time and energy trying to understand a situation, and distinguishing between different explanations, than they will actually comparing possible action alternatives.

The emphasis here is clearly on understanding a situation, interpreting a situation in terms of the appropriate semantic significance of events, both in terms of their causal origins and implications for future projected states. Diagnostic activity, in particular, is invoked to assist with the appropriate interpretation of the current situation, especially in conditions of high uncertainty. Two common diagnostic strategies are feature matching and story building. Feature matching consists of identifying the relevant features of a situation in order to categorize it; whereas story building involves a form of mental simulation in which a person attempts to synthesize the features of a situation into a causal explanation that can be evaluated and used in a number of ways. Research has demonstrated that, when invoked, feature matching is by far the most common strategy adopted in situation diagnosis (Kaempf et al., 1992). Mental simulation is used to understand a situation in terms of a decision maker’s commonsense knowledge and background understanding of a domain (schematic representations of situation events and contingencies), and can be used as a means of improving overall situation awareness:

> “Mental simulation can be used to project a course of action forward in time, and it also can be used to look backwards in time as a way of making sense of events and observations. Here, the decision maker is trying to find the most plausible story, or sequence of events, in order to understand what is going on – a process of diagnosis that is intended to result in situation awareness.” (Klein, 1997; pg. 290)

Again the emphasis is on establishing an appropriate mental model of the current situation in terms of comprehending the meaning of the situation elements and providing useful explanatory accounts of situation events and information states.

Endsley’s model shows situation awareness as separate from both decision making and performance. In the context of this model, situation awareness is cast as the operator’s internal mental model of the state of the environment and forms the basis for subsequent decisions and actions. The separation between situation awareness, decision-making and task performance is proposed for several reasons. Firstly, it is possible to have perfect situation awareness, yet make an incorrect decision. For example, the battlefield commander may understand where the enemy is, what the enemy’s capabilities are, yet select a poor or inappropriate strategy for launching an attack. They may have inadequate strategies or tactics guiding their decision processes or individual personality factors (such as impulsiveness, indecisiveness or riskiness) may make some individuals more prone to making poor decisions. Furthermore, the link between decision-making and
performance is necessarily distinct. A desired action may be poorly performed due to physical errors, workload factors, inadequate training or system problems. Moreover, in certain situations the success of implemented actions may depend on the relative skill of an adversary. None of this should detract from a recognition of the critical importance of situation awareness in relation to decision-making and performance issues: Klein’s work in the area of recognition-primed decision-making shows strong evidence of a direct link between situation recognition/classification and associated action selection (Klein, 1989; Klein et al., 1986). A recognition of the distinction between situation awareness and decision-making/action selection is important in that many errors that are attributed to decision-making actually involve problems with the situation awareness portion of the decision making process as opposed to the action selection portion of the process (Endsley, 1997). Errors resulting from either poor action selection or poor situation awareness may have distinct causal precursors, may yield different response outcomes and certainly dictate the adoption of different remediation strategies.

2.1.3 Measurement and Operationalization of Situation Awareness

The notion of situation awareness is central to operational effectiveness in a number of domain areas and, as such, it is important to possess operational definitions of the construct that enable its measurement and empirical evaluation. Unfortunately, the operationalization of situation awareness is not straightforward. Endsley (2000) outlines a number of issues of relevance to the derivation of situation awareness metrics. He argues that such metrics need to:

- measure the construct they actually intend to measure and not be influenced by other processes
- provide the required insight into situation awareness in the form of sensitivity and diagnosticity, i.e. measures should indicate why aspects of system design fail to improve or degrade situation awareness
- avoid substantially altering the construct, providing biased data and altered behaviour

Moreover, ideal measures of situation awareness should not distract the operator from essential tasks, thereby compromising safety and influencing ongoing levels of situation awareness and task performance.

Following on from the model of situation awareness outlined in Section 2.1.2 it is possible to identify a number of problems confronting the adequate derivation of situation awareness metrics. Firstly, the fact that decision-making and performance are considered as distinct from situation awareness means that operational metrics cannot be based on the quality of decision outcomes or task performance criteria. With high levels of expertise in well-understood environments there may be a direct link between the quality of decision outcomes and situation awareness, whereby understanding what the situation is leads directly to selection of an appropriate action from memory. This is not always the case, however. Individuals can still make poor decisions with good situation awareness. In some cases the context may also dictate when the implementation or non-implementation of actions adversely affects performance outcomes. For example, a poor understanding of aircraft altitude is more likely to have negative outcomes when the aircraft is flying at low altitudes as opposed to high altitudes! Secondly, a focus on the processes by which operators acquire information is largely insignificant from the perspective of measuring situation awareness. Different individuals may use different processes to arrive at the same state of knowledge, or they
may arrive at different states of knowledge based on the same processes. Thirdly, measurement techniques that affect the allocation of attentional resources should be avoided because these are likely to compromise existing levels of situation awareness, especially in high workload situations. Finally, because measures of situation awareness often depend on the ability to recall situations and associated information states it is important to consider human memory limitations when one aims to measure situation awareness. With time there is a rapid decay of information in working memory and this complicates the measurement of situation awareness based on mnemonic retrieval mechanisms. Nisbett and Wilson (1977) have also argued that the recall of mental processes tends to be over-generalized, over-summarized and over-rationalized and this has obvious implications for the accuracy of memory-dependent tests of situation awareness.

2.1.4 Measurement Techniques

A number of measurement techniques for situation awareness have been proposed. These include SAGAT (Endsley, 1988; Endsley, 1995), SPAM (Durso et al., 1998) and SART (Taylor, 1990). Each of these techniques is discussed in subsequent sections.

2.1.4.1 SAGAT

SAGAT (Situation Awareness Global Assessment Technique) aims to provide an objective and unbiased assessment of situation awareness with respect to all levels of situation awareness (see Figure 2.1). With this technique, a simulation is frozen at randomly selected junctures in the scenario timeline, the system displays are blanked and the operator is required to quickly answer questions about his or her current understanding of the situation. Operator perceptions are then compared to the real situation (based on information drawn from the computer or from SMEs who answer the SAGAT queries while looking at the displays). Comparing the data in this manner provides a putative objective measure of situation awareness; however, SAGAT is difficult to implement in many real-time operational scenarios (e.g. battlefield operations) due to the problem of suspending operational procedures. Real-time probes may help to address some of these problems (see Section 2.1.4.2).

2.1.4.2 SPAM

In an effort to meet some of the perceived limitations of the SAGAT technique, Durso et al (1998) advocate the use of the SPAM technique (Situation Present Assessment Method). This technique is derived from SAGAT and allows the operator to be verbally queried in a concurrent fashion with real-time activities. It is therefore known as a real-time probe for situation awareness. With this method, subjects are queried regarding the current situation at periodic intervals throughout the scenario timeline, but in a departure from the SAGAT technique, the system displays remain in full view of the participants. Because operators may simply look for information to answer each probe, response accuracy measures potentially provide very little information about operator situation awareness. Far more important are measures of response latency. Reaction time to each probe may theoretically correspond to the degree to which the requested information is already known (e.g. is present in working memory) or understood (e.g. the operator is fully aware of the situation and knows where in the environment to retrieve information as the basis for answering the query).

A number of concerns about the use of real-time probes have been raised (Jones & Endsley, 2004). Of central concern is the extent to which such probes interfere with ongoing operations by distracting the user, incur additional overheads in terms of workload that detracts from primary task...
performance, and the extent to which the probe cues operators to attend to information that might otherwise have been missed. Response latency measures may be relatively more sensitive to the current level of operator workload, with greater workload levels producing longer latency scores, than with situation awareness per se. In a study designed to compare the use of SAGAT and SPAM approaches, Jones and Endsley (2004) report a weak correlation between real-time probes and SAGAT scores, indicating that real-time probes were indeed measuring some aspect of situation awareness. However, correlations between SPAM and operator workload were also found, which indicates the inter-dependency of real-time probes with workload factors.

2.1.4.3 SART
SART focuses on subjective measures of situation awareness. This measure consists of a 10-dimensional bipolar scale on which participants can subjectively rate their situation awareness. The ratings provided by the participants on each of the 10 items are then combined to form a rating for each of three major factors: supply of attention, demand for attention, and understanding. Although this measure effectively provides information regarding a subject’s confidence in their situation awareness, it does not provide an objective measure of situation awareness. It is potentially susceptible to memory decay (since it is administered at the end of a test, simulation or training scenario) and by performance factors (i.e. a person who successfully performs the task may provide higher ratings of situation awareness based on positive outcomes). It is also susceptible to individual differences concerning confidence levels (i.e. some individuals may be overly cautious when it comes to their perceived levels of situation awareness). Perhaps more importantly, people do not know what they do not know, i.e. they are not aware of things they perhaps should have been aware of from the perspective of optimal situation awareness. Thus, it is entirely possible for someone to have high confidence in their level of situation awareness, even though, objectively, their level of situation awareness was quite poor.

2.1.4.4 Conclusions
All the techniques reviewed in this section involve the use of queries (verbal or textual) to provide a measure of the operator’s level of situation awareness. Techniques that involve concurrent measures of situation awareness (real-time probes) with task performance suffer from the potential affect that such probes have in terms of the ongoing performance and attention, while techniques that involve post-trial recall suffer from the problem of memory decay. Another factor that is inherent to all the tests is that they rely on conscious, introspective access to scenario-specific knowledge - that is, the knowledge to be retrieved about a situation is explicit rather than implicit. This is problematic in the sense that it assumes explicit knowledge is constitutive of situation awareness. In contrast, expert performance, in many real-world situations, may rely on knowledge that is largely implicit (tacit) and not easily verbalized (Schreiber et al., 2000). Nisbett and Wilson (1977) argue that introspective analyses about the causal influences on behaviour are limited in the sense they tend to rely on a priori causal theories:

“When people are asked to report how a particular stimulus influenced a particular response, they do so not by consulting a memory of the mediating process, but by applying or generating causal theories about the effects of that type of stimulus on that type of response.” (Nisbett & Wilson, 1977; pg; 248)
For example, when people were asked to select from an array of equivalent objects, they failed to recognize the predominant role played by spatial position in influencing their response choices (Nisbett & Wilson, 1977). The central concern is that in some situations experts may have limited conscious introspective access to the principles underlying their competency in the domain, particularly with respect to the causal determinants of their behaviour. Rather, much of the knowledge underlying expert task performance may be largely implicit and unavailable to conscious awareness. This is likely to present a particular problem in situations where problem-solving procedures have become heavily routinized or automatic (Logan, 1988) and attention to task-relevant stimuli is reduced, but the findings of Nisbett and Wilson (1977) also suggest that our understanding of the causal influences underpinning our behavioural responses to environmental stimuli is somewhat limited in general. As such, it would seem that recall of situation-specific information via verbally-mediated mnemonic recall is highly problematic in terms of providing an objective measure of situation awareness. In fact, some studies have suggested that the ability to provide verbal reports about the principles underlying task performance may be negatively associated with actual task performance (Berry & Broadbent, 1984), and it is thus not clear to what extent the ability to explicitly recall situation-specific information is relevant to an understanding of the relationship between situation awareness and decision-making competency. Ericsson and Simon (Ericsson & Simon, 1980; Ericsson & Simon, 1984) have addressed some of these concerns by specifying criteria about the kind of contexts in which verbal reports may provide useful data about cognitive processes. They suggest that it is preferable to obtain introspective reports during the performance of the task, rather than retrospectively. In addition they argue that subjects are more likely to produce accurate introspections when asked to describe what they are attending to, or thinking about, than when required to interpret a situation or their own thought processes. Notwithstanding the obvious implications of Ericsson and Simon’s criteria in terms of when to probe a subjects current level of situation awareness (i.e. they would, presumably, advocate the use of real-time probes), their analysis does little to salve the concern that many subjects may seek to establish an understanding of the situation in the context of situation assessment, perhaps to formulate a mental model of the current situation, and that the use of verbal reports may be inadequate in these contexts. To the extent that situation awareness depends on a process of interpreting available information and formulating a mental model, as would be suggested by extant models of situation awareness (Endsley, 1997; Endsley, 2000), the distinction between implicit and explicit knowledge may be important in terms of evaluating the adequacy of available metrics for situation awareness.

The problem is further highlighted by studies investigating the phenomenon of implicit learning, wherein learning is not associated with complete verbalisable knowledge of what is learned. Berry and Broadbent (1984) investigated implicit learning in the context of a complex task in which a sugar production factory had to be managed to maintain a specified level of sugar output. Subjects learned to perform this task effectively, but most of them could not explain the principles underlying their performance. Indeed those subjects who revealed good knowledge of the principles underlying task performance tended to perform less well than those with a poor explicit understanding. The notion of implicit learning is also apparent in models of skill acquisition such as Anderson’s theory of knowledge compilation (Anderson, 1982; Anderson, 1983; Anderson, 1993). Anderson argues that the transition from novice to expert performance is associated with a move from the use of declarative to procedural knowledge. Part of knowledge compilation involves proceduralization in
which initial attempts to solve a problem via the application of weak methods, such as hill climbing and means-end analysis, result in the creation of new production rules to capture the link between situation contingencies and associated transformations of the problem space. Proceduralization is associated with a correlative reduction in verbalization by the problem solver (Anderson, 1982) as problem-solving behaviour becomes increasingly routinized and automatic. The danger, it seems, is that an over-reliance on techniques that exploit conscious introspective access as a means to measure situation awareness may fall foul of the role played by implicit knowledge in the execution of fluid, adaptive response sequences that are the hallmark of expert problem solving behaviour.

Issues of introspective access to information also arise in the context of Jens Rasmussen’s (Rasmussen, 1983) performance model and Shadbolt’s distinction between samurai, practitioner and academic expert types (Schreiber et al., 2000). Rasmussen discriminated between a number of levels of performance in an effort to formulate a better cognitive theory to the design of human-machine interfaces. His levels include:

1. **Skill-based behaviour**: Skill-based behaviour is characterized as smooth, automated and highly integrated and occurs without conscious awareness or control. Examples are bicycle riding or automobile driving.

2. **Rule-based behaviour**: Rule-based behaviour consists of a sequence of routines in a familiar work situation, where the sub-routines follow previously stored rules. Rule-based behaviour is typically associated with conscious, introspective access to knowledge, but the boundary with skill-based behaviour may be somewhat indistinct.

3. **Knowledge-based behaviour**: Knowledge-based behaviour is based on a mental model of the situation and is implemented when skill-based behaviour and rule-based behaviour are not up to the task at hand. This type of behaviour is typical of the problem-solving efforts applied to relatively novel behaviour when an analytical approach to problem decomposition and option generation is required.

Shadbolt (see Schreiber et al., 2000) has also suggested that subject-matter experts can be discriminated along a number of dimensions, which determines the propriety of different knowledge elicitation techniques in knowledge acquisition contexts:

- **Academic**: The academic type regards his domain as possessing a logically organized structure in which the emphasis is on theoretical understanding. Their knowledge is likely to be well-structured and accessible, but they may be remote from everyday problem solving.

- **Practitioner**: The practitioner is engaged in day-to-day problem solving in a domain. Their practice may often be explicit and what they desire as an outcome is a decision that works within the constraints and resource limitations of the problem-solving environment. It may be that the generalized theory of the academic is poorly articulated in the practitioner.

- **Samurai**: The samurai is a pure performance expert. The only reality is the performance of optimal response sequences. Practice is often the only training and responses are typically automatic and the underlying knowledge explicit.

The distinction between different types of experts and different forms of behaviour one sees in problem-solving situations is highly suggestive of the need to perhaps apply different types of analytic technique in different situation awareness contexts. Aspects of the problem solving environment, the state of possessed knowledge, the type of training regime adopted, the status and
responsibilities of domain experts, the relative level of expertise manifested by subject-matter experts, the information sources used in the task, and the outcome of expert deliberations would all seem relevant to an analysis of situation awareness in problem solving contexts. In this respect, a number of knowledge elicitation techniques have been used in the context of knowledge engineering initiatives to capture knowledge from domain experts and some of these techniques are differentially sensitive to the distinction between tacit and explicit knowledge (Shadbolt & Burton, 1990; Shadbolt et al., 1999). As such, it may be worthwhile considering the applicability of such approaches to the measurement of situation awareness in the current research context.

2.2 Information Fusion

2.2.1 Importance of Data Fusion
Data fusion is an increasingly important element of diverse military and commercial systems. The term is used to refer to the strategic combination of information from various sources in order to improve the information associated with various entities and to understand their inter-relationships with other entities. There is widespread recognition of the importance of information fusion in the military domain where the notion of information sources subsumes a wide variety of physically distributed sensor systems differing with respect to the type of information provided. Moreover, as the role of the military expands to encompass operational situations as diverse as counter-insurgency, peace-keeping, humanitarian assistance and counter-terrorism activities in addition to armed conflict, the need to exploit and integrate information from structurally and semantically diverse sources becomes ever greater. Some of the information sources that feature in the context of the current project and which serve as the basis for fusion-related processes include:

- field reports
- institutional web sites
- web services
- online database
- emails
- procedural manuals and background information documents, e.g. SOPs
- intelligence information and briefings
- multimedia information, e.g. video footage, satellite imagery, photographs, audio recordings
- datalink systems
- knowledge-based systems

The idea of knowledge-based systems as an information source enables us to implement a variety of meta-cognitive processes, e.g. levels of trust and certainty in internally-derived information, identification of knowledge gaps and implementation of knowledge acquisition activities to address epistemic deficiencies, explanations of why a particular decision was reached or an inference made, etc. Such capabilities demand ontologies geared towards representing the problem-solving elements used by the knowledge system to fulfil its own problem-solving commitments or to provide explanatory accounts of its own problem-solving and decision-making activities. This requirement necessitates an explicit representation of the system within its own concept space. This allows the system to treat itself in a similar fashion to any number of external agents.
With such a broad range of information sources, the mechanisms used to model the information gleaned from such sources becomes of paramount significance. In order to integrate information received from multiple sensor sources in a semantically-coherent and operationally useful manner we need to model the information acquired from sensors at a semantic level, i.e. we need to provide a common semantic basis against which the meaning of information acquired and disseminated by sensors can be interpreted and aligned with high level operational goals and strategic knowledge requirements. Not only does such semantic representation facilitate the implementation of fusion-related processes, it also enables operators to query information sources in a semantically-relevant fashion. Query languages can therefore be specified at the knowledge-level of representation (Newell, 1982), exploiting the kinds of conceptual distinctions made within a domain of discourse.

In addition to the information content provided by sensor systems, we also need to give careful consideration to the way in which information resources are described, especially with respect to their capabilities, their mode of access and security profile (e.g. what limits exist with respect to sensor access at different levels of the command hierarchy in different mission contexts?). Semantically-enriched representations of sensor characteristics provide the starting point for a range of desired capabilities including, but not necessarily limited to the following:

- dynamic discovery of new information sources, e.g. web-accessible resources and services
- *ad hoc* configuration of sensor networks to meet changing operational and mission contexts
- dynamic re-configuration of sensor systems settings
- calibration and registration of information derived from multiple sensor systems
- intelligent sensor deployment and re-purposing of existing sensor systems
- maximal exploitation of limited communications networks, e.g. bandwidth limitations

and to reflect on its own processing activity accordingly. Such capabilities may be essential in terms of Level 4 information fusion processes as described in the JDL Data Fusion Model (Steinberg & Bowman, 2004).
2.2.2 Data Fusion Model

The notion of data fusion has been formalized in the data fusion community in the form of the JDL Data Fusion Model (Llinas et al., 2004; Steinberg & Bowman, 2004; Steinberg et al., 1999; Steinberg et al., 1998). The Data Fusion Model (see Figure 2.3) was developed to subserve a number of purposes:

- to provide a common frame of reference for fusion-related discussions
- to facilitate understanding of the types of problems for which data fusion techniques are applicable
- to codify commonality among fusion-related problems
- to aid in the extension of previous solutions
- to provide a framework for investment in automated solutions
- to categorize different types of fusion-related processes

The Data Fusion Model provides a functional view of fusion-related processes defined in a number of distinct, but heavily inter-related levels (see Steinberg & Bowman, 2004). The levels include:

- **Level 0 – Signal/Feature Assessment**: estimation and prediction of signal or feature states
- **Level 1 – Entity Assessment**: estimation and prediction of entity parametric and attributive states (i.e. of entities considered as individuals)
- **Level 2 – Situation Assessment**: estimation and prediction of the structures of parts of reality (i.e. of relations among entities and their implications for the states of related entities)
- **Level 3 – Impact Assessment**: estimation and prediction of the utility/cost associated with entities, signals or situation states, including predicted impacts of a system’s potential courses of action (this subsumes the notions of simulation, evaluation of predicted outcomes, implementation of ‘what-if’ scenarios and so forth)
Level 4 – Performance Assessment: estimation and prediction of a system’s performance as compared to desired states of operation and measures of effectiveness.

Level 0 was introduced to address the problems of detecting and characterizing signals and features within complex, multi-dimensional data sets as in feature extraction from images and video footage. The aim of processes within this level is to derive estimates of the various characteristics of entities in terms of their values and associated confidence limits. The features of an entity can be estimated based on attributes inferred from one or more signal observations. For example, signal-level associations and estimation problems appear in ELINT pulse train de-interleaving or feature extraction of an entity in satellite imagery. The process involves inferring the existence of an entity and its associated characteristics using a variety of top-down and bottom-up approaches. Level 1 data fusion is the process whereby sensor measurements are processed and combined to determine entity characteristics. The identity, location, track and activity state of an entity (whether it be military personnel, a vehicle, or military formation) can be estimated within Level 1 data fusion processes. The output of Level 1 is aggregated into a composite tactical picture at Level 2 on the basis of which situation assessment and analysis can occur. Situation assessment focuses on the inter-relationships between units in order to inform higher-level conceptual abstractions such as force composition and cross force relationships. Typical relationships that feature at this level include:

- relationships among objects in terms of their deployment, kinetic interaction, organization role, communications, type similarity, etc.
- relationships among blue sensor and weapon platforms (spatio-temporal alignment, measurement calibration, confidence limits, communication and coordination, etc.)
- relationships between sensors and sensed entities (inter-visibility, assignment, countermeasures, etc.)
- relationships between red and blue tactical entities (e.g. targeting, jamming, engaging, etc.)
- relationships between entities of interest and other entities (e.g. terrain features, solar and atmospheric effects, weapon launch and impact points, etc.)

Level 3 processes are related to threat or impact assessment. These, largely knowledge-based, processes attempt to project the current situation into the future in order to infer information about the impact of the assessed situation, the vulnerability of assets to perceived threats (threat assessment) and force capabilities. Threat assessment, in this case, is aimed at evaluating engagement outcomes as well as assessing an enemy’s intent based on knowledge about enemy doctrine, levels of training, socio-political factors and perceived capability. Mission planning is often a critical component of this stage of the fusion process. Level 4 processes are directed to the problem of evaluating system performance with respect to MOE/MOPs. A critical aim at this level of the fusion hierarchy is to assess the performance of fusion-related processes with respect to some acceptable level of performance or accuracy. For example, in assessing the performance of a fusion system the analyst is assumed to have access to real-world data that can be used to assess the integrity of fusion-related processes, i.e. to what extent do the fusion processes accurately represent the real-world data and is the error within acceptable limits. It is important to bear in mind that

---

8 Smith and Grenon (2004) provide a useful overview of the types of ontological relations that typically feature in ontology modelling.
although the abstractions made in (ontological) models are couched in the real world, fusion processes do not see the real-world data; they see the sensor- and information source-provided world, i.e. the observed world. As a consequence, the fusion algorithms that attempt to estimate the states of interest need to be cast as observation-constrained variants of real-world data. Level 4 fusion processes typically provide the basis for debugging and reconfiguration actions that aim to optimise system performance vis-à-vis operational goals, as well as serving as the basis for empirical evaluation of the viability of different fusion systems for real-world deployment. Table 2-1 summarizes the characteristics and products associated with each of the aforementioned fusion levels.

<table>
<thead>
<tr>
<th>Fusion Level</th>
<th>Association Process</th>
<th>Estimation Process</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.0 Signal/Feature Assessment</td>
<td>Observation-to-Feature</td>
<td>Feature Extraction</td>
<td>Estimated Features and Confidences</td>
</tr>
<tr>
<td>L.1 – Entity Assessment</td>
<td>Signal/Feature to Entity or Entity State</td>
<td>Entity Characterization</td>
<td>Estimated Entity States &amp; Confidences</td>
</tr>
<tr>
<td>L.2 – Situation Assessment</td>
<td>Inter-Entity Relations</td>
<td>Relational Modelling</td>
<td>Situation &amp; Confidences</td>
</tr>
<tr>
<td>L.3 – Impact Assessment</td>
<td>Situation to Courses of Action</td>
<td>Cost/Benefit Analysis</td>
<td>Predicted Information States &amp; Confidences</td>
</tr>
<tr>
<td>L.4 – Performance Assessment</td>
<td>System States to Goals</td>
<td>Performance Analysis</td>
<td>Estimated MOP/MOEs &amp; Confidences</td>
</tr>
</tbody>
</table>

Table 2-1: Characteristics of Data Fusion Levels

It is important to bear in mind that the fusion model does not imply anything about the order in which fusion processes are undertaken. Level 3 analyses can be performed upon Level 1 entity state estimates, for example, and any one level can occur independently of the others in a particular implementation context.

The JDL Data Fusion Model has been subject to considerable revision over the course of the past few years. A primary driver for change consists in an appreciation of the changing operational roles of the military (the essence of which is epitomized in the notion of the “3-block war”), the existing information requirements of the UK MoD and Homeland Security communities, and the vision of future operational concepts, such as the Common Operational Picture, Network-Enabled Capability, Asymmetric Warfare, Information Superiority and so on. Much of the value of the Data Fusion Model derives from its functional perspective, particularly to the extent that the identified fusion functions are recognizable to human beings as a model of functions they themselves undertake in their own minds when organizing and fusing data (Llinas et al., 2004). It is arguably important to maintain this “human-centric” approach to fusion functionality since it allows the fusion model to serve as a vehicle for communication between a variety of stakeholder groups involved in fusion-related

---

Issues of performance assessment are relevant in the context of the current project since they relate to the empirical evaluation of the AKTiveSA TDS. The critical issue here concerns the ability of the system to make reliable inferences that yield representational states commensurate with the real-world state of affairs.
research, e.g. theoreticians, practitioners and system developers. The framework of the model appears to have been of considerable significance in terms of guiding the theoretical debate about information fusion research and highlighting the difficulties of building knowledge-based systems that provide functionality in support of human decision-making processes.

2.2.3 Knowledge-Based Information Fusion

Knowledge-based processes are essential to, at least some of, the challenges faced by the information fusion community. In this section we review a number of issues related to the implementation of information fusion systems based on knowledge-based approaches.

<table>
<thead>
<tr>
<th>Fusion Level</th>
<th>Problem/Opportunity Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.0 Signal/Feature Assessment</td>
<td>Semantic annotation and processing of high-dimensional data sets, e.g. multi-spectral information sources, satellite imagery, video footage, vibration data, voice communications. Derivation of semantically-relevant features from such sources.</td>
</tr>
<tr>
<td>L.1 – Entity Assessment</td>
<td>Improved certainty estimates with respect to fused data derived from multiple sources, facilitation of entity characterization in terms of implied features and feature values (e.g. default values), support for identity inference, etc.</td>
</tr>
<tr>
<td>L.2 – Situation Assessment</td>
<td>Knowledge-filtered awareness, including support for contextual relevance reasoning, information triage, representation of situation state, etc.</td>
</tr>
<tr>
<td>L.3 – Impact Assessment</td>
<td>Support for rules-based processing of situation-relevant data in relation to decision support processes, e.g. automated mission planning, threat assessment, battlefield planning, deployment of defensive measures.</td>
</tr>
<tr>
<td>L.4 – Performance Assessment</td>
<td>Identification of knowledge gaps/epistemic inadequacies and the implementation of appropriate remedial activities. Provision of explanatory support to enable system evaluation and validation of knowledge system operation.</td>
</tr>
</tbody>
</table>

Table 2-2: Role of Ontologies in Information Fusion Processes

2.2.3.1 Ontologies

Information fusion processes involve the intelligent combination of information from a variety of sources as well as reasoning processes that operate over the fused or non-fused data. We see ontologies as an essential component of information fusion at all levels of the data fusion hierarchy (see Table 2-2). In particular, we see ontologies as a key enabling technology in the following fusion-related areas:

- **Agent Inter-Operation & Communication**: Agent communication and inter-operation is a key aspect of data fusion. In order to fuse data from multiple information sources, agents (both human and software) need to communicate and inter-operate effectively. A common semantic basis is often a prerequisite for such inter-operation. Indeed it has long been recognized that independently developed software agents can only communicate if they have a shared understanding of the meaning of the data being exchanged. Ontologies provide a partial solution to this problem of semantic inter-
operability, but the current state-of-the-art is often inadequate from the perspective of separating the domain-neutral communicative intent of a message (considered in terms of speech acts) from its domain specific content (Gibbins et al., 2003). In this sense the application of speech act theory (Searle, 1969) may have much to commend itself in terms of delivering more effective solutions to the problem of inter-agent communication.

- **Information/Knowledge Acquisition:** One of the key purposes of the OWL specification was to facilitate an understanding of web content in a manner that would enable dynamic resource discovery, effective search and retrieval, composition of automated semantic services, etc. (Berners-Lee et al., 2001). Free text and semi-structured documents (doctrinal documents, CIA World Fact Book, and other relevant military sources) are not available in a form that is directly amenable to semantic integration and information fusion. Meta-data annotations are needed to specify the semantics of these information sources in an ontologically-circumscribed fashion.

- **Service Characterization:** A battlefield network consists of many information sources including in-theatre sensors, platforms, intelligence reports and remote information such as archival intelligence and satellite data. These information sources not only provide information to enable a variety of problem-solving and fusion-related activities, they also serve as resources that can be directed and re-purposed to meet the information demands posed by the particular operational environments. In conjunction with information resources, the future military information environment will feature a variety of systems with diverse capabilities, and the operation of such systems needs to be orchestrated and exploited in a variety of operationally-useful ways. How can we architect technology solutions that utilize and maximally exploit the range of information sources and system capabilities in the future operational environment? One solution, proposed by Sycara et al (2003), is to model information sources and system capabilities as service providers, which can be exploited within the framework of a Service-Oriented Architecture (SOA). Effective resource exploitation within such a framework is, however, not without its problems. Key issues concern how to interact with the service (i.e. how to describe the capabilities and parameters of the service). This is typically referred to as the Service Profile. A second issue concerns how to represent the operation of the service in terms of the workflow and possible execution paths (Process Model). Thirdly, how can we enable opportunistic discovery of new services that may become available throughout the operational lifespan of a system without being explicitly told of their existence from the outset. Finally, the question still remains as to how we can best enable the inter-operation of these services in a manner that permits the construction of ever more elaborate workflows to meet the demands of increasingly complex service requirements. The answer to many of these questions may reside in the use of ontologies to describe services within the context of a SOA approach. Languages such as DAML-S (Ankolekar et al., 2002; Ankolekar et al., 2002) and OWL-S (Martin et al., 2004) are specifically aimed at providing these service descriptions. The confluence of SOA approaches and Semantic Web technologies may therefore provide a suitable technological basis for the integration and exploitation of future military capabilities.

- **Semantic Integration & Interoperability:** Issues of semantic inter-operability arise from the ambiguities inherent in the language terms used by diverse user-communities. The problem is perhaps most apparent in coalition operations where the close inter-operation of allied forces is an operational prerequisite. Ambiguities are apparent in the different meaning applied to ostensibly similar terms used by US and UK military coalition partners. In addition, lexically dissimilar terms may, in fact, be semantically
equivalent with regard to either their extensional or intensional meanings. Similar problems may be expected to arise in terms of the communicative transactions between different service divisions within the military and in terms of the military's inter-operation with a variety of culturally, ethnically, and organizationally diverse communities (e.g. NGOs, foreign military factions, local government agencies, aid agencies, charities, UN agencies, etc.). Ontologies may provide one solution to this spectre of semantic ambiguity. We should also consider the implications of speech act theory (Searle, 1969) from the perspective of understanding the pragmatics of different message types in terms of both their ‘locutionary nature’ and ‘illocutionary force’ (e.g. How well does the message content fully express a military commander’s intent? Does intent in this situation rely on communication aspects that are not explicit within the content of the information exchange?, etc.).

- **Reasoning, Inference and High-Level Conceptual Abstractions:** Reasoning is an essential ingredient of information fusion at all levels of the fusion hierarchy. Inferential processes may be used to provide high-level conceptual abstractions that are implicit in patterns of sensor data and reliant on featural characterizations and relational inter-dependencies with other entities, e.g. assessing whether an entity represents a threat requires inferences that operate over information such as the location, identity and velocity of the target, as well as contextual information regarding current threat status. Inferences, deriving either from the formal semantics of the knowledge representation language, or based on more complicated types of inference, in the form of implication rules, constitute the basis for high-level information fusion and decision support. Knowledge representation languages that avail themselves of formal semantic notations, such as OWL, and are easily amenable to rule-based transformations of the constituent knowledge elements are therefore to be favoured in terms of fusion-related applications.

- **Sensor Calibration and Configuration:** Optimal exploitation of sensors may rely on adequate models of the sensor in terms of its configuration parameters. Different sensor configurations may be required to satisfy different epistemic requirements, or they may vary across mission and operational contexts. One example concerns the optimal configuration of the SearchWater 2000 radar for AEW operations. The radar features a complex range of settings, which can be used to gather different types of information in particular contexts. Note that the meaning of the information gathered by the radar in these contexts varies according to the value of its configuration parameters, and this guides interpretive processes accordingly. Sensor configuration may be constrained by epistemic and contextual (e.g. meteorology, mission context) factors and it is therefore a candidate knowledge-based process in its own right.

- **Sensor Information Modelling:** In order to be amenable to higher-level knowledge-based fusion processes, sensor information needs to be represented or processed in a form that facilitates its transition to ontologically-motivated descriptions. We are not aware of any Level 1 sensors in existence today that exploit ontologies or are able to annotate sensor information with ontological terms in a manner that would enable their semantic processing in upstream systems. Nevertheless, we are confident that techniques for such capabilities will be available in the near future as this is one of the objectives of the DARPA Information Exploitation Office (Wishner, 2002) and is supported by the DAML Experiment (Flynn & Dean, 2002).

- **Semantically-Informed Query Capability:** Ontologies permit the use of query languages that are more closely tied to the semantics of the underlying dataset than its physical structure. This is important because many of the desired queries may execute over information that is implicit in the data set rather than explicitly specified, e.g. one might
be interested in knowing the location of an aggregate of objects where the conditions of aggregate membership are determined in an *ad hoc* fashion based on changing mission contexts and operational constraints.

- **Dynamic Knowledge Infrastructure:** Knowledge is liable to change over time and knowledge-based systems must deal with issues of change in a sensible fashion. One concern relates to the need to re-factor the knowledge landscape in a manner that reflects changing epistemic requirements and operational needs. For example, an operator may wish to define a new concept, query, relationship or rule contingency and derive all the data objects affected by the inclusion of this structure. Ontologies enable this form of knowledge infrastructure modification.

A question that typically arises in the course of ontology research, specifically those that focus on OWL as a representation language, is ‘why not use the XML schema language?’ This question highlights a fundamental failure to fully appreciate the differences between OWL and XSD, so it is worth elaborating on this issue.

- **Syntax vs. Semantics:** Perhaps most importantly, an XML schema provides a syntactic specification that defines the structural organization of data. While this is valuable as a mechanism for data exchange, it does not provide any means for the effective representation of semantic information, i.e. what the data means in terms of its actual relationships to other data within the same dataset and potential relationships to data that may be defined elsewhere and received at a different time. To capture the semantic significance of data requires knowledge about classes of data objects and how these objects relate to one another. This type of information is precisely what ontologies capture.

- **Reasoning & Inference:** OWL permits certain types of automated reasoning as determined by the formal semantics of the language. This is not something that is apparent in XML schema technologies. OWL-based reasoning not only enables automatic classification of the taxonomic hierarchy (subsumption reasoning), it also permits identity inference (two or more individuals are semantically equivalent) and individual differentiation (two or more individuals represent distinct entities). The parallels with information fusion in this sense should be clear.

- **Logical Consistency Checking:** Modelling the knowledge infrastructure of a domain is a difficult process, typically the preserve of experienced knowledge engineers. Fortunately, OWL enables a variety of forms of feedback, which can assist with the knowledge modelling process. OWL is amenable to a variety of logical consistency checks that ensure the logical integrity of the model and these can help avoid common modelling mistakes. The development of an OWL symptom ontology (Baclawski et al., 2004) allows informative feedback to be provided in an ontological fashion, which heralds the possibility that symptom reports can be automatically processed by other OWL-cognizant programs.

- **RDF Compliance:** OWL is an extension to the RDF vocabulary and, as such, is an RDF-compliant language. This affords a number of advantages not least of which is the provision of a common representational syntax in the form of RDF/XML. The existence of a common syntactic specification promotes information exchange in a manner similar

---

10 Identity inference allows us to infer that seemingly distinct information sets are associated with a single individual. This would seem to be one of the key information fusion capabilities afforded by OWL-based ontologies, although it does present problems concerned with the determination of sufficiency criteria as to when two ostensibly unique individuals should, in fact, be regarded as identical.
to XSD, but it avoids the overhead of having to maintain multiple syntactic specifications of domain information.

- **Tool Support:** One of the advantages of OWL is the expected availability of general purpose tools that can reason over OWL-based representations in order to yield useful decision outcomes. As Smith et al (2004) comment: “Building a sound and useful reasoning system is not a simple effort. Constructing an ontology is much more tractable. It is our expectation that many groups will embark on ontology construction. They will benefit from third party tools based on the formal properties of the OWL language, tools that will deliver an assortment of capabilities that most organizations would be hard pressed to duplicate.”

- **Existing Semantic Web Infrastructure:** The continuing development of the Semantic Web is itself a motivating factor in the adoption of an ontological approach to information fusion. As new capabilities become available it will become increasingly important to exploit these capabilities. Most visions of future military capability are based on modern information and networking technologies including web services, agent-based computing, and the Semantic Web (Llinas et al., 2004).

- **Open World Assumption:** Since information fusion in the battlespace environment, and in military operational contexts in general, typically involves integration and fusion with respect to spatio-temporally distributed and semantically heterogeneous information sources, representational formalisms that do not endorse monotonicity assumptions become increasingly unwieldy and cumbersome. It is difficult to specify syntactic constraints for information that is sourced from different sources at different times, since some data items may not be readily available from a particular source or at a particular time point. This argument does not rule out the possibility of using syntactic specifications, such as XSD, but it does raise pragmatic concerns about the utility of representational formalisms that target the purely syntactic, as opposed to semantic, dimensions of information. Such arguments countenance the adoption of semantic-level representation languages, such as OWL, in characterizing the information infrastructure of fusion-related applications and this is apparent in our choice of OWL as a modelling language.

- **Ontology Normalization:** Information sources supporting information fusion processes refer to different aspects of the operational environment. This is particularly so in situations where military operations encompass conflict, humanitarian aid, peace-keeping, counter-insurgency, etc. In some cases the required knowledge can be extensive, subsuming political and geographical knowledge, platform characteristics, mission guidelines, weapon characteristics, corridors and flight paths, lethality, emitter characteristics, doctrine, organizations, ethnicity, religious affiliation, etc. It would not be possible to build models for every aspect of the operational environment, either practically or philosophically and this applies to whatever knowledge representation language is used. OWL, however, has much to commend itself in preference to plain XML. OWL supports types of reasoning that are constrained by the semantics of the OWL language. Subsumption reasoning, for example, enables a reasoner to automatically compute the taxonomic hierarchy for a set of objects in the absence of an explicit specification of subsumption relationships. Why is this useful? Firstly, it enables us to delegate much of the modelling activity to the reasoner. Based on an initial characterization of ontology elements we can rely on the reasoner to infer a lot of the structural detail relating to the model. This process is typically referred to as ontology normalization and is an essential element of engineering large-scale ontologies.
• **Semantic Integration**: XML schemas are sufficient for data exchange, but systems interoperability issues typically extend beyond data exchange mechanisms. Coalition interoperability often relies on the meaning or semantic significance of information content rather than an ability to deal effectively with the syntactic organization of communicated data. The terms used by different communities of individuals can often have quite subtle shades of meaning that differentiate them from the terms used by other groups. A term can have different meanings despite lexical equivalence and lexically distinct terms may have the same underlying meaning, extensionally or intensionally defined. As was mentioned earlier, these meanings are not captured by the XML schema specification and they are therefore unsuitable for information fusion processes in coalition inter-operability contexts.

A number of studies have examined the role of ontologies in information fusion (Boury-Brisset, 2003; Johnson & Hall, 1999; Matheus, 2005; Matheus et al., 2003; Scherl & Ulerly, 2004; Sycara et al., 2003). In general, the consensus is that ontologies provide an effective means to address many of the issues confronting the data fusion community with respect to the implementation of fusion systems. The unique features of the current project with respect to previous studies includes the following:

• **Application Domain**: most fusion-related studies have been devoted to a discussion on ontologies in conventional armed conflict situations. While there is some recognition of the need to extend the focus of studies beyond this domain, for example into logistics (Matheus et al., 2005), the combined focus on both military and humanitarian relief operations in the context of the current study is unique (Smart et al., 2005).

• **Changing Operational Commitments**: Related to the first point, our study is the only one we are aware of that addresses the evolving role of the military in areas such as humanitarian operations, peace-keeping and counter-insurgency operations as well as armed conflict. Our study presents a scenario wherein a number of humanitarian relief operations occur against a backdrop of ongoing military conflict and this simultaneous overlay of diverse operational commitments is unique within the research literature. Our emphasis reflects a widespread recognition of the changing role of the military forces in relation to current and future operational deployments. The notion is epitomized in the concept of the ‘Three Block War’, first coined by General Charles Krulak (former Commandant of the United States Marine Corps): “On the first block of the three-block war, we will deliver humanitarian aid or assist others in doing that. On the second, we will conduct stabilization or peace support operations. On the third, we will be engaged in a high-intensity fight. We must be ready to conduct these operations simultaneously and very close to one another. We must be prepared to conduct them in large urban centres and complex terrain” (Krulak, 1997). The three-block war presents a range of challenges for military agencies vis-à-vis information fusion and our study aims to focus on strategies to resolve these issues.

• **Decision Support**: Decision support in the current project is aimed at assisting with information fusion at all levels of the information fusion hierarchy. In comparison to previous studies that focus primarily on Level 2 fusion, we aim to apply knowledge technologies to other fusion-related problems, such as impact/threat assessment, planning, sensor integration and entity characterization.

### 2.2.3.2 Uncertainty

In real-world situations sensory information is not always accurate. To account for this, fusion-related processes need to avail themselves of effective strategies to deal with the problem posed by
uncertainty. This is particularly important in data fusion systems that attempt to combine information gleaned from a variety of sources in order to derive higher-order abstractions, or in systems that attempt to perform high-level reasoning and inference over fused and non-fused data. Uncertainty is usually discussed in the context of belief states, i.e. what can the system reliably believe and what confidence should be assigned to particular beliefs. Llinas et al (2004) describe the process of belief change with regard to information fusion. They argue for a consideration of two processes: Belief Revision (BR) and Belief Update (BU), collectively referred to as Belief Change (BC). The Belief Revision process modifies existing estimates about a particular time ‘t’ based on new information about the same point in time. In other words BR refers to adjustments in the interpretation of a state estimate at a given time. Belief Update modifies existing information about the world at time ‘t’ based on new information from time ‘t+1’ to describe the world at time ‘t’. BU thus refers to a dynamic situation in which the world is evolving over time. According to Llinas et al (2004), and following Gardenfors (1992), most of the methods for belief change obey the following rationality principles:

1. **Consistency**: revised epistemic states should be consistent with previous epistemic states
2. **Minimal Change**: revised epistemic states should be as close as possible to current epistemic states
3. **Priority of Incoming Information**: recent information is to be preferred over existing information

Llinas et al argues that these principles commit BC to the notion of ‘epistemic entrenchment’, in which beliefs are ordered according to our willingness to give them up. If some beliefs must be removed in order to accommodate some new information and keep the belief set consistent, the less entrenched belief will be abandoned, while the more entrenched beliefs are preserved. While a full discussion of issues related to belief modification are beyond the scope of this review, it is worth pointing out that typical notions of epistemic entrenchment in belief modification seems to make knowledge-based systems susceptible to the same cognitive biases and fallibilities that confront the human reasoner. The task of knowledge-based information fusion should not be to merely replicate or model existing cognitive processes, it should rather aim to extend and refine these processes in a manner that makes them less prone to error and system failure.

Issues of uncertainty are particularly important in knowledge-based processes that attempt to reason over existing information from multiple, distributed information sources. The key issues here include, among other things:

- How does certainty information propagate along complex chains of inference execution?
- How should certainty information be combined in the context of fusion processes?
- How do we dynamically modify existing certainty information based on the receipt of new information?
- What strategies should be adopted for identifying the quality of data in fusion processes and how should poor quality data be eliminated?
- How should we modify fusion-related processes to account for the relative reliability of different information inputs, perhaps based on notions of trust?
Issues of uncertainty introduce a variety of theoretical and practical problems into information fusion processes and we do not claim to deal with them all in the context of the current project. Such issues are, however, important and it is essential to be aware of them in the context of fusion-related research.

2.2.3.3 Trust, Security & Provenance
In addition to issues of uncertainty, notions of trust, security and provenance are also of particular importance in military contexts. If, for example, a reasoning process operates over multiple sources of information with different levels of security classification, what kind of classification should be assigned to the derived (inferred) information? The key issue here is that, in some cases, knowledge-based processes are required to dynamically infer a security classification level. This is particularly so in situations where the operational and mission context is likely to change, e.g. change of role from humanitarian aid to military conflict. It is also important to understand that similar issues arise based on contextual factors such as ROE (Rules of Engagement).

Issues of trust and provenance are important in contemporary military operations because of the wide variety of information that must be integrated from different sources. Key issues here relate to how best to represent trust information for particular information sources as well as the trust relationships that exist between particular military (and other) agencies.

2.2.4 Information Fusion & Situation Awareness
Information fusion is deemed of central importance to enhanced situation awareness. Indeed the JDL Data Fusion Model (see Section 2.2.2) describes situation awareness as a by-product of the fusion process, specifically Level 2 information fusion (Steinberg & Bowman, 2004). Matheus (2005) thus comments:

“The analytical processes that go into establishing situation awareness necessarily involve information fusion, the processes by which data/information from multiple sources are combined to produce new enhanced information that incorporates aspects of the raw, original sources.”

Information fusion is thus cast as a necessary precondition for situation awareness: situation awareness cannot occur without information fusion. Personally, I am not sure whether I can agree with this position. It seems to me that situation awareness can be established in the absence of information fusion processes, at least as defined by the JDL Data Fusion Model. In addition, it does not seem to be the case that information fusion is sufficient for enhanced situation awareness. The Data Fusion Model seems to imply that greater levels of Level 2 information fusion are sufficient for improved situation awareness; however, this relationship has been challenged by recent empirical investigations of situation awareness in information fusion-related contexts (Howes et al., 2004). As part of the DIF DTC, Project 4.9 (“Designing Integrated Displays to Support Team Situation Awareness”) aims to experimentally evaluate the putative benefits of information fusion with respect to situation awareness using a variety of cognitive performance measures. The experimental method focuses on spatial localization memory for a target object (e.g. SAM site) in a number of conditions apparently differing with respect to the level of information fusion. Results suggest that the level of information fusion, i.e. the fusion condition, deleteriously affects subsequent localization ability, in particular recall is compromised, or at least more variable, in high fusion conditions. The overall conclusion seems to be that information fusion may reduce cognitive workload, but may
serve to compromise performance on post-test measures of spatial memory underpinning situation awareness. It is difficult to know how to interpret these results. Do they indicate negative affects of information fusion on situation awareness? Do they undermine the importance of situation awareness for operational effectiveness? Has the role of situation awareness been overplayed? Should the proper focus for situation awareness research be extended to include the human operator and elements of the problem-solving environment in which they operate, e.g. automated fusion processes? Is the operational metric for situation awareness poorly formulated in such conditions, thereby warranting an alternative methodological approach? A number of important comments have been made by our group with respect of such findings. The following discussion is devoted to a summary of the key points.

Firstly, it is difficult to determine whether tests of spatial memory necessarily provide us with any useful measures of either task performance or situation awareness against which the value of fusion-related processes could be evaluated. The finding that information fusion may compromise subsequent information recall is interesting from the perspective of cognitive science, but is not necessarily an adequate reflection of the potential value of information fusion in respect of operational effectiveness. In conditions of high information fusion, for example, military operators may not need to process information or attend to the specific details of information to the same degree as information in low fusion conditions. This may compromise subsequent recall of information without necessarily affecting task performance or situation awareness to any notable degree. One potential psychological explanation of these results therefore draws on Craik & Lockhart’s (1972) ‘levels of processing’ theory in which the extent of mnemonic recall is related to the depth with which recalled information is originally processed:

“Trace persistence is a function of depth of analysis, with deeper levels of analysis associated with more elaborate, longer lasting, and stronger traces.” (Craik & Lockhart, 1972; pg 675)

In the context of fusion-related studies, the kind of cognitive support provided by fusion processes may mitigate the need to process situation-specific information to the same kind of depth or level in order to derive a useful decision outcome. This reduction in processing depth may negatively affect recall without necessarily affecting either situation awareness or task performance. Similarly, in a significant refinement of the ‘levels of processing’ theory, Tyler et al (1979) argue that the level of effort devoted to stimulus processing is the critical determinant of whether information is easily retrieved from memory. Against the backdrop of this research it is possible to argue that studies that reduce operator workload or relieve the operator of the need to marshal significant cognitive resources in the processing of situation-relevant stimuli may undermine subsequent mnemonic retrieval without necessarily compromising situation awareness. This suggests that measures of situation awareness based on the memory of events and situation-relevant information may not be suitable in studies that investigate the role played by information fusion, especially when some of the fusion-related workload is delegated to automated processes.

Another subtly different, albeit related, account of Howes et al (2004) research posits that high fusion conditions allow subjects to avoid memorization of material during the task itself. In such conditions subjects may be able to treat the external problem-solving environment as a mnemonic crutch that they can repeatedly revisit to acquire information as and when required. As such they do
not need to maintain an internal cognitive model of aspects of the problem space in order to fulfil their problem-solving objectives. These types of explanatory account suggest that decrements in post-task information recall need not negatively reflect on information fusion as a means to propitiate better decision outcomes and improved operational efficiency.

2.3 Summary

This section has provided a characterization of key concepts such as situation awareness and information fusion. A number of problems associated with the attempt to deliver operationally-useful improvements in situation awareness and fusion processes were discussed and the applicability of a variety of knowledge technologies were discussed in relation to these problems. We argue that knowledge-based approaches to the problem of information fusion and situation awareness have general applicability in solving a number of problems inherent in current military operations and visionary proposals. For example, the basic problems of current C4ISR identified by the Scientific Advisory Board (*Building the Joint Battlespace Infosphere: Volume 2 - Interactive Information Technologies*, 1999, *Building the Joint Battlespace Infosphere: Volume 1 - Summary*, 2000) on the JBI included:

- Information overload
- Lack of interoperability
- Immaturity in [higher level] fusion
- Limits in display technology
- Legacy tactics, techniques, and procedures

Additional problems identified by Sycara et al (2003) include:

- Rapid network stand-up
- Information source discovery
- Dynamic sensor and network reconfiguration

We maintain that knowledge-based approaches can be used to tackle, at least some of, these problems. Specifically, the problem of information overload can be addressed by the adoption of knowledge-based approaches to information filtration (information triage) and the provision of decision support aids; inter-operability problems can be addressed with formal ontologies that provide a common semantic basis for the interpretation of domain-relevant information; the lack of maturity in higher-level fusion processes can be tackled by the use of inferential processes that integrate information with respect to semantic criteria; issues of dynamic information discovery can be mitigated by the semantic characterization of information sources and their information content; finally, Semantic Web-based technologies can assist with the process of sensor network configuration, constraining the information that is transmitted over existing communication networks so as to maximize exploitation of limited bandwidth and enabling the intelligent deployment and configuration of sensor systems so as to meet epistemic requirements and operational constraints.
3 Cognitive Processes in Situation Awareness

Section 2.1 outlined the notion of situation awareness in terms of the selective focus on particular sources of environmental information. Situation awareness, we have argued, is critically important in today’s military environments due to the dazzling array of information that system operators and executive decision-makers may be confronted with. Despite the torrent of data, operators may actually be less informed than ever before, in part because of the gap between the quantity of data disseminated and people’s ability to filter and process such information in operationally-useful ways. Due to developments in a variety of types of datalink and internet technologies, today’s systems can provide a complex mix of local and remote data that is often difficult to interpret and synthesize into a coherent model of actual events and information states – a Gestalt comprehension of partial views of reality. Clearly, what is required are new technologies to assist with the process of acquiring situation awareness in different contexts, and the current report outlines just such a system in the form of the AKTiveSA TDS. Besides proposing technological solutions to the problems confronting today’s operators, it is also important to consider the complex cognitive processes that underpin situation awareness in ecologically realistic scenarios. In the absence of such an analysis we risk developing systems that are ergonomically misaligned with the cognitive profile of human operators. It is generally recognized as important for systems to address the cognitive capabilities of human operators in a manner that ‘affords’ (cf. Gibson, 1976) their effective use and exploitation.

This section focuses on the cognitive processes that underpin situation awareness. We aim to describe the intricate complexities of how people select, integrate and interpret information against a dynamic contextual backdrop that includes both situation, context and operational goals. For the most part the discussion is based around the conceptual framework provided by Endsley (2000), which itself is grounded in Wickens (1992) information processing theory see Figure 3.1.
3.1 Perception

Perceptual processes are clearly important in terms of maintaining situation awareness. If an information item is not perceived, then it is unlikely to feature in subsequent decision-making processes. Jones and Endsley (1996) report that 76% of situation awareness-related errors in pilots could be attributed to problems in the perception of required information. Physical dissimilarity may be used to disambiguate information from background noise (e.g. Broadbent, 1958), and it may be difficult to restrain orienting responses to highly salient stimuli (e.g. Muller & Rabbit, 1989).

3.2 Cognition

3.2.1 Attention

Knowledge-filtered awareness, we have argued, relies on the ability to effectively monitor a subset of the total information available in an operational context. In particular, this information subset should be geared to the specific problem-solving objectives of the monitoring agent, thereby promoting selective attention to the features of the environment that are relevant to some decision-making process. This process is analogous to the mechanism of focused attention that has been the subject of much research in the cognitive psychology community (e.g. Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964), and, as such, some discussion of the key issues arising from research in this area is germane to the current discussion. This section provides an overview of such issues.
3.2.1.1 Adaptive Significance of Attentional Processing

The literature on mechanisms of attentional processing suggests that we are capable of focusing on a particular subset of the information available to us at any particular moment and that this focus is important in terms of formulating adaptive behavioural responses. Most theories of attention posit the existence of a filter that serves to limit the amount of information and type of information that reaches conscious awareness (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964). The concept of a filter is important since real-world environments feature a bewildering array of sensory inputs that could easily overload limited cognitive and behavioural resources. Cognitive agents avoid sensory overload by selectively attending to those sources of perceptual input of greatest importance to their ongoing needs and concerns. In this way the frenetic pandemonium of the sensory world is reduced to just a handful of stimulus cues to which a behavioural response is justified. The adaptive value of attentional processing is seen in cases where attentional mechanisms appear to be disrupted. The deficits seen in many neuropsychiatric disorders, most notably schizophreniform psychopathologies, have all been attributed to deficits in the ability to focus attention on a subset of task relevant information. Schizophrenia, for example, has been attributed to the inability to adequately filter information from the incoming information stream (e.g. Cohen et al., 1998). Similarly the cognitive impairments seen following frontal lobe lesions have been attributed to a deficit in a supervisory attentional system or ‘central executive’ (Baddeley, 1986; Baddeley, 1990). According to Shallice (1982), the supervisory attentional system has limited capacity, and is used for a variety of purposes, including: troubleshooting when lower processing systems seem inadequate, tasks requiring planning or decision making, and situations where poorly mastered response sequences are involved. This seems to confirm to the kind of behavioural and cognitive disturbances seen in individuals with frontal lobe damage. For example, Rylander (1939) described the classical frontal syndrome as involving:

“disturbed attention, increased distractibility, a difficulty in grasping the whole of a complicated state of affairs...well able to work along old routine lines...cannot learn to master new types of tasks in new situations.” (pg. 20)

The behavioural and cognitive impairments seen following various types of drug administration have also been attributed to an disturbance in attentional process. Drugs affecting the functional neurotransmission of dopaminergic systems have been observed to produce a constellation of behavioural affects consistent with a disruption in attentional processes or sensorimotor gating. Oades (1985) thus comments that:

“Dopamine promotes the likelihood of switching between alternative sources of information. The act of switching may increase the probability of a new input to a given brain region influencing the output and/or result in an ongoing input being shut off from influencing the output. The effect is likely to be seen either in a change of temporal patterning or a behavioural sequence or in the initiation of a new response.” (pg 262)

It is perhaps significant, in this respect, that our current understanding of schizophrenia implicates a role for central dopaminergic systems, e.g. Snyder (1972). Lesions to the nucleus accumbens, an efferent target of the mesolimbic dopamine system, produce a syndrome of behavioural switching...
that seems to interfere with the normal execution of temporally protracted response sequences (Clifton & Sommerville, 1994; Cromwell & Berridge, 1996; Smart, 1998).

These studies illustrate that attention is essential for protecting the execution of behavioural sequences from distraction by irrelevant stimuli. Distraction, in this sense, is intended to account for a feature of behaviour whereby the completion of a goal-oriented cognitive or behavioural response is disrupted by task-irrelevant stimuli. As such, we would anticipate those behaviours most sensitive to disruption would be those that are extended in the temporal domain, since such behaviours require the continued marshalling of attentional resources to task-relevant stimuli responsible for sustaining the response sequence. As Fuster (1989) comments:

“Perhaps the most consistent and characteristic of all attention disorders resulting from prefrontal damage is the inability to concentrate on any given trend of action or thought. It seems as if the prefrontal patient were unable to actively maintain attention on any behavioural or mental task. Especially vulnerable as a result are all those activities that for the purposes of reaching a goal tax attention in a temporally sustained manner.” (pg 129) [my emphasis]

Consistent with this interpretation prefrontal lesioned animals have been described as excessively distractible, appearing to experience difficulty in suppressing orienting reactions to stimuli, regardless of their motivational value or behavioural relevance (Fuster, 1989).

Attention is also important in terms of avoiding information overload. The notion of information overload implies that that information processing resources of the individual are in some way limited, a recurring theme in the attention literature, and that attention serves as a filter or gate that regulates information flow. Studies of information overload in the context of divided attention tasks have invariably demonstrated compromised performance on tasks involving attention to multiple input streams and the deleterious affects of information overload have been well-documented in the business studies literature (Waddington, 1996). In a recent study commissioned by Hewlett Packard for TNS Research, Glen Wilson reports that the effect of frequent phone calls and emails can compromise performance on a range of problem-solving tasks.\(^{11}\) The study required 80 volunteers to carry out problem-solving in a quiet environment and then in an environment characterized by frequent emails and phone calls. Despite being told to ignore the interruptions, the average IQ of the volunteers dropped by about 10 points. Wilson comments that the information overload resulting from ‘infomania’, or our obsession with modern communications technology, can reduce a person’s ability to focus as much as losing a night’s sleep. The findings of this study highlight the need to carefully regulate the types of information that may impinge on a user so as to avoid unnecessary behavioural switching and disengagement of attentional focus.

To reinforce the point, Jones and Endsley (1996) report that the single most frequent cause of errors associated with situation awareness involved situations where all the needed information was present, but was simply not attended to by the operator. This accounted for 35% of all situation awareness errors and was most frequently attributable to distraction due to other tasks.

\(^{11}\) From issue 2497 of New Scientist magazine, 30 April 2005, page 6
3.2.1.2 Goals
Attention is clearly biased in favour of information of perceived relevance to problem-solving goals. Gugerty (1988), for example, found that drivers paid more attention to cars in front of and near to them than those behind or farther away. Such strategies serve to distribute attentional resources in an manner commensurate with operational goals and problem-solving objectives. Endsley (1995) argues that individual goals serve to influence situation awareness in a number of ways:

- Firstly, active goals direct the selection of mental models appropriate to the current situation (see Section 3.2.3). For example, the goal of ‘diagnose the warning light’ would activate the mental model associated with that particular system and elicit diagnostic behaviour.
- Secondly, the goal and its associated mental model are used to direct attention in selecting information from the environment. They serve to direct scan patterns and information acquisition activities. For this reason, the selection of the correct goals is critical for achieving situation awareness. If the individual is pursuing the wrong goal (or a less important goal), critical information may be missed or not attended to.
- Finally, goals, and their associated mental models, are used to interpret and integrate information so as to achieve comprehension. The goal determines the ‘so-what’ of the information.

Goals serve to influence situation awareness in a top-down, as opposed to a bottom-up fashion. In a bottom-up, data-driven process, environmental features are processed in parallel through pre-attentive sensory stores and cue salience serves to guide the orientation of focal attention. Cue salience, therefore, has a large impact on which portions of the environment are attended to, these elements forming the basis for the first level of situation awareness. In addition, people can operate in a top-down, goal-driven, fashion in which goals serve to influence how attention is directed, how information is perceived, and how it is interpreted. In a top-down decision process, the person’s goals and plans dictate which aspects of the environment are attended to. That information is then integrated and interpreted in light of activate goals to form higher levels of situation awareness. The perception-action cycle (Neisser, 1976) is then closed by action selection mechanisms, implemented against the backdrop of currently active goals, that will align the perceptual environment with a person’s goals based on their understanding of the situation.

3.2.1.3 Expectations
Expectations and preconceptions play an important role in directing attentional processes. People may have certain expectations about what they expect to see or hear in a particular environment, which may be due to mental models, prior experiences, instructions or other communications, etc. These expectations will influence how attention is deployed and how environmental information is perceived. In some situations these expectations can serve to undermine situation awareness, especially if they lead to the activation of inappropriate mental models (representational error). However, expectations may also have positive affects as well. Expectations can improve one’s confidence in otherwise uncertain information, e.g. our expectation that a certain individual is likely to appear in a particular locale can be used to improve the certainty associated with ambiguous biometric signature information. In addition, expectations raised by prior information, e.g. mission briefings, can be invaluable in terms of orienting attention to relevant subsets of environmental stimuli. Moreover, Jones (1997) found that the absence of expected cues was highly successful in
3.2.1.4 Background Knowledge

Background knowledge may be important in understanding the long-term relevance of information in terms of operational goals. For instance, information that currently appears irrelevant may nevertheless have predictive significance in terms of the later occurrence of events that are relevant. The recognition of these cues therefore supports the execution of pre-emptive or preparatory actions that can prevent the occurrence of undesirable events and propitiate the occurrence of favourable ones. Any knowledge filtration process needs to account for the predictive relationships that inhere in the problem domain and ensure that information of predictive relevance is presented to the operator.

3.2.1.5 Workload

Workload may have a variety of affects on situation awareness in terms of narrowing the attentional filter such that less information is perceived and processed. Taylor (1990) includes a consideration of supply and demand of cognitive resources as central to situation awareness, while Adams et al (1995) also discuss task management problems related to work-load in terms of task prioritisation and task scheduling. Workload factors may be expected to impact on the amount of effort invested in the processing of stimuli and this has implications for the empirical evaluation of situation awareness. Following Tyler et al’s (1979) refinement of the ‘levels of processing’ theory (Craik & Lockhart, 1972), it seems entirely appropriate that the mnemonic retrieval of information may be related to the amount of initial effort spent processing such information. In this case we would expect any manipulation that reduced workload, including automated fusion-related processes, to negatively affect the recall of situation-relevant information without necessarily compromising situation awareness. Such issues were discussed in relation to recent empirical research within the DIF DTC that attempts to measure situation awareness in different fusion conditions (see Section 2.3). In fact high workload loads may produce theoretical increments and decrements in mnemonic recall ability within the framework of the ‘levels of processing’ theory. Firstly, an operator may be unable to devote as much effort in processing specific stimuli because the task demands dilute the distribution of cognitive effort across multiple stimulus configurations or task contexts. Secondly, situations of high workload may force operators to process specific stimuli to a greater depth than would otherwise have been the case, thereby improving mnemonic recall. While the impact of high-workload levels are generally considered to undermine situation awareness, it is also important to remember that low workload levels may also affect situation awareness in a negative manner. Such affects may be attributable to problems with vigilance and sustained attention. The precise relationship between workload level and situation awareness, particularly in terms of the theoretical impact on assessments of operator situation awareness, is therefore unclear and further investigation is required to address these issues.

In simple situations or in situations of low workload it may be relatively easy for human operators to maintain optimal situation awareness. For more complicated scenarios it is apparent that one can no longer rely on human operators to perform the entire situation awareness task alone. Some form of knowledge-based approach is desired in such situations. Knowledge technologies can assist with the processes of filtering information (contextual relevance reasoning), facilitation of fusion processes, and inferring features of entities and their relational dependencies. They may also involve some
degree of decision support, i.e. some aspects of the operator’s task commitments are undertaken by automated processes as a means of easing operator workload.

3.2.1.6 Emotional State
Cognitive psychologists have argued that emotional state can exert a profound influence on attentional processing. Eysenck (1992) thus proposed that anxiety can influence attentional processes in a number of ways including:

- **Selective attentional bias**: anxious individuals are likely to selectively attend to threat-related stimuli
- **Distractibility**: anxiety promotes distractibility in which individuals cannot avoid attending to task-irrelevant stimuli
- **Attentional breadth**: anxiety causes a narrowing of the attentional filter limiting the amount of the information that can be attended to
- **Interpretive bias**: anxiety promotes a form of interpretive bias characterized by the tendency to interpret ambiguous stimuli and situations in a threatening fashion

These ideas have been largely supported by empirical studies (see Eysenck, 1992; for a review). To the extent that military operations are undertaken in anxiogenic situations, some of the issues relating to the impact on anxiety on attentional processing may be of relevance to the current project. We aim to address these issues from a technological perspective, i.e. by adopting technologies that mitigate against the processing limitations and interpretative biases that have been found in the cognitive psychology literature.

3.2.1.7 Switching Attention
Just as important as the need to maintain attention on a subset of relevant stimuli is the need to switch attention to new sources of information. One of the limitations of Broadbent’s (1958) model is its failure to account for the variety of factors that promote a shift in attentional focus. In certain situations unattended information can disrupt the focus of attention and such shifts of clearly of adaptive value in terms of responding to information of greater importance than that which is the current subject of focal attention. Moray (1959), and later Wood & Cowan (1995), found that subjects would respond to the sound of their name if it was presented in a stream of unattended information. Such findings seem to suggest that the significance of information is evaluated at an early stage in the processing cycle and that unattended information can promote attentional shifts if it is of sufficient perceptual (and perhaps semantic) salience. We are all aware of this process in the form of the ‘cocktail party phenomenon’, i.e. our attentional focus to a speaker in a crowded room is momentarily interrupted when we hear someone calling our name from a previously unattended information source. Further evidence suggests that such pre-processing of unattended information can be considerably complex. For example, Corteen and Wood (1972) and Corteen and Dunn (1973) conducted a series of studies using the galvanic skin response to measure responses to the name of cities, previously paired with electric shock, in an unattended input stream. In spite of the fact that participants denied awareness of any words in the unattended channel, shock-associated words produced a pronounced GSR. In addition, the GSR was preserved when subjects were presented with the names of cities that had not been previously paired with electric shock. This suggests that unconscious processing of unattended information can involve semantic generalization, which is suggestive of a greater level of processing than that proposed by Broadbent’s model.
Other factors that promote a shift in attentional focus include enduring dispositions and momentary intentions, both discussed in the context of Kahneman’s capacity model of attention (Kahneman, 1973). Enduring dispositions are responses to external stimuli, which are outside voluntary control, such as shifting attention to a nearby conversation when one’s name is unexpectedly mentioned. Momentary intentions are voluntary shifts in attention, typically motivated by a need to acquire further information. Such voluntary shifts in attentional focus are important in the context of the current initiative because of the need to facilitate the active acquisition of information. Such ‘information foraging’ activities are usually undertaken to improve one’s understanding of current events or to determine whether an event with particular features has actually occurred.

Shifts in attentional processing are clearly adaptive in some contexts, but it is important to counterbalance this functionality with the concerns caused by overloading limited capacity processes. In the context of our own development work the key issue, in light of this discussion, concerns the need to evaluate and filter incoming information so as to limit disturbances to ongoing information processes without rejecting information that may warrant a shift in attentional focus. The attention literature suggests that a variety of factors may elicit a shift in attentional processing including, enduring dispositions, momentary intentions and goal states, but in the context of most problem-solving tasks such automatic shifts are not necessarily motivated by the mere receipt of information. This issue raises concerns about how best to implement interface devices that alert the operator to the occurrence of important events, thereby prompting a disruption in ongoing attentional processes.

3.2.2 Working Memory

Working memory capacity is a potential limiting factor in situation awareness. The need to combine, interpret and evaluate information in working memory suggests that working memory limitations may compromise situation awareness, especially under conditions of high-workload. This is reflected in the errors associated with situation awareness wherein information is initially perceived and subsequently forgotten, typically as a result of task distractions and interruptions. Jones and Endsley (1996) report that 8.4% of errors associated with situation awareness could be attributed to displacement or decay of information from working memory as a result of such distractions.

In the face of limited working memory resources, operators often resort to strategies to reduce working memory load. Dorso and Grunland (1999) outline four strategies actively used by operators to reduce working memory load associated with situation awareness, including

- information prioritisation
- chunking
- ‘gistification’ of information (such as only encoding the most relevant values of information items)
- environmental restructuring (i.e. imposing structure on the external environment so as to provide mnemonic cues)

Endsley (1995) found that experienced pilots could report on information relevant to situation awareness for as long as five to six minutes following freezes in an aircraft simulation without the kind of memory decay that would typically be expected in a working memory-dependent mechanism. Such results argue in favour of the cognitive model proposed by Cowan (1988) in which working
memory is represented as an activated subset of the contents of long term memory. Cowan (1988) argued that information proceeds directly from sensory memory to long term memory where it is subject to pattern recognition, coding and interpretation. Those portions of the environment that are relevant to ongoing tasks therefore exist in working memory as an activated subset of the long term memory store.

3.2.3 Long Term Memory, Mental Models and Schemata

Long term memory in the form of mental models is deemed to play a significant role in achieving and maintaining situation awareness (Endsley, 2000). The notion of a mental model is intended to reflect the conceptual representation of the operational environment or the monitored system in the mind of the operator. The mental model is instrumental in terms facilitating comprehension and adaptive behavioural responsivity to situation-relevant contingencies. In particular, the mental model is deemed to provide a mechanism for:

- orienting attention to relevant aspects of the situation
- the integration and comprehension of information
- the projection of future states of the system based on current information and an understanding of system dynamics (this relates to the ability to predict and understand the implications of the current situation in terms of future events)

The concept of a mental model is closely related to the notion of a schema (e.g. Schank, 1972). The schema is equivalent to a situation model, which captures the essential form and structure of situation-relevant information. The actual elements of a situation, reflecting the contents of situation awareness (the mental model), can, within this theoretical formulation, be cast as specific instances of the currently active schema. Such instantiation permits certain forms of ‘automatic’ knowledge-based inference, e.g. the automatic specification of default values for concept attributes (the default speed for a Eurofighter 2000 aircraft is 500 knots) and constraints regarding relational dependencies (a brigade is a type of military unit). Schemata stored in long-term memory are deemed to be relevant to situation awareness in a number of ways (see Figure 3.2)
Once acquired, schemas may be activated by the perception of environmental cues indicative of particular types of situation. The activation of a particular schema can serve to make sense of ambiguous or noisy information and, in some cases, schemas may be associated with stereotypical action sequences, or scripts (see Schank & Abelson, 1977), that enable the instant retrieval of appropriate actions from memory. The ability of such associations to provide for very rapid decision making has been noted by Klein (1989) and schemas are generally considered of quintessential significance in the establishment and maintenance of situation awareness.

Mental models and schemata\(^\text{12}\) are central to most discussions of situation awareness and decision-making, particularly in naturalistic contexts (Zsambok & Klein, 1997). Schemata drive the establishment of better mental models of a situation, which in turn yields greater levels of situation awareness and better decision-making ability. Schemata are cognitive structures that subserve a variety of functions relevant to adaptive patterns of decision-making and action selection. Neisser (1976) argues that schemata:

1. direct external information search
2. specify which available information will be attended to and which information will be ignored
3. organize information in memory
4. direct the retrieval of information from memory

\(^\text{12}\) Following Neisser (1976) we distinguish schemata from mental models. The term mental model is reserved for situation specific representations, whereas the notion of a schema refers to an abstract, generic conceptualisation of situations in terms of their common characteristics.
5. become more differentiated as a function of experience

Similarly, Endsley (1997) argues that in the case of situation awareness a schema can provide:

- knowledge of the relevant elements of the system that can be used in directing attention and classifying information in the perception process;
- a means of integrating elements to form an understanding of their meaning;
- a mechanism for projecting future states of the system based on its current state and an understanding of its dynamics;
- a means of establishing expectations regarding future states of the environment (indicating what to expect as well as what not to expect) based on the projection mechanisms of the model.

Serfaty et al. (1997) argue that schemas assist battlefield commanders in building an understanding of the situation, allowing experts to organize available information in a meaningful way. Schemata may provide default information for decision-makers, that allows them to cope with missing or incomplete information. These default values (expected characteristics of elements based on their conceptual classification) may be used by experts to maintain reasonable levels of performance in situations that easily thwart the decision-making efforts of individuals with less well developed schemata. Default information may furnish an important coping mechanism for experts in forming situation awareness in many challenging domains where information is missing or information overload prevents them from acquiring all the information they need. Schema activation can also be useful in terms of guiding further information retrieval in order to fill in the missing details associated with a mental model derived from the schema and available information. Once instantiated the mental model can then be used to select between alternative decision options, some of which may have become associated with the schema through training and experience:

“This initial representation is associated with possible course of action and, as such, helps the expert to focus immediately on the most critical aspects of the situation, to ask the right questions, and to gather the most relevant information. This information is then used a richer mental model that captures the situation dynamics in both space and time, and enables the expert to visualize the outcomes of possible course of action.” (Serfaty et al., 1997; pg. 237)

Differences in schemata have been proposed to account for the relative differences between experts and novices while performing tasks that depend on situation awareness (Lipshitz & Shaul, 1997). The central argument here is that experts are able to make better decisions because they are able to construct more accurate and comprehensive mental models of the situation. Many of the purported differences in the behaviour of experts and novices when confronted with a task environment, incorporating elements of both situation awareness and strategic decision making, have been attributed to the effort to derive adequate mental models of a situation (Lipshitz & Shaul, 1997). Experts have been observed to spend more time trying to understand the problem at hand in an effort to build a mental model of the task environment compared to novices (Amalberti & Deblon, 1992; Gott et al., 1986). Experts have also been found to engage in situation assessment tasks, whereas novices are more likely to engage in option evaluation (Calderwood et al., 1988). In addition, experts are more likely to consider alternative interpretations of a situation and extract information that non-experts are prone to overlook or unable to see (Shanteau, 1988). Finally, it has
been argued that experts collect more information from more sources on more varied aspects of the situation before making a decision (Lipshitz & Shaul, 1997). Lipshitz and Shaul (1997) argue that such differences arise from the schemata used by experts and novices in decision making contexts. Points 1, 2 and 5 of Neisser’s (1976) model account for why experts conduct more detailed information search during situation assessment compared to novices, whilst points 3, 4 and 5 account for why novices repeatedly asked the same information about a situation compared to experts (Lipshitz & Shaul, 1997). A key difference between expert and novice decision makers therefore seems to relate to the greater emphasis on situation assessment for expert problem solvers. In particular the performance of novices seems to be constrained by the nature of the perceptual environment, the information they can immediately glean from the environment via sensory modalities, whereas expert performance seems to rely on mental models and emphasizes an understanding of the situation beyond that which is merely ‘visible’:

“...both experts and novices combined situation assessment with serial option evaluation, but experts conducted more thorough situation assessment and referred to imagined friendly and enemy actions, whereas novices focused on their own actions and reacted to the display on their screens.” (Lipshitz & Shaul, 1997; pg. 297)

Experts should therefore develop high-fidelity mental models that accurately reflect the current situation and which are indicative of greater levels of situation awareness. This greater understanding of the situation enables experts to coordinate their response outcomes with the actual situation on the ground rather than the limited and partial view of reality provided by intermediary sensor devices and representations. Note that the finding that experts engage in more situation assessment is largely inconsistent with Klein’s (1997) RPD model in the sense that it implies experts will only seek further information about the environment when:

- the decision maker cannot recognize the situation, that is, identify plausible goals, relevant cues, expectancies and a typical course of action
- some of the decision maker’s expectancies are violated
- the decision maker envisions that a course of action fails in a mental simulation

Lipschitz and Shaul (1997) thus argue that the RPD model is deficient in this respect and that Neisser’s (1976) schema theory can be used to provide explanatory leverage in accounting for differences between expert and novices on decision making tasks involving situation awareness. In particular, is probably important to bear in mind that much of expert decision making competency relates to the need to activate appropriate schematic representations in order to establish a mental model of the current situation that may then be used to facilitate the execution of appropriate action sequences by situation recognition-primed action selection mechanisms.

Schemata are central to the notions of recognition-primed decision making. We have seen (Section 2.1.2) that one strategy adopted by experts in naturalistic decision-making context is the process of situation diagnosis (Klein, 1997). Situation diagnosis features both feature matching and story building techniques, with the former being the most prevalent (Kaempf et al., 1992). Feature

---

Presumably novices are unable to encode, store and retrieve information as efficiently as experts owing to underdeveloped schemata.
matching is essentially akin to pattern recognition, in that a pattern of activity is recognized as being sufficiently similar to a previous experience to motivate action on the part of the decision maker. Story building, however, occurs when the current situation is not sufficiently similar to previous experiences, thereby failing to activate an existing situation template or schema. As a result of the failure to activate an existing schema, the decision maker constructs a causal explanation for the current circumstances, based on domain specific background knowledge and, perhaps, bodies of commonsense knowledge. Schemata are important in terms of the mental simulation processes that accompanies situation diagnosis (and evaluation of courses of action) because they indicate what is likely to happen in the future, based on previous encounters with similar situations. They also serve as the basis for constructing explanatory accounts of the current situation because the decision maker is able to fall back on previous experiences that gave rise to the current set of situation contingencies.

The mechanism by which schemata are activated by sets of environmental information is somewhat problematic. The crucial factor seems to rest on the ability of the individual to recognize key features of the environment – critical cues – that will map to key features in the activated schema. The identification and recognition of these cues may be an inherent aspect of the relative ability differential between expert and novice problem solvers. As Endsley (1997) comments:

“The cues used to achieve these classifications are very important to SA [situation awareness]. With higher levels of expertise, people appear to develop knowledge of critical cues in the environment that allow them to make very fine classifications. (pg. 276)

The relative salience of critical cues is something that speaks directly to knowledge-based system development initiatives that aim to improve situation awareness and decision-making competency. The requirement, it would seem, is to highlight critical cues in such a manner that they are processed with high priority by observers and so lead to the rapid activation of appropriate schematic representations of the current situation. The ability to classify sets of environmental information with respect to a conceptual cartography of the problem domain is critical to schema activation. Well developed schemata support very fine categorizations and may enable an expert to cope with very noisy or incomplete data sets. The importance of this mechanism has led some researchers to advocate the use of hybrid, neuro-symbolic models for decision making in which situation recognition and classification is performed by a neural network that subsequently distributes classification outcomes to symbol-level processors (Smith & Marshall, 1997). Again this is something that makes sensible contact with ontological approaches to knowledge-driven situation awareness applications since the ontological infrastructure provides the basis for classification decisions in terms of conceptual taxonomies associated with the domain. As well as facilitating initial classifications, such processes facilitate the activation of appropriate schemas by presenting the user with a semantically-refined data set, the components of which can be mapped to various schemata and used to establish a mental model of the current situation.

Schema activation serves to facilitate problem-solving activity because goals and scripts, associated with the schema, can be rapidly deployed to the situation at hand, without requiring a process of option evaluation and exhaustive problem space search. In some cases, a set of action sequences may become part of the normal response to a situation of a particular type, perhaps mediated by
the proceduralization method described by Anderson (1982) as part of an agent’s knowledge compilation capabilities. However, schema may also serve to activate particular goals, representing intermediary problem-solving steps that must be resolved, perhaps via more analytic problem solving strategies such as means-end analysis, en route to the realization of a more global task objective. Such goals can further serve to constrain attention and influence information gathering strategies underpinning a more refined level of situation awareness required for goal realization.

Unfortunately, every silver lining has a cloud, and the same is true of the role played by schemata in situation awareness. Essentially, schemata may serve to undermine situation awareness in some circumstances. Fracker (1988) thus notes that while schemas may be very useful for facilitating situation assessment by providing a reduction in working memory demands, they can also lead to significant problems in terms of biasing the selection and interpretation of information. In a study aimed at investigating the impact of mental models on the development of situation awareness, Jones (1997) reported that the inappropriate activation of a mental model (resulting in a mental model not representative of the current situation - a phenomenon typically known as representational error) caused operators to misinterpret incoming cues and information. Once activated, schemas proved profoundly resilient in terms of their subsequent displacement by more appropriate mental models. For instance, when conflicting information was presented, operators developed elaborate stories to account for the inconsistent information, preferring to discount conflicting information rather than revise their mental model of the situation. Psychological mechanisms of anchoring and confirmation clearly come into play here and may contribute to a number of performance errors related to situation awareness.

3.2.4 Automatic Processing

With experience, the pattern-recognition/action-selection sequence, inherent to the RPD model, can become highly routinized contributing to a level of automaticity (Logan, 1988). Automaticity provides a mechanism for good performance with low attention overheads in well understood environments. In this sense, automaticity can positively affect situation awareness by reducing demands on attentional resources; however, it can also adversely affect performance by reducing responsivity to novel task-relevant stimuli. Endsley (2000) suggests that the negative impact of automaticity is manifested through a number of distinct processes, including:

- lack of responsivity to novel events
- inability to modify learned response patterns in the face of highly dynamic situations
- attenuation of fusion processes related to the integration of information in novel and performance-enhancing ways

A discussion of automaticity reminds us of the issues relating to the role played by conscious awareness in situation awareness. Clearly conscious awareness is not required for successful performance in all situations (e.g. think of the case of driving a car), but the extent to which subconscious processing of information can impact performance is unclear. Early models of automatic processing in the attention literature suggested that the semantic significance of unattended information was limited and this underpins the aforementioned limitations of automatic processing outlined by Endsley (2000). Some studies, however, suggest that unattended information can be subject to semantic processing (Corteen & Dunn, 1973; Corteen & Wood, 1972) and, as such may serve to promote adaptive attentional shifts that are relevant to task objectives.
3.3 Action

It is critical to note that although the structure of this section would seem to imply that situation awareness is a process rooted in the passive perception and processing of environmental information, this is not entirely accurate. Crucially, operators can influence situation awareness in the form of a variety of top-down processes. For example, the operator can control what information is displayed by a system by setting a number of configuration parameters and visualization options, each of which affords different perspectives of the state of monitored systems and the environment. In addition, the orientation and direction of sensor systems themselves can be specified against a variety of knowledge-based constraints concerning contextual factors, expectations, epistemic requirements, and an understanding of sensor capabilities and availability. Typically, theories of attention have focused on cognitive processes of filtering information from the input stream, but it is important to bear in mind that behavioural processes may also contribute to this process. An organism may regulate information input by orienting its perceptual apparatus so as to selectively perceive a subset of available information from the environment. Such is the case when we foveate on a particular part of the visual scene to the exclusion of other parts of the visual world. An organism may also use the orientation of sensory systems as a means of introducing physical variables as a means to disambiguate between competing stimuli. We often exploit such a mechanism when listening to a speaker in a noisy environment by orienting one ear towards the speaker, thereby introducing a physical disparity in terms of the time-dependent processing of acoustic information from each ear. Organisms may also structure their environment in ways that promote attention to stimuli at critical junctures in a larger problem-solving task, e.g. highlighting words or phrases in source materials (or physically rearranging source materials) as a means of facilitating the process of writing a technical paper\textsuperscript{14}. Operators may also resort to a variety of information acquisition and ‘information foraging’ activities in order to address perceived knowledge gaps or to test hypotheses about the state of the monitored system. Finally, the social and communicative networks in which people participate establishes a supportive framework for knowledge transfer and collaborative problem-solving activities that can address shortcomings in individual levels of situation awareness.

The crucial point from an action-oriented perspective is that situation awareness is very much an ‘active’ process with perception guiding action and action influencing what is perceived. Such notions are already explicit in the psychological literature. Neisser (1976), for example, refers to the perception-action cycle (see Figure 3.3) as a process wherein the receipt of information can serve to guide information acquisition processes that in turn influence what is perceived and such theories have been readily adopted by the situation awareness community (e.g. Adams et al., 1995).

\textsuperscript{14} Another kind of ‘in-built’ attentional mechanism may be seen in the way in which an organism’s perception is selectively skewed to specific aspects of the external environment.
The overriding concern, it seems, is that factors such as sensor deployment, use and configuration all reflect the information and epistemic requirements of different user groups. If information and knowledge gaps have been identified with respect to current levels of situation awareness (reflecting perhaps the kind of processes inherent in Level 4 information fusion), then these need to be addressed in the form of a variety of remedial activities, including:

- Information foraging
- Environmental restructuring
- Sensor re-orientation, configuration and re-purposing
- Hypothesis testing
- Information sharing and collaboration

Of course, knowledge requirements and operational goals may change throughout the lifecycle of a mission and in response to changes in operational/mission context. This again has a significant impact in terms of the implementation of specific information gathering activities.

### 3.4 Summary

This section has presented an overview of the cognitive psychology literature as it relates to the notion of situation awareness. We have outlined a variety of processes subtending all levels of the perceptuo-motor hierarchy, but with a selective focus on cognitive processes. The discussion has raised a number of important issues relating to the design and implementation of knowledge-based systems for information fusion and situation awareness. As such this discussion may be useful in terms of constraining design decisions about the kind of user interfaces developed for the current
application. It also serves to highlight a number of theoretical issues related to the most appropriate way to exploit Semantic Web technologies in subservience of knowledge-filtration processes.
4 Requirements Analysis

This section presents the results of a requirements analysis based on the material presented in Sections 2 and 3. The requirements relate directly to issues of situation awareness or they describe pre-conditions for measuring situation awareness and improved operational effectiveness. In some cases the relationship is indirect, e.g. attempts to manage information overload that may disrupt or hinder situation awareness and understanding. Each requirement is described in terms of:

- **Label**: the textual label used to refer to the requirement
- **Number**: a numeric identifier assigned to the requirement
- **Priority**: the importance of the requirement: high, medium, low.
- **Description**: a textual description of the requirement

<table>
<thead>
<tr>
<th>Label:</th>
<th>Ability to view the past, present and future situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>1</td>
</tr>
<tr>
<td>Description:</td>
<td>The ability to view the current situation in respect of previous events is important in terms of understanding the current situation. The capability is particularly relevant to decision making in naturalistic contexts, which features aspects of both mental simulation and story building. The user should be able to view a projection (prediction) of the current situation into the future based on background knowledge about the dynamics of situation contingencies.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Explanations surrounding the existence and information state of entities and events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>2</td>
</tr>
<tr>
<td>Description:</td>
<td>This requirement relates to the ability to explain why the current situation is the way it is in terms of the information sources from which situation-relevant information was derived. In the cases of inferences the system should provide an explanation of why a inference was made based on the knowledge infrastructure of the application and the set of information items over which the inference was made. The system should attempt to account for existence of all elements of the situation in terms of their conceptual classification and featural characterization as a means of improving a user’s understanding of the situation.</td>
</tr>
<tr>
<td>Label:</td>
<td>Good time-constrained behaviour</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Number:</strong></td>
<td><strong>3</strong></td>
</tr>
<tr>
<td><strong>Priority:</strong></td>
<td><strong>High</strong></td>
</tr>
<tr>
<td><strong>Description:</strong></td>
<td>The system should support the rapid retrieval of information from various sources and execute inferential and fusion-based processes as quickly as possible. Because certain computations will have to provide an answer within a limited time period, computing in time-constrained environments is of importance. Unfortunately, many of the reasoning methods used by extant decision-support systems do not necessarily have good time-constrained behaviour. Therefore techniques for performing reasoning within a certain timeframe are likely to be critical in the development of decision-support aids in applications that demand real-time behaviour.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Classification of situation elements in a semantically-coherent fashion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number:</strong></td>
<td><strong>4</strong></td>
</tr>
<tr>
<td><strong>Priority:</strong></td>
<td><strong>High</strong></td>
</tr>
<tr>
<td><strong>Description:</strong></td>
<td>The system should be able to interpret the semantic significance of events and entities in terms of the ontology developed for the domain. At a practical level this means classifying elements based on, perhaps limited, information so that their conceptual categorization is made explicit to the operator. This capability is aimed at improving the rapid recognition and classification of a situation as the basis for recognition-primed decision making.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Dynamic modification of cue salience</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number:</strong></td>
<td><strong>5</strong></td>
</tr>
<tr>
<td><strong>Priority:</strong></td>
<td><strong>High</strong></td>
</tr>
<tr>
<td><strong>Description:</strong></td>
<td>This requirement relates to the ability to highlight critical features of the situation in an appropriate attention-attracting manner. Cue salience should be related to the relative importance of situation information in terms of current operational goals and ongoing task commitments. Examples may include the occurrence of unexpected events or information states of perceived critical relevance. Reasoning processes will need to be deployed to determine the degree of salience assigned to environmental information against the backdrop of the operator’s operational and mission foci. The notion of expectation may be critical here. An understanding of situation dynamics allows an agent to establish certain expectancies based on projection mechanisms. When they do not match because values of some parameter are different, an event occurs that should not, or an event does not occur that should, this signals that something is wrong, and indicates a need for change in goals, plans or revisions of one’s current understanding of a situation.</td>
</tr>
</tbody>
</table>
### Situation recognition and classification

**Number:** 6  
**Priority:** Medium

**Description:** The system should avail itself of the capacity to recognize the similarity of the current situation to previous, prototypical situations. The notion of typicality will be difficult to determine and may require careful attention to the level of abstraction used in representing the elements if a situation. Case-based reasoning approaches may be useful here, although it may that symbolic-level descriptions of the environment are unsuited to this kind of recognition/classification capability. This has prompted some researchers to adopt hybrid neuro-symbolic approaches wherein the task of situation classification is delegated to a neural network, which mediates classification decisions to symbol-level knowledge processors (Smith & Marshall, 1997).

### Support for flexible modes of interaction and visualization

**Number:** 7  
**Priority:** High

**Description:** The system should provide a flexible and adaptable mode of visualization and interaction that is necessarily independent of the knowledge/information infrastructure. Visualization and interaction strategies may be constrained with respect to device display limitations or the selective preference for certain forms of visualization, e.g. NATO symbology. It will be important to make sensible contact with existing modes and styles of information presentation since, in some cases at least, the interaction with a variety of interface devices may become an intrinsic part of problem-solving performance acquired through training and in-theatre operation.

### Knowledge-based information filtration and information triage

**Number:** 8  
**Priority:** High

**Description:** It will be important to restrict the kind of information that is disseminated to various agencies based on the relevance of that information to operational goals and task commitments. The system should avail itself of a mechanism of contextual relevance reasoning in which all information is assessed with respect to dimensions of contextual relevance.
<table>
<thead>
<tr>
<th>Label: Library of semantic-level queries</th>
<th>Number:</th>
<th>Priority:</th>
<th>Description: The system should maintain a library of semantic queries that represent the knowledge filters used in contextual relevance reasoning. A library of existing queries of query templates will enable operators to select pre-existing queries based on previous experiences and operational roles.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The ability to modify and adapt pre-existing queries as well as create new queries</td>
<td>Number:</td>
<td>Priority:</td>
<td>Description: As an expression of an operator’s epistemic requirements and information monitoring goals, the process of adapting and creating semantic queries should be relatively easy, requiring little or no special-purpose training. A query-builder could assist the operator in creating new queries to fit their current task demands.</td>
</tr>
<tr>
<td>Ability to select and retrieve semantic queries relevant to current tasks</td>
<td>Number:</td>
<td>Priority:</td>
<td>Description: Semantic queries should be annotated and represented in such a way that the query library can be browsed and queries selected based on semantic constraints.</td>
</tr>
<tr>
<td>Ability to re-factor the information space</td>
<td>Number:</td>
<td>Priority:</td>
<td>Description: End users should be able to dynamically modify the knowledge infrastructure to meet current requirements, address inadequacies and contribute to the epistemic enrichment of the application.</td>
</tr>
<tr>
<td>Visualization and communication of ontology elements</td>
<td>Number:</td>
<td>Priority:</td>
<td>Description: End users should be able to visualize and interact with the knowledge infrastructure of the application in a manner that little training in knowledge engineering techniques and which facilitates understanding and communication between a variety of different stakeholders.</td>
</tr>
<tr>
<td>Label:</td>
<td>Semantic querying and information pull</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number:</td>
<td>14</td>
<td>Priority: High</td>
<td></td>
</tr>
<tr>
<td>Description:</td>
<td>The system should allow end users to query the knowledge base in a manner that closely aligns itself with the kind of conceptual distinctions made in the domain. In other words the system should enable users to retrieve information in an ad hoc manner using queries that are semantically aligned with the elements of the ontology infrastructure.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Intimate epistemic contact between users and knowledge infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>15</td>
</tr>
<tr>
<td>Description:</td>
<td>The user should be able to interact with the knowledge system and receive information in a manner that closely aligns itself with the cognitive/perceptual capabilities of the end user agent. Ideally, information retrieval and assimilation capabilities should be as effortless as accessing information from one’s long term memory stores. The emphasis here is on investigating better ways to exploit cognitive technology in the form of visualization strategies and better modes of interaction to support an augmented epistemic profile and improved operational effectiveness. A key psychological question is whether the closer alignment of cognitive technologies with our cognitive and perceptual apparatus is sufficient to yield a fundamental shift in our distribution of epistemic credit at both the social and subjective level.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Selective visualization of situation elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>16</td>
</tr>
<tr>
<td>Description:</td>
<td>The visualization afforded to users should enable them filter the display with respect to semantic criteria, perhaps exploiting a conceptual taxonomy. For example, the operator should be able to specify that they only want to view blue force airborne elements or the disposition of enemy assets.</td>
</tr>
<tr>
<td>Label:</td>
<td>Exploitation of ontology infrastructure to enrich knowledge about situation elements</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Number:</td>
<td>17</td>
</tr>
<tr>
<td>Description:</td>
<td>The system should maximally exploit background knowledge to infer the characteristics of entities or determine their inter-relationship with other entities, especially in situations where this information is not readily accessible or when dealing with noisy and incomplete data sets. The ability to compute relationships between entities is a key feature of Level 2 Data Fusion and may help to circumvent some of the differences between novices and experts with respect to situation awareness tasks. For example, research indicates that experts extract information that non-experts are likely to overlook or are unable to see (Shanteau, 1988) and novices restrict their situation assessment and decision-making processes to what is immediately ‘visible’ via display mediums (Lipshitz &amp; Shaul, 1997).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Support for testing the inferential and operational integrity of the knowledge system component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>18</td>
</tr>
<tr>
<td>Description:</td>
<td>For the purposes of assessing the inferential integrity and knowledge capabilities of the system a distinction should be made between the actual situation and the ‘perceived’ situation. The perceived situation corresponds to the system’s interpretation of the situation-on-the-ground- based on the information reports, message feeds and information content it is able to glean from external information sources. The actual situation corresponds to a ‘God’s-eye’ view of the scenario in which complete knowledge about the situation is available.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Semantic enrichment of situation elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>19</td>
</tr>
<tr>
<td>Description:</td>
<td>In order to promote an operator’s understanding of the current situation the system should make explicit the semantic significance and relevance of perceived situation elements. This includes alignment with conceptual representations and an explicit specification of the relationships with other entities and events.</td>
</tr>
<tr>
<td>Label:</td>
<td>Support for certainty, provenance and trust</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Number:</td>
<td>20</td>
</tr>
<tr>
<td>Description:</td>
<td>The system should provide support for dealing effectively with uncertainty and trust issues. Notions of trust will form the basis for initial certainty estimates applied to information gleaned from a variety of physically disparate and semantically heterogeneous information sources, e.g. host sensors, tactical datalinks, institutional websites, news agency reports, online databases, etc. Knowledge-based processes must deal with issues of trust by countenancing the selection of information from trustworthy sources and dynamically evaluating the trust model in response to the temporal evolution of the battlespace environment. One problem concerns how to implement a certainty model in which the values are constantly changing. This is problematic in terms of dynamic systems modelling because the certainty values will often be susceptible to time-dependent decay, e.g. one’s certainty in the position of a moving object is dependent on the amount of time that has elapsed since positional information was last updated. Equally problematic in terms of fusion-based systems, and knowledge systems more generally, is an understanding of how trust and certainty information propagates along (sometimes complex) chains of inference execution. Given a set of information items that differ in terms of their relative reliability, accuracy and certainty, the problem is what level of certainty to assign to the outputs of the fusion process that executes over these items, and how do these values change in subsequent execution cycles.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Exploitation and integration of physically disparate and semantically heterogeneous information sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>21</td>
</tr>
<tr>
<td>Description:</td>
<td>The system should enable the effective exploitation and integration of information from diverse information sources with respect to a common semantic frame of reference. The variety of information sources exploited in the context of the future strategic battlespace will extend well beyond those encountered in traditional battlespace environments, with its emphasis on geographically-delimited theatres of operation and symmetric adversaries. The system will need to access and harvest information from information sources as diverse as institutional websites, online database, geographic and meteorological services, etc. As such, we need to consider a range of techniques for content acquisition relating to natural language processing (e.g. <a href="http://gate.ac.uk/">http://gate.ac.uk/</a>) and the scraping of publicly available data from various websites. The system will also need to possess facilities for fusing or integrating the information derived from these sources, e.g. to recognize that information derived from different sources all refer to the same entity.</td>
</tr>
<tr>
<td>Label:</td>
<td>Semantic integration across the functional interfaces of the land, air and maritime environments</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Number:</td>
<td>22</td>
</tr>
<tr>
<td>Priority:</td>
<td>Medium</td>
</tr>
<tr>
<td>Description:</td>
<td>The system be able to interpret the semantic significance and integrate the information from conventional communications systems used by the land, air and maritime operational environments, e.g. Link 16 and BOWMAN, so as to provide a common view of the operational environment (CROP).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Support for semantic inter-operability and information exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>23</td>
</tr>
<tr>
<td>Priority:</td>
<td>High</td>
</tr>
<tr>
<td>Description:</td>
<td>The vision of network-enabled capability and joint service operations requires a common understanding of the current operational context and the prevailing tactical situation. The emphasis here is on shared situation awareness. However, in order to be useful the information made available by network infrastructures needs to be interpreted with respect to common semantic frame of reference. The aim is to develop a ‘common understanding’ of the operational environment, not merely just a common visualization. The issue of semantic inter-operability requires an ability to establish mappings between the conceptual spaces adopted by different elements of the armed forces, e.g. across service components, between coalition allies and across military functions. Such integration can only be established with respect to formal ontological characterizations of the domain that make explicit the meanings of the conceptualisations exploited by various military and non-military agencies.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Support for dynamic service discovery and service integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>24</td>
</tr>
<tr>
<td>Priority:</td>
<td>Medium</td>
</tr>
<tr>
<td>Description:</td>
<td>The key requirement here concerns the need to characterise information sources in such a manner as promotes their dynamic discovery and exploitation in response to situation contingencies. The requirement focuses on the opportunistic discovery of new services that may become available through the operational lifespan of a system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Service composition and orchestration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>25</td>
</tr>
<tr>
<td>Priority:</td>
<td>Medium</td>
</tr>
<tr>
<td>Description:</td>
<td>How we can best enable the inter-operation of these services in a manner that permits the construction of ever more elaborate workflows to meet the demands of increasingly complex service requirements? This requirement addresses the need to represent the capabilities of different service providers in a manner that enables their effective exploitation and inter-operation.</td>
</tr>
</tbody>
</table>
### Support for collaborative problem-solving and knowledge retrieval

**Label:** Support for collaborative problem-solving and knowledge retrieval  
**Number:** 26  
**Priority:** Medium  
**Description:** A crucial feature of operational effectiveness in complex problem-solving environments concerns the exploitation of social networks as a means of bolstering problem-solving competency. In the current context we should aim to facilitate the exchange of information about a situation via social networks and communicative links between individuals that may have different perspectives and information about the current situation. It may be important to model the expertise and operational role of actors in order to identify who has what knowledge and how their expertise/knowledge can be co-opted into the current situation model. This may assume the form of support regarding who should be contacted in what situation and how to establish a communicative link. Consistent with this requirement are research findings that suggest that experts communicated more frequently and elaborately with collaborative agents when trying to develop and understanding of a situation (Lipshitz & Shaul, 1997).

### Decision support facilities

**Label:** Decision support facilities  
**Number:** 27  
**Priority:** Medium  
**Description:** Decision support tools can help reduce the workload burden on operators and thereby permit a more effective distribution of cognitive resources to aspects of the current situation. Partial automation of some aspects of the decision-making process may therefore be valuable to enhanced situation awareness.

### Exploitation of multi-modal interface devices

**Label:** Exploitation of multi-modal interface devices  
**Number:** 28  
**Priority:** Low  
**Description:** The ability to exploit multi-modal forms of information presentation, e.g. verbal as well as visual cues, may prove useful in terms of distributing cognitive load more effectively over multiple modalities, thereby enabling greater assimilation of information whilst avoiding information overload.

### Support for user-driven selection of information sources

**Label:** Support for user-driven selection of information sources  
**Number:** 29  
**Priority:** Medium  
**Description:** The user should be provided with a means to review extent information sources and to dynamically select/de-select which information sources should be used in retrieving information about a situation.
<table>
<thead>
<tr>
<th>Label:</th>
<th>Ability to fuse information and from higher-level abstractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>30</td>
</tr>
<tr>
<td>Description:</td>
<td>The system should be able to establish high-level conceptual abstractions based on information, possibly derived from multiple information sources, e.g. assessing whether an entity represents a threat requires inferences that operate over information such as the location, identity and velocity of the target, as well as contextual information indicating current threat status.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Ability to the assess the long-term strategic relevance of information states and events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>31</td>
</tr>
<tr>
<td>Description:</td>
<td>Background knowledge may be important in understanding the long-term relevance of information in terms of operational goals. For instance, information that currently appears irrelevant may nevertheless have predictive significance in terms of the later occurrence of events that are relevant. The recognition of these cues therefore supports the execution of pre-emptive or preparatory actions that can prevent the occurrence of undesirable events and propitiate the occurrence of favourable ones. Any knowledge filtration process needs to account for the predictive relationships that inhere in the problem domain and ensure that information of predictive relevance is presented to the operator.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Identification of knowledge gaps and advice as to remediation strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>32</td>
</tr>
<tr>
<td>Description:</td>
<td>This requirement relates to Level 4 fusion processes identified in the context of the JDL Data Fusion model. The aim is to identify lacunas in the system’s knowledge of the current situation and to advise as to appropriate remediation strategies that could used for epistemic enrichment. This may include advice as to the need to access certain information sources in particular situations.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Label:</th>
<th>Ability to specify event triggers and subscribe to information sources providing information about the occurrence of particular events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>33</td>
</tr>
<tr>
<td>Description:</td>
<td>It will be important to enable agents to register their interest in particular events and information contingencies that exist in the strategic battlespace environment, e.g. ‘tell me when the value of a particular object-attribute reaches a critical threshold’ or ‘notify me when an event of a particular type occurs in a particular location’.</td>
</tr>
</tbody>
</table>
The system should respect the user’s authority to override the system’s operation in respect of defining or modifying the information state. Military operators, in particular, may wish to override the functionality provided by knowledge-based systems in certain situations and there are good political and legal reasons why the operator’s view is always sacrosanct in these circumstances.

Table 4-1 summarizes the requirements discussed in the current section in terms of their relative priority for implementation activities in the context of the current initiative.
<table>
<thead>
<tr>
<th>Number</th>
<th>Label</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Selective visualization of situation elements</td>
<td>High</td>
</tr>
<tr>
<td>17</td>
<td>Exploitation of ontology infrastructure to enrich knowledge about situation elements</td>
<td>High</td>
</tr>
<tr>
<td>18</td>
<td>Support for testing the inferential and operational integrity of the knowledge system component</td>
<td>Medium</td>
</tr>
<tr>
<td>19</td>
<td>Semantic enrichment of situation elements</td>
<td>High</td>
</tr>
<tr>
<td>20</td>
<td>Support for certainty, provenance and trust</td>
<td>High</td>
</tr>
<tr>
<td>21</td>
<td>Exploitation and integration of physically disparate and semantically heterogeneous information sources</td>
<td>High</td>
</tr>
<tr>
<td>22</td>
<td>Semantic integration across the functional interfaces of the land, air and maritime environments</td>
<td>Medium</td>
</tr>
<tr>
<td>23</td>
<td>Support for semantic inter-operability and information exchange</td>
<td>High</td>
</tr>
<tr>
<td>24</td>
<td>Support for dynamic service discovery and service integration</td>
<td>Medium</td>
</tr>
<tr>
<td>25</td>
<td>Service composition and orchestration</td>
<td>Medium</td>
</tr>
<tr>
<td>26</td>
<td>Support for collaborative problem-solving and knowledge retrieval</td>
<td>Medium</td>
</tr>
<tr>
<td>27</td>
<td>Decision support facilities</td>
<td>Medium</td>
</tr>
<tr>
<td>28</td>
<td>Exploitation of multi-modal interface devices</td>
<td>Low</td>
</tr>
<tr>
<td>29</td>
<td>Support for user-driven selection of information sources</td>
<td>Medium</td>
</tr>
<tr>
<td>30</td>
<td>Ability to fuse information and from higher-level abstractions</td>
<td>High</td>
</tr>
<tr>
<td>31</td>
<td>Ability to the assess the long-term strategic relevance of information states and events</td>
<td>High</td>
</tr>
<tr>
<td>32</td>
<td>Identification of knowledge gaps and advice as to remediation strategies</td>
<td>Low</td>
</tr>
<tr>
<td>33</td>
<td>Ability to specify event triggers and subscribe to information sources providing information about the occurrence of particular events</td>
<td>High</td>
</tr>
<tr>
<td>34</td>
<td>Responsivity to user input</td>
<td>High</td>
</tr>
</tbody>
</table>

*Table 4-1: Summary of System Requirements*
Section 2 provided some operational definitions of situation and knowledge-filtered awareness, while Section 3 discussed issues relating to cognitive processes and their impact on the awareness of events in a given scenario. Section 4 discussed a number of requirements surrounding the development of situation awareness-enhancing systems in regard to knowledge-based systems development initiatives. This section, and the following section, focus more on issues related to the technological realization of such systems against the backdrop of the requirements analysis outlined in Section 4. This section, in particular, focuses on the technological realization of improved situation awareness in the context of the AKTiveSA TDS. The section aims to illustrate how a variety of Semantic Web technologies can be harnessed to subserve the goal of improved situation awareness and how these resources are exploited in the context of a Semantic Web application.

5.1 Existing Systems

An appreciation of the importance of information fusion for enhanced situation awareness has already prompted considerable research into the use of Semantic Web technologies (Baclawski et al., 2003; Matheus et al., 2003; Matheus et al., 2004; Matheus et al., 2005; Matheus et al., 2003; Sycara et al., 2003). Notable among these is the work of Christopher Matheus, Mieczyslaw Kokar and Kenneth Baclawski who describe a formal ontology for situation awareness (see Figure 5.1) as well as SAWA, a system for enhanced situation awareness. SAWA is relevant to the current discussion since it exploits a number of Semantic Web technologies, namely OWL, SWRL and OWL-QL (Fikes et al., 2003) that we intend to use in the context of the current application.

Figure 5.1: SAW Ontology (from Matheus et al., 2005)
SAWA is based on the ability to derive ‘higher-order’ relationships between entities in an operational environment. The idea is provide a domain ontology that captures the objects and relationships of interest in a domain. The user controls the system situation monitoring functionality by specifying ‘standing relations’ or high-level relationships between objects. An operator may, for example, be interested in detecting and monitoring relationships that indicate the threat status of particular entities. In this case, relationships such as ‘firingAt’ or ‘advancingTowards’ become of paramount significance and SAWA permits an operator to select these relationships as the basis for subsequent monitoring activities. The appeal of this approach is that it delegates the computation of such relationships to automated knowledge processes that reduce operator workload while simultaneously attracting attention to information of specific relevance to an operator’s goals and objectives. Nevertheless, the research surrounding the development of SAWA raises a number of concerns, which we have enumerated as part of our review activities. These concerns include:

- The way in which classes, their attributes and relationships are modelled in SAWA deviates from conventional approaches in ontology engineering. In fact SAWA represents relationships and attributes as classes and then depicts their association with situation entities in terms of OWL ObjectProperties. This adds an extra layer of meta-representational primitives to the OWL language that, while appealing from the perspective of subsequent domain-specific modelling, has a number of drawbacks including: the inability to maximally exploit OWL-based inferences, most notably subsumption reasoning, and the difficulty associated with the re-use of existing domain ontologies. The apparent inability to interface with existing ontologies is particularly damaging since it is unlikely that sufficient ontology engineering efforts can be directed to modelling all aspects of the environment relevant to situation awareness, even in military contexts, and the notion that the representational strategy adopted by SAWA can be standardized across the OWL community seems, to us, untenable.

- Reasoning in SAWA seems to be limited to the derivation of relations between objects, it does not seem to avail itself of the capability to infer the existence (or non-existence) of domain objects. This is significant since some of the powers of Semantic Web-based approaches to situation awareness and information fusion would seem to derive from their ability to infer the existence of an object based on available information.

- Closely related to the previous point, is the notion of mechanisms for identity inference. Identity inference (i.e. the ability to infer that two ostensibly different objects are in fact the same) would seem to be of critical significance in information fusion contexts, based on our notions of fusion functionality. The SAWA approach does not readily lend itself to these types of inferential capability, at least in terms of the formal semantics of the OWL specification.

- SAWA seems to assume that the values of attributes, defined for domain objects, are always apparent from the input stream, since its reasoning processes are specifically geared to the computation of ‘higher-order’ relationships. This seems overly optimistic from our standpoint. Occasions may arise when such information is not readily available and may need to be computed or inferred on the basis of existing data. In other words, we argue that inferential capabilities are relevant to all aspects of the knowledge infrastructure and should not be restricted to, perhaps rather arbitrary assumptions, about whether certain types of association or inter-dependence constitute ‘higher-order’ relationships.

- The (over-)emphasis on ‘standing relations’, or ‘higher-order’ relations, entails a further problem in that monitoring capabilities would seem to be much broader than that
heretofore suggested. In particular, we may encounter situations when we need to be alerted as to the existence of particular objects, or when the values of certain attributes reach a critical threshold. Knowledge-filtration processes, in these cases, need to include mechanisms for selecting objects on the basis of their information state, not merely whether they participate in relationships with other objects.

- SAWA provides no mechanism to explain or account for its actions in terms of the reason why a particular decision outcome was reached. This seems to be a critical aspect of knowledge systems, in our view, especially in military domains where the reasons underlying why a particular decision was reached may be almost as important as the nature of the decision itself.

- The SAWA model appears to countenance the assertion of new information based on the order in which it appears in the event stream. This emphasis on ‘chronological recency’ is untenable in our view of information fusion. In some cases, at least, it seems we should focus on the relative reliability or certainty of information as the basis for updating existing information states. We note that many existing fusion processes assume that information sources are equally reliable (Delmotte et al., 1996) and this is clearly unsatisfactory in a situation where information fusion operates over a variety of information sources that differ with respect to their relative reliability. This is particularly apparent in the military domain where operators need to take into account deliberate attempts to sabotage situation awareness and subvert the decision-making process as part of an ‘information warfare’ strategy. Of course, certainty in existing information is clearly time-dependent: the more time that has transpired since the assertion of an information item, the less certain we can be of its accuracy with respect to the current state of the world. This does not, however, mean that more recent information is necessarily more accurate or reliable. Knowledge-based information fusion processes need to account for the time-dependent decay of certainty information and the reliability of new information in an intelligent and adaptive manner.

- Rule-based reasoning in SAWA is restricted to the assertion of new relationship instances (tuples) between existing objects. This seems inadequate from the perspective of implementing more complicated decision support functions that are of essential significance in reducing operator workload. More complicated reasoning processes may need to be defined to assist the operator in this respect, e.g. partially automated mission planning.

- SAWA co-opts a rule-based inference engine in the form of JESS and a rule-representation language in the form of SWRL. The authors note some of the limitations associated with SWRL from a representational perspective and delegate much of the reasoning process to JESS-based mechanisms. While we are generally in support of this strategy, it would seem that the attempt to integrate a, seemingly inadequate, rule-based language (SWRL) with JESS-based reasoning considerably complicates the knowledge engineering process. Future efforts should perhaps reconsider the role played in SWRL and the necessity for its inclusion in the overall process.

- The approach adopted by Matheus et al does not seem to account for the ability of the operator to override existing information or to insist that certain types of informational contingency should not be overridden by the knowledge system. This appears as a significant limitation in respect of our knowledge engineering experience. Military operators, in particular, may wish to override the functionality provided by knowledge-based systems in certain situations and there are good political and legal reasons why the operator’s view is always sacrosanct in these circumstances.
SAWA does not adequately deal with ongoing changes to knowledge requirements particularly well. Certain types of concepts may not be immediately apparent, but may emerge and evolve as a situation progresses. For instance, an operator may want to retrieve information about all earthquakes that have occurred within a given timeframe, are within a certain spatial frame of reference and are of a certain magnitude. This implicitly defines a task-specific conceptualisation that is unlikely to appear in a priori specifications of the domain ontology. The point here is that the concept is not defined in advance and, as such no standing relations that involve this concept can be specified. In these cases what is required, we argue, is a means of dynamically modifying the kind of objects and relationships that feature in a particular situation, while using the existing ontology infrastructure as a supportive framework for these specifications. The notion is implicit in what Shadbolt (2005) has termed ‘refactoring of the information space’. The idea is that specific information requirements may require the ad hoc specification of new concepts and relationships in order to capture information about particular states of the world or to simplify subsequent inference execution and query capabilities. In their defence, Matheus et al (2005) do note that “SAWA provides a flexible querying and monitoring language that can be used to request information about the current situation, predicted situations and request notifications of current or potential future emergency conditions”. It is, however, somewhat difficult to understand what exactly is meant by this statement in terms of the specific query language used. In addition, is it difficult to know whether the query language addresses the kind of issues raised by the need to dynamically ‘refactor the information space’ in the sense in which it is applied here.

Finally, the types of relationships specified in the context of the SAWA system reflect a somewhat limited view of what is important from a monitoring perspective. The focus on relationships seems to ignore the fact that often what is important is not so much the existence of a particular relationship as what objects feature in that relationship. So, for example, the fact that some objects are ‘firingAt’ at other objects in a situation is important, but not necessarily as important as information about which objects are doing the firing and which objects are being shot at! Importantly, the type of objects featuring in these relationships would sometimes seem to be the critical determinant of whether they are legitimate subjects for further attentional processing. Some objects, for instance, may fall outside the responsibility or jurisdiction of an operator at a particular level of the command echelon.

Our own research differs from previous research in a number of important ways. These differences are aimed at addressing some of the aforementioned shortcomings of current research while attempting to push the boundaries of the current state-of-the-art. They include, but are not necessarily limited to the following:

- **Maximal exploitation of OWL-based Semantics**: exploitation of the semantics of the OWL language to support certain types of inference, e.g. subsumption reasoning and identity inference.

- **Exploitation of Existing Ontologies**: ability to interface to and import elements of pre-existing ontologies such as the AKT Reference Ontology\(^{15}\), SUMO\(^{16}\) and DOLCE\(^{17}\).

\(^{15}\) http://www.aktors.org/publications/ontology/
\(^{16}\) http://ontology.teknowledge.com/
\(^{17}\) http://www.loa-cnr.it/DOLCE.html
• **Multi-Level Information Fusion:** fusion processes distributed throughout all levels of the information fusion hierarchy, not necessarily restricted to Level 2 information fusion.

• **Refactoring of the Information Space:** ability to dynamically specify new queries and restructure the conceptual infrastructure of the application to meet problem-solving requirements.

• **Information Acquisition from Physical Distributed and Semantically Heterogeneous Information Sources:** ability to exploit information from a wide variety of diverse information sources.

• **Use of Limited, but Stable, set of Semantic Web Technologies:** preferential selection of common and well-researched Semantic Web technologies, such as RDQL, SPARQL and OWL. In most cases these technologies have been endorsed by the W3C community.

• **Support for Future Coalition Interoperability:** provision of a common semantic framework to support ad hoc trans-national alliances and military coalitions.

• **Focus on Diverse Operational Contexts:** i.e. humanitarian relief.

• **Incorporation of Uncertainty, Information Reliability and Trust Models**

• **Use of Audit Trails and Explanatory Capabilities:** provision of explanatory information underlying the basis for a particular decision or inference.

• **Dynamic Computation of Attribute Values and Relational Contingencies**

### 5.2 Ontologies

Ontologies make an appealing case to facilitate information fusion from heterogeneous data and knowledge sources in support of high-level fusion functionality. The relative benefits of ontologies were outlined in Section 2.2.3.1 and will not be reiterated here. Suffice to say that ontologies buy us significant advantages in terms of semantic integration, decision support, semantic inter-operability and content acquisition. Crucially, they provide the basis for a common semantic frame of reference for different communities that must inter-operate in a collaborative fashion in order to solve some larger problem-solving objective. Such features are particularly attractive when one considers that future military operations will, in all likelihood, be undertaken in the form of trans-national alliances. Common terms used by the military both within and between nation states can be semantically ambiguous despite their lexical equivalence and this focuses attention on the need to provide a common basis for semantic interpretation in terms of the intensional and extensional meaning of domain terms. As such, we consider ontologies a integral component of systems that aim to provide shared understandings of a domain and promote shared situation awareness.

The centrality of ontologies to fusion-related processes raises issues regarding how best to construct and maintain them. The issue of ontology construction demands attention to the kinds of ontology editing environments currently available and whether they are fit-for-purpose. In addition, ontology learning is an active research area that aims to semi-automatically construct an ontology using text processing and machine learning techniques. These may be valuable for future studies, although they fall outside the bounds of the current discussion. The process of updating and revising the ontology is also important, especially when one considers that aspects of the ontology may need be changed, e.g. new concepts may need to be defined throughout the course of operational deployment to reflect changes in the conceptual infrastructure, points of interest and the knowledge requirements of particular operators and/or operations. We can also, I think, add the need to have...
meta-representational formalisms that enable dynamic exploitation of ontologies, in terms of the ability to select and combine different ontologies for different purposes.

5.3 Knowledge Repository

The need to use and exploit ontologies to meet key operational objectives imposes significant design constraints on the nature of the knowledge repository adopted for particular solutions. Above all, such systems should be fast, scalable and enable the execution of semantically-informed queries. The latter constraint is of particular relevance because there will often be a significant gap between required information and the structural organization/information content of the knowledge repository. Certain types of information may need to be inferred based on the query, e.g. return all instances of X. In these situations, the repository may need to process existing data in a semantic fashion in order to yield the desired query outcomes. In the context of the current project we intend to use 3Store as the knowledge repository since this meets many of the design constraints required of a knowledge storage mechanism for knowledge-based information fusion and situation awareness applications (Harris & Gibbins, 2003).

5.4 Semantic Query Capabilities

As implied in Section 5.3, the natures of queries to be executed against the knowledge base are formulated at a semantic level and are geared to the provision of semantically-enriched information. As such they differ substantially from conventional query languages, such as SQL in that they do not necessarily exploit the structural organization of the data storage device, so much as the supervenient semantic glosses that are applied to the data. Semantic Web query languages, such as RDQL and SPARQL, are therefore inherently more powerful than conventional query languages because they exploit the meaning of the data rather than its structural organization. A second, related advantage is that semantic queries can exploit the nature of conceptualisations employed by operators to reason and think about a problem. They are thus more likely to be both easier to specify and to return information more relevant to a user’s specific epistemic requirements.

In the current project we aim to use queries as the basis for specifying goal states representing the kinds of information an operator is interested in. The information returned by these queries serves to return information that is relevant to the monitoring and problem-solving functions of the operator concerned; they therefore constitute the basis of knowledge-filtered situation awareness. In effect, queries within our conceptual model, serve as a filter that acts to constrain the types of information to be delivered to an operator. This mechanism has the advantage that it is endlessly flexible: an operator can adjust and adapt the query to reflect their changing information monitoring requirements, or they can select a pre-existing query defined with respect to their operational role and task commitments. This strategy does, of course, raise concerns about how best to design interface devices so as to promote the correct specification and selection of queries relevant to diverse operational roles. The design of user interfaces optimised for this task is an on-going focus of research in the context of our project.
5.5 Reasoning and Inference

5.5.1 Reasoning in OWL
The semantics of the OWL language support a number of types of inference. OWL-based reasoning enables us to automatically compute taxonomic hierarchies (also called subsumption reasoning) as well as to infer the identity of individuals based on their asserted characteristics and the logical formalisms inherent in the OWL model. These types of deductive inference can be quite powerful under some circumstances and it is clear that ontological approaches should aim to make maximal use of them.

5.5.2 Limitations of OWL-Based Reasoning
As we have seen the semantics of the OWL language support certain types of reasoning, most notably subsumption reasoning. However, there are forms of inference for which OWL is not suited. These include the ability to represent arbitrarily complex implications in which knowledge of the existence of a collection of facts \((X_1, X_2, \ldots, X_n)\) implies the truth of some other information (i.e. \(X_1 \land X_2 \land \ldots X_n \rightarrow Y\)). For example, there is no way in OWL to define the relationship uncleOf(\(X, Y\)), which requires knowing that \(X\) is male, \(X\) has a sibling \(Z\) and \(Z\) has a child \(Y\). The ability to make such implications is a prerequisite for most knowledge-based systems and information fusion/situation awareness applications are no exception. For this reason we need to define rules that serve to enrich and refine ontology elements in a manner that is carefully aligned with the kinds of knowledge-rich contingencies one encounters in a problem domain. Of crucial importance is the ability to exploit statistical regularities and predictive contingencies as a means of deriving useful decision outcomes. At present there is a lack of suitable languages to capture this type of knowledge. SWRL and RuleML are traditionally used to model the forms of inference we have discussed so far, but they are unhelpful and restrictive in a number of important ways. One strategy is to define a new Semantic Web rules language aimed at addressing these deficiencies, another consists in the attempt to extend or modify an existing language. In the context of the current initiative we have sought to circumvent these issues by delegating rules-based inference to an expert system in the form of JESS. Rather than build an ontology layer on top of JESS, i.e. to incorporate OWL-based representational formalisms within the JESS environment, we prefer a strategy based upon the notion of ‘triples-based reasoning’. Triples-based reasoning models facts as a set of RDF triples\(^{18}\) and builds rules based on these facts to assert (infer) new triples (or modify existing ones), thereby increasing the complexity and richness of the corresponding knowledge infrastructure.

5.5.3 Uncertainty
Uncertainty is an important aspect of knowledge-based fusion applications, especially when the aim is to deliver an operationally-effective improvement in situation awareness. Unfortunately, uncertainty issues are particularly problematic in these application contexts and this has caused researchers to make optimistic assumptions based on the notion that all information sources are equally reliable (Delmotte et al., 1996), or to avoid a discussion of uncertainty issues altogether. Clearly, this situation is unsatisfactory and automated fusion-relation applications need to avail themselves of suitable mechanisms for dealing with issues of uncertainty and the related notions of

\(^{18}\) In RDF, information is simply a collection of statements, each with a subject, predicate and object - and nothing else. Each statement comprises three elements, hence the use of the term ‘triple’ and ‘triples-based reasoning’.
trust and reliability. Such issues raise a number of problems, which are widely recognized by the data fusion community:

“Incorporation of reliability into the fusion process gives “richer behaviour” to the fusion system while producing many theoretical and practical problems not very often addressed in the data fusion literature, largely concerned with modelling information credibility. Among these problems are the problem of estimation of reliability of sources and their temporal analysis; the problem of interrelationships between reliability of information sources and their number and fusion results; the problem of incorporating contextual information into evaluating source reliability; and the problem of incorporating reliability into fusion processes.” (Llinas et al., 2004)

One problem concerns how to implement a certainty model in which the values are constantly changing. This is problematic in terms of dynamic systems modelling because the certainty values will often be susceptible to time-dependent decay, e.g. one’s certainty in the position of a moving object is dependent on the amount of time that has elapsed since positional information was last updated. Equally problematic in terms of fusion-based systems, and knowledge systems more generally, is an understanding of how trust and certainty information propagates along (sometimes complex) chains of inference execution. Given a set of information items that differ in terms of their relative reliability, accuracy and certainty, the problem is what level of certainty to assign to the outputs of the fusion process that executes over these items, and how do these values change in subsequent execution cycles.

One inadequacy mentioned in respect of the SAWA system (Matheus et al., 2005) concerns the manner in which existing knowledge structures should be revised in the face of new information. It was made clear that simply relying on the most recently received information is inappropriate because the most recent information is not always the most reliable or credible. In the case when uncertain information about the world is coming from different (often unreliable) sources at different times, especially in a distributed information environment, the priority of incoming information is not justified because the chronological sequence of information has nothing to do with its importance. As such, knowledge-based systems should always revise their conceptual model of the world in a manner that is consistent with the relative certainty assigned to information inputs.

5.5.4 Explanation
The ability to provide explanatory information is the hallmark of cognitively-transparent, symbolic knowledge-based systems and allows the user (both expert and non-expert alike) to evaluate the logic of the reasoning process underlying a particular decision outcome. The explanatory support components of the AKTiveSA TDS enable the system to justify every inference it makes in terms of a human-readable text string that describes why the inference was made. As part of the explanation, the system is also required to list all of the information items upon which an inference was based. Since the output of one inference may constitute the input to a subsequent inference, as part of a chain of inference execution, this technique allows the system to provide explanations of every transformation to the conceptual state space in a recursive fashion. It is, however, unclear whether the explanations provided in the context of the current development initiative are sufficient to account for the level of explanatory support required in real operational contexts. One potential
problem concerns the issue of time constraints, especially in military scenarios. It is unlikely that military operators will have sufficient time to evaluate elaborate explanations and we therefore suggest that a distinction be made between the kind of explanations provided during the course of system execution and the types of explanatory materials made available for off-line analysis, e.g. as part of post-mission analysis and evaluation.

5.6 Technological Realization of Information Fusion Functionality in Support of Enhanced Situation Awareness

This section outlines the proposed technological realization of the knowledge-based information fusion system for enhanced situation awareness (AKTiveSA TDS). We discuss the range of technologies exploited in the context of the current initiative and outline the way in which these technology choices meet the requirements for knowledge-filtered awareness described earlier in the report.

5.6.1 Conceptual Modelling

The conceptual infrastructure of the AKTiveSA TDS is represented using OWL. We have developed a number of ontologies to represent distinct aspects of the problem domain relevant to situation awareness and information fusion in humanitarian relief operations. These ontologies include:

1. **Geography Ontology:** This ontology deals with all the geographical aspects of the problem domain. It encompasses a wide variety of conceptualisations including terrain features, transport routes, rivers, shorelines, terrain elevation data, etc.

2. **Transportation Ontology:** This ontology covers all aspects of transportation in the problem domain. This overlaps, to some extent, with the geography ontology in the sense that transportation routes, e.g. airways and roads, may also be considered elements of the geographical (geo-spatial) domain.

3. **Humanitarian Aid Ontology:** This ontology covers information of relevance to humanitarian operations. It includes knowledge about humanitarian hazards (e.g. floods), humanitarian organizations, humanitarian aid programs, humanitarian aid workers, and the types of resources that may be used for humanitarian relief operations.

4. **Meteorology Ontology:** This ontology deals with all aspects of the climate and weather. The meteorology ontology is important in enabling the prospective system to interpret and utilize information derived from local weather reports and forecasts as well as long term data about regional rainfall, snowfall, seasonal temperature, etc.

5. **Information Sources Ontology:** This ontology details the information sources available to the prospective system. This includes the totality of information available from public domain databases, websites and web services, as well as briefings, emails and tactical datalink systems. It also includes a conception of the knowledge system itself, which serves as the source of internally-derived or inferred information.

6. **Geo-Political Ontology:** This ontology details the conceptualisations used in the geopolitical domain. This includes notions of countries, provinces, states, regions, settlements and the like. It is also subsumes ethnic and linguistic (also religious) groupings.

7. **Military Ontology:** This ontology includes all relevant conceptualisations in the military domain, including tactical operational areas and zones, military platforms, intelligence information, weapons, etc.
8. **Datalink Ontology:** This ontology details the information infrastructure of the tactical datalink systems used by the military to communicate information about the digital battlespace.

9. **Equipment Ontology:** This ontology details the various equipment items that may be used in the course of both military and humanitarian operations. It has substantial overlaps with the content of both humanitarian aid and military ontologies.

10. **Knowledge System Ontology:** This ontology details the problem-solving elements used by the knowledge system to fulfil its problem-solving objectives or to provide explanatory accounts of its own problem-solving and decision-making activities. The requirement to account for its own reasoning activities necessitates an explicit representation of the system within its own concept space. This allows the system to treat itself in a similar fashion to any number of external agents and to reflect on its own processing activity accordingly.

11. **Agent Ontology:** This ontology provides detailed characterizations of the various agents with which the system is required to inter-operate. The information captured by this ontology includes information about the operational role performed by the agent, the position of the agent in power and communication hierarchies, contact details associated with the agent, and information about the kinds of events the agent is subscribed to.

12. **Communication Device Ontology:** This ontology characterizes the various equipment items that are used to communicate or transfer information to inter-operating agents. The capabilities of a particular communication device are important in terms of limiting the kind of information that can be presented as well as the manner in which it should be presented to end user agents.

13. **Weapons Ontology:** The Weapons ontology is an extension of the Military ontology and deals with all aspects of weapons systems, including typology and operational status.

14. **Organization Ontology:** The Organization ontology provides an ontologically-motivated characterization of organizations. It includes military organizations, e.g. NATO, research and monitoring organization, e.g. NOAA, religious organizations and sects, and terrorist organizations. Humanitarian organizations are detailed in the humanitarian aid ontology, which imports the constructs defined in the Organization ontology.

15. **Upper Ontology:** The Upper ontology details generic, top-level constructs that are common to all ontologies.

16. **Terrorism Ontology:** The terrorism ontology provides an ontologically-motivated description of terrorist acts, terrorist organizations and intelligence information relating to terrorist activities.

The ontologies developed in the context of the current initiative represent the basis for a number of processes related to information fusion and situation awareness including:

- the ability to execute queries over the knowledge base as a means retrieving situation-relevant information;
- the ability to retrieve and interpret the information content of source information, irrespective of its structural, syntactic and lexical representation;
- the ability to filter information with respect to contextual constraints (i.e. relevance reasoning); and
the ability to engage in inferential processes geared to the provision of situation-relevant information and decision outcomes.

Both the conceptual models (i.e. ontologies) and the instances created in respect of specific operational scenarios rely on 3Store (Harris & Gibbins, 2003) technology as a storage device. 3Store is implemented on top of a MySQL database engine, which can be manipulated using conventional queries formulated in SQL. However, in order to provide more sophisticated query capabilities, the 3Store incorporates an RDQL interface. The 3Store RDQL engine transforms an RDQL query into a SQL query, which can then be executed against the RDBMS representation of the RDF data. A key advantage of 3Store technology as opposed to competing RDF storage and retrieval solutions, such as Jena\(^{19}\), concerns the speed at which query results can be returned. 3Store can return query results within a few milliseconds, which is a pre-requisite for real-time Semantic Web applications that involve the rapid execution of multiple queries within a limited timeframe\(^ {20}\).

### 5.6.2 Characterization of Situation Awareness Requirements and Goals

In the context of the AKTiveSA TDS, operator goals regarding situation awareness are specified as queries that indicate the type of information to be returned in particular situation contexts. This provides a mechanism for knowledge-filtered awareness in which the type of information presented to operators is specified in terms of semantic constraints. A typical query used in the context of the AKTiveSA TDS is:

```sql
SELECT ?x
WHERE
  (?x, <rdf:type>, <geo:Earthquake>)
  (?x, <geo:hasRichterScaleValue>, ?m1)
  (?m1, <rdf:type>, <top:QuantitativeMeasurement>)
  (?m1, <top:hasValue>, ?v1)
  (?v1, <rdf:type>, <top:NumericValue>)
  (?v1, <top:hasMagnitude>, ?r)
  (?x, <top:causeOf>, ?h)
  (?h, <rdf:type>, <hum:HumanitarianEvent>)
  (?h, <hum:hasFatalities>, ?m2)
  (?m2, <rdf:type>, <top:QuantitativeMeasurement>)
  (?m2, <top:hasValue>, ?v2)
  (?v2, <rdf:type>, <top:NumericValue>)
  (?v2, <top:hasMagnitude>, ?f)
  (?x, <geo:hasEpicentre>, ?e)
  (?e, <geo:hasCountryLocation>, ?c)
  (?c, <rdf:type>, <geo:Country>)
  (?c, <top:hasName>, "Afghanistan")
  AND ?r >= 5.0
  AND ?f > 100
USING
  geo FOR <http://www.aktors.org/AKTiveSA/Geography#>
  top FOR <http://www.aktors.org/AKTiveSA/TopLevel#>
  hum FOR <http://www.aktors.org/AKTiveSA/HumanitarianAid#>
```

The natural language equivalent of this query is given as:

\(^{19}\) http://jena.sourceforge.net/
\(^{20}\) Because certain computations will have to provide an answer within a limited time period, computing in time-constrained environments is of importance. Unfortunately, many of the reasoning methods used by extant decision-support systems do not necessarily have good time-constrained behaviour. Therefore techniques for performing reasoning within a certain timeframe are likely to be critical in the development of decision-support aids in applications that demand real-time behaviour.
“return all objects representing earthquake phenomena that have a magnitude greater than 5.0, that are located within Afghanistan, and which are associated with a minimum of 100 fatalities”

Clearly such queries rely on ontologically-motivated descriptions of domain objects and conceptualisations, and it is in this sense that the provision of ontologies is integral to intelligent search and retrieval operations. It is also clear that such queries are not easy for those unfamiliar with Semantic Web technologies to formulate, and this focuses attention on the need to design appropriate user interfaces enabling end-users to select and design queries. Our approach casts semantically-informed queries as a specification of an operator’s goals vis-à-vis situation awareness, i.e. the query specifies the type of information that is relevant to an operator’s monitoring objectives in relation to the current situation. We accept that although such queries can be pre-defined, i.e. a library of operationally-specific queries can be defined in advance of operational deployment, in most cases the operator will need to adapt and modify existing queries (as well as create new ones) in order to meet their situation-specific information requirements. In this case we allow for such queries to be specified or edited by an operator throughout the timeframe of an operation.

In some cases we recognize that certain queries, particularly those that re-appear across multiple operational contexts and monitoring sessions, may reflect inadequacies in the original conceptual model. For example, the aforementioned query may be seen as defining a particular type of concept that is the focus for multiple situation awareness contexts. In these cases we argue that the query definition process could be simplified by explicitly specifying the conceptual referents of the query in the context of the ontology (the notion of ‘re-factoring the information space’ referred to earlier). This raises important issues regarding the modification of existing knowledge in a logically-consistent manner. Specialized knowledge editing facilities may be required for this purpose.

5.6.3 Query Capabilities
In addition to their role as a specification of situation awareness goals, we also recognize the importance of queries in enabling information retrieval. The ability to retrieve information in an ad hoc fashion is an essential component to situation analysis since it allows for the incorporation of novel information based on current epistemic requirements, not all of which may be satisfied in the terms of the operator’s initial goals and expectations. Semantically-constrained queries formulated in the aforementioned (see Section 5.6.2) manner can also be used to for this purpose. Semantic Web query languages that exploit the semantics of pre-defined conceptual models therefore provide a generic mechanism for situation awareness functionality in the sense that they both enable knowledge-filtered awareness and enrich the representation of the situation state with ad hoc information.

5.6.4 Decision Support & Inference
The task of inference and the provision of decision support is delegated to a specific component of the AKTiveSA TDS, namely an expert system shell based on JESS21. JESS is an expert system shell that co-opts both a rule-based inference engine with object-oriented programming facilities. It represents a Java implementation of CLIPS22 and incorporates JDBC technologies, which is a useful...
feature in terms of the proposed inter-operation with the 3Store knowledge repository component. Given the syntactic similarity of JESS to CLIPS, CLIPS code can be easily adapted for JESS-based solutions. In addition, since JESS is open source, JESS can easily be extended and embedded within existing application environments. In terms of the current project JESS has a number of advantages that commend its use over other expert-system shells:

- **cost**: JESS is free (for academic use), which means that project resources can be spent on development time rather than software
- **size**: JESS has a small memory footprint, which means that it can be easily transported for testing and demonstration to other locations
- **system requirements**: JESS can be limited to run with little memory and few processor demands — while top-end computers give the best performance, it can run on low-end computers where necessary, which again gives benefits for transport to other locations for testing, integration and demonstration
- **interoperability**: JESS is multi-platform, which means that versions are available for different operating systems

The form of reasoning we propose to undertake with JESS assumes the form of triples-based reasoning in which the RDF triples inherent in the ontology specification are instantiated in the JESS-based reasoning environment as fact assertions. A set of rules defines the kind of reasoning processes that operate over these facts in a manner that reflects domain-specific knowledge contingencies and situation-specific reasoning objectives. The JDBC capability of JESS enables us to interface to the 3Store knowledge repository and dynamically update the knowledge infrastructure of the application in an ongoing fashion. We recognize that there are a number of potential issues regarding the nature of this interaction that may have to be addressed in the context of the current implementation initiative. These issues include the following:

- Does the reasoning agent periodically access the knowledge base in order to undertake knowledge-based inference? If so what is the frequency of access? Should the access be made contingent on the occurrence of external events, e.g. the receipt of new information?
- Does the reasoning agent instantiate all triples contained in the knowledge store prior to inference execution? If so what are the memory limitations and temporal constraints associated with this process? If we limit the assertion of triple-based facts to a subset of those defined the ontology, how do we select these triples and what implications does this have on the kind of conclusions that can be reached (particularly with respect to issues of logical consistency)?
- How should the results of inference execution be used to update the knowledge base? How can we ensure that inferred information does not violate logical consistency constraints inherent in the existing model?

At present to we do not claim to have effective solutions to these problems although these are the subject of ongoing research efforts.

5.6.5 Support for Certainty, Explanation and Provenance

In order to provide effective decision support, the knowledge system component of the AKTiveSA TDS system will need access to rich sources of information about relevant domain objects and events. The various tactical datalinks (e.g. JTIDS Link 16, BOWMAN) used by the military represent one obvious source of information about the operational environment. To the extent that such
datalinks (and battlespace digitisation initiatives generally) can promote situation awareness and improve the quality of decision support, it is imperative that the proposed system should be capable of establishing a suitable informational contact with such systems. Other sources of information include sensors, news agency reports, institutional websites and services, online databases, direct entry of information by the system operator and the knowledge system itself\(^ {23}\). A full list of potential information sources is detailed in Section 2.2.1. As we can see from this list, available information sources range from highly structured information sources, such as tactical datalinks and online databases, to highly unstructured sources, such as text-based sources and institutional websites. In order to fully exploit these structurally and semantically heterogeneous information sources we need to provide a detailed model of the sources as part of an ontological characterization of the problem domain. The idea is that the system can use ontologically-motivated characterizations of information sources as the basis for information retrieval and query capabilities. We also note that information sources are an integral element of the reasoning process of a knowledge-based fusion system with respect to assessments of reliability and accuracy. Issues of trust are also important here and the key problem faced by the reasoning agent is how to modify the certainty associated with information items based on their provenance. Furthermore, we also note that information sources are important from the perspective of explanations generated by a reasoning agent to account for its internal processing activity. We advocate the inclusion of all information sources as part of the trace information generated for a particular explanation of knowledge system activity. Finally, we note the importance of the dynamic discovery of information sources from the perspective of exploiting new information service providers as they become available\(^ {24}\).

In light of these factors we have developed an ontology of information sources that provides a taxonomy of source types and also models some of the critical information required by a reasoning agent to deal effectively with such sources in terms of information retrieval and dynamic reasoning.

![Source Concept Hierarchy](image)

**Figure 5.2: Source Concept Hierarchy**

Figure 5.2 illustrates a partial representation of the information source hierarchy developed for the current application (note that concepts representing other information sources have been omitted)

\(^{23}\) The ability to represent internally-derived information, i.e. the information asserted as a by-product of inference execution, provides a mechanism through which the knowledge system can represent itself as part of the process of the inference execution. This is particularly important with multi-step reasoning processes in which decisions reflect the outcome of complex chains of inferences.

\(^{24}\) While we do not intend to devote much effort to this problem in the context of the current research initiative we have established contact with DIF DTC Project 7.5 with a view to investigating these issues more closely in the context of the Phase II funding initiative.
for purposes of clarity). At the highest level of the hierarchy is the ‘source’ concept, which provides a
generic representation of an information source, subsuming all other types of information sources.
The ‘source’ concept features a timestamp attribute (here represented using UML notation), which
represents the time at which information derived from a particular source, was actually processed
by the knowledge system. The ‘system-source’ concept represents host sensors as an information
source, e.g. radar, vibration sensors, satellite imagery, etc. The ‘system’ property assigned to the
‘system-source’ concept denotes the actual sensor (as a type of equipment item) from which the
information was originally derived. Information received from tactical datalinks is represented by the
‘datalink-message’ concept. The concept references the actual message context in which
information was originally asserted via the ‘message’ property. Note that this concept is specifically
gear to represent information received from datalink systems, such as Link 16, and may be
inadequate, from a representational perspective, when it comes to a consideration of other digital
battlespace systems, such as BOWMAN, SKYNET 5, CORMORANT and FALCON. We are currently
investigating the applicability of our representational schema to these concepts, and other visionary
concepts for information exchange, as part of our ongoing research activities.

The relationship between knowledge objects, instantiated as part of a particular situation, and the
elements of the Information Sources ontology is illustrated in Figure 5.3. In this figure, the ‘thing’
concept represents the super-type of all objects created in the context of the ontology. The ‘datum’
sub-concept stores meta-information about object-attribute-values (OAVs)\(^{25}\). It inherits the ability to
represent the source of a particular information item from the ‘thing’ super-type. The attributes of
the ‘datum’ concept allow a datum to refer to a particular attribute on a particular object. For
instance, the attribute slot holds the name of an object attribute, while the ‘object’ attribute refers
to a particular object on which the attribute is specified. A number of subtypes are defined for the
datum concept, which provides for the requirement to reference different types of values that the
attribute could feasibly hold. These datum concept subtypes are defined as:

- **single value datum**: instances of the ‘single-value-datum’ concept represent meta-
  information about a particular OAV where the attribute takes a single value at a time. This is
  the most common type of datum object.
- **list datum**: instances of the ‘list-datum’ concept represent meta-information about a
  particular OAV where the attribute takes a value that is an ordered list
- **multi-value datum**: instances of the ‘multi-value-datum’ concept represent meta-
  information about a particular OAV where the attribute takes multiple, unordered values.
- **minimum datum**: instances of the ‘minimum-datum’ concept represent meta-information
  about a particular OAV where the attribute has a numerical value. In this case the
  minimum-datum defines the minimum value specified for the OAV
- **maximum datum**: instances of the ‘maximum-datum’ concept represent meta-information
  about a particular OAV where the attribute has a numerical value. In this case the
  maximum-datum defines the maximum value specified for the OAV

\(^{25}\) In the context of the present discussion we use the notion of attribute to refer to both atomic properties
(represented as DatatypeProperties within OWL) and relationships between objects (OWL ObjectProperties).
The value of an attribute can thus take the form of a simple datatype (e.g. integer), or more complex datatype
(e.g. object).
When object-attribute-values are defined at the same time as the creation of an object, i.e. when
the default value for an attribute is overridden during the course of creating an object, a datum will
be automatically created with the same source as the object’s source for each OAV defined.

According to this conceptualisation, the KBS will have the ability to represent the source of
information corresponding to the creation of objects, including the time at which they were created.
It will also have the ability to represent information about the source and time of creation of each
OAV via the datum concept. When a value for a particular object-attribute tuple is defined, the
source of the value is recorded, i.e. a datum object is created to store this information. The
definition of an OAV always involves the creation of a datum representing that information rather
than the direct assignment of the value to the object attribute. This permits the KBS to engage in
meta-level reasoning over different datum representations of the same OAV tuple in order to assign
the most appropriate value to the object-attribute. This enables the KBS to take into account the
relative reliability of different information sources as well as operator preferences for a particular
source of information.

Although we do not wish to elaborate on issues related to explanatory support at the present time,
it is relatively easy to see how explanatory capabilities could be specified within the current
conceptualisation. For example, when the KBS creates an object or assigns a value to an object’s
attribute, then the reasoning behind that creation or value assignment can be represented within a
KBS-source object. This requires the specification of additional attributes on the ‘source’ concept
corresponding to:

- a human-readable sentence giving the heuristic behind the inference (i.e. the reason)
- a list of facts that have led to this particular inference (i.e. the basis)
The conceptual scheme developed to support the representation of information sources also represents the time at which information was provided from a particular information source. The timestamp attribute of the ‘source’ concept can therefore be used to determine the age of an information item, i.e. the data latency, relative to a particular source. This may be important in certain forms of reasoning behaviour which require access to up-to-date information. Unfortunately, the representation of an information item’s source cannot necessarily be used to determine the latency of information updates for attribute-values utilised by the KBS during the course of its reasoning activity. The reason for this lies in the fact that multiple representations of the same information item may derive from different information sources. For example, if an air track was correlated, the location of a track could be received via a Link 16 message and also via the host mission system (i.e. from the host radar) at two different points in time. This would necessitate the creation of two independent source concept representations, i.e. one corresponding to the J series message data element and one referencing the host tracker/radar data. The choice between these two information items could incorporate criteria such as the relative reliability of the information source and operator preferences.

In a situation with multiple representations of the source of some information item it will be important to define an explicit representation of the last time OAVs were specified or updated. In order to realise this requirement we advocate the specification of a data-latency concept (see Figure 5.4) which provides an explicit representation of the last time KBS information was established, i.e. one source of information was selected to update the KBS’s internal representation of the information item.

5.7 Summary

This section has outlined our vision with respect to the technological realization of knowledge-based information fusion systems for improved situation awareness within the framework of the Semantic Web. Our approach is based on the exploitation of semantically-enriched representations of domain models strategically aligned with the conceptual infrastructure of problem domains in which situation awareness operations are undertaken. Ontologies provide the basis for modelling the conceptual infrastructure of the problem domain and simultaneously support a number of functions related to semantic integration, semantic inter-operability, and semantically-based querying activities. They also provide the ontological substrate for a variety of inferential capabilities relevant to the decision-making and reasoning capabilities of the knowledge system with respect to decision support and knowledge-driven fusion processes. Semantic Web query languages, such as RDQL and SPARQL, provide a mechanism for representing situation awareness goals and information retrieval
requirements. Such languages constitute the bedrock for knowledge-filtered awareness in which information is filtered with respect to contextual relevance criteria, defined in terms of the semantics of the conceptual model developed for the problem domain.

We have attempted to outline our vision with respect to support for explanatory information and mechanisms for dealing with certainty information. Information associated with instances of concepts, including their featural characterization and relationships with other concepts are modelled using a number of meta-representational primitives in the form of datum instances. This meta-level information represents the reason underlying the existence of information items in terms of natural language text strings. Closely allied to the representation and storage of meta-level information for the purposes of providing explanatory information, is the problem of representing the certainty the system has in a particular information item at a particular time. The level of certainty will determine the extent to which the system can use information as the basis for strategic decision-making. It will also impact on the confidence the system has in the output of its reasoning processes. The framework developed in the context of the current application allows for the explicit representation of certainty information for every information item within the application domain. Moreover, the system continuously evaluates its confidence in information throughout the course of system execution according to both the ‘age’ of the information item and the information source from which it was derived. At present, only arbitrary decisions have been made with respect to how certainty levels for a given information item from a given information source degrade over time. Further KA or empirical evaluation is required to establish reasonable values for certainty factors. Ideally, one would like to construct a 3-dimensional matrix for each information item in the domain plotted against information source categories along one axis and time along the other. One could then feasibly derive equations that captured the time-dependent decay of certainty information for each information item from a particular information source.
6 System Architecture

This section provides an architectural overview of the AKTiveSA TDS. The architecture of the system is discussed in terms of the various components of the system. While this architectural specification is still somewhat provisional and subject to revision based on the results of further research, we include it in the context of the current discussion as a means of indicating a proposed implementation strategy for knowledge-based information fusion systems that aim to increase situation awareness and operational effectiveness in both combat and humanitarian relief scenarios.

6.1 Overview

Figure 6.1 illustrates the various architectural components of the AKTiveSA TDS. The arrows indicate the proposed pattern of interaction between the various components. The architectural components include:

- **3Store Knowledge Repository**: represents the knowledge repository used to store both schematic knowledge and knowledge instances.
- **Query Library**: represents a library of existing queries of generic relevance to a variety of situation contexts, operator roles or mission scenarios.
- **Query Execution Engine**: executes queries against the knowledge repository and returns information to the GUI component.
- **Event Management Component**: implements information retrieval and event processing functionality.
- **Reasoning Agent**: implements knowledge-based inferences and decision support activities.
- **System GUI**: represents the GUI presented to the end-user agent, it comprises the following sub-components:
  - **Query Selection Agent**: enables the (partially-automatic) selection of queries reflecting situation-relevant goals.
  - **Query Builder Component**: allows for the dynamic specification of queries relevant to the current situation context.
  - **Tactical Picture Visualization Component**: provides visualizations of the operational environment (differential visualizations may be required to suit particular user groups).
  - **Ontology Visualization Component**: enables the visualization of ontology elements.

Each of these architectural components is discussed in greater detail in subsequent sections.

---

The dashed arrow between the ‘Query Execution Engine’ component and the ‘Event Management Component’ indicates the potential ability of the system to directly query external information sources.
6.2 Knowledge Repository

The knowledge repository consists of a 3Store knowledge repository as discussed in Section 5.6.1. Its purpose is to provide a storage mechanism for the knowledge infrastructure of the application. The knowledge infrastructure in this case subsumes both schematic knowledge (i.e. conceptual models) and instance knowledge (i.e. instances of the concepts defined in the context of the conceptual models). Instance knowledge is represented as ontology elements (mostly individuals) and their associated information state (relationships with other values and objects), that are apparent in a particular operational context.

6.3 Knowledge Specification & Management

The knowledge specification and management components subsume a variety of tools that enable operators to manage and edit existing ontologies reflecting required changes to the knowledge infrastructure. Changes to the knowledge model may arise as a result of perceived deficiencies in the existing models as regards current epistemic requirements, or they may reflect the fact that
knowledge is dynamic and liable to change over time. Knowledge editing and management facilities in the context of the AKTiveSA TDS could assume the form of existing tools, e.g. Protégé, or they may be derived from the components of such tools, e.g. the Protégé-OWL plug-in API. In either case, it may be important to determine whether the representational and visualization capabilities afforded by these tools and components match the expertise level of those expected to perform knowledge management and editing activities, e.g. do these tools provide appropriate interfaces for the elicitation, acquisition and assertion of new ontology elements?

6.4 Reasoning Agent

The reasoning agent in the current application is based on JESS. The reasoning agent exploits the JESS API for the purposes of asserting knowledge into the reasoning environment and retrieving the results of inference execution. A code wrapper is used to facilitate the inter-operation of the JESS subsystem with other components of the AKTiveSA TDS.

6.5 Query Library

The query library consists of a collection of predefined queries (or query templates) that may be of generic use across multiple operational contexts and missions. We make no assumptions here regarding the storage device used for the query library, although we note that the such queries may demand their own form of (meta-level) ontological characterization in order to facilitate selection and retrieval. Interestingly, the notion of pre-defined queries provides a mechanism for role-based situation awareness in which queries are defined with respect to operator roles, rather than on an individual basis. This affords the possibility of adapting the operation of the AKTiveSA TDS to meet the demands faced by operator’s at different levels of the military command hierarchy.

6.6 Decision Support

The decision support component is perhaps the least clearly understood element of the AKTiveSA TDS at the present time. The main problem relates to the lack of adequate information regarding useful problem/opportunity areas for decision support processes. A number of focus areas have been proposed by military SME’s including automated mission planning and battlefield planning (primarily involving the appropriate placement of battlefield assets for both offensive and defensive operations), but these clearly relate to purely military engagement operations and it is presently unclear what the prime areas for decision support would be in terms of humanitarian assistance and peace-keeping operations. In the absence of such information it is difficult to envisage the precise capabilities of the application with respect to decision support (both in terms of knowledge infrastructure and visualization requirements), although we believe the best strategy is to select a particular focus area, e.g. battlefield planning, as the basis for showcasing the decision support capabilities of the knowledge system. Our choice of battlefield planning principally relates to specific requests from representatives of the military customer and a recognition that this is a knowledge-intensive task in which the configuration of a number of elements (military assets) is specified against a backdrop of well-understood design constraints.

6.7 Event Management & Information Retrieval

The event management and information retrieval components are devoted to the processing of incoming information. We regard the operation of this component as including both passive and
active modes of operation. In the passive ('client push') mode, the component 'listens' for the receipt of information from any sources or services to which it is subscribed. In this mode of operation the Event Management subsystem is required to process incoming information and represent it in a form compatible with the ontological infrastructure of the application domain. This entails both semantic interpretation (perhaps using natural language techniques) and structural/syntactic reorganization (perhaps using XSLT or other transformation approaches). In the active ('server pull') mode, the system actively retrieves (harvests) information from recognized information service providers using a variety of information retrieval techniques. We make no commitment as to the nature of this information harvesting activity at this stage, but we recognize the existence of a variety of models for content acquisition including natural language techniques (Ciravegna et al., 2004) and the scraping of publicly available data from institutional websites (Leonard & Glaser, 2001).

6.8 Visualization & Interface Components

The visualization and interface components represent the GUI developed for the current application. The design and implementation of GUI components needs to take into account the specific visualization requirements of different user groups, as well as the ergonomic alignment of such interfaces to the cognitive profile of end-user agents. Issues of cognitive ergonomics are of paramount significance in this respect and, as such, the issues discussed in relation to the cognitive processes underlying situation awareness are of particular relevance (see Section 3).

6.8.1 Operational/Tactical Picture Visualization

A number of factors limit the optimal design of user interfaces for situation awareness. Some of these relate to the cognitive profile of the end user agent and are widely acknowledged in the HCI literature. In the context of the current application a number of other issues must also be addressed including the organizational affiliation of agents (military vs. civilian) and their operational role within the organization (e.g. commander vs. surveillance operator). There may also be device-dependent constraints that limit the information that can be presented to an end user and the manner in which it is presented (e.g. bird table vs. handheld PDA). In some cases the types of visualization and modes of interaction will be invariant with respect to specific user groups. Such will be the case when military authorities or codes of practice sanction the use of particular types of user interface, or when the exploitation of interface structure has become in an intrinsic and inextricable part of expert performance. Military personnel may, for example, require types of interface congruent with existing military standards, e.g. NATO symbology. Figure 6.2 illustrates a decision support environment developed in the context of a previous project that utilizes interface elements consistent with accustomed modes of visualization and representation. In other cases more flexible strategies of information transfer can be adopted and these need to take into account the specific cognitive and perceptual preferences and biases of end users. While, our investigation into optimal user interface design is yet to be completed, we aim to countenance the selection of those information-bearing environmental structures that best support operationally effective modes of working and thinking.
Given that the actions of the military are overwhelmingly in the physical domain, as opposed to the information, cognitive and social domains, the use of a physical frame of reference for the battlespace is the focal point for our user interface design initiative. In this respect, we need to consider a (rather bewildering) assortment of technologies in the form of GIS products. Based on a review of the existing state-of-the-art with respect to GIS technology we have opted to use OpenMap\textsuperscript{27} as the basis for implementing GIS functionality in the current initiative (see Figure 6.3). OpenMap has a number of features that commend itself in this respect, including the fact that it is free, Java-based, exposes a rich API with significant user documentation, and supports a number of existing geospatial data formats (e.g. ESRI Shapefiles and MapInfo files, DCW, VPF, VMAP, CIB, RPF and DTED formats). Moreover, OpenMap is open source and therefore enables us to adapt the existing technology to our own representational and visualization requirements. Figure 6.3 illustrates a Java applet based on OpenMap technology.

---

\textsuperscript{27}http://openmap.bbn.com/
Ontology Visualization

Ontology visualization is an important element of understanding, editing and manipulating the ontological infrastructure of the application. A simple form of interaction consists in the presentation of a taxonomic hierarchy of ontology concepts, which could constitute the basis for query specification functions and interface configuration (e.g. the user could select/deselect elements for display in the interface based on their position in taxonomic hierarchies). Unfortunately, we suspect that existing visualization techniques are somewhat inadequate in terms of the inter-related goals of comprehension, change and manipulation. Figure 6.4 illustrates a common form of knowledge representation commonly used in knowledge acquisition tools, such as PCPACK\(^{28}\). In practice, we have found such techniques invaluable in terms of communicating acquired knowledge structures to individuals unfamiliar with knowledge engineering techniques. Other types of visualization, such as those afforded by hyperbolic trees (e.g. Alani, 2003) may be of some value in this respect, although we have not empirically evaluated their value as a vehicle for knowledge communication.

\(^{28}\) http://www.epistemics.co.uk/Notes/55-0-0.htm
6.9 Summary

This section has reviewed the architectural components of the AKTiveSA TDS. The discussion presented herein serves as a provisional architectural blueprint for the design of knowledge-based information fusion systems that aim to improve situation awareness in military conflict and MOOTW contexts.
7 Conclusion

This report has discussed a number of issues that need to be addressed in the context of development initiatives geared to the provision of knowledge-based information systems that aim to increase situation awareness. We see ontologies as a central element of such initiatives. Ontologies, we argue, serve as a representational vehicle for modelling the conceptualisations used by operator’s in talking (and perhaps) thinking about a domain. We have outlined contextual relevance reasoning as a critical component of knowledge-filtered awareness in which the salience of incoming information is assessed with respect to a number of semantically-circumscribed criteria. Contextual relevance reasoning serves as a ‘filter-like’ mechanism, similar to that purported to underlie human attentional processing (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964). The filter focuses attention on specific subsets of task-relevant information, thereby reducing information overload and maximizing the exploitation of available cognitive resources. In addition, the ability to reason about incoming information, by virtue of ontological models, enables the system to infer the value of missing information, assess the implications of current information states in terms of future events, alert the operator to unexpected or priority information and integrate (fuse) information in semantically sensible ways. Ontologies also provide the foundation for interpreting the meaning of information content from a wide variety of distributed information sources. These knowledge processes, we argue represent the sine qua non of knowledge-filtered awareness in which information must be selectively processed, interpreted and then evaluated in terms of its implications for future states of the world (Endsley, 2000). The technological realization of the filter mechanism has been described in terms of queries, corresponding to the goals of situation analysis in particular operational contexts. We have also provided a provisional characterization of the architectural components of the AKTiveSA TDS, which we hope affords some insight into the interplay between various Semantic Web technologies in fulfilling the requirements for improved situation awareness in knowledge-based fusion contexts.
8 References


# Appendix A Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEW</td>
<td>Airborne Early Warning</td>
</tr>
<tr>
<td>AKT</td>
<td>Advanced Knowledge Technologies</td>
</tr>
<tr>
<td>API</td>
<td>Application Programmatic Interface</td>
</tr>
<tr>
<td>BC</td>
<td>Belief Change</td>
</tr>
<tr>
<td>BR</td>
<td>Belief Revision</td>
</tr>
<tr>
<td>BU</td>
<td>Belief Update</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4ISR</td>
<td>Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance</td>
</tr>
<tr>
<td>CIA</td>
<td>Central Intelligence Agency</td>
</tr>
<tr>
<td>CLIPS</td>
<td>C Language Integrated Production System</td>
</tr>
<tr>
<td>CROP</td>
<td>Common Relevant Operational Picture</td>
</tr>
<tr>
<td>DAML</td>
<td>DARPA Agent Markup Language</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defence Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DIF</td>
<td>Data and Information Fusion</td>
</tr>
<tr>
<td>DOLCE</td>
<td>Descriptive Ontology for Linguistic and Cognitive Engineering</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
</tr>
<tr>
<td>DTC</td>
<td>Defence Technology Centre</td>
</tr>
<tr>
<td>DTED</td>
<td>Digital Terrain Elevation Data</td>
</tr>
<tr>
<td>ELINT</td>
<td>Electronic Intelligence</td>
</tr>
<tr>
<td>ESRI</td>
<td>Environmental Sciences Research Institute</td>
</tr>
<tr>
<td>FOAEW</td>
<td>Future Organic Airborne Early Warning</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>GSR</td>
<td>Galvanic Skin Response</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HCI</td>
<td>Human-Computer Interaction</td>
</tr>
<tr>
<td>IQ</td>
<td>Intelligence Quotient</td>
</tr>
<tr>
<td>JBI</td>
<td>Joint Battlespace Infosphere</td>
</tr>
<tr>
<td>JDBC</td>
<td>Java Database Connectivity</td>
</tr>
<tr>
<td>JDL</td>
<td>Joint Directors of Laboratories</td>
</tr>
<tr>
<td>JESS</td>
<td>Java Expert System Shell</td>
</tr>
<tr>
<td>JTIDS</td>
<td>Joint Tactical Information Distribution System</td>
</tr>
<tr>
<td>KA</td>
<td>Knowledge Acquisition</td>
</tr>
<tr>
<td>KBS</td>
<td>Knowledge-Based System</td>
</tr>
<tr>
<td>MOD</td>
<td>Ministry of Defence</td>
</tr>
<tr>
<td>MOE</td>
<td>Measures of Effectiveness</td>
</tr>
<tr>
<td>MOOTW</td>
<td>Military Operations Other Than War</td>
</tr>
<tr>
<td>MOP</td>
<td>Measures of Performance</td>
</tr>
<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
</tr>
<tr>
<td>NDM</td>
<td>Naturalistic Decision Making</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-Governmental Organization</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>OAV</td>
<td>Object Attribute Value</td>
</tr>
<tr>
<td>OWL</td>
<td>Web Ontology Language (W3C)</td>
</tr>
<tr>
<td>OWL-QL</td>
<td>OWL Query Language</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>PCPACK</td>
<td>PC-Enabled Portable ACquisition of Knowledge</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
</tr>
<tr>
<td>RDBMS</td>
<td>Relational Database Management System</td>
</tr>
<tr>
<td>RDF</td>
<td>Resource Description Framework</td>
</tr>
<tr>
<td>RDQL</td>
<td>RDF Data Query Language</td>
</tr>
<tr>
<td>ROE</td>
<td>Rules of Engagement</td>
</tr>
<tr>
<td>RPD</td>
<td>Recognition-Primed Decision-making</td>
</tr>
<tr>
<td>RuleML</td>
<td>Rule Markup Language</td>
</tr>
<tr>
<td>SAGAT</td>
<td>Situation Awareness Global Assessment Technique</td>
</tr>
<tr>
<td>SAM</td>
<td>Surface-to-Air Missile</td>
</tr>
<tr>
<td>SART</td>
<td>Situation Awareness Rating Technique</td>
</tr>
<tr>
<td>SAW</td>
<td>Situation Awareness</td>
</tr>
<tr>
<td>SAWA</td>
<td>Situation Awareness Assistant</td>
</tr>
<tr>
<td>SME</td>
<td>Subject Matter Expert</td>
</tr>
<tr>
<td>SOA</td>
<td>Service-Oriented Architecture</td>
</tr>
<tr>
<td>SOP</td>
<td>Standard Operating Procedure</td>
</tr>
<tr>
<td>SPAM</td>
<td>Situation Present Assessment Method</td>
</tr>
<tr>
<td>SPARQL</td>
<td>Simple Protocol and RDF Query Language</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>SUMO</td>
<td>Suggested Upper Merged Ontology</td>
</tr>
<tr>
<td>SWRL</td>
<td>Semantic Web Rule Language</td>
</tr>
<tr>
<td>TDS</td>
<td>Technical Demonstrator System</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UML</td>
<td>Unified Modelling Language</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>USAF</td>
<td>United States Air Force</td>
</tr>
<tr>
<td>W3C</td>
<td>World Wide Web Consortium</td>
</tr>
<tr>
<td>XML</td>
<td>eXtensible Markup Language</td>
</tr>
<tr>
<td>XSD</td>
<td>XML Schema Definition</td>
</tr>
<tr>
<td>XSLT</td>
<td>eXtensible Stylesheet Language Transformations</td>
</tr>
</tbody>
</table>