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RESULTS OF AN INVESTIGATION OF CONCEPTS FOR DEVELOPING COMPUTER-BASED DECISION SUPPORT FOR A MODERN FRIGATE

by

Bruce A. Chalmers

October/octobre 1998

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ABSTRACT

DREV is investigating concepts for the development of a computer-based, real-time decision support system that can provide combat system operators with advanced support capabilities for countering the current and anticipated threat to the Canadian Patrol Frigate. Among its principal roles, this system will continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate tactical picture derived by fusing all available data, leading to enhanced situation awareness; and assist in determining and selecting a response to anticipated or actual threats. This document examines a range of concepts for the design of the system, focusing on automation, cognitive and methodological issues. It also exposes preliminary ideas of a novel model-based framework that is being developed to support design.

RÉSUMÉ

Le CRDV a mis en place un projet de recherches dans le but d'étudier des concepts qui permettront de développer un système informatisé d'aide à la décision fonctionnant en temps réel afin d'améliorer la capacité des opérateurs du système de combat de la Frégate de patrouille canadienne à contrer la menace actuelle ou future. Un tel système aura comme fonctions principales de saisir continuellement les données et les informations provenant des capteurs du navire et de sources externes; de fusionner toute l'information disponible dans le but de construire, maintenir et afficher une image tactique précise; d'assister l'usager dans l'interprétation de cette image; et de formuler et fournir l'aide appropriée pour contrer les menaces anticipées ou actuelles du navire. Ce document décrit de nombreux aspects, concentrés sur l'automatisation, et les aspects cognitifs et technologiques de l'approche d'aide à la décision. De plus, il examine les bases préliminaires d'un nouveau cadre basé sur des modèles qui supportera le développement de ce système.

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EXECUTIVE SUMMARY

Technological advances in threat technology, the increasing tempo and diversity of open-ocean and littoral scenarios, and the volume and ambiguous nature of data to be processed under time-critical conditions will pose significant challenges to shipboard Command and Control Systems (CCSs) and the operators who must use these systems to defend their ship and fulfill their mission.

To address these challenges, DREV is investigating a diverse range of concepts for designing and evaluating a real-time decision support system (DSS), to be integrated into the ship's existing CCS, aimed at providing enhanced decision support capabilities to combat system operators. These capabilities include support for: (i) integration of data from the ship's sensors and other sources; (ii) formulation, maintenance and display of an accurate dynamic situation picture, leading to enhanced situation awareness of operators; (iii) identification and selection of courses of action in response to anticipated or actual threats to the mission; and (iv) action implementation once a decision to act has been made and is being carried out.

Developing this type of decision support system is a difficult task. A key problem is that the system must operate in a highly dynamic and open environment that imposes variable and unpredictable demands on operators. Operators must be able to effectively handle the demands of new and unanticipated situations that have not been addressed by the system designer or by doctrine. The system must certainly support operators so that they can follow established principles and recommended procedures. Yet it must not overconstrain them so that they are hampered from taking advantage of their abilities to reason, improvise, and respond, while at the same time calling on the system for the support they need.

This document examines a range of concepts being investigated for the design of the DSS, focusing on automation, cognitive and methodological issues. Automation concepts address principles and paradigms for computer-based decision support. Fundamental questions relate to which operator roles and positions need to be aided, why,

when, and how. Two approaches to aiding are examined and contrasted: a prosthetic approach and a decision-aid-as-tool approach. Various possibilities for providing a variety of operator-system modes for delegating authority, varying in degree of synergy and work distribution between the operator and the system, are also proposed.

Cognitive concepts deal with specifics of the various cognitive-level behaviours which the DSS must exhibit and/or support. Emphasis here is put on a new cognitively based model of the Command and Control (C2) process as a means of structuring the problem of identifying computer-based, decision-aiding interventions. A fundamental premise is that an effective cognitive support tool rests on cognitive compatibility between the tool and the decision maker.

Methodological issues are concerned with managing the complexity of the design problem. Establishing decision requirements emerges as the critical problem. Preliminary ideas of a novel model-based framework for structuring the capture and analysis of requirements are presented. It is based on the development of operator-environment models with both descriptive and predictive abilities to allow the designer to understand current operator behaviour and predict consequences of design choices. Representational models of the environment identify the content and structure of the information that the system must provide the operator with, while models of the mechanisms that the operator uses to deal with complexity in the environment give its form.

The results of this research are expected to contribute to DREV's ongoing investigation of enhancements to the HALIFAX Class Command and Control System as part of its mid-life upgrade, thus ensuring that the ship can counter new challenges.

LIST OF ACRONYMS

AH	:	Abstraction Hierarchy
ASM	:	Anti-Ship Missile
ASWC	:	Assistant Sensor Weapons Controller
AWW	:	Above Water Warfare
C2	:	Command and Control
CCS	:	C2 System
CIC	:	Combat Information Center
CIO	:	Communications Intercept Operator
CIWS	:	Close-In Weapon System
CO	:	Commanding Officer
CPF	:	Canadian Patrol Frigate
CPU	:	Central Processing Unit
CRAD	:	Chief Research And Development
CRDV	:	Centre de recherches pour la défense Valcartier
CTA	:	Cognitive Task Analysis
CWA	:	Cognitive Work Analysis
DCIEM	:	Defence and Civil Institute of Environmental Medicine
DF	:	Data Fusion
DFRM	:	Data Fusion and Resource Management
DMPPD	:	Directorate Maritime Policy and Project Development
DMSS	:	Directorate Maritime Ship Support

DND	:	Department of National Defence
DRDB	:	Defence Research and Development Branch
DRE	:	Defence Research Establishment
DREA	:	Defence Research Establishment Atlantic
DREO	:	Defence Research Establishment Ottawa
DREV	:	Defence Research Establishment Valcartier
DSAM	:	Deputy Scientific Advisor Maritime
DSS	:	Decision Support System
ECM	:	Electronic Counter Measures
EID	:	Ecological Interface Design
ESM	:	Electronic Support Measures
EWS	:	Electronic Warfare Supervisor
HCI	:	Human-Computer Interface
IEEE	:	Institute of Electrical and Electronic Engineers
IFF	:	Identification Friend or Foe
IR	:	Infrared
IRST	:	Infrared Search and Track
JDL	:	Joint Directors of Laboratories
MSDF	:	Multi-Sensor Data Fusion
MTP	:	Maritime Tactical Picture
NETE	:	Naval Engineering Test Establishment
ORO	:	Operations Room Officer
R&D	:	Research and Development

RM	:	Resource Management
RTS	:	Real-Time System
SA		Situation Awareness
STA	:	Situation and Threat Assessment
SWC	:	Sensor Weapons Controller
TA	:	Task Analysis
TA	:	Threat Assessment
TADMUS	:	Tactical Decision Making Under Stress
TEWA	:	Threat Evaluation and Weapon Assignment
TS	:	Track Supervisor
USN	:	United States Navy

1.0 INTRODUCTION

Combat system operator activities in the conduct of shipboard Command and Control (C2) involve a number of data and information processing tasks which must be continually performed in real time as part of tactical decision making. These tasks include: compiling a picture of the tactical situation using both real-time and non-real-time data from a variety of sources; using this picture to monitor the tactical situation and assess and comprehend its elements; and responding to perceived or potential threats in a manner that complies with various rules of engagement. Operator responses can include: directing available sensors and/or surveillance assets to investigate suspicious elements in the tactical picture; increasing the level of ship preparedness; executing various countermeasures to limit the threat's capability and opportunity to mount an effective attack; preparatory measures to enhance ship survivability and increase weapon system effectiveness in case of an attack; executing various warning actions; and engaging threats using a variety of weapon systems.

These various tasks are performed in a highly dynamic, complex environment and call for a high degree of coordination among operators to achieve the various objectives in a timely and responsive manner. Unfortunately, there are a number of factors that increasingly challenge the ability of operators to perform effectively with current shipboard Command and Control Systems (CCSs). Examples include technological advances in threat technology, the increasing tempo and diversity of open-ocean and littoral (i.e., near land) scenarios, and the growing volume of data that needs to be processed under time-critical conditions. For example, advanced missile threats are characterised by high speeds, deceptive terminal manoeuvres to penetrate hardkill defences, and a variety of guidance systems to counter softkill defences. The littoral environment, in particular, imposes a number of inherent difficulties (Ref. 1), including:

(a) geographical constraints which significantly reduce the size of the battlespace and increase the vulnerability of ships operating in littoral areas;

(b) increased numbers of threats and reduced reaction times against attacks from modern coastal defence systems which give an enemy the ability to strike at any time with little or no warning, while employing highly coordinated attacks aimed at stressing a ship's defence systems;

(c) sensor and guidance system degradation due to heavy land clutter which leads to increased uncertainty; and

(d) intrinsic congestion within littoral waters from tankers, freighters, fishing boats, and commercial air traffic, which, combined with the effects of sensor degradation in this environment, results in increased uncertainties in identification and deconfliction.

Developments such as those just described will significantly increase the complexity of scenarios that a ship can face, reduce the time available for decision making and increase the perceptual and cognitive demands on operators needed for effective performance. In the littoral environment, for example, operators can be forced into the unreasonable and unmanageable situation of having to make extremely rapid, complex decisions, based on a limited understanding of the tactical situation, for which they are accountable (see, for example, Refs. 2-4). A key difficulty for the human decision maker in this environment is clearly stated in Ref. 1: failure to resolve situation uncertainty and hesitation to act may lead to a missile hit; on the other hand, rapid reaction to what appears to be a threat may lead to undesirable consequences. The well-known incident involving the US Navy (USN) ship, USS VINCENNES, seemingly typifies this difficult predicament of trading off inadequate knowledge about a situation against limited time to act and is a frequently cited naval example which resulted in a severe loss of civilian lives. Compounding these problems is the growing volume of data pertinent to a ship's area of interest that can leave operators unable to cope with the deluge and to extract key pieces of information needed to understand the situation and respond effectively.

One is forced to the inescapable conclusion that future shipboard CCSs will need to provide increased or new kinds of tactical decision support if the limits of human capacity and capability is not to be exceeded. For the purposes of this document, the CCS is viewed as a sub-system at the heart of the ship's combat system that includes various other sub-systems like weapon and sensor systems, a navigation system, and an environment monitoring system. The purpose of the CCS is to assist human operators in best utilising the fighting capabilities of the ship. Unfortunately, current operational systems generally provide little support for operator tactical decision-making processes in complex, highly dynamic scenarios. For example, one can envisage additional computer-based capabilities that automates tracking to speed up reactions, provides threat analysis to assist in decision making, presents a common force-level tactical picture, and assigns weapons under human veto. The need for such support is particularly pressing given the current emphasis on littoral warfare that results in reduced reaction times and the need to deal quickly and correctly with complex rules of engagement designed to avoid undesirable consequences (Ref. 5).

The Data Fusion and Resource Management Group at Defence Research Establishment Valcartier (DREV), with its industrial and university collaborators, have for several years now been investigating algorithms to augment or enhance the existing CCS capabilities by: continuously fusing data from the ship's sensors and other sources; dynamically maintaining a tactical picture; and supporting response to actual or anticipated threats. The emphasis of this work has been put on automated capabilities that work in semi-autonomous control mode, with the operator playing a mostly passive, supervisory or monitoring role. Consequently, operator-in-the-loop issues and their impact on system design have not previously received detailed consideration.

DREV is now broadening the scope of this work. It is involved in a new project to explore concepts for the design, development, implementation, and evaluation of a computer-based, real-time decision support system (DSS) that can be integrated into the ship's CCS to assist operators in conducting tactical Command and Control (C2), focusing on Above-Water Warfare (AWW). Reference 6 describes some of the ongoing research aimed at application to the HALIFAX Class ship (also referred to as the Canadian Patrol Frigate (CPF)). The operator serves three primary roles in the C2 process: situation interpreter, decision maker and effector. The purpose of the DSS is to support operators in each of these roles. A key goal is the design of a joint system, comprised of both operators and automated decision aids, that optimises overall mission performance, leading to improved operational effectiveness. Importantly, this work extends the scope of the problem to include human-machine interaction and team-machine collaborative issues, particularly where higher level cognitive processing involving human judgements and decision making is involved.

This document examines a range of concepts currently being investigated for the development of the DSS, focusing on automation, cognitive and methodological issues. Automation issues address principles and paradigms for computer-based decision support. Cognitive issues deal with the specifics of the various cognitive-level behaviours that the DSS must exhibit and/or support. Emphasis is placed on a cognitively based model of the C2 process that appears promising for guiding system design. Methodological issues are concerned with managing the complexity of the system design problem in a systematic and effective manner. Key ideas of a specific model-based framework for design are exposed.

This document is organised as follows. Chapter 2.0 describes the decision-making environment of shipboard Command and Control. Chapter 3.0 provides a brief background on computer-based real-time decision support and describes difficulties for the development of a computer-based decision support system. Chapter 4.0 examines a wide range of automation issues related to providing computer-based decision support in this environment. Chapter 5.0 exposes a model-based framework for decision support system design. Chapter 6.0 briefly describes a model of data fusion and some of its consequences on decision making. Chapter 7.0 looks at the domain of naturalistic decision making to identify characteristics of human decision processes in naturalistic environments. A cognitively based model for the Command and Control process is presented in Chapter 8.0. Chapter 9.0 discusses the current version of a high-level framework for a decision support system for shipboard Command and Control. Finally, Chapter 10.0 provides conclusions.

This work was carried out at DREV between January and November 1997, under Work Unit 1ba12: "Investigations of MSDF/STA/RM Concepts".

2.0 DECISION-MAKING ENVIRONMENT OF SHIPBOARD C2

Most tactical decision making in a modern frigate like the CPF is performed within the ship's Operations Room. There, a team of combat system operators interact with a CCS through consoles, aided by a number of other systems. They perceive and interpret information available from ownship sensors (organic data) or data linked from other cooperating platforms (non-organic data), and plan and conduct mission operations.

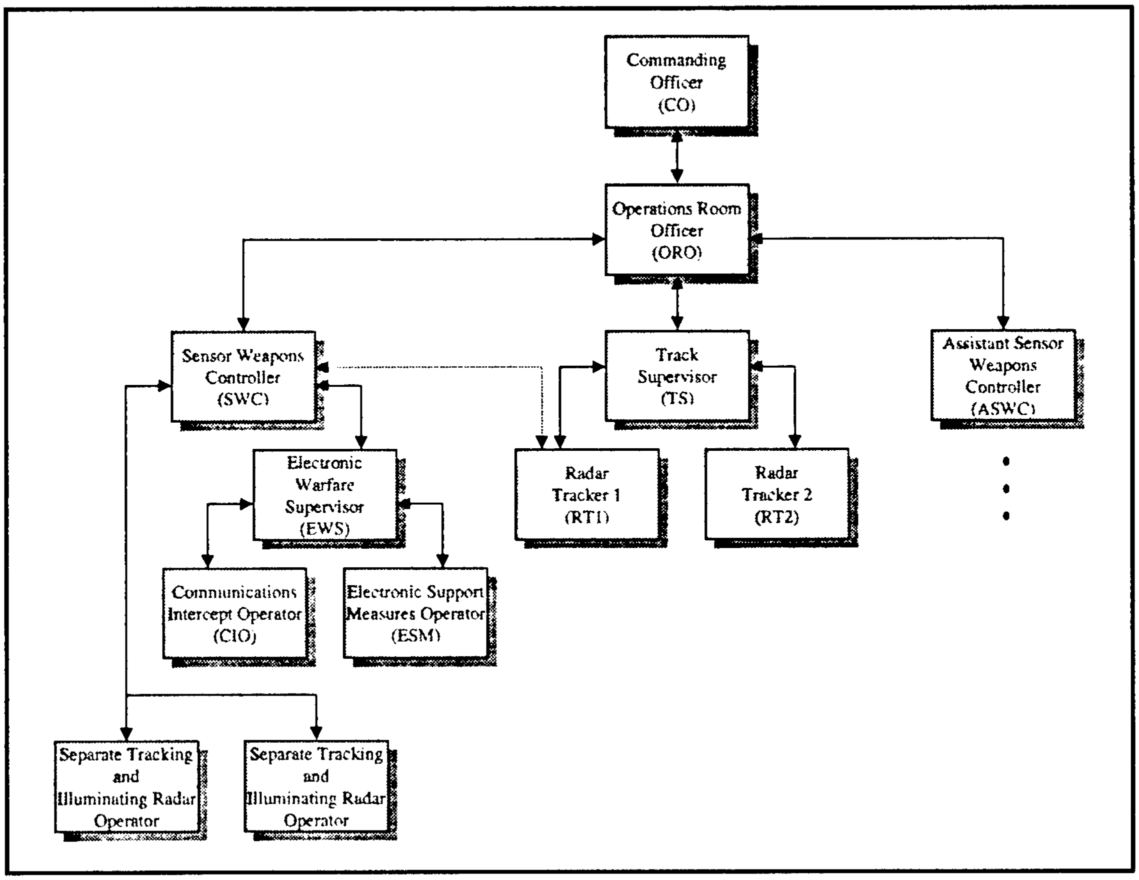

FIGURE 1 – Combat system operator organization

Major C2 tasks include: weapon and sensor systems control, tactical picture compilation, situation interpretation and threat evaluation, weapon selection and engagement monitoring, navigation and ship manoeuvres, and mission planning and evaluation. The C2 process necessitates highly dynamic information flows and decision making involving a number of operators, with a concomitant requirement for developing a common, shared representation of the situation.

We describe in this chapter various elements of the C2 process, focusing on aspects of situation representation. This description is not meant to be definitive. Rather, the aim is twofold: first, to expose key elements of the domain's complexity (summarised in Section 2.3); and second, to touch on some of the aspects of tactical decision making that influenced the development of the C2 process model presented in Chapter 8.0.

2.1 Overview

A ship's command structure is typically organised hierarchically. In such a structure, the team of combat system operators is divided into sub-teams, generally along warfare areas, with immediate control exercised by a sub-team supervisor. The AWW organisational structure for the CPF is illustrated in Fig. 1. The Commanding Officer (CO) is responsible in all respects, but normally delegates control and charge of the ship to personnel of his choice, usually the Operations Room Officer (ORO), to allow the most efficient deployment of the ship.

Effective tactical decision making depends on a coordinated team effort and communication among its members is critical in sharing information. Various means are provided to enable this communication and help establish a common situation understanding needed for coordinated action. For example, operators monitor information disseminated to and from other units at sea and ashore, communicate with each other and provide feedback by means of headphones. In addition, stateboards disseminate current information on perceived threats and assist in activating pre-planned responses to highly time-stressed events such as the sudden detection of an anti-ship missile (ASM) flying towards the ship.

Tactical C2 tasks require demanding perceptual and cognitive processing to be continuously and iteratively performed. For example, with respect to the event sequence from "birth" to "death" of a single contact (track), operator activities span the moments from first contact detection, its investigation and evaluation in the context of the current mission, development of one or more courses of action, to a course of action decision, potentially involving an engagement and monitoring of that engagement.

Contact data from sensors and other sources are continually analysed to determine a contact's kinematics (position, velocity, etc.), classify it at various levels of specificity (e.g., surface combatant, name of contact), and evaluate it to decide whether it is a neutral, a friend, or a threat. A given contact may undergo several changes in evaluation status over its lifespan - pending, unknown, assumed friend, friend, neutral, suspect, hostile (see Ref. 7) - as new pieces of evidence are acquired and integrated.

Evaluating a specific contact may require a variety of investigative actions to be taken. For example, insufficient information on a contact might involve, time permitting, taking action to acquire additional information (e.g., sending a helicopter for closer surveillance; manoeuvring the ship and observing the contact's response; requesting additional information from a participating unit) which must then be integrated with existing information. There may be a need, therefore, to trade off seeking additional information to resolve uncertainty against the time available for the feasible implementation of a specific action against a contact. A potentially hostile platform must be evaluated for its capability to detect, track, mount an attack or play a role in an attack, and defend itself or be defended. In addition, its status and behaviour must be monitored, the implications of its likely intentions understood, and various preparatory or anticipatory decisions and actions taken, as necessary, in readiness for an attack.

Even if it has been evaluated as a threat, a contact may never be involved in engagement processing for a variety of reasons. For example, a contact may have been perceived to be a threat because its behaviour suggests that it is preparing to make a stand-off attack whereby it remains outside the engagement range of ownship's weapon systems. In fact, even if a threat does come within the ship's weapon engagement envelope there could still be a conscious decision not to engage it, for example, because of rules of engagement constraints or a desire to remain covert in some way.

Beyond the above snapshots of processing activities related to a single contact, at any moment numerous contacts may have been detected, and, in addition to dividing their attention between individual contacts, operators may need to identify, monitor and interpret a variety of intercontact relations.

For example, grouping related contacts according to various spatial and functional relations helps to reason about them as a group. An operator might do this to establish potential links in their purpose and significance and extract additional clues to permit refining assessments about a contact's identity, intentions and tactical impact on the mission. Importantly also, grouping allows structured representations of the tactical picture at different levels of abstraction. The operator can use this to ease the load on perceptual and cognitive processing by zooming in or out in the level of detail represented in his mental picture of the tactical situation. Effectively, this shifts focus to a more abstract or less abstract representation of the picture, as required. One simple example of this strategy is that an air platform may have been detected communicating with a surface contact. An analysis of this grouping and their individual capabilities might then suggest that the air platform is providing the surface platform with targeting information. As a second example, a specific engagement action is judged to be unwise because the threat is determined to be in the path of a friendly contact with an unavoidable risk of fratricide. Focusing attention on contacts and their spatial relations in the region of space concerned is sufficient for this type of analysis.

Another important example of intercontact relations are value relations, which assign values to individual threats. This helps with ranking threats in case of weapon contention and allows to select appropriate response actions.

Adding to the perceptual and cognitive processing demands described above is the fact that in this domain the underlying information is derived by continuously fusing data from a variety of organic and non-organic sources, including radar, electronic support measures, infrared search and track, identification friend or foe transponder responses, data links, and intelligence information from shore and various deployed units.

This information is used to build a coherent Maritime Tactical Picture (MTP) of the ship's area or volume of interest. This creates a number of processing problems.

First, the data to be fused is generally imperfect. It can be uncertain, incomplete, imprecise, inconsistent, or ambiguous, or some combination of these, due to limited sensor coverage, report ambiguities, report conflicts, or inaccuracies in sensor data (Ref. 8). Problems also arise as a result of deliberate interference and deception countermeasures by the enemy. Second, non-organic information is generally less timely than organic information, which makes it difficult to correlate the two types of information. Because of problems of imperfect data and correlation ambiguity, the MTP only approximates the true state of affairs and there can potentially be several likely interpretations of the tactical situation. Finally, even in moderately complex scenarios large amounts of data may need to be processed under stringent time constraints. At present, in the CPF for example, these various fusion tasks are performed manually by operators.

2.2 Problems and Opportunities

While the discussion in Section 2.1 focused exclusively on potential problems that stem from the presence of contacts in the tactical picture, there is in fact a variety of other situation elements that may serve to alert the operator about other types of pending "threats" in the environment, both internal and external to the ship, and which, therefore, may also need to be "tracked" in case a problem does develop.

Context independent examples include: various numeric or symbolic state variables that reflect the status of the ship's fighting resources (number of missiles and shells remaining, operational and engagement status of sensors and weapons, and so on); logistics and personnel status; and social and political status. Another type of example arises from the need to monitor the effects of a plan for problems in its implementation due to plan execution error, action outcome uncertainty, or unanticipated variability in the external environment. Context-dependent examples of problems are specific to situation context. For example, geographical and environmental constraints of the littoral environment can significantly reduce the size of the battlespace or degrade weapon and sensor performance (Ref. 1). This may force the operators to react to a new set of problems that could negatively impact the achievement of the mission and which are not of importance in an open-ocean scenario. This can include problems with perception and action (e.g., an increase in the number of false alarms of a sensor unless its detection threshold is lowered; limits in ship manoeuvrability that impact feasibility of a particular countermeasure).

The common feature of all the above examples is that at the highest level they relate to the need by operators to understand the meaning and significance of potential problems for the success of the mission and the survival of the crew and ship. More generally, we define a *problem* to be a feature of the situation that has the potential to negatively impact the achievement of one or more *goals* or which should at least alert the decision makers to consider a change in the way these goals are being, can be, or should be achieved. A problem therefore represents an important goal-relevant property of the environment in that it has the potential to shape some aspect of an operator's behaviour. The detection of a problem is an event signaling a possible need for corrective measures to avoid or resolve the problem. We shall return to this observation in Chapter 8.0.

However, another important type of goal-relevant property for an operator interacting with a complex, dynamic environment is related to opportunities. An *opportunity* is defined as a feature of the situation that represents a possibility to achieve one or more goals, or to accelerate their achievement, or to resolve the obstacles to their achievement. Opportunities may present themselves fortuitously and unexpectedly, or they may be planned for as part of purposeful action. Whereas a problem can be thought of as a constraint on behaviour, recognition or identification of an opportunity in an existing situation is an event that offers potential for enlarging the degrees of freedom for that behaviour. For example, a particular geographical or environmental feature may offer an opportunity for concealing detection from the enemy. In some cases, there may be a cost attached to taking advantage of an opportunity (e.g., manoeuvring the ship from a pre-planned course to take advantage of terrain masking to hide from a threat, which intelligence sources have suddenly signaled, uses fuel but increases the chances of ship survivability). This cost may need to be estimated as a precursor to a decision.

We suggest in Section 8.2 that the three dynamic elements, consisting of *goals, problems* and *opportunities*, along with their dynamic *relations*, can be used in a cognitively plausible triad to permit structuring a situation representation for tactical decision making that has psychological relevance for the operator. This is the basis for our cognitively based model of the C2 process presented in Section 8.3.

2.3 Domain Complexity

The AWW environment calls for operators to work effectively in a highly coordinated manner towards common objectives. They must: (i) continuously scan consoles and monitor communication nets for significant events and alerts; (ii) exchange information among themselves or pass information up the chain of command; (iii) issue or respond to orders depending on an operator's position and role in the chain of command; and (iv) focus attention at any given moment among several competing stimuli and divide attention between several competing or complementary multiple tasks. In fact, so much needs to be done at any given time that careful attention and time management at both the individual operator and team levels are crucial for effective performance. Critical incidents (problems or opportunities) can happen at indeterminate times, resulting in dynamically shifting, multiple goals and numerous perceptual and cognitive tasks to be performed by various operators towards cooperatively accomplishing these goals. The result is a complex, dynamic, real-time, data- and goal-driven multi-tasking environment in which goals are continuously created, prioritised and steps taken towards their achievement with continuous attentional shifts between goals. It is therefore vital that both human and machine resources, including weapons, sensors, computers and communications, be effectively managed. Such problems are particularly difficult when careful scheduling of shared resources is required to achieve time-constrained goals.

We have described the complexity of this environment in terms of the perceptual and cognitive demands imposed on operators. Woods (Ref. 9) states that there are four characteristics that modulate the cognitive demands an environment places on a person interacting with it: dynamism, the number of its parts and the extensiveness of interconnections between those parts, uncertainty, and risk. In view of our description of the AWW environment, it evidently rates as a highly demanding domain in all these dimensions. In practice, of course, complexity can vary, depending on the specific context and nature of the conflict. Complexity in a given situation is also likely to be perceived differently by individual operators depending on their roles, the nature of their individual processing tasks and their workloads.

Future combat scenarios are expected to span low to high intensity levels of conflict in open-ocean and littoral areas. In high clutter, terrain-masked littoral environments where there may be many kinds of platforms of many nationalities, with potential for interactions with neutrals becoming embedded within engagements, operator tasks such as establishing and identifying the numerous contacts, determining their intentions, interpreting dynamic, complex rules of engagement and taking appropriate action, will be very challenging. Complexity also increases with advances in missile technology (e.g., higher speeds, sea skimming attack profiles, smaller signatures) that lead to reduced detection ranges and reaction times against such threats, and increases in a ship's region of interest.

Finally, with increasing pressure to reduce the through-life costs of future naval platforms, coupled with demographic data suggesting a reduction of available personnel, we note that various navy research efforts in the US and UK are already examining the problem of leaner operator manning of ships (Refs. 10-12). Reduced manning may have the effect of further increasing complexity as there will be fewer people to share the processing load.

3.0 PROVIDING COMPUTER-BASED SUPPORT FOR TACTICAL C2

3.1 Universe of Solution Approaches

Chapter 2.0 highlighted the perceptual and cognitive processing demands of tactical C2 for shipboard combat system operators. While we are concerned in this document principally with providing computer-based support to help operators meet these demands, it is important to note that there are in fact a number of other approaches, some of which are indicated in Fig. 2, for addressing potential decision-related problems in the tactical C2 process.

- Change Combat System Operator Organization
- Change Doctrine
- Change H/M Function Allocation
- Change Tasks
- Change Manning
- Improve Automation
- Change Ops Room Layout
- Improve Training
- Better Selection

FIGURE 2 – Universe of solution approaches

These various approaches can each be considered separately or in combination with computer-based decision aiding. In fact, their evident interdependencies strongly indicates a need for their joint analysis during the solution implementation process. This analysis would also compare the benefits and costs of the various approaches and establish trade-offs and shortfalls. However, this type of analysis is not the aim of the work reported here. Furthermore, while the relative benefits of effecting improvements in each of the various approaches is currently unknown, opportunities for providing enhanced computer-based support in the CCS in the areas of information management, information display and decision aids appear sufficiently substantial to warrant their research and evaluation, particularly given the limited capabilities of the existing systems.

3.2 Architecture of a Real-Time Decision Support System

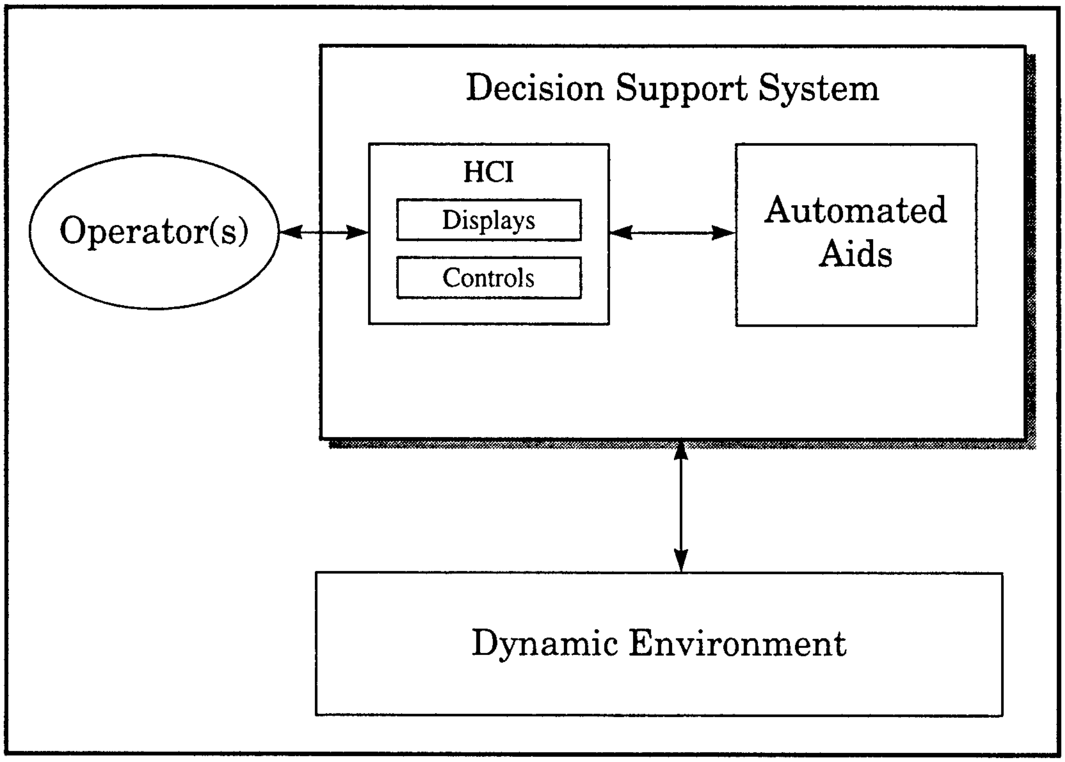

FIGURE 3 – General architecture of a real-time decision support system

A general architecture of a real-time, computer-based decision support system is shown in Fig. 3. Only high-level components are represented; for example, sensors that provide data on the state of the dynamic environment and actuators that allow the environment to be influenced or impacted by the control actions of the operator(s) are not shown. The human-computer interface (HCI) mediates between an operator's perceptual, cognitive and motor systems and the environment with which he interacts, while the automated aids provide data and information processing tools that are intended to facilitate and enhance the execution of the various decision-making processes in response to events occurring in the environment. To underscore the real-time aspect of the support system, we emphasise that the primary role of the DSS is broadly interpreted as being there to help operators keep up with, or even better, keep ahead of, and respond effectively to, significant events occurring in real time in the dynamic environment.

3.3 The DSS Development Problem

Developing a DSS is extremely challenging for a number of reasons. We examine a few of them here.

Reminiscent of the Gestalt principles in perception, overall operator-machine performance is an emergent property. Their combined performance emerges from interactions of operators with an external battle environment, with the aid of the DSS, as technology both supports and constrains operators in what they can do to achieve their mission. The joint operator-machine system is therefore more than the sum of its parts (Ref. 13). This suggests that it will be difficult to make effective system design decisions simply on the basis of isolated assessments of performance improvements derived by special purpose technological solutions. Ignoring this point (as is often the case) can lead to problems of operator acceptance of technological solutions and difficulties in their ultimate integration into their work environment for viable operator use.

For example, it has been suggested that, when tools dominate, rather than constrain, the joint system, the designer runs a strong risk of solving the wrong problem, and of creating new problems and undermining critical, existing work strategies in the process (Ref. 9). Certainly, the literature provides a number of examples in other domains, including the airline cockpit and process control domains, where failures have been associated with a technology-centred approach to automation at the expense of operator-in-the-loop issues. This argues for addressing both tool building and tool use if a successful joint operator-machine system is to be achieved. Moreover, failure to do this at the outset, at the concept analysis stage, or proceeding from a technologically centred perspective, runs the risk of designing a system that forces operators to adopt procedures and strategies that might in the end degrade, instead of enhance, total performance because of the resulting cognitive dissonance between the operator and the automated system. These remarks are not a criticism of technology per se, but of the failure to appreciate the difficulty of designing truly supportive technology, particularly at the level of aiding the human's cognitive processing.

Interestingly, observations in the same vein can be found in both the Cognitive Systems Engineering (Refs. 9 and 13) and Management Information Systems (Refs. 14-15) literatures. Recent work by Cohen (Refs. 16-17) argues that the idea of an effective cognitive support or intellectual tool rests on cognitive compatibility between the tool and the decision maker. Such a tool would match the pattern of decision makers' knowledge and ignorance by using what they know to generate what they need to know, using reasoning processes they are familiar with and trust.

These remarks clearly place considerable emphasis on the need to understand the process of decision making to design effective support systems. Yet it is only relatively recent that work in the cognitive science community has begun to examine naturalistic models of decision making (Ref. 18). We provide a brief review of this work in Chapter 7.0. Unfortunately, there remains a shortage of models of human decision-making behaviour, competence and performance that can guide requirements-driven design of decision aids. For example, Endsley observes that despite a concerted thrust to provide military pilots with decision aids through programs like Pilot's Associate, information on how tactical aircraft pilots actually process their environment and make decisions has largely remained anecdotal (Ref. 19). Judging from the literature, the situation with respect to the naval environment is not very different.

It is evident then that a deep understanding of cognitive issues and the nature of the role of the operator in the C2 process, accounting for human capabilities and performance limitations, must provide an important foundation to principled design of decision aids. However, designers are confronted with the problem that despite many recent advances in naturalistic domains (Ref. 18) directed at understanding human decision-making processes in complex dynamic environments, knowledge in these areas to support system design is still somewhat fragmentary and incomplete. This forces the adoption of a pragmatic approach to the development of practical, viable decision aids, based on a blend of solidly grounded design principles and an informed appreciation of areas where knowledge is limited. This is all the more important in the current DREV project because what is involved is more than a conceptual exploration for the purposes of technology investigation. Rather this ongoing work is aimed at contributing to a specification of a DSS for the mid-life upgrade of the CPF. A critical constraint is the timing of this upgrade which is expected to take place in phases commencing early in the next century.

4.0 AUTOMATION ISSUES

This chapter examines a number of automation-related issues germane to the development of a DSS to support operators in their various roles in the tactical C2 process.

4.1 Overview

Natural questions to ask concerning the provision of automated aids for improving operational effectiveness of decision making in the Operations Room are: which operator roles and positions in the Operations Room need to be aided, why, when, and how? Answers to such questions need to be derived based on an appropriate system development philosophy and a coherent design methodology (Refs. 20-21).

It is evident from Chapter 2.0 that computer-based support is potentially a highly beneficial option, if not a must, for improving performance in most, if not all, operator positions. For example, in highly dynamic scenarios handling the large amounts of data could quickly overwhelm human capabilities. This also arises from increases in the ship's region of tactical interest that require tracking and understanding the significance of a large (and growing) number of contacts. The fact is that human information processing is subject to a number of limitations and deficiencies, such as finite cycle time, limited working memory, limited ability to perceive and process information and cognitive biases (Ref. 22). It is also negatively impacted by environmental factors or stressors and almost random mistakes (errors of judgement) or slips (errors of execution) (Ref. 23).

The form and variety of support would need to be carefully tailored to an operator's position, depending on the nature and mix of the perceptual and cognitive processing involved, and ideally be capable of personal adaptation to suit the variety of support requirements of an operator in that position. The various processes of an operator's role in the decision process would need to be established, decomposed into sub-processes, and decisions made about which of these various sub-processes are candidates for receiving some kind of computer-based support. An important consideration in making such decisions is the relative capabilities of humans and machines for performing various tasks (Ref. 24, p. 84) (e.g., the human is generally considered better at tasks that involve inductive or common-sense reasoning, whereas the machine is better at deductive reasoning; the human is better at acting in novel situations, whereas the machine is better at monitoring prespecified events, especially infrequent ones). Despite these considerations, we continue in this document to speak about a single DSS to support operators without differentiating individual operator support requirements.

4.2 Aiding Metaphors

An aiding metaphor is concerned with how support is provided by a decision aid to a decision maker on some perceptual or cognitive component of a decision-making process. The decision aid acting as a prosthesis or as a tool are two extremes that lead to two very different metaphors. The differences are related to the role of the aid in the decision process.

The prosthetic approach focuses primarily on decision outcomes. The role of the aid is essentially to replace the operator in some way or to compensate for human deficiencies in reasoning or problem solving. It does this by prescribing the "correct" decision or output given its inputs. Expert systems that provide advice or decision outcomes typically fall into this category of aid. The operator is largely out of the loop and plays a mostly passive role. A frequent criticism of this approach is that it leads to brittle systems, because of limitations in their encoded domain knowledge and assumptions that narrowly bound their view of real-world complexity. This makes them prone to poor performance in the face of environmental variability that has not been anticipated by the system designer. There is an extensive literature in the cognitive engineering (Refs. 13 and 9) and naturalistic decision-making communities (Ref. 18) which argues instead for an alternative approach.

In the decision-aid-as-tool metaphor, focus is on the process of decision making itself. The aid is viewed as a tool in the hands of a competent but resource limited agent (Ref. 21). There is sufficient flexibility, however, for the aid to adapt to a novice, with limited experience (or maybe just a battle-fatigued expert!). Importantly, the operator plays an active role and the tool assists in accordance with the decision maker's support requirements. Design emphasis for such an aid is on supporting the strengths and complementing the weaknesses of the operator. In addition, support is provided for the operator's naturally preferred strategies (at the expense of enforcing a normative or prescriptive approach). In this case, then, the aid is a tool to amplify strengths and attenuate weaknesses of the human by providing increased or new kinds of resources (e.g., an intelligent alarm and information display system; an aid that automates time consuming resource scheduling computations).

Given the wide range of expected task loads likely to prevail in a ship's Operations Room and the variety of types of processing involved (monitoring, detection, assessment, diagnosis, planning, and acting), there appears to be a place and need for both metaphors, or some adaptable hybrid of these extremes, in aiding operators, depending on situation context, the specific nature of the processing, and the role of the operator. For example, a prosthetic mode would seem appropriate in situations where the operators' current cognitive resources are momentarily overwhelmed and they are incapable of active, effective participation. There needs, however, to be some understanding by both designer and operator of how the aid's performance itself degrades in such circumstances to avoid the problem of "the blind leading the blind". Also, the minimal involvement of the operator must be determined to avoid, or at least limit, the effects of "the out-of-the-loop performance problem" (Ref. 25). These effects leave the operator handicapped in the ability to resume control in case of automation failure or once the cognitive demands of the situation have diminished to an acceptable human level. In less demanding situations, a decision-aid-as-tool mode would keep the operator in the loop.

4.3 Need for Design Principles and Guidelines

The "out-of-the-loop performance problem" has been linked to a loss of situation awareness (SA) and skill decay (Ref. 25). The former suggests a number of questions.

When environmental tempo and situation complexity increase, leading to cognitive processing overload of operators, what aspects of the environment do they continue to need to maintain an understanding of? If the operators are withdrawn from a decision loop in stages as a means of lightening the human processing load, what support for maintaining their SA should the system provide at each stage to allow making judgements and decisions that remain part of their responsibility (i.e., not part of the system's)? How should the operator be able to influence the behaviour of support components of a system and how much does the operator want or need to understand about their processing (e.g., models and algorithms used; assumptions made)? How is the authority for deciding the outcome of a supported cognitive process to be distributed between the operator and machine, and how does this depend on the type of process (whose consequences or effects may vary from benign to lethal)?

The need for design principles and guidelines that address these and other questions is evident. Jones and Mitchell (Ref. 26) have proposed only general principles on human authority, mutual intelligibility, openness and honesty, management of trouble in case of problems in human-machine communication, and support for multiple perspectives. Further research is needed to provide more specific additional guidance for design.

4.4 Delegation of Authority

Section 4.2 dealt with the issue of how automated support should be provided (i.e., the various aiding metaphors, depending on situation context) once the design decision has been made to provide a decision aid for a given sub-process of a particular decision process. Examples of separate, but related, issues include: mechanisms for **delegating authority to the system for making the decision about the outcome or result of** an automated sub-process; dynamically triggering a change in delegation based on changing situational factors; an override capability for the operator when the operator and the system have overlapping responsibilities for a sub-process; and the capability for the operators to influence system behaviour when they have delegated or lost authority.

Two design approaches to dynamic task delegation are adaptive automation (implicit delegation) and providing a fixed variety of operator-system modes (explicit delegation). Adaptive automation involves a computer-controlled, adaptive allocation, depending, for example, on which party has at the moment more resources or is the more appropriate for performing the task (Ref. 27). A potential problem, however, is that it requires operators to keep up with who is doing what as the allocation changes.

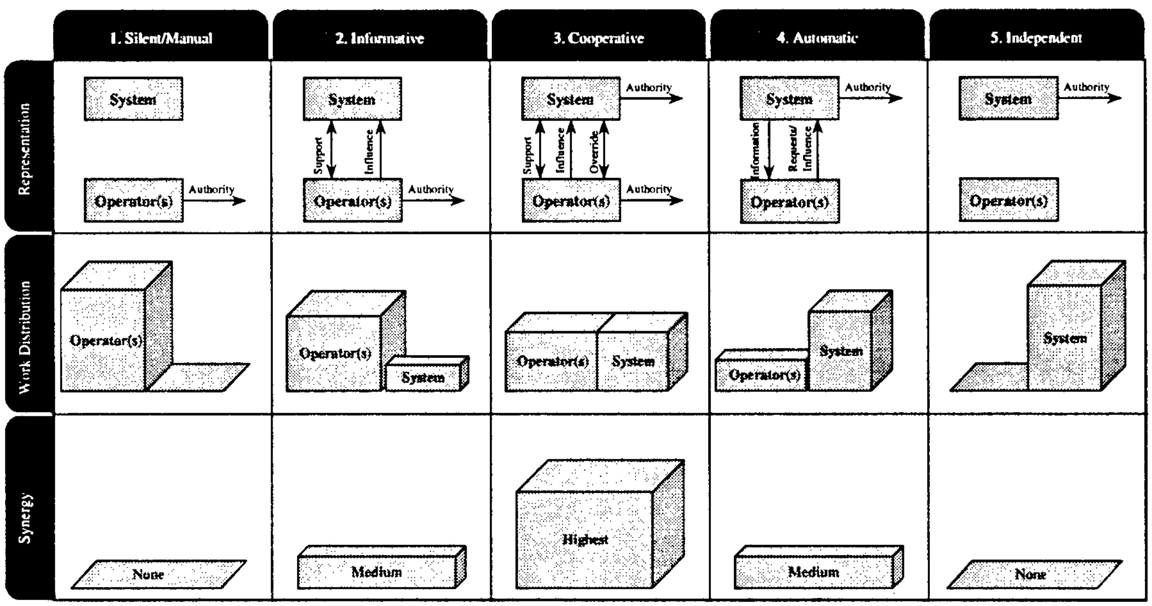

FIGURE 4 – Operator-system modes of operation

One possible version of the approach of providing various modes of operator-system delegation, which bears some resemblance to that currently implemented in the CPF for threat evaluation and weapon assignment (TEWA) related tasks, is illustrated in Fig. 4. Representations are given of five operator-system modes of operation, along with variations in the levels of work distribution and synergy between the automated system and the operator involved in these various modes. Mode selection is made by the human decision maker and applies until mode transition is triggered by the decision maker choosing a new selection. If this is done at the system level (instead of at the level of particular decisions), each mode implies a fixed delegation of authority for all the various sub-processes of the decision processes for which automated support is available and use of a fixed support paradigm. The bi-directional arrows for support in Fig. 4 indicate that the support paradigm in a specific mode could involve the operator in an active role (as in the decision-aid-as-tool metaphor). The actual support paradigm used in a given mode is fixed, but it does not have to be the same for each mode.

In the silent/manual mode, the operator has total authority. Moreover, the system is completely passive and provides no support whatsoever to the operator.

In informative mode, the system only provides the operator with support information (the limit of its work responsibility), some of which may be a consequence of a request from the operator; however, authority again rests totally with the operator. The operator can also influence characteristics of the support provided.

In cooperative mode, the system and the operator work together. Authority may be divided (e.g., some judgements, decisions and action responsibilities allocated totally to the operator, the rest to the system, depending on type) or shared by the two parties. However, in the shared case, one of the two parties (operator or system) has ultimate authority to override the other. This requires an override protocol. For example, suppose that the operator decides to retain overriding authority for some types of decisions but is supported in these decisions by the system's processing. Two possibilities for an override protocol in this case are: the system processes, decides and acts accordingly only if the operator first concurs; and the system processes, decides and acts automatically unless the operator vetoes. The operator can also influence the system's processing in sub-processes for which authority has been allocated entirely to the system; for example, by requesting that a specific algorithm be used. There is maximum synergy between the system and the operator in cooperative mode.

In automatic mode, the system has total authority, but the operator can influence its behaviour and request information. Apart from such influence, the system can operate in complete autonomy.

The independent mode completely excludes the operator from the process. The system has full authority. It processes information and acts autonomously without consulting the operator. In this mode, the system operates as a black box without any required operator interface.

The division of roles between the system and the operator in the various modes is summarised in Table I.

TABLE I

Operator-system roles in the various modes of operation

Mode	Operator's Role	System's Role
1. Silent/Manual	Decide and act	Passive
2. Informative	Decide and act Influence system behaviour	Support
3. Cooperative	Decide and act Influence system behaviour Override system	Decide and act Support Override operator
4. Automatic	 Request information Influence system behaviour	Decide and act Provide information Respond to operator influence
5. Independent	Passive	Decide and act

It is possible to develop an adaptable, hybrid approach encompassing aspects of the two possibilities for delegating authority described above (i.e., implicit versus explicit) along two dimensions: specific sub-process and situation context. For example, depending only on the specific (type of) judgement or decision, and under specific conditions on the context approved in advance by an operator, the system could make a judgement or decision on his behalf. Adaptive, mixed-initiative operator-computer behaviour is also possible in one or both of these dimensions. In the extreme, the system would identify and decide how to satisfy the needs of operators based on some embedded operator model.

4.5 Operator Trust

Whatever automation approach is adopted, the operator must have sufficient confidence in the technological solution to use it and be able to delegate his authority to judge, decide or act to the system as and when the need arises. Delegating authority implies that the operator will need a basis for establishing trust in the system (Muir, Ref. 28). General principles for calibrating this trust so that the operator can use an aid discriminatingly and effectively are provided by Muir, i.e., so that the operator does not consistently underestimate or overestimate the aid's capabilities. Design guidance is needed for ways of achieving and maintaining an operator's trust.

5.0 TOWARDS A METHODOLOGICAL FRAMEWORK FOR DESIGN

This section describes key ideas of a design framework for a DSS to support operators in their various roles in the tactical C2 process. The methodological approach is suggested by recent work on a theoretical, model-based framework, known as Ecological Interface Design, for designing interfaces for complex human-machine systems (Ref. 29).

5.1 Overview

The traditional software engineering approach to system development follows a life-cycle approach involving various activities like requirements gathering and analysis, specification, design, implementation, testing and evaluation, and maintenance (Ref. 30). There are a variety of user participatory refinements that relate to how and when the end users (or stakeholders) of the system are involved in the design process. One of the most common of such refinements is rapid prototyping (Ref. 31) which uses logical system models or prototypes to represent some part or all of a proposed solution. Among a number of benefits for the system development cycle, rapid prototyping aids communication between members of the user population and the system developer and helps define and establish user requirements.

That a critical problem is to elicit user requirements so that a system is produced that indeed meets these requirements is evident from statistics quoted by Wilson and Rosenberg (Ref. 31) which indicate that as much as 67% of a system development effort is in the maintenance phase (correcting errors and adapting to new requirements). Furthermore, 56% of the errors can be traced to failures in the requirements phase of software development, and these account for 82% of the cost to fix errors in the final product.

Unfortunately, despite the evident good sense of user participation in the process, there is not much evidence in the literature of its successful application in building real support systems. In fact, there is a surprising paucity of examples of operational decision support systems. Moreover, approaches like rapid prototyping are not as rapid as one might expect or want, and many developers feel that the existing methods for decision aid development are inadequate (Ref. 32). Sharp (Ref. 21) cites a number of problems with user participatory methodologies, including: their essentially empirical trial and error approach; users have a difficult time predicting what they would really like, even if they are expert at what they do; and users' time for involvement in system design is very limited.

Why is the design of a DSS such a difficult problem? We have already touched on several of the issues in Section 3.3. The reality is that in the absence of an intelligent strategy for investigating a large design space, DSS design is fundamentally an ill-defined problem, likened to solving a jigsaw puzzle consisting of uncertain pieces and an uncertain goal picture, with the pieces representing design choices and the goal picture the system. Faced with this dilemma, it would appear that the only possible strategy is to engage in many iterative, bottom-up design probes, with continual technology assessment and user evaluation and feedback at each step to direct the search from one prototype to the next. However, consistent application of such an approach by itself is problematic. It is potentially very ad hoc, expensive in both time and cost, and can result in much wasted effort. For example, Ref. 33 cites one example in the development of a medical decision support system where features that were most strongly rejected at field tests of the system were those included in the prototype at the specific insistence of doctors involved in its development. While a search of the design space that actively involves users in the development process is both advisable and essential, the problem is primarily that this search process alone does not incorporate any mechanism beyond user feedback and the developer's intuition to guide it (Ref. 21).

5.2 Model-Based Methodologies and Ecological Interface Design Theory

Recent work (Refs. 33, 34 and 21) appears to offer a well-founded alternative for developing cognitive support systems. It represents a top-down approach, based on an improved life-cycle that derives power from the use of a variety of operator-environment models that effectively help search the design space efficiently.

Not unexpectedly, the power of this model-based approach lies in the availability and choice of models. Some general requirements on operator-environment models to support DSS design are: (i) they should have both descriptive and predictive abilities (Ref. 21); and (ii) they should be operator-centred, i.e., based on knowledge of the operator's processing requirements and their psychological relevance to the operator. The descriptive abilities of operator-environment models allow for understanding current operator-environment behaviour. Their predictive abilities allow the designer to anticipate the consequences of design choices. Item (ii) is related to our remarks in Section 3.3 about the need to consider tool use in the analysis stage of producing a DSS. These various models also permit identifying ways in which the system designer can provide support that reduces the processing demands on operators by matching their perceptual and cognitive resources to the demands of the work environment.

Some model-based approaches concentrate on modeling data, information and knowledge needs of the operator (Refs. 33-34). However, as Sharp (Ref. 21) points out, such models alone address only *content* issues: *what* is the information that the DSS could usefully provide to the operator? Additional models are needed to identify: the *structure* of this information, that is, how the information should be organised to capture relations that are truly significant to the operator (as opposed to the designer); and its *form*, that is, how the information should be mapped onto display features of the interface. The need for these types of models can be traced to two key concepts in Ecological Interface Design (EID) theory. Although originally introduced as a theoretical framework for designing interfaces for complex human-machine systems, they also help to structure the DSS design problem. Motivated by Vicente and Rasmussen's work (Ref. 29), these structural prescriptions applied to DSS design can be summarised, along with their model requirements, by:

(a) describe the complexity of the external environment in a psychologically relevant way for the operator based on suitable representational models of the environment; and

(b) communicate this complexity in an effective manner based on a model of mechanisms people use to reduce the processing demands of environmental complexity.

The connection of EID theory to the three types of issues described previously is that the representational models provided in response to (a) help identify the *content* and *structure* of the information that the DSS needs to provide to the operator. The model of mechanisms that people use to deal with environmental complexity, referred to in (b), give its *form*.

EID theory has strong motivating connections to Gibson's theory of perception (Ref. 35) and work in ecological psychology (Ref. 36), with important specific principles as consequences for guiding the design of the interface of the DSS (Ref. 29). EID theory currently promotes a specific environmental representation formalism in answer to (a), viz., Rasmussen's Abstraction Hierarchy (AH), while Rasmussen's cognitive control model, known as the skills, rules, knowledge (SRK) framework, provides the answer to (b) (Ref. 29).

The AH is a multilevel representation that describes the various layers of behaviour inducing constraints in the environment. Its power is that it structures the knowledge representation of the environment in a computationally efficient and psychologically valid representation for problem solving to allow the operator to efficiently and quickly cope with unanticipated events, even when they have not been anticipated and designed to be directly supported by the system designer (Ref. 29).

The SRK framework defines three qualitatively different cognitive levels on which people process information and which the DSS should therefore support to some degree. These levels are based on the operator's degree of familiarity and expertise in dealing with the environment and on the nature of this information which can either correspond to a familiar event, an unfamiliar but anticipated event, or one that is both unfamiliar and unanticipated. At the skill-based level, the operator engages in fluid perceptual-motor control; at the rule-based level, a decision situation is recognised allowing decision rules to be implemented based on previous experience; finally, at the knowledge-based (also referred to as model-based) level, rational, knowledge-based or analytical problem solving methods are employed by novices and experts facing unfamiliar or unanticipated situations.

TABLE II

Field study data collection techniques (Ref. 21)

Thinking Aloud	Professionals describe what they are doing as they are doing it.
Guided Tour	Professionals are asked to give a guided tour of their work space, both private and shared.
Structured Observations	Used to record meetings, face-to-face and phone interactions.
Written Artifacts	Formal and informal written artifacts are collected and the professionals' descriptions of these artifacts are recorded.
Retrospective Verbalizations	The professionals being studied are asked to comment on their activities after the activity has taken place (often with the aid of video/audio recordings).
Interruption Analysis	The professionals are observed, interrupted by the observer who asks questions about what has been previously observed.
Focused Interviews	Used to explore specific aspects of work that cannot be satisfactorily captured through other techniques.

It is worth noting that despite the novelty of EID theory and the fact that it is a very recent development in the field, its technology transfer to industry has already been occurring, primarily in the nuclear and process control industries (Ref. 37). It has also been examined recently for its applicability in aviation (Ref. 37) and the neonatal intensive care domain (Ref. 21). In either case, preliminary results established the potential for meaningful and useful application. The latter application also drew attention to some of the limitations of the AH as a specific environmental representation for capturing the full set of diagnostic behaviours of physicians. However, this only emphasises the need for the careful selection of a model structure for the environment. In fact, as our cognitively based model of the C2 process in Chapter 8.0 indicates, there are a variety of cognitive processes of operators that an environmental representation may need to support in applying the framework of this section to the DSS design problem.

Another important aspect of model-based methodologies is that they use field studies to do data collection in situ (Ref. 21), i.e., in a realistic work setting like a team trainer. The idea is to observe and record in an exploratory manner (as non-intrusively as possible) the actual behavioural streams of the work environment for purposes of instantiating the various models identified by (a) and (b). Various structured techniques derived from ethnographic research have been used. These techniques structure verbal protocols according to a conceptual framework or assumptions about the nature of the cognitive activities to guide the data collection. The reader can consult Sharp's work (Ref. 21) for a review of field study techniques in this vein. Table II from Ref. 21 provides a summary.

Finally, we note that there are a number of other important issues that need to be addressed at the data collection and work analysis level of a model-based approach to design. For example, we need to be able to identify the various cognitive strategies (how they do what they do), competencies (what they know) and knowledge structures (how they represent what they know) operators employ in processing information. We also need knowledge on how operators deal with work demands and models of how their performance degrades under increasing cognitive demands, and so on. This is to enable identifying ways of providing automated support along the lines of the considerations discussed in Section 4.2.

A framework for organizing these types of cognitive analysis is suggested by Rasmussen's Cognitive Work Analysis (CWA) framework (Ref. 38). CWA is distinguished by its focus on the work domain instead of the more usual focus on tasks in a cognitive task analysis (CTA) (Ref. 39). CWA is one particular layered work analysis framework concerned with explicitly identifying the goal-relevant constraints that can shape the behaviour of operators in an open, complex dynamic system. The primary levels of this framework are: developing a representation of the functional structure of the work domain; identifying the decision activities associated with the different functions to be performed; analysing the various mental strategies and heuristics that can be used to perform each of the decision activities; identifying the competencies and performance limits of operators; and determining the constraints imposed by organizational factors.

CWA can be viewed as a complement to behavioural task analysis (TA) and cognitive task analysis activities in that it retains the benefits of methods (Ref. 40) for those analyses. The advantage of CWA over a CTA, however, is that it permits analysing knowledge-based behaviours of operators in handling unanticipated events for which a pre-planned response is likely to fail, as well as more usual procedural behaviours associated with enacting pre-planned responses. At the same time, it combines an analysis of both usefulness and usability issues of computer-based support tools for the work domain.

6.0 A FUNCTIONAL MODEL OF DATA FUSION

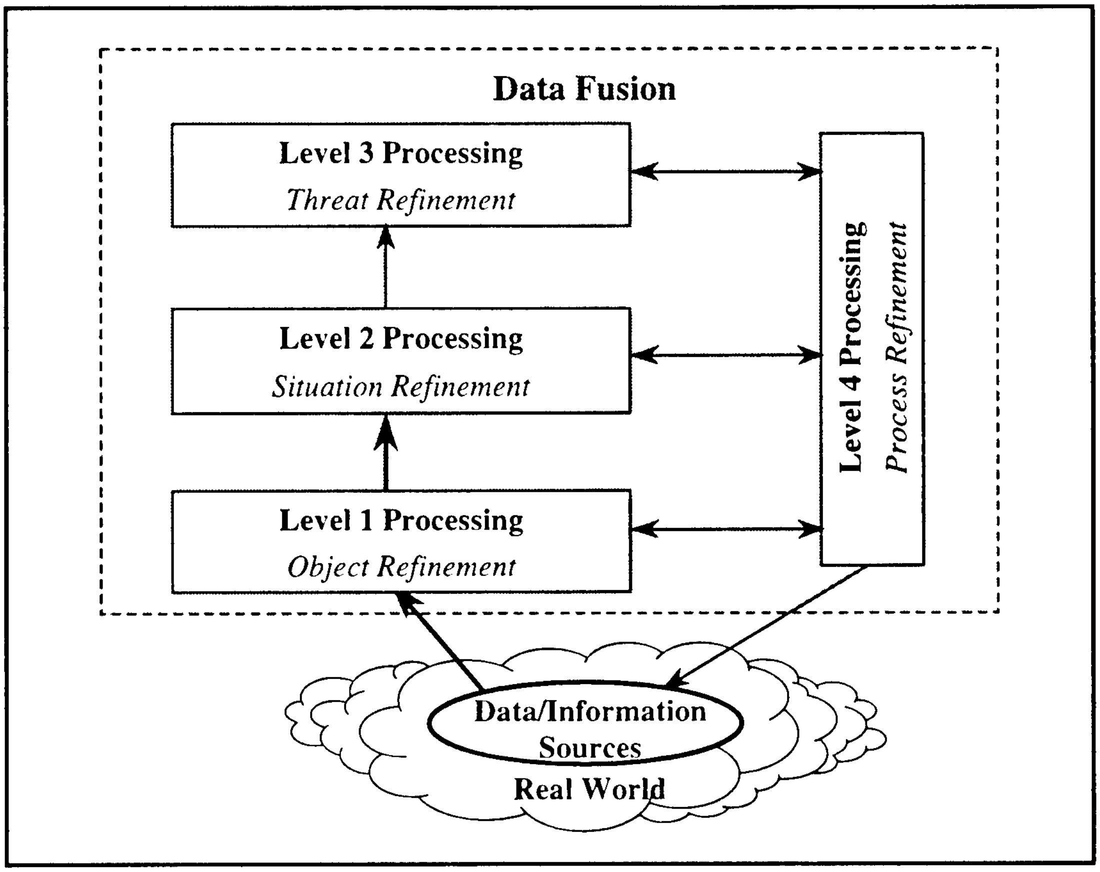

FIGURE 5 – The JDL data fusion model

One question that we have not broached so far in this document concerns details of specific automated data and information processing technologies that are receiving significant attention in military applications and which are expected to play an important role in next generation military systems for aiding decision makers. A key emerging technology with consequences for decision making is data fusion. Reasons for interest in this technology include the rapid increases in the available data that can be used to compile a tactical picture, leading to huge increases in computational requirements for its production, and the potential for improvements in the tactical picture derived from extended spatial and temporal coverage, increased confidence, reduced ambiguity and improved target detection (Ref. 41).

Based on the work of the Joint Directors of Laboratories (JDL) Data Fusion Subpanel, Waltz and Llinas have defined data fusion as "a multilevel, multifaceted process dealing with the detection, association, correlation, estimation and combination of data and information from multiple sources to achieve refined state and identity estimations, and complete and timely assessments of situation and threat" (Ref. 42). The process is also characterised by continuous refinements of its estimates and assessments, and by evaluation of the need for additional data and information sources, or modification of the processing itself, to achieve improved results. Data fusion is therefore a multi-layered processing strategy.

Figure 5 shows the four processing levels defined in the JDL data fusion model. In this representation, only multi-source data samples of the real world are available. The interpretation of the real world will be facilitated by data fusion processing. The arrow widths in the figure represent the relative data bandwidths between the processing levels. Each successive level represents a higher level of abstraction and refinement. Level 1 processing corresponds to Multi-Source Data Fusion (MSDF), while Level 2 and Level 3 processing form the basis for Situation and Threat Assessment (STA). In Level 4 processing, inferences drawn from the data fusion system may be used to select and/or control the input sources, or alter the fusion techniques themselves.

An unfortunate aspect of the JDL data fusion model is that the human role in the process is not evident or even defined. Furthermore, the model provides no formal way of explicitly tying data and information processing capabilities that could be provided by automated data fusion to the perceptual and cognitive demands and decision-making requirements of decision makers who are supposed to benefit from the improvements in the tactical picture. This makes it potentially quite difficult to use the JDL model as a basis for developing an operator support system for shipboard C2 that incorporates data fusion processing and embodies the variety of automated aiding paradigms discussed in Section 4.2. The cognitively based model of the tactical C2 process presented in Chapter 8.0 is a step towards resolving these problems.

It is worth noting that we use the term resource management (RM) later in this document to imply the management of both system resources, which are used to provide input or support for processing functionality, and tactical resources, which are used to affect the environment to achieve some tactical or strategic goal. System resources include "base systems" (e.g., CPU, memory, bandwidth) and software processes (e.g., algorithm choices). Tactical resources include weapons (e.g., missiles, guns, tracking and illuminating radars) and navigational mechanisms (e.g., control of vessel speed and direction). In this general sense, therefore, RM extends the Level 4 processing implied by a strict adherence to the JDL data fusion model.

7.0 NATURALISTIC DECISION-MAKING MODELS

We have already described in Section 5.2 the need in a model-based approach to DSS design for a variety of models of the operator and his environment. To this end, an important consideration is the development of models of operator activities in terms of their various perceptual and cognitive processes. This is in fact useful for the entire C2 process. Our focus here is on descriptive models of decision making in the literature that can guide the development of a cognitively based C2 process model in Chapter 8.0.

The characteristics of the decision-making environment of shipboard C2 described in Chapter 2.0 correspond closely to those considered by the naturalistic decision-making community which is concerned with how human decision makers actually make decisions in complex, real-world settings. Such settings involve ill-structured problems, uncertain, dynamic environments, conflicting, shifting, or ill-defined goals, many action-feedback loops, time constraints, high stakes and pressures, multiple decision makers, and organizational goals and norms. The naturalistic approach emphasises the point "that phenomena observed in complex natural environments may differ substantially from those observed in the laboratory based on decontextualised tasks performed by novices with little stake in the outcomes" (Ref. 18). In fact, much of the more traditional, analytically based decision-making research that appears in the literature has been criticised on this very point, viz., these efforts study human subjects operating in artificially created laboratory settings using normative models to prescribe rational decision-making behaviour on reasonably static tasks. This certainly raises the possibility of the limited representativeness and generalizability of the results of this type of research to the AWW environment.

Some general characteristics of decision making which manifest themselves in some form in all the various naturalistic models (Ref. 18) can be summarised as follows.

Human decision making is a cognitive process that is triggered in any specific situation by an initial perception of an occurrence in the environment (a cue) that signals a need or opportunity for a decision. Once triggered, decision making involves two cognitive components: situation assessment and selection of a course of action or a response. Once the commitment to a specific response has been made, it is implemented, usually accompanied by monitoring and feedback from the environment.

Situation assessment, the first cognitive component, is an uncertainty reduction process involving judgements needed to extract pertinent information from the uncertain environment. The nature of the situation is interpreted based on the various perceived environmental cues. A number of components of this process are possible, including: continuous attention to and monitoring of cues; diagnosing and interpreting the significance of cues in light of current goals; assessing whether information is adequate for making an interpretation and seeking further information, as may be needed in uncertain situations where there are insufficient, ambiguous, vague, conflicting or contextually uninterpretable cues; and assessing the level of risk and time pressure present in the situation.

Selection of a course of action or a response, the second cognitive component of decision making, extracts a course of action from the judgements made in situation assessment. This involves recognising the response requirements posed by the situation, identifying options, evaluating their merits in the context of the assessed situation, taking account of the constraints imposed by the situation, and deciding on a response. Klein's model (Ref. 18), in particular, emphasises the point that expert decision makers in naturalistic settings match the immediate problem situation to a condition in memory and retrieve a stored solution which is then repeatedly evaluated for adequacy in a serial evaluation strategy. This strategy is based on mentally simulating the effects of an option until one is found that is deemed adequate (Ref. 43). The recognitional process of matching solutions to the situation is exemplary of Rasmussen's rule-based level of cognitive control, indicative of the human's propensity for perceptual processing over more cognitively demanding knowledge-based processing (Ref. 29).

8.0 A COGNITIVELY BASED MODEL OF THE C2 PROCESS

8.1 Overview

Command and Control (C2) is defined as the process by which commanders plan, direct, control and monitor any operation for which they are responsible (Ref. 44). The physical environment of a given C2 decision maker consists of all entities external to the decision maker (e.g., people, machines, databases, weapon and sensor systems). His sphere of control may not extend to all of these entities (e.g., threats, neutrals). Moreover, entities may only be under partial control and the set of these entities may vary with time and context. For example, contrast the situation of a lone ship acting in a single-ship operation with the same ship involved in a federated architecture of ships conducting cooperative engagement tactics to optimise use of the force's fighting resources (Ref. 45).

We note that the cognitively based model of the C2 process presented in Section 8.3 is expected to be applicable to a wide range of settings, involving one or several operators interacting with a dynamic environment. For example, we anticipate its application in situations from a single operator in front of a console to a team of operators organised hierarchically, as in the shipboard application (see Fig. 1). In the team setting, two possibilities are: the model is applied at a macro-level to the team with a single decision maker and the various behaviours in the model distributed among the team players; alternatively, a macro-level, network-based process model could be assembled by connecting separate micro-level operator models according to their functional relationships in the team hierarchy. In the latter case, each operator would become the decision maker for his nodal model in the network. In team situations where authority for various (types of) decisions can be dynamically delegated (i.e., a dynamic organizational hierarchy), a dynamic, networked-based process model (i.e., either/both of the inter-model links between nodal models or/and the mappings between processes and people in the team are dynamic) would be required to represent such a dynamic structure. These observations generalise in a natural way to higher level organisational structures (e.g., task groups).

Only key ideas underlying our cognitively based C2 process model are presented in this document as it is still being developed and refined. This type of model should play a valuable role in applying the model-based approach described in Chapter 5.0 to DSS design. For example, such a model permits structuring either verbal protocols according to a conceptual framework or assumptions about the nature of the cognitive activities to guide the data collection in field studies. This is consistent with Sundstrom and Salvador's observations (Ref. 34) that cognitive models do not just emerge from verbal protocols but must be constructed by making assumptions about the nature of cognition.

However, to be useful in this endeavour, it is evident from Chapter 5.0 that models cannot be ad hoc. They need to adhere to the requirements of psychological relevance in their environmental representations for the operator. They must be consistent with the need of a DSS to communicate, via its interface, domain complexity in a manner consistent with the natural mechanisms that the operator uses to reduce the processing demands of such complexity. In addition, these models should reflect the variety of human behaviours that indeed take place (their descriptive ability) or are likely to emerge with automated decision aiding in conducting C2 (their predictive ability). The latter predictive requirement, arising from the impact of new aiding technologies, is an important and often overlooked one - for example, it is not generally represented in naturalistic decision-making models (Ref. 18).

The C2 model was developed as an important step towards responding to these stringent requirements. While model validity undoubtedly remains an important issue, its incorporation of a range of reasonably well accepted cognitive models from the literature provides a well-founded basis for its claim of cognitive plausibility and relevance to design.

There is an abundance of models of the C2 process in the literature. The reader can consult Foster (Ref. 46) for an overview of several competing conceptualisations of this process, including the SHOR (Ref. 47), OODA (Ref. 48), MORS (Ref. 49) and M/A-Com (Ref. 50) models and the Lawson C2 cycle (Ref. 51). However, these various models fail to provide several of the characteristics that we are after. Their principal problem, like that of the JDL model described in Chapter 6.0, is that they are not expressed in a language appropriate for easy identification of operators' perceptual and cognitive processes in conducting C2. They also fail to capture some essential elements of human behaviour with their heavy emphasis on data-driven behaviours. As observed in Chapter 2.0, operators engage in both data- and goal-driven behaviours. Our C2 model is distinguished by its emphasis on psychologically relevant problem structuring components and the inclusion of both data- and goal-driven behaviours, modulated by a meta-level.

Finally, we summarise some additional features of the military C2 process that have influenced model development in this report. They include:

(a) In the military domain, the C2 process takes place at various command levels and in various phases at each level. There can be a variety of possible timescales and spatial extents of interest to its decision makers, which may also be prioritised for their significance. Furthermore, each situation will have its own requirements on information quality in the various temporal and spatial regions to support the decision making and action execution activities involved. Although our focus is on the shipboard tactical arena, this alone does not justify the development of a totally separate model of human perceptual and cognitive processes in conducting the C2 process in this specific environment. Naturally, the demands for decision support would be expected to vary with setting, but this is an orthogonal consideration. A truly generic process model should therefore readily accommodate the growing need in C2 to inter-operate between the various levels and within the various phases at each level. For example, the model should be compatible with C2 activities that take place at the various phases of pre-deployment of a mission, in-theatre activities, and with actual real-time tactical activities in both a single-ship and force-level context.

(b) Another consideration in the above vein is that since the process of C2 can touch a wide range of settings as indicated above, involving one or several people, a truly versatile, cognitively based model of the C2 process has to permit mappings between processes and people that are one-to-one, one-to-many, many-to-one, or many-to-many. In view of the multitude of possibilities for concurrency of the various behaviours, a sequential structure on behavioural interactions would be inadequate. In fact, there are good arguments why even in the case of a single operator a sequentially based process model would lack the required features. Work by Rasmussen (Ref. 38) and Bainbridge (Refs. 52-53) provides arguments in this direction.

(c) Surprisingly, little appears to require modification in our C2 model at the structural, process decomposition level to accommodate the directions established in (a) and (b). However, the nature of the specific cognitive processing can certainly be impacted. For example, in pre-deployment and in-theatre operations where there is more time for mission-level planning and determination or tailoring of pre-planned responses to be used in the various tactical operations themselves, we would anticipate more evidence of the knowledge-based level of cognitive processing (as defined in the SRK framework), reflective of more anticipatory (and therefore less reactive), pro-active planning behaviours (Ref. 54). We also expect that such processing is already present in the tactical arena itself when, for example, unanticipated variability in the environment (as must be expected in any hostile situation) forces a pre-planned response to be adaptively repaired online before it is implemented. It is certainly the case that, in this environment, in view of its complexity and the need to establish common intent among command personnel, heavy emphasis is placed on established doctrine concerning pre-planned tactics in case a ship/force-protected asset is suddenly attacked (Ref. 55). We would anticipate, however, that knowledge-based processing by operators in the tactical environment will further emerge with the presence of automated decision aids that permit, for example, "optimising" online the use of fighting resources. In view of these various considerations, the C2 model includes both rule-based and knowledge-based behaviours. This is different from the purely recognitional type of behaviour that largely dominates naturalistic models of decision making (Ref. 18).

(d) Current C2 models focus on contacts in the external environment and their status. This is not surprising given the underlying reasons for C2 in the military domain. However, as we observed in Section 2.1, there are a variety of other potential problems that are likely to be encountered in conducting C2.

(e) An important aspect of human behaviour in dynamic environments is that it is opportunistic. Humans have a creative ability for identifying opportunities in a situation and taking advantage of them. This needs to be reflected in a cognitively based C2 model so that designers can determine if and how it should be aided.

8.2 Structuring the Decision-Making Environment

We present here a framework for dynamically structuring an environment in a manner that, on the grounds of cognitive plausibility at least, appears psychologically relevant to a decision maker operating within the environment. The need for psychological relevance has already been discussed. The framework represents a personalised structuring of the environment, *from some frame of reference considered relevant by the decision maker.* For example, the frame of reference could be his own, a participating unit's, his enemy's, and so on. It is based on the concept that what the decision maker would probably want to *comprehend* about the environment at any given time to be able to make judgements and decisions can be phrased in the language of the *problems* or *opportunities* posed by the environment at that time, given the *goals* and the state of various *relations* that the decision maker deems relevant among these problems, opportunities and goals at that time. In short, they are specific, time-dependent, goal-relevant properties of the environment that can shape the decision maker's behaviour. We refer to these as *situation structures*. We have chosen this term in place of *situation assessments* to avoid the clash that exists between the term situation assessment as used in the naturalistic decision-making literature (Ref. 18) and the JDL terminology in data fusion (Ref. 7) that differentiates between situation assessments and threat assessments. In addition, calling them structures emphasises their functional role: they provide a structured representation for understanding the environment as a prerequisite for (rule-based or knowledge-based) action.

The decision maker could be interested in a variety of types of relations among goals, problems and opportunities, including enabling relations (between an opportunity and a goal), causal or subset relations (between pairs of problems or opportunities), value relations (for prioritising goals, problems and opportunities), impediment relations (between a problem and a goal), and so on.

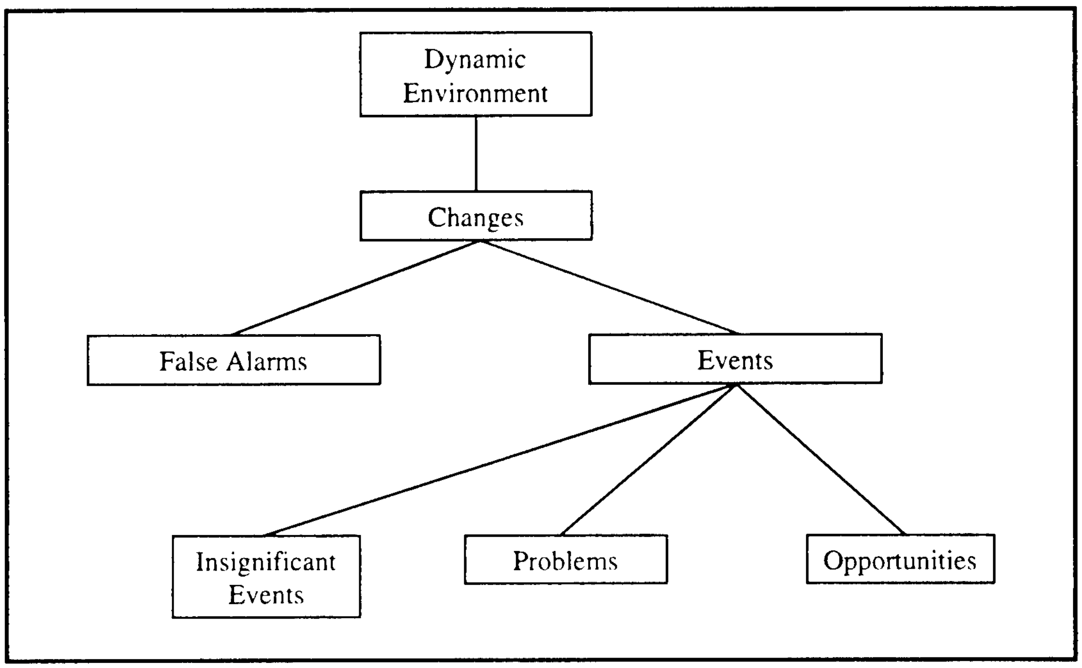

FIGURE 6 – Identifying problems and opportunities

Definitions of the various terms used above have previously been given in Section 2.2. The motivation behind this general structuring framework has also been illustrated there in the context of the shipboard setting. We note that the separation of events into insignificant events, problems and opportunities, indicated in Fig. 6, is not really an event partition. An event could represent both a problem and an opportunity. For example, the presence of a particular geographical or environmental feature in a ship's vicinity, which route planning could avoid, might represent a problem (reduced sensor detection envelope) for achieving one of the decision maker's goals (optimise detection) but an opportunity (increased chance of concealment) for another (optimise survivability). This arises from conflicting goals. There is also a potential for duality between problems and opportunities. For example, a problem in one frame of reference (e.g., his own) could represent an opportunity in another (e.g., his enemy's). This structuring in a variety of frames of reference should be an important element of a decision maker's need for simultaneous, multiple perspectives in understanding the situation in some cases as a precursor to making a decision.

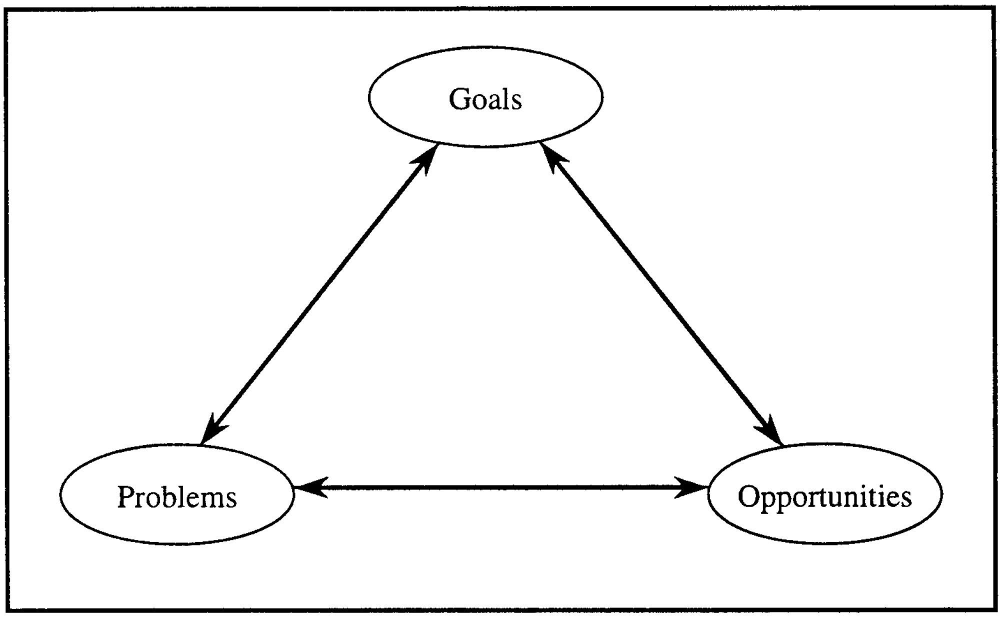

FIGURE 7 – Dynamic structuring of goals, problems and opportunities

This representation-based structuring of situation understanding can be thought of as a dynamic triad of psychological relevance to the decision maker. It is illustrated in Fig. 7. Although the triad shown there seems to have a flat relational structure, it is not difficult to see that there are advantages that come from abstraction and decomposition (e.g., computational efficiency, iterative refinement) for developing the triad, or portions of it, into a hierarchy. For example, goals could be decomposed into a hierarchy of sub-goals; problems and opportunities might be represented at varying levels of granularity and detail; elements of the work space can be organised by means of links to show structural constraints for "proper" operation or behaviour of domain elements. This raises the question of the form of a psychologically relevant framework for such a hierarchy. Something similar to Rasmussen's two-dimensional abstraction-decomposition hierarchy for means-ends relations and part-whole relations (Refs. 29 and 38) naturally comes to mind. We do not pursue this matter further in the present document.

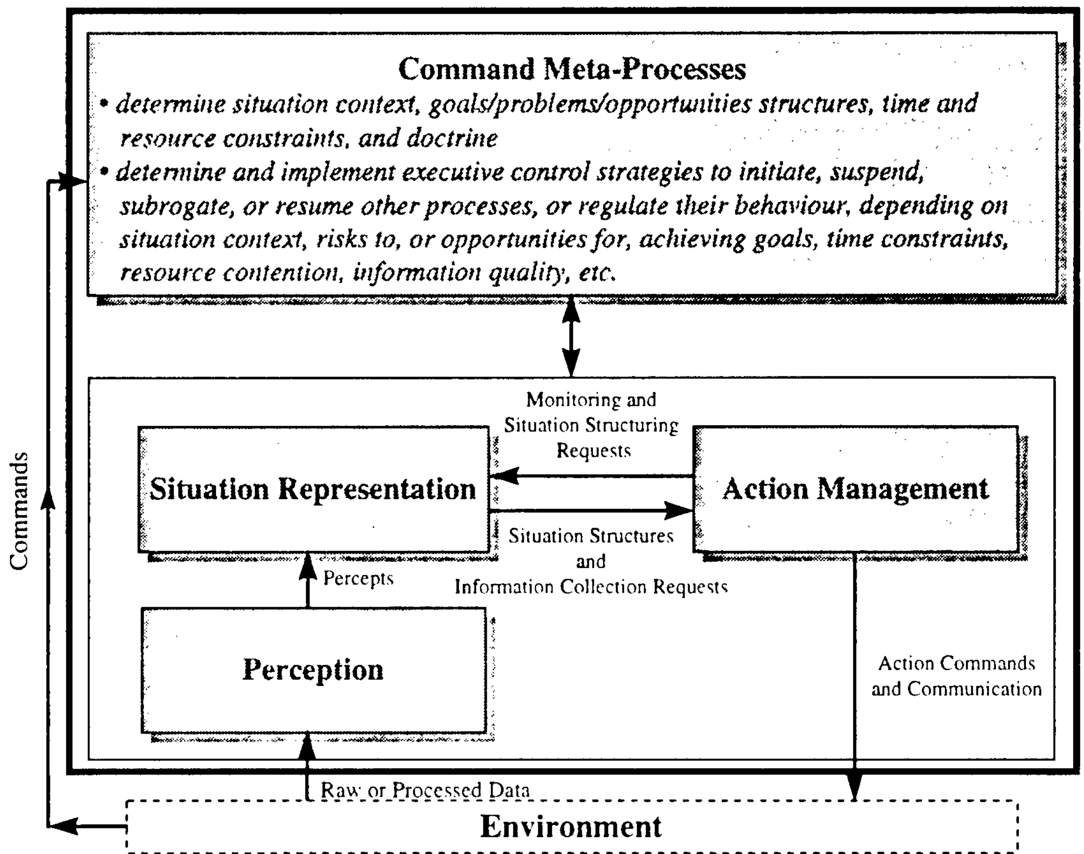

FIGURE 8 – Command and Control process model

Finally, we mention that no claim is made here that the decision maker wants or needs to be aware of *all* elements of the dynamic situation structure shown in Fig. 7 at any given moment for successful performance in his environment. In fact, it is surely possible that the decision maker is not actually aware of *all* these elements at any one time and is still able to achieve quite satisfactory performance. This touches on the larger question of what exactly the link is between situation awareness and performance (Ref. 56).

8.3 Description of the Model

We now present our cognitively based, behavioural model of the C2 process. The model decomposes the C2 process into two levels: a lower level involving the three processes *Perception*, *Situation Representation* and *Action Management*, and a higher level consisting of various *Command Meta-Processes*. The details of Situation Representation, Action Management, and the Command Meta-Processes are explained in almost self-explanatory manner in three figures, Fig. 8, Fig. 9, and Fig. 10. We now examine some of the highlights of the model.

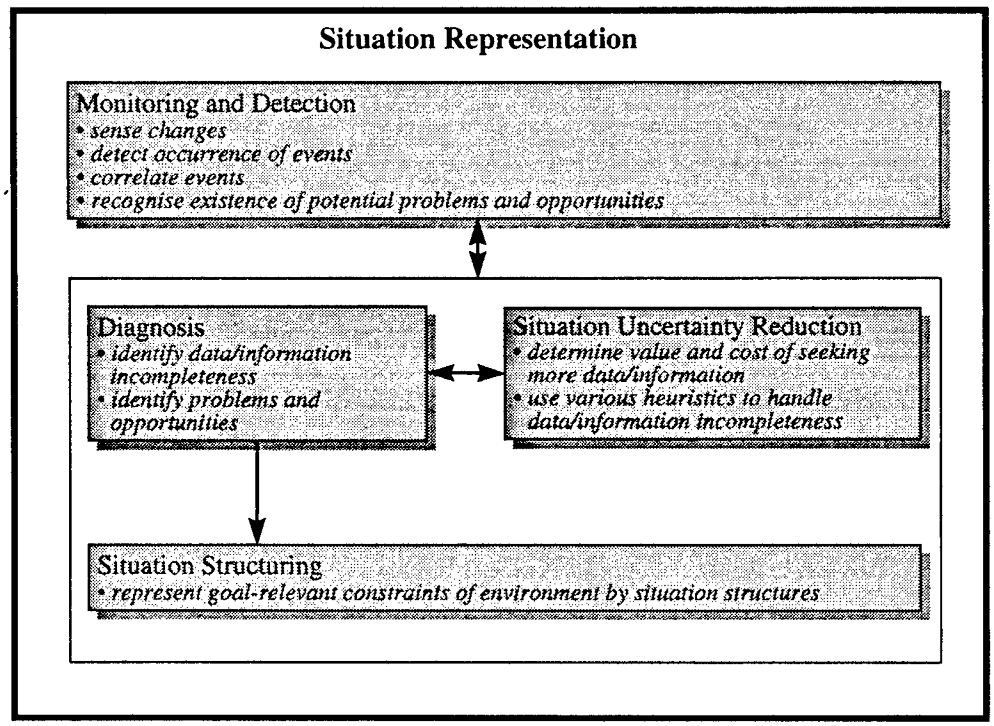

FIGURE 9 – Situation Representation process

The Command Meta-Processes, shown in Fig. 8, dynamically manage the goals and choice of situation structures, and control various parameters (like frequency with which to monitor for changes in a specific environmental feature) and the sequencing and cognitive level (in the sense of the SRK taxonomy) of lower level processes. Suspension and subrogation control strategies serve to shift the focus of attention between various processes. For example, a process might be suspended during its execution because of a higher priority process that suddenly demands the decision maker's attention or simply because it cannot be performed to completion at the moment.

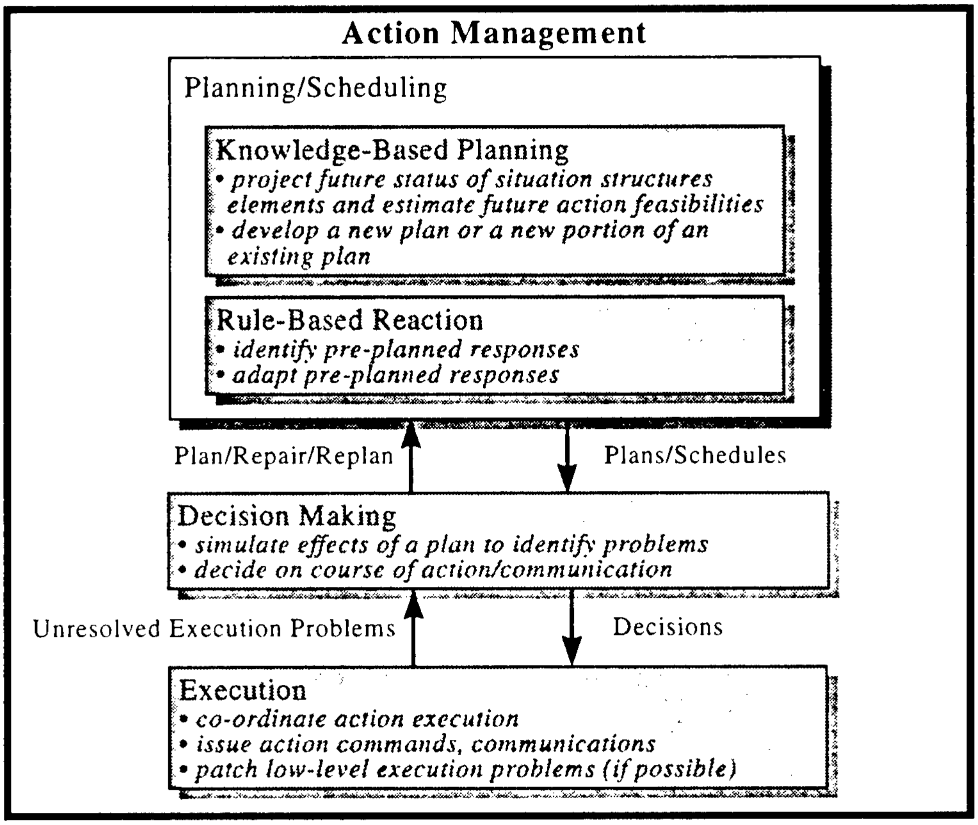

FIGURE 10 – Action Management process

Feedback from the lower level can cause new goals and situation structures to be generated and old goals and structures to be removed from consideration, as well as new control strategies to be employed. Commands from higher-level command echelons originating in the environment can also induce changes in these processes.

Situation Representation (Fig. 9) and Action Management (Fig. 10) are uncertainty reduction processes, but in different senses. The first reduces uncertainty in understanding the situation. In this case, it involves judgements about where there is uncertainty, incompleteness, imprecision, inconsistency, or ambiguity, or some combination of these in data/information (short-term knowledge) and in the resolution of such uncertainty. In cases where it is deemed worthwhile to reduce this uncertainty by obtaining more data/information, it can issue an information collection request to Action Management (e.g., send a helicopter for closer surveillance; manoeuvre the ship and observe the contact's response). Action Management reduces uncertainty in the selection of actions.

In either case, it is possible to add the need to reduce uncertainty due to incomplete long-term knowledge (purposeful learning behaviour), by first evaluating benefits and costs of seeking this knowledge and the likelihood of being successful in doing so. Situation Representation would issue a request to Action Management which would handle its own needs and those of Situation Representation with subsequent feedback to Situation Representation. However, these various considerations are not fleshed out in the figures shown.

Situation Representation is the process of producing or generating abstract descriptions or representations of a dynamic environment. The particular descriptions are in terms of situation structures as defined in Section 8.2 which the decision maker (in the Command Meta-Processes) dynamically determines to be relevant for determining and managing action. Situation Representation generates these structures either at the request of Command Meta-Processes or at the request of Action Management when it needs to better understand specific situation elements for planning or for managing the coordination and execution of its action decisions. Situation Representation is analogous to the human situation assessment process described in the naturalistic decision-making literature (Ref. 18). It combines the situation assessment and threat assessment processes of the technologically centred JDL data fusion model (Ref. 42), but from the perspective of the human. The reasons for introducing the new terminology are similar to those previously stated for situation structures. It is also useful to distinguish between process and product. Another important nuance, which distinguishes our approach from previous efforts, has to do with the way the model handles situation projection (i.e., extrapolation **of the current tactical situation into the future). While a given situation element (goal,** problem, opportunity, relation) may well involve an aspect of the future (e.g., the problem related to a contact might be "Time to ship intercept is less than 30 seconds"), we use the term projection in an action-oriented sense in that its need is determined within Action Management to support knowledge-based planning.

Process sequencing in Situation Representation essentially follows the identification strategy suggested by Fig. 6, with feedback loops arising from the need to resolve problems of incomplete data, information or knowledge.

Action Management handles all processes related to determining feasible courses of action, action selection, and management of action execution. Actions commands are commands to physical actuators (sensors, weapons, navigation, etc.) or lower levels in the organisational hierarchy. We also include as part of Action Management decisions related to sharing information with other parties in the environment. This leads to the communication shown in Fig. 8 (e.g., a speech turn or set of words spoken to another person in the decision maker's environment; information data linked to a participating unit or a shore-based C2 centre, etc.). Another reason for communication is to request additional information/knowledge to be supplied from an entity in the environment.

The presence of both rule-based and knowledge-based processing in Action Management for reasons previously given in Section 8.1 should be noted. This is also the case for Situation Representation. For example, diagnosis could be entirely rule-driven or employ, in addition, various knowledge-based heuristics to make judgements that reduce uncertainty in situation understanding. Evidence of both types of behaviour have been found in the naturalistic decision-making literature. For example, Kaempf, Wolf and Miller (Ref. 57) report findings of a study in which they analysed results of interviews based on use of the critical decision method (Ref. 58) to identify the primary situation diagnosis strategy used by anti-air warfare officers in the Combat Information Centre of an AEGIS cruiser as essentially rule-based feature matching. This strategy consists in matching existing cues with a remembered set of cues. However, in situations of insufficient information or when the situation was novel and unfamiliar, the officers used a knowledge-based strategy of story generation in which the information available is used to build an explanatory story of the situation.

Finally, we draw attention to a couple of additional omissions in Fig. 8. First, the complex process of human perception has not been elaborated. Second, a direct processing path between perception and action that would correspond to Rasmussen's notion of skill-based behaviour (Ref. 29) of an operator is not shown. Such a path would be posited by Gibson's approach to perception from ecological psychology (Ref. 35). This approach suggests that some behaviours in organisms (including humans) relate perception to action by a process of direct attunement – that is, important invariant relations in the environment (known as affordances) are perceived and lead to directly determining the organism's behaviour without need for time-consuming mediation by rule-based or knowledge-based processing.

9.0 CURRENT HIGH-LEVEL FRAMEWORK OF A REAL-TIME DECISION SUPPORT SYSTEM

At present, in the CPF, the various data and information integration tasks that are used to build the tactical picture of the environment external to the ship are manually performed by operators, communicating amongst themselves.

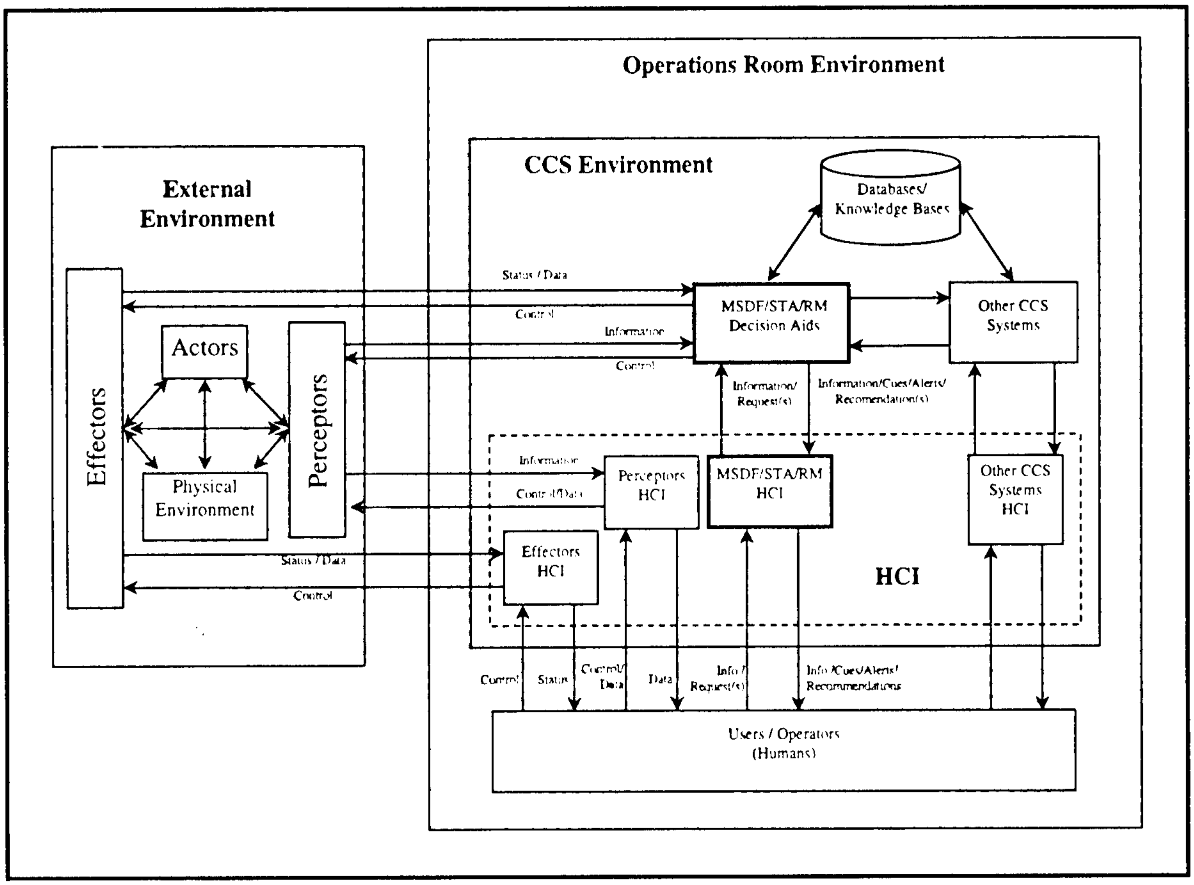

FIGURE 11 – Operations Room environment with an MSDF/STA/RM DSS

Capabilities for computer-supported situation representation are limited essentially to threat evaluation in the form of threat ranking. As a simple example, the capability for operators to request the CCS to monitor a specific contact or group of contacts for a certain potentially threatening behaviour (either pre-defined or defined on the fly by the operator) while attention is shifted to a more immediately threatening part of the tactical picture, and alert them if such a behaviour occurs, does not exist. In addition, explicit situation representation in the human-computer interface (HCI) is limited to the level of contacts only and does not extend to representation of contact groupings based on assessed relationships of individual entities. General situation representation as defined in this document, which can cover a variety of potential problems that stem not only from the presence of contacts, is done in the heads of operators.

There is some automated support in the CCS for reactive action management related to the allocation of the fighting resources (weapon allocation) in terminal engagement. However, there are a number of areas where additional support should be highly beneficial, particularly in complex littoral scenarios. These include support for: planning at both the operational and tactical levels; doing "what-if" analyses of options to permit keeping ahead of the current tactical situation, including visualization of options; and co-ordinating the use of weapon and sensor systems or evaluating their effectiveness in the current environment and determining improvements. Current tactical decision aids that provide the necessary support are limited or non-existent.

In theory at least, there is therefore a lot of scope and opportunity for introducing much advanced computer-based support into the operational environment of the CPF.

DREV's current work is expected to lead to a specification of a DSS to support operators at least in: (i) the integration or fusion of data from the ship's sensors and other sources; (ii) the formulation, maintenance and display of an accurate dynamic situation picture, leading to enhanced situation awareness; (iii) the identification and selection of courses of action in response to anticipated or actual threats to the mission; and (iv) action implementation once a decision to act has been made and is being carried out. With respect to particular DSS capabilities, item (i) relates to its Multi-Source Data Fusion (MSDF) capability. It will support perception activities in Fig. 8, for example by enhancing the quality and coverage of the processed data that feeds perception. Item (ii) relates to its Situation and Threat Assessment (STA) capability. It will support the situation representation process in Fig. 9. Finally, items (iii) and (iv) relate to its Resource Management (RM) capability. This capability will support the action management process in Fig. 10. Current DREV work on automating the processing for MSDF, STA and RM is reported in Refs. 59-61.

It is envisaged that this DSS, which we refer to as an MSDF/STA/RM system, will become an embedded component of the ship's combat system, integrated within the CCS. A rough, high-level perspective of this integration is shown Fig. 11 (Ref. 6). The environment in Fig. 11 is decomposed into the portion within the ship's Operations Room and the portion outside, including the perceptors (organic and non-organic information sources), effectors (active and passive weapon systems), the actors (threats, friends, neutrals) and the physical environment external to the ship. The CCS environment is everything in the CCS of a hardware or software nature, including the various HCIs, databases/knowledge bases and other CCS systems. These databases/knowledge bases contain a variety of a priori knowledge, including standard operating procedures and pre-planned tactical responses, and strategic, Electronic Warfare (EW) and intelligence information.

10.0 CONCLUSIONS

This document examined a wide range of issues currently being investigated for the design of a decision support system to assist combat system operators of a modern frigate in their tactical decision making and action execution activities as part of the Command and Control process. Automation, cognitive and methodological issues were highlighted.

Fundamental issues in providing computer-based decision support are related to the questions of which operator roles and positions need assistance, why, when, and how. These are very complex questions that require a coherent methodology to be followed if a joint system, comprised of both operators and computer-based aids, is to lead to improved operational effectiveness in conducting shipboard Command and Control. A key problem for the design of such aids is that they must be capable of operating in a highly dynamic and open environment that imposes variable and unpredictable demands on operators. Operators must be able to effectively handle the demands of new and unanticipated situations that have not been addressed by the system designer or by doctrine. The system must certainly support the operators so that they can follow the established principles and recommended procedures. Yet it must not overconstrain them so that they are hampered from taking advantage of their abilities to reason, improvise, and respond, while at the same time calling on the system for the support they need.

These considerations certainly argue for developing aids according to the decision-aid-as-tool paradigm whenever possible, especially if the human is to play an active role in the decision-making process. Design emphasis in this paradigm is on supporting the strengths and complementing the weaknesses of the operator in a manner that offers cognitive compatibility between the tool and the operator. The advantages of this approach include: the operator is kept actively in the loop and therefore in a better position to be situationally aware and intervene, particularly when a computer-based solution begins to operate on the edge of the capability envelope for which it was designed; and it matches the pattern of the decision makers' knowledge and ignorance by using what they know to generate what they need to know, using reasoning processes that they trust.

The decision-aid-as-tool approach should be contrasted with the more usual prosthetic approach of providing an expert system to give advice on the "correct" decision or judgement in a given situation. Unfortunately, as Ref. 62 points out, in situations where the human needs to remain part of the decision loop, increasing evidence suggests that the addition of expert system-like decision aids may not lead to the desired benefits. To better appreciate the difference between the two approaches in supporting an operator's situation representation processing, consider:

- an aid that builds and displays a situation picture using normatively based automated reasoning processes; and
- one that acts as an intelligent alarm system that monitors the situation and alerts the operators to the potential occurrence of problems in the mission and opportunities for achieving the mission goals which they have requested the system to track.

In the former aid, automation is playing a prosthetic role. It has the effect of replacing the operator. Of course, it may be necessary to take this approach for some aspects of the situation in certain instances simply because the operator is (temporarily) inundated by a large number of contacts and cannot cope. In the case of the second aid, it is acting as a tool only. The primary role of this aid is clear: it is there to aid the human's limited attentional resources. The challenge for designing this latter system would be to ensure that it does not generate so many false alarms that it becomes totally ignored and is simply tuned out or turned off.

This document suggests that the recent emergence of model-based frameworks for design offers a significant potential for rescuing the design process from falling into the trap of pursuing an ad hoc approach with high risk for incurring large expense in time, cost and wasted effort. The specific model-based framework presented in this document structures the capture and analysis of requirements within a Cognitive Work Analysis framework. This is aimed at developing operator-environment models that have both descriptive and predictive abilities. The purpose of these models is to allow the designer to understand the current operator behaviour and predict the consequences of design choices. Representational models of the environment identify the content and structure of the information that the system must provide to the operator, while models of the mechanisms that the operator uses to deal with complexity in the environment give the form in which this information needs to be presented.

Undoubtedly, the dilemma of fragmentary and incomplete understanding of the process of designing effective computer-based support remains. However, we now need to turn the various insights offered by what is known into a pragmatic approach for the development of practical, viable decision aids, based on a blend of solidly grounded design principles and an informed appreciation of areas where knowledge is limited. This document has described some preliminary ideas we are exploring towards developing this pragmatic approach.

Ongoing and future work is aimed at developing such an approach in the context of designing the MSDF/STA/RM support system described in Chapter 9.0. Other work is related to refining the cognitively based process model for the Command and Control process, described in Chapter 8.0, and examining the implications of this model. While it was derived from thinking about the naval problem, it appears to have wide applicability to a number of other military and non-military settings. This is probably not very surprising since human behaviour and strategies for coping with complexity in a variety of dynamic environments are likely to share much commonality. Like the ant on the beach in Simon's well-known parable (Ref. 63), detailed aspects of human behaviour arise from the impact of the environment. In fact, it is tempting to conjecture that there are equivalence classes of environments in which human behaviour, and therefore its need for support, as well as the nature of effective support, impact support design similarly regardless of the specific member of that class.

In another direction, thinking about the notion of models that have psychological relevance to the operator certainly helped the author better appreciate the immense difficulty, if not the impossibility, of a system designer anticipating all variabilities in a complex dynamic environment. Consider, for example, the problem of designing to support the operator in situation representation. Choosing even a representative set of situation structures that would be needed for effective performance in a given situation appears to be a difficult task. The capability for the operators to create and customise their own situation structures on the fly is therefore likely to emerge as an important design consideration.

Finally, work is needed to establish the relation of the present effort to other work in the literature on tactical decision aiding (Refs. 64-66) and situation and threat assessment (Ref. 67). Certainly, an important difference from previous efforts is the emphasis of the current work on developing a principled, holistic approach, encompassing modelling methodologies and cognitive and environmental models, as a formal prerequisite to design. This is in opposition to an approach which does not offer any specific signposts on how to search the design space but rather rests on ad hoc methods and the developer's intuition.

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