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Role of cognition in a future naval combat management system

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PSPC Contract Number: W7714-4501667362
Technical Authority: Peter Moo
Contractor's date of publication: March 2018

Defence Research and Development Canada

Contract Report
DRDC-RDDC-2018-C070
September 2018

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IMPORTANT INFORMATIVE STATEMENTS

This document was reviewed for Controlled Goods by Defence Research and Development Canada (DRDC) using the Schedule to the *Defence Production Act*.

Abstract

This report provides a non-technical introduction to Naval Combat Management Systems (NCMS) and concludes with the proposal for a Holistic-NCMS designed to meet the future requirements of the Royal Canadian Navy.

NCMS is a cognitive aid that naval forces use to manage their resources. The NCMS connects the sensor suite to the weapon systems via the Command and Control (C2) system. The C2 system ingests and processes sensor data to supports operator cognitive tasks including planning, re-planning, sense-making and situational assessment. The core functions of the NCMS are to observe, analyze and take action.

The NCMS supports objective reasoning to facilitate a commander to take subjective actions. The overall objective is to gain a competitive advantage over an adversary. That is, to enable a commander to take the best action given their current understanding of the situation. The NCMS manages conventional systems, semi-autonomous and fully autonomous systems. The NCMS is required to function as a standalone entity and work within a collaborative network of coalition forces.

The sensor and weapons suites are mature technologies and no significant innovation is expected to occur in the near future. Therefore, advances in the performance of NCMS will be gained primarily by processing data from existing systems and utilizing this data in such a way that the resulting product is greater than just the sum-of-the-parts.

The report proposes a new Holistic-NCMS that is based on a system-of-systems approach to sensor resource management. This approach utilizes recent advances in networking and computational intelligence. This report discusses the emergence of cognitive computing as the enabling technology.

Cognitive computing can be used within the sensor suite to optimize performance based on the known environment, current threat and historical data. The Sensor Resource Manager (SRM) uses data from across the sensor suite as well as external sources to achieve this goal. Cognitive computing also plays a critical role in the C2 system where it has the capability of exploiting big-data to enhance timely informed decision support, planning and engagement

The proposed SRM dynamically allocates resources and tasking across sensor suite. The SRM adds placidity to the system such that in the event of sensor failure, the system optimally reallocates resources and tasking to fill the void.

The Holistic-NCMS incorporates real-time simulation and modelling of an adversary’s kill-chain during an evolving engagement to highlight weaknesses and strengths that can be exploited or avoided. Similar modelling is also be applied to the host vessel’s kill-chain to highlight own weaknesses and strengths during an evolving mission.

The report includes a section on recommended future R&D that has been compiled using input from both NCMS suppliers as well as researchers in the area of cognitive computing and cognition, big-data, decision support, sensor resource management, and real-time simulation and modelling.

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Acknowledgements

The author wishes to acknowledge the support of member of the Canadian Tracking and Fusion executive who have unselfishly shared their ideas in research and development associated with NCMS. Specifically I would like to thank Dr. *Rami* Abielmona (Vice-President of Research & Engineering at Larus Technologies Corporation), Dr. Thia (Kiruba) Kirubarajan (Professor, Department of Electrical & Computer Engineering at McMaster University) and Dr. Elisa Shahbazian, (President Ooda Technologies) for their valuable contribution to the Research and Development Section. I would also like to acknowledge Dr Raviraj Adve (Professor, Communications, University of Toronto, Faculty of Applied Science & Engineering for insight into the next generation of signal processing algorithms and Maria Rey (Vice President and Chief Science Officer, Space Strategies Consulting Lt) for her thoughts and insights to the challenges and benefits of big-data and human machine interface.

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1. Introduction

This report provides a non-technical introduction to the application of machine learning and cognition and their role in a configurable networked sensor and response systems for naval combat vessels.

Configurable networked sensor and response systems incorporate adaptive sensor technology with semi-autonomous and autonomous systems that are interconnected by networks. The network enables the systems to collaborate and self-adapt to both the environment and threat. At its core is the Naval Combat Management System (NCMS).

The NCMS is a cognitive aid that naval forces use to manage their resources and is designed to support operator cognitive tasks in high threat settings [1]. This is achieved by undertaking cognitive activities including planning, re-planning, sense-making and situational assessment [2]. To meet mission requirements that vary widely in type, scale, and location NCMS are by necessity designed to be highly adaptive.

The NCMS combines the Command and Control (C2) function with the Weapons Control System (WCS). The C2 function relates to the exercise of authority and direction by a designated leadership over resources in the accomplishment of a mission [3]. The C2 component is largely software based and provides strategic objective decision support to the commander to aid in subjective decision making leading to the engagement of the WCS. The WCS consists of a number of physical components (sensors) working together to aid weapons system to complete their mission.

The report discussed two types of cognition and their relevance to NCMS.

- Conscious or slow-time cognition that emulates the conscious thinking of the mind. It analyzes related information sources to extract knowledge to solve a stated problem. This cognition is applicable to the Decision Support activities of the C2 system.
- Subconscious, or fast time cognition emulates the subconscious actions undertake by the mind such as motion. This requires a sense and adapts model where the local environment is sensed and assessed and action taken in real-time without conscious thought. This can be applied to sensors to optimize performance in a sensed environment.

1.1 Historical Overview

Prior to the development of modern computers combat management systems were operator intensive. Operator overload was initially addressed by controlling various parameters, at the sensor level, using a basic feedback loop of sensing and actuation. These loops were very effective in managing parameters such as automatic gain control. The digital age allowed simple conditional programming (if, then, else) to be introduced to adapt sensor parameters as well as assisting operators in making informed decisions. Implementation of these decision trees requires prior knowledge about the environment and threat in order to recommend appropriate actions. This predictive approach to decision making assumes the mission can be planned in advance. They were also generally applied at the sub-system level with results flowed up through a hierarchy with minimum or no interaction between systems.

This is an appropriate assumption when facing a conventional threat. The modern NCMS must however be capable of addressing both the evolving conventional threat as well as addressing the unknown asymmetric threat. Addressing the evolving conventional threat requires that the threat is detected and identified at a greater range in order that a responsive action can be taken earlier. Meeting this requirement requires that future NCMS adopt an adaptive approach that is flexible and adapts to changing needs as the mission progresses.

The onboard sensor and weapons suites are mature technologies and no significant innovation is expected to occur in the near future. Therefore, advances in the performance of NCMS will be gained primarily by processing data from existing systems and utilizing this data in such a way that the resulting product is greater than just the sum-of-the-parts. The report proposes a new Holistic-NCMS that is based on a system-of-systems approach to sensor resource management. This approach utilizes recent advances in networking and computational intelligence. This report discusses the emergence of cognitive computing as the enabling technology.

1.2 Report Structure

This report reviews the current state of the art in NCMS and introduces the potential for software to undertake the cognitive tasks to improve the overall performance. The report outlines an architecture of a future Holistic NCMS, applicable to the Royal Canadian Navy (RCN) based on a systems-of-systems approach that physically decouples the complex interactions between the multitude of sub-systems such allows each component of the system to perform its tasks independently of the others whist simultaneously collaborating by sharing learnt knowledge.

The proposed system is holistic in nature due to the fact that it encompasses all missions and including the local vessel health within its structure as well as the crew’s capability that is derived based on gaming and training.

The report is composed of 6 sections.

- **Section 2** provides an introduction to the key elements of a NCMS and the application of cognition. The section starts with an introduction to the RCN mission and the requirement to address both symmetric and asymmetric threats. Models for kill-chain-cycle are introduced and their use in developing capability is discussed. The section also introduces the cognitive aspects of the C2 system including, domain awareness, planning and execution and decision support. Gaining knowledge superiority from big-data using software processes is also discussed.
- **Section 3** formulate**s** and develop**s** a high-level framework for a cognitive sensors and weapons suite. The chapter presents an overview of ship-borne sensors and weapon systems. The application of fast time, subconscious, cognition in the form of the perception-action cycle is introduced and the ability to sense the environment and adapt

sensor parameters accordingly is discussed. The Sensor Resource Manager is introduced as a means to dynamically allocated resources to sensors and systems on an as required basis. The SRM enables collaboration between sensors by transferring knowledge that can be used by the local resource manager to optimally configure a sensor.

· **Section 4** outlines a number of principles that form the basis of state-of-the-art NCMS. This includes a discussion of Power-to-the-Edge philosophy that is the enabler of Network Centric Warfare (NCW) and Network Centric Operations (NCO). Key software architecture and network topology options for a future NCMS system are presented. This is followed by a review of current NCMS and associated subsystems. The section concludes with a proposed formulation a high-level functional design for a holistic-NCMS system that addresses key requirements, as postulated by the author, of the RCN.

· **Section 5** provides recommendations on future Research and Development (R&D) activities to be taken to address challenges in the design and development of cognitive sensors and weapons suites.

· **Section 6** summarises the report and provides a conclusion.

· **Annex A includes** various marketing brochures from industry outlining their NCMS capabilities.

2 Introduction to the Naval Combat Management System

The NCMS is a decision support system that provides objective recommendations to a commander such that appropriate subjective and objective actions can be taken.

The primary missions of a NCMS are to provide superior wide-area air defence capability, anti-submarine warfare capability, as well as anti-shipping capability. Consideration in the design must also be given to meeting the requirements of other roles that the RCN may be required to undertake.

Therefore, ideally the NCMS should support without compromise to its primary missions, both maritime security and safety operations where;

- **Maritime Security:** This is a combination of preventative and responsive measures to protect the maritime domain against threats and unlawful acts, protect a country's vessels as well as protecting economic and social interests at home and abroad.
- **Maritime Safety:** This is s combination of preventative and responsive measures intended to protect the maritime domain against (and limit the effects from) accidental or natural threats.

2.1 Royal Canadian Navy Mission

The role of the RCN is to generate combat-capable, multipurpose maritime forces that support Canada's efforts to participate in security operations anywhere in the world [4]. In addition, naval vessels are used for coastal surveillance and patrol including general naval operations and exercises, search and rescue, law enforcement, resource protection and fisheries patrols [5]. Naval forces may also be deployed to support humanitarian aid, peace keeping missions and monitoring/enforcement of sanctions.

Navy vessels are primarily designed to engage an enemy using conventional warfare. Conventional warfare is referred to as being symmetric, in the sense that the two combating forces are similar in size and capability. Conventional warfare matches weapons to threats for example anti-air warfare involves defending against aircraft and incoming missiles. Anti-surface warfare defends against surface warships and anti-submarine warfare defends against submarines.

Large navies such as the U.S., deploy specialized vessels that are designed to operate in battle groups. The Canadian Navy is a small navy and vessels are required to be capable of supporting multiple, diverse, missions either as a single unit or as part of an international fleet.

A smaller or less capable force must use non-conventional or asymmetric tactics that exploit a weakness in the more dominant adversary. The following sections discuss asymmetric threats as used by militaries, insurgents and organized crime that the RCN may encounter.

2.2 Asymmetric Threats

Asymmetric warfare uses unconventional means to exploit vulnerabilities in a stronger adversary. Navy vessels are primarily designed for open sea warfare but near-shore and in restricted waterways can be vulnerable to asymmetric threats. This shortfall has been exploited by adversaries throughout history who have used asymmetric tactics and weapons to defeat stronger military forces. These tactics can be used by hostile military power, insurgents or criminal activity such as piracy. Adversaries' exploit weakness in the kill-chain to gain an advantage over a superior force, the strategy avoids an enemy's strength and probes for a weakness [6]. This often results in hit-and-run tactics using fast attack vessels.

2.2.1 Military use of asymmetric tactics

Militaries have used asymmetric tactics to defeat a stronger adversary since the beginning of structured warfare. For example during the Greek War of Independence (1821–1832) the Greeks deployed small fire ships to counterbalance the Turkish naval superiority in terms of ship size and artillery power [7]. The fire ships were much more manoeuvrable than the larger Turkish ships operating in the restricted waterways of the Aegean Sea. The fire ships inflicted significant damage to the Turkish navy resulting in the Greeks achieving independence.

Today, the Iranian Revolutionary Guard Corps Navy (IRGCN) has been configured to pose a significant asymmetric threat to a superior navy. The IRGCN is structured as a parallel navy that exists alongside the traditional Iranian Navy (IRIN) and is specifically trained and equipped for asymmetric warfare [8]. The IRGCN consists of a large number of fast attack craft and small boats. Most of these small boats are capable of high speeds, have very shallow drafts, can be difficult to detect, and may not be positively identified even when detected. These advantages make them well suited for conducting hit-and-run style attacks in restricted waterways [9].

The availability of a large number of small attack craft permit the use of swarming tactics designed to overwhelm or saturate the defenses of the principal target.

2.2.2 Insurgent use of asymmetric tactics

Asymmetric tactics are generally used against navy vessels when operating in littoral regions. Tactics can be very simple yet very effective. For example, on March 6 2014, pro Russian sailors prevented the Ukrainian Navy leaving its base at Novoozerne by scuttling a number of ships in the channel connecting Lake Donuzlav with the Black Sea. This simple action resulted in the isolation and eventual surrender of a large number of Ukrainian Navy vessels [10].

In Sri Lanka, the Sea Tigers of the Liberation Tigers of Tamil Eelam (LTTE) proved to be a significant adversary during Tamil uprising (1989-2009). The Sea Tigers used small high speed boats with a mixture of weaponry. During their existence the Sea Tigers gained a reputation as a capable adversary and over the years sunk at least 29 SLN inshore patrol boats [11]. The Sea Tigers employed both agile at-sea-command and swarming hit-and-run tactics.

Frogmen also served with the Sea Tigers and were used in sinking at least one freighter at the Sri Lankan Navy base at Kankesanturai [12]. They were also involved in the sinking of a SLN supply ship in Trincomalee harbor in May 2008 [13].

2.2.3 Piracy and Organized Crime - use of asymmetric tactics

Canadian navy vessels are also tasked to protect international shipping lanes by undertaking counter piracy operations. The definition of the crime of piracy is contained in article 101 of United Nations Convention on the Law of the Sea (UNCLOS), which reads as follows:

> *"Piracy consists of any of the following acts:*
>
> *(a) any illegal acts of violence or detention, or any act of depredation, committed for private ends by the crew or the passengers of a private ship or a private aircraft, and directed:*
>
> *(i) on the high seas, against another ship or aircraft, or against persons or property on board such ship or aircraft;*
>
> *(ii) against a ship, aircraft, persons or property in a place outside the jurisdiction of any State;*
>
> *(b) any act of voluntary participation in the operation of a ship or of an aircraft with knowledge of facts making it a pirate ship or aircraft;*
>
> *(c) any act of inciting or of intentionally facilitating an act described in subparagraph (a) or (b)."*

Piracy continues to be a significant threat to merchant vessels in various waterways around the world.

The Canadian navy is a partner in the Combined Maritime Forces (CMF). The CMF is a multinational naval partnership of 32 nations, which exists to promote security, stability in international waters including some of the world's most important shipping lanes. The CMF has three task force of which Combined Task Force (CTF) 151 addresses counter piracy [14].

Tactics used by pirates are evolving as counter piracy operations become more effective. There is one common tactical theme: exploit your adversary's weakness and avoid their strengths. For example, piracy operations are now frequently conducted from mother ships, thereby extending the pirate's range of operation. Target vessels tend to be slower and also sail in isolation. Pirates will frequently approach from the rear where both radar and visual coverage is poor [15].

Navy vessels may also be involved in preventing transnational maritime organised crime. This includes the acts of illegal, unreported and unregulated fishing, assisted illegal migration and smuggling of narcotics. Organized crime generally flourishes in areas where their activities cannot be easily monitored.

2.2.4 Cyber asymmetric threat

The Navy's ability to communicate securely to and between its assets across the globe is crucial to its mission [16]. A compromise to this ability can result in a significant degradation in capability. Cyber Security is defined by the U.S. Navy as The "prevention of damage to, protection of, and restoration of computers, electronic communications systems, electronic communications services, wire communication, and electronic communication, including information contained therein, to ensure its availability, integrity, authentication, confidentiality, and nonrepudiation" [17].

Cyber threats to the Navy can be sub-divided into four categories;

- Theft of information and technical data on fleet operations
- Preventing the use of information capabilities
- Providing false information
- Hijacking an asset (taking control)

2.2.5 GPS Spoofing – an asymmetric threat

In June 2017, the U.S. Coast Guard Navigation Center issued a navigation alert related to possible GPS interference in the Black Sea [18]. The New Scientist conjectured that the interference was the result of Russia's spoofing the GPS signal and that this could be the first hint of a new form of electronic warfare [19]. It is worth noting that for a number of reasons the noted interference was almost certainly a coordinated spoofing attack [20].

- Firstly, it didn't happen to one ship – it happened to over 20 separate vessels, confirming that it was an external incident of some kind
- Secondly, a large number of ships in the area reported identical or very close locations. This is a symptom of a large-scale spoofing attack
- Thirdly, ships reported that their positions would periodically jump from the true location to the incorrect location

As reported in [21] Iran also has the capability to spoof navigation systems. As an example, it was reported that the Iranian cyber warfare unit deceived the navigation of an U.S. Air Force RQ-170 Sentinel UAV resulting in the unit landing in Iran [22].

It has also been noted that North Korea, a long-time technology partner with Iran, regularly attempts to spoof the GPS on ships near its territorial waters [23].

2.2.6 Implications for a tailored RCN Naval Combat Management System

By the nature of their mission, RCN vessels must be capable of addressing both conventional symmetric warfare as well as asymmetric threats from other militaries, insurgents and organized crime. RCN warships must therefore be capable of rapidly adapting and defending against asymmetric tactics as well as employing them.

To successfully execute a mission, regardless of the adversary, it is essential that the commander understands the strengths and weakness of the adversary as well as their own. This information can be extracted using kill-chain models.

2.3 Kill Chain Models

The primary goal of NCMS is to provide ‘knowledge superiority’ over potential enemies, shorten decision-making cycles and execute rapid and accurate weapon engagement, by providing optimum response to changing events [24]. These actions can be described by the kill-chain model.

The kill-chain is an integrated, end-to-end process where an interruption at any stage will interrupt the entire process. The kill-chain can be used as an aid to help decide how the navy invests time, money and other resources to build capabilities to gain a tactical advantage over adversaries.

2.3.1 F2T2EA Kill-Chain Model

Figure 1 illustrates the popular F2T2EA kill-chain model [25] where the chain consists of six primary actions.

1. Find: Locate the target.
2. Fix: Fix their location; or make it difficult for them to move.
3. Track: Monitor their movement.
4. Target: Select an appropriate weapon or asset to use on the target to create desired effects.
5. Engage: Apply the weapon to the target.
6. Assess: Evaluate effects of the attack, including any intelligence gathered at the location.

Figure 1 F2T2EA Kill Chain Model

The model can be used to determine the most efficient and effective way to implement a robust kill-chain that cannot be readily compromised by an adversary. Analysis of an adversary's kill chain can reveal vulnerabilities that can be exploited to break the chain. An example of this would be using Electronic Counter Measures (ECM) to prevent an adversary's radar from seeing friendly assets. This disrupts the first link in the enemy's kill chain and hence stops the attack [26].

2.3.2 F5 Kill-Chain Model

The F2T2EA kill-chain was introduced in the1990s and has been shown to require updating to accommodate the current era of cognitive weapons with levels of autonomy only limited by policy [27]. Figure 2, illustrates the F5 kill-chain that includes plasticity in design to accommodate conventional, semi-autonomous and autonomous systems. The model consists of four dependent variables that must always be completed in the same order — find, fix, finish, and feedback. The fifth is the independent variable, fire. Approval to fire occurs after the target has been identified and fixed [28]. In this model the action to fire occurs at different points in the chain, for example;

- Conventional weapons: immediately after APPROVAL received. This is essentially the same as the F2T2EA Kill Chain Model.
- Semi-autonomous weapons after FIND: Once detection is verified (find) by other surveillance resources the semi-autonomous weapon is fired. While en route, its on-board sensors work to fix the track of interest and signal it is ready to complete the remainder of the kill-chain.

- Autonomous weapons after FEEDBACK: Depending on the level of autonomous permissions granted, these weapons send a signal back confirming that a target has been fixed, along with the evidence required to receive strike approval. With approval, a command signal is sent, the weapons engage, and the kill chain is completed (finish and feedback).

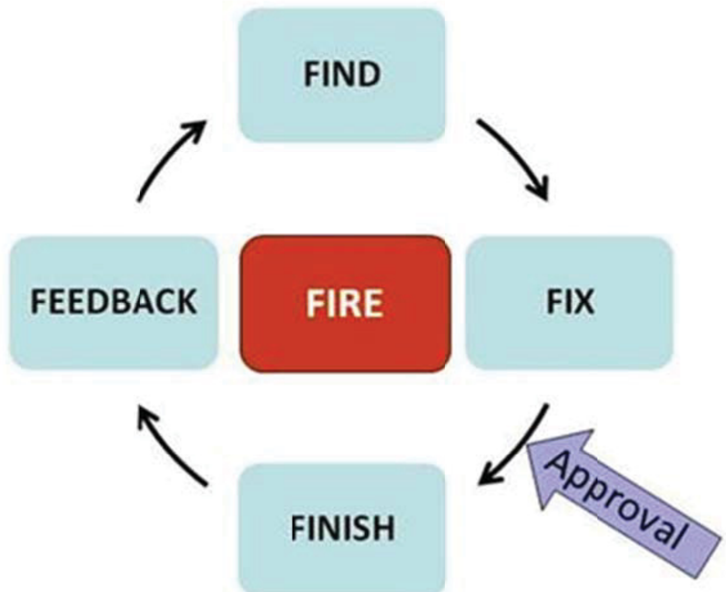

Figure 2 F5 kill-chain model

2.3.3 Cyber Kill-Chain model

Cyber warfare consists of two components Cyber Attack (CA) and Cyber Defence (CD).

The underlying philosophy in countering a CA is an understanding of the cyber kill-chain as illustrated in Figure 3 [29]. The kill-chain consists of a number of steps that a hacker must complete in order to succeed from first scouting out the target to getting inside it to extract data or sabotage software. Two levels of protection are typically evoked: Preventive that is, do not let a hacker in and Responsive where access to data is limited to isolated enclaves once hackers do break in.

The cyber kill chain model can also be used to understand vulnerabilities in an adversary's cyber systems and exploit them to deny or corrupt cyber functionality.

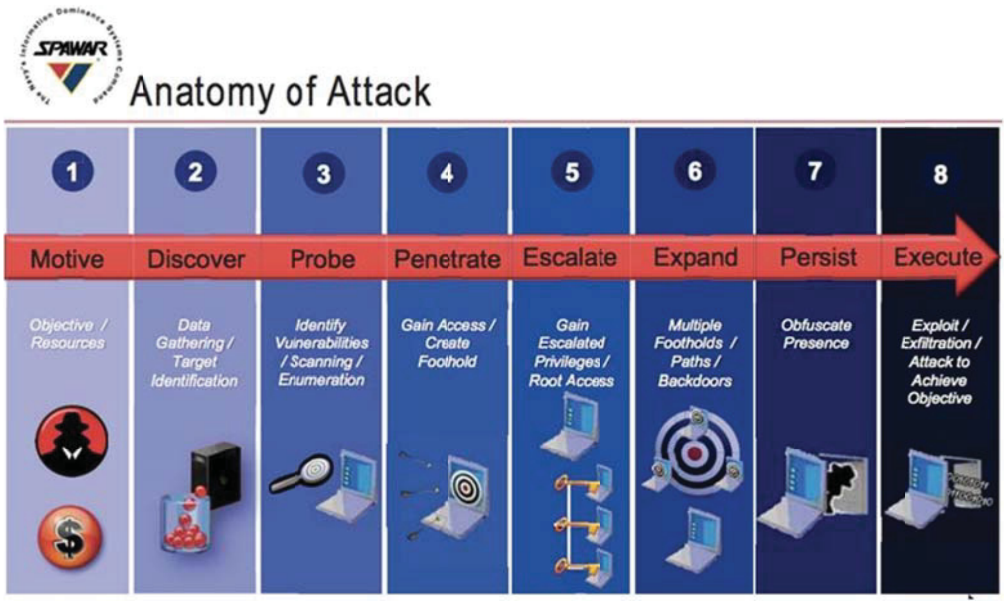

Figure 3 Navy depiction of the cyber kill-chain

2.4 The role of the NCMS in completing the Kill Chain

To accomplish the elements of the kill-chain the NCMS must performs the following key functions:

- **Situational Awareness**: The battle environment at sea includes surface, subsurface and air contacts. This information is collected using sensors including radars, electro–optical systems and sonar.
- **Intelligence:** Convert the above information into actionable intelligence by interpretation, collation and evaluation to generate a Common Operational Picture (COP).
- **Planning and Decision-making:** These strategic steps help commanders to rapidly develop an actionable plan in a dynamically changing, complex, environment.
- **Weapon Systems Command and Control**: An effective NCMS will also direct weapon sensors and weapons to engage and destroy incoming threats. Other actions may include deployment of resources to support non-destructive actions.
- **Feed-back:** This provides an assessment of the consequences of the action taken to aid in further planning and decision-making.

These functions are completed within the C2 sub-system of the NCMS.

2.5 Command and Control System of the NCMS

At the core of the NCMS system is the Command and Control (C2) System. The C2 system is a combination of people, procedures, and hardware used to enhance the ability of the operator to perform command and control functions. C2 operations are characterized as functioning in the context of hierarchal organizations that operate in hazardous, rapidly changing environments under severe constraints such as high risk, time pressure, complexity and ambiguity [30].

As illustrated in Table 1, the C2 system performs eight primary distributed functions that link to a cognitive attribute [31].

Table 1 C2 function and distributed cognitive attribute ontology

C2 Function	Cognitive Attribute
Information Gathering	Situation Assessment
Data Manipulation	Workload Management
Situation Understanding	Situation Assessment
Establishing Intent	Coordination Across Agents
Decision Making	Recommended Action(s)
Planning	Coordinating across Agents
Writing/Verifying Orders	Coordination across Agents
Monitoring Execution	Situational Assessment

2.5.1 All Domain Situational Awareness

An effective NCMS system requires detailed knowledge of what is happening within the area of interest. Knowing the current location, identity, and activity of vessels, aircraft and submersibles operating within its region of interest is a key discriminator in determining how well navies perform.

Gathering the information to develop All Domain Situational Awareness (ADSA) requires a suite of on-board sensors and systems as well as data from a variety of trusted external sources. Knowledge that is obtained from within the NCMS is known as endogenous knowledge whilst data that is obtained external to the system is referred to as exogenous knowledge.

ADSA is achieved through the use of multiple and diverse sensors, data bases and other sources. Sensor resource management can be used to optimization of sensor parameters using knowledge previously collected. This maximizes the sensor value in creating the COP.

The level of surveillance for any given area of interest is defined by traffic (target) type, density, activity and perceived threat. Surveillance capabilities are analyzed using sensor modeling and simulation to determine the level of coverage and gaps. Limited sensor coverage, sporadic target reports, environmental effects and the sheer size of the ocean, inlets and waterways of the maritime domain present significant challenges to generating a reliable operational picture.

The complexity of monitoring maritime activities is compounded by a vast geographical area, the large number of 'players' and the cultural and legal barriers that exist in the world-wide maritime community. Maintaining Domain Awareness requires a collaborative network on complementary systems that continually collects, fuses, analyzes, displays and disseminates global maritime intelligence and information to operational commanders and multi-national partners. This information is used to better anticipate, detect, identify, validate, plan and respond in a timely manner.

Along with a near real time picture, it is important to collect; store and share target characteristics and threat histories to aid future missions.

2.5.2 Intelligence

The objective of the C2 component of the NCM is to generate actionable intelligence derived from available information sources and to provide confidence-based decision support to aid the commander in developing a strategy of engagement. As illustrated in Figure 4, intelligence reflects a progressive refinement of data and information [32]. Data is refined to intelligence using a sequence of collecting and correlating information, processing and exploiting data to gain information and the analysis of this information to extract intelligence. Intelligence provides knowledge regarding the identification, type, identity, and quantification of current and historical activities. The NCMS uses this knowledge to conducting a threat assessment and advise an appropriate course of action.

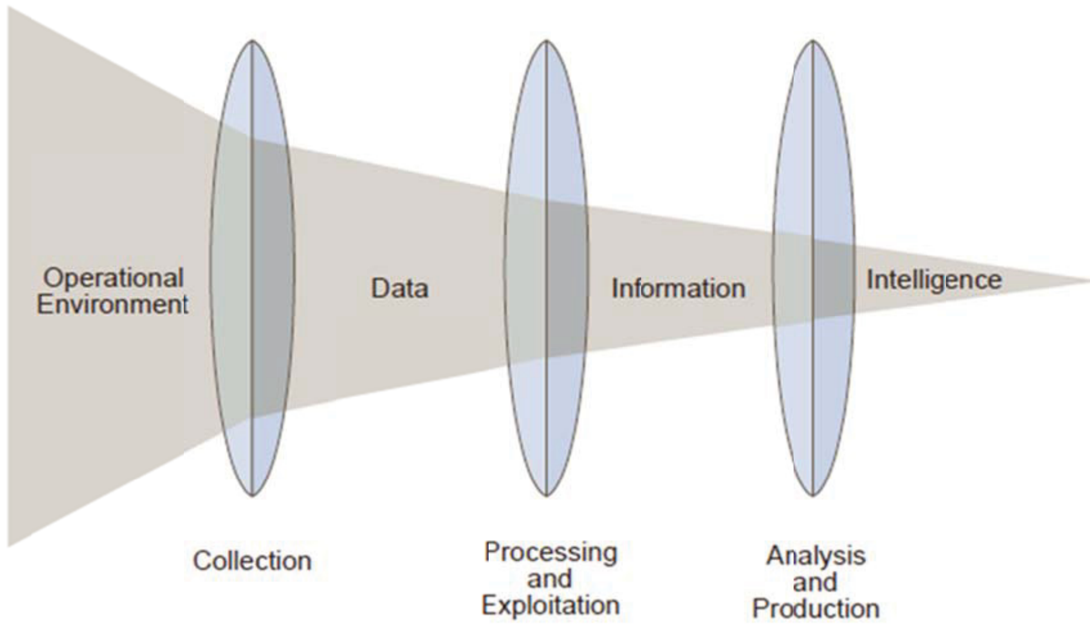

Figure 4 Relationship between Data, Information and Intelligence.

The C2 system filters and displays relevant, prioritized, information on a universal COP. Where identified gaps cannot be filled by new sensors, these gaps must be filled using analytical, predictive techniques. For example, analytical tools that "time-cast" forward last known position reports to generate the best estimate of their current position in the COP.

However, generating the COP is only part of the solution. Decision support tools that automatically analyze target information and identify anomalous behaviours are critical to creating an accurate understanding of the surveillance area. Operators are alerted to targets undertaking anomalous or threatening behaviours so they can be investigated and action taken in a more timely fashion.

2.5.3 Planning and Decision Making

The NCMS system must be capable of providing a complete range of continuous planning and execution capabilities to support operations at strategic and tactical levels.

A simplistic planning and execution model is presented in Figure 5. Planning is a reasoning process that generates an ordered set of tasks derived from a given goal description. Execution is the enactment of these tasks. The NCMS is required to continually assess the situation, monitor the execution of mission plans and react to conditions affecting the defined goals and plans before and during the mission by dynamically re-planning so that the end goals may still be achieved [33].

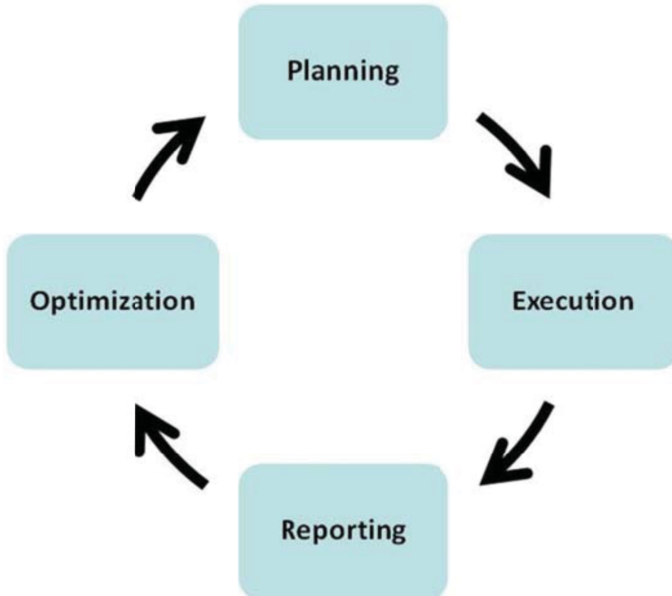

Figure 5 Planning and Execution Cycle.

A continuous planning and execution framework for cognitive systems combines plan-generation with plan-use capabilities to solve complex tasks in unpredictable and dynamic environments. Plans are dynamic, open-ended artifacts that must persist and evolve in response to an ever-changing environment. In particular, plans must be updated in response to new information and requirements in a timely fashion to ensure that they remain viable and relevant [34].

Decision-making is a high-level cognitive process based on perception, attention, and memory. Real-life situations require a series of decisions to be made, with each decision depending on previous feedback from a changing environment [35].

The basic steps of decision making process are illustrated in Figure 6.

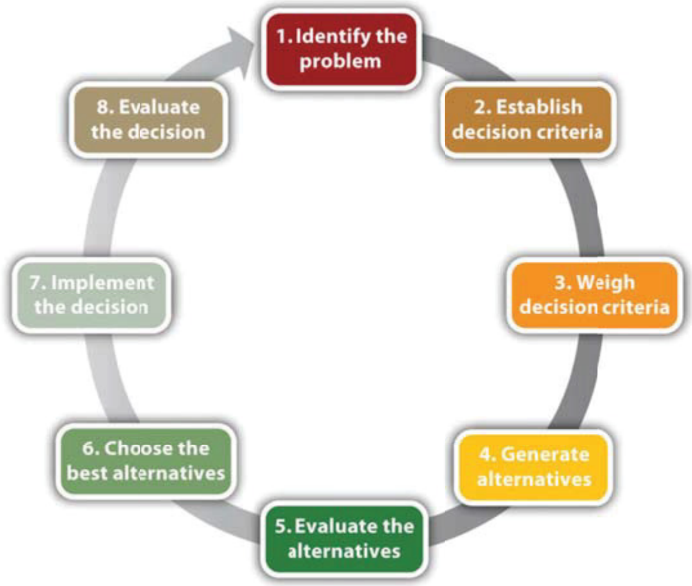

Figure 6 Basic Decision Model

The human approach to problem solving is to proceed in a logical sequence of well defined steps. Initially the problem is defined and then separated into a number of sub-problems that are intrinsically easier to solve than the whole problem. However this approach is fundamentally flawed since it largely ignores the inter-dependencies between the various sub-problems.

Human conscious reasoning capability is primarily sequential and uses short term memory. At any given time this short term memory has a limited capacity to retain more than a few data elements. Consequently, operators are challenged when concurrently assessing multiple relationships [36].

2.5.4 Decision Support System

The Decision Support System (DSS) is an information system that provides objective reasoning to the commander to develop and enact a strategy. The DSS is a software application that collects, organizes and analyzes data to facilitate quality, objective, and decision-making for management, operations and planning. A well-designed DSS aids decision makers in compiling a variety of data from many sources such as data, documents, personal knowledge and past events.

Providing cognitive support is very challenging for operators when working in dynamic situations that are evolving in real-time [37], which is the typical environment of a C2 system.

The objective of a cognitive enhanced DSS is to support the human users to achieve coordinated and effective cognitive work. The DSS is designed to aid the operator to remain on task when faced with distractions such as task-irrelevant visual stimuli or auditory signals.

Key cognitive components within the NCMS DSS include

- **Situation Monitoring**
- **Attentional Control/Management**: i.e. capacity to choose what to pay attention to and what they ignore
- **Planning and Coordination of Activities**

The role of cognition in a NCMS system is discussed in the following section

2.6 Cognition

Cognition is the general term for all forms of knowing and awareness. This section outlines the concepts of cognition and how it can be applied to both C2 and sensor management segments of the NCMS.

Execution of the C2 functions within the NCMS employ a number of cognition processes such as [38]:

- Monitoring
- Recognition
- Casual learning
- Search
- Planning
- Judgement
- Choice

The ability to successfully manage these cognitive resources under time constraints is critical for the successful completion of a mission.

Elements of cognition in the context of C2 systems, as illustrated in Figure 7, include perceiving, judging, reasoning, learning, evaluating and remembering.

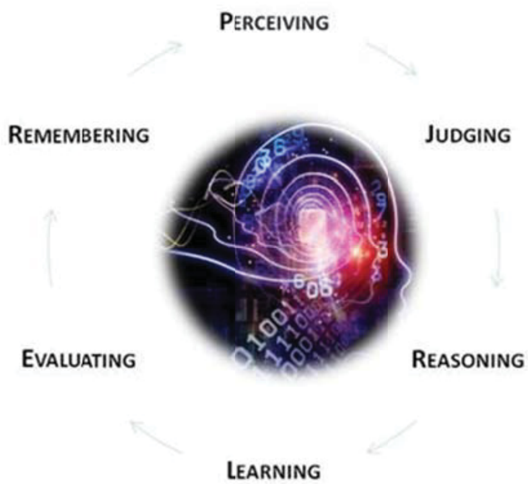

Figure 7 Elements of Cognition

2.6.1 Perception-Action Cycle

All goal directed behavior is performed within the broad context of the 'perception-action cycle', as illustrated in Figure 8, which is grounded in a basic biological principle: the circular cybernetic flow of cognitive information that links the organism to its environment [39]. Each action causes changes in the environment that are analyzed from the bottom-up through the information hierarchy as illustrated in Figure 9. This leads to the selection, prioritization and processing of further action from the top-down through the executive hierarchy. These actions cause changes that are analyzed and result in new actions [40].

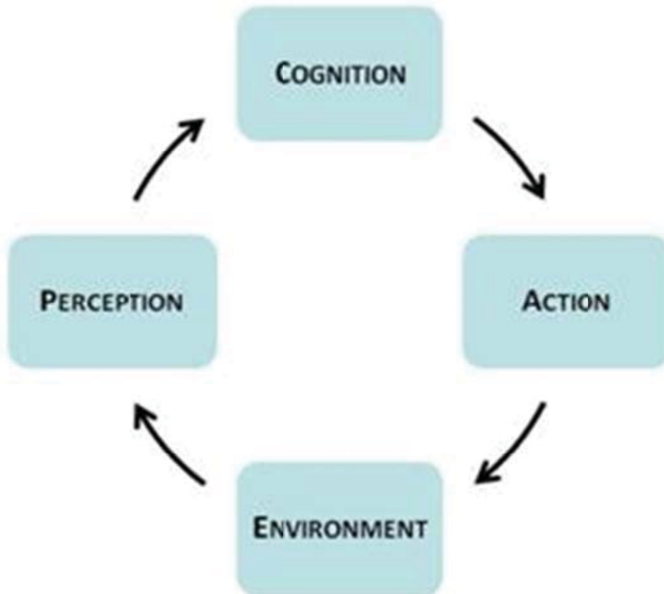

Figure 8 Perception-Action Cycle

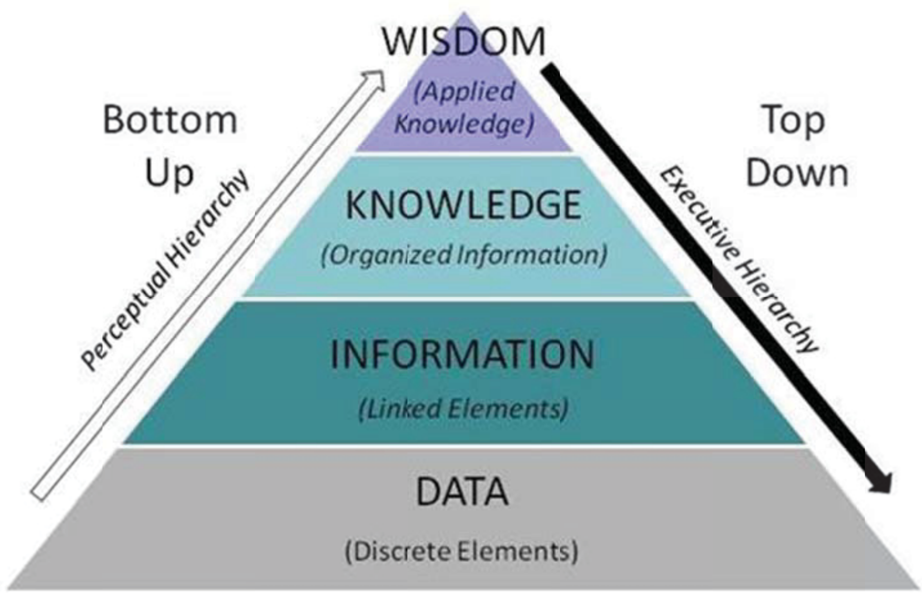

Figure 9 Bottom-Up Information Hierarchy, Transforming Data to Wisdom and Top-Down Executive Hierarchy using Wisdom to obtain better Data

The goal of cognitive sensing is to mimic this cycle. In the sensor domain, perceptual hierarchy uses fast time or 'sub-conscious' cognition to adapt the sensor parameters based on the sensed environment to maximize the probability of success for a given mission objective as defined by the command centre.

Within the C2 system the executive hierarchy uses slow-time or 'conscious' cognition to analyze the data to develop strategies and make informed decisions. The data is then flowed down to the sensor systems so the sensors can be optimized based on the dynamic and evolving needs.

2.6.2 Big Data

The availability of 'big-data' to the NCMS is a game-changer and a paradigm that's now driving change in military computing [41]. As illustrated in Figure 10, big-data available to a NCMS is high volume, high velocity and high variety information. This information is stored, combined and analyzed to extract patterns and reveal trends that can be used to gain system superiority over competitors. However, the wealth of information that is available within the big-data set must be processed in order to extract actionable intelligence.

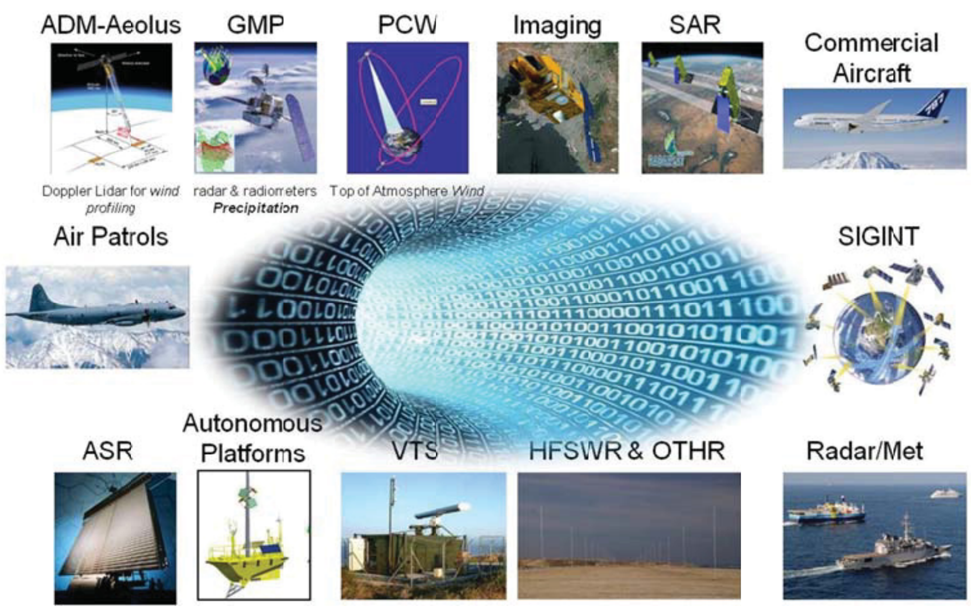

Figure 10 Some of the many sources that contribute to big-data

One of the major problems, as illustrated in Figure 11 [42], is how to shrink big data to small data and gain a competitive advantage. That is achieved by transitioning data to information and then to knowledge.

Figure 11 The Problem: How Transform Information to Knowledge

2.7 Transforming Information to Knowledge

Information is the ideas, facts, stats, and concepts. Information, in its most basic form, is not open for interpretation; it is the content, itself. Information is individual units of data that exist independently of each other. Operators may interconnect the data differently leading to varying conclusions.

Whilst information is the individual pieces, knowledge is the association of this information. Knowledge is obtained when the interrelationships between the information pieces is comprehended. When comprehension occurs, information is assimilated and becomes part of the operators' cognition [43].

Cognitive overload is one of the most significant challenges in regards to knowledge transfer and knowledge retention. An individual's mind can only absorb a finite amount of information. When they reach the limit, their working memory reaches full capacity. As a result, they are no longer able to assimilate the data or connect it to pre-existing knowledge. This is why knowledge is build gradually through experience and training

Assigning meaning is an integral part of the knowledge transfer process. Information is just information. As such, an operator's brain may not necessarily consider it to be relevant or valuable. This requires that information must be put in to context to make the brain take notice. Finally it is worth noting that the human mind can make false connections between ideas and concepts, even if there is absolutely no relationship between them. Consequently, when presenting information to an operator there should be a clean demarcation between unrelated information sets.

2.7.1 High and Low Level Information Fusion

The process by which data is transformed into information and from information into knowledge is known as information fusion. Information fusion is dived into two basic levels

- **Low Level Information Fusion:** concerns numerical data such as location, kinematics and target attributes
- **High Level Information Fusion:** concerns abstract symbolic information such as threat intent and goals.

Different levels of fusion can take place at all levels within the C2 structure. The Data Fusion Information Group (DFIG) model describes 7 levels of fusion [44] all of which are relevant to the NCMS,

Level 0: Data Assessment (DA): estimation and prediction of observable states

Level 1: Object Assessment (OA) estimation and prediction of entity states on the basis of data association.

Level 2: Situation Assessment (SA) estimation and prediction of relations among entities

Level 3: Impact Assessment (IA) estimation and prediction of effects on situations of planned or estimated actions

Level 4: Process Refinement (PR) adaptive data acquisition and processing to support sensing objectives

Level 5: User Refinement (UR) adaptive determination of who queries information and who has access to information

Level 6: Mission Management (MM) adaptive determination of spatial-temporal control of assets

High-level information fusion relates to levels beyond the DFIG Model Level 1and refers to the ability of a fusion system to use cognition in the form of knowledge, expertise, and understanding to: capture awareness and complex relations, reason over past and future events, utilize direct sensing exploitations and tacit reports, and discern the usefulness and intention of results to meet system-level goals [45].

2.8 Computer Processes for Generating Actionable Intelligence from Big-Data

Computers are a pre-requisite for transitioning of big-data to actionable intelligence. Computers have traditionally solved deterministic problems using precisely stated analytical models. This is known as ‘hard-computing’. Programs are written using binary logic such as decision trees, with problems solved sequentially. The models require a complete set of input data with results presented as precise answers.

'Soft-computing', or computational intelligence, is an emerging field of computer programming that attempts to model the human mind. Soft-computing uses techniques such as fuzzy logic, neural networks and probabilistic reasoning to determine likelihood. Models are tolerant of incomplete data, imprecision, uncertainty, partial truth and approximation.   Problems can be solved in parallel with answers presented as reasonable conclusions.

A comparison of hard and soft computing is presented in Figure 12.

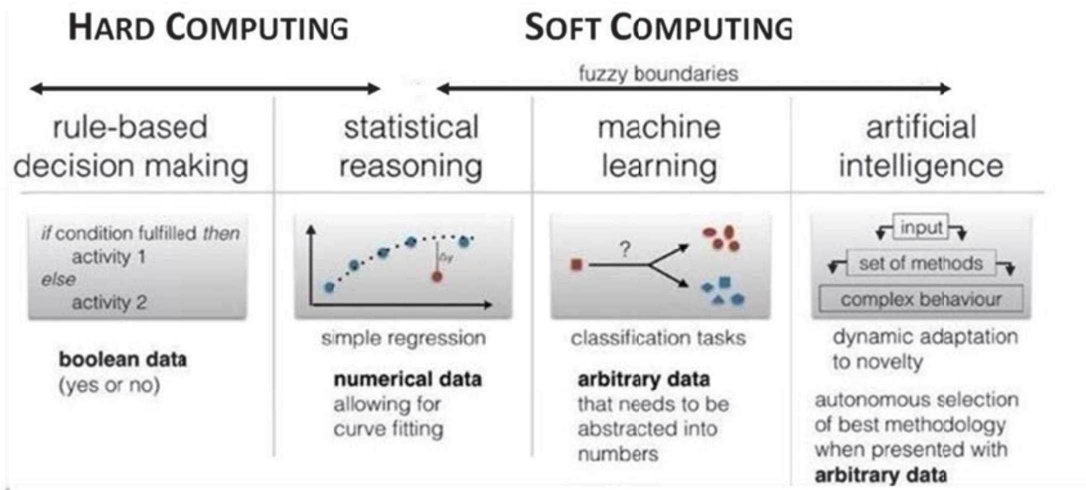

Figure 12 Comparion of Hard and Soft Computing

Traditional C2 systems and adaptive sensor systems have been developed based on hard computing concepts. Soft computing however has many advantages that are applicable to the NCMS.

The following sub-sections introduce various concepts related to soft computing and big-data.

2.8.1 Cloud Computing

Cloud computing refers to the infrastructure that provides a cost effective means of managing Big Data and enables the timely processing of big data on a laptop or similar device. It has a significant relevancy for NCMS in that it allows remote access to bid-data and big-data processing techniques such that only required data products are required to be broadcast to the requesting vessel thereby minimizing bandwidth requirements.

Cloud computing is infrastructure as a service (IaaS) and is an enabling technology that aids in the exploitation of big-data by:

- Providing the means to store and access very large amounts of data
- Providing the ability to host data from multiple disparate sources in a common environment
- Providing the tools to extract meaning from and enrich data on a massive scale, including correlation of data from multiple domains

It is worth noting the U.S. Navy is in the process leveraging the cloud to get out of the data center business for good [46]. Expectation is that this will not only result in a considerable cost saving but will also result in better services and quality of data [47].

2.8.2 Predictive Analytics

Predictive analytical tools use current and historical information to attempt to predict the future. Predictive analytics encompasses a variety of statistical techniques from predictive modelling, machine learning, and data mining to analyze current and historical facts to make predictions about future or otherwise unknown events [48].

Predictive Analytics traditionally requires a well defined objective with an expected outcome. The Process can be defined by 7 steps [49].

1. **Define Project**; project outcomes and deliverables, scope of the effort, objectives and identify the data sets that are going to be used.
2. **Data Collection**: Data mining for predictive analytics prepares data from multiple sources for analysis.
3. **Data Analysis** : Data Analysis is the process of inspecting, cleaning and modelling data with the objective of discovering useful information, arriving at conclusion
4. **Statistics**: Statistical Analysis is used to validate the assumptions, hypothesis and test those using standard statistical models.
5. **Modelling**: Predictive modelling provides the ability to automatically create accurate predictive models about future. There are also options to choose the best solution with multi-modal evaluation.
6. **Deployment**: Predictive model deployment provides the option to deploy the analytical results into everyday decision making process to get results, reports and output by automating the decisions based on the modelling.
7. **Model Monitoring**: Models are managed and monitored to review the model performance to ensure that it is providing the expected results.

The process can be seen to be similar to the six sigma (6σ) DMAIC process [50]. This process, illustrated in Figure 13, refers to a data-driven improvement cycle used for improving, optimizing and stabilizing business processes and designs.

Figure 13 Six Sigma "Define Measure Analyze Improve Control" process (DMAIC)

Soft computing and neural networks are now being used in predictive analytics as an efficient way to forecasts what might happen in the future when the exact nature of the relationship between inputs and output is not known and when the input data is incomplete.

2.8.3 Machine Learning

Machine learning (ML) is a blanket term that refers to a wide variety of algorithms and methodologies that enable software to learn and improve performance over time as more data becomes available [51].

ML is an extension of predictive analytics and is a method used to devise complex models and algorithms that lend themselves to prediction. As the name implies, machine learning allows computers to learn without being directly programmed, enabling computer programs to evolve and adapt as new data is added.

ML techniques are appropriate when the problem is well defined and input data is complete. Commonly used machine-learning techniques include neural networks, support vector machines, decision trees as well as regression techniques. Computational Intelligence is a branch of ML that aims to find a solution to solve a previously unknown problem.

Deep learning techniques are based on multiple layers of ML algorithms such that the output from one layer becomes the input to the next.

2.8.4 Machine Intelligence, Artificial Intelligence and Computational Intelligence

Machine Intelligence (MI), Artificial Intelligence (AI) and Computational Intelligence (CI) all refer to the same branch of software engineering that enable computers to learn from data and experimental observation. However these techniques differ from machine learning in that they aim to find a solution to solve a previously unknown or poorly defined problem.

- **Artificial/Machine Intelligence** relates to machines making decisions
- **Machine Learning:** relates to algorithms that learn from data and create foresights based on the analysis of the data
- **Cognitive Intelligence/Computing:** relates to systems that learn at scale (that is process big-data), reason with purpose and interact with humans naturally

All can be used to automate cognitive functions [52].

The 'Seven Spectrum of Outcomes for AI', illustrated in Figure 14 outlines the process from perception to achieving situational awareness and from situation awareness to perception [53].

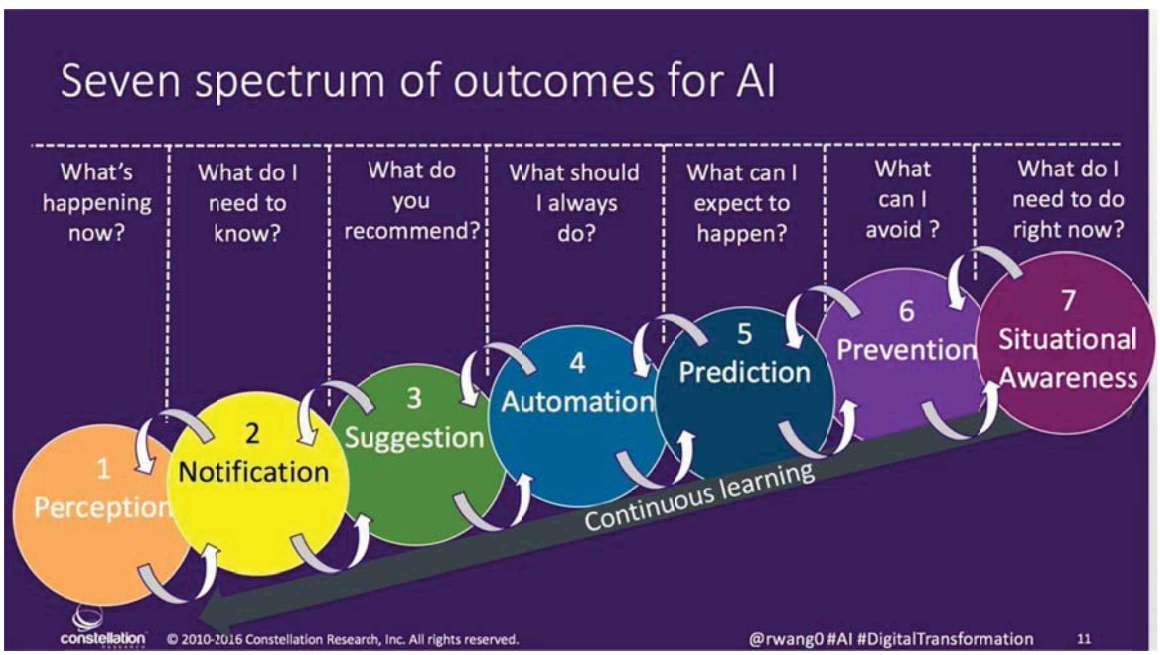

Figure 14 The Seven Spectrum of Outcomes for AI – from Perception to Situation Awareness and from Situation Awareness to Perception.

Perception describes what's happening now. The first set of outcomes rudimentary describe surroundings as manually programmed.

Notification tells you what you asked to know. Notifications through alerts, workflows, reminders, and other signals help deliver additional information through manual input and learning.

Suggestion recommends action. Suggestions build on the past behaviors and modify over time based on weighted attributes, decision management, and machine learning.

Automation repeats what you always want. Automation enables leverage as machine learning matures over time and tuning.

Prediction informs you what to expect. Prediction starts to build on deep learning and neural networks to anticipate and test for behaviors.

Prevention helps you avoid bad outcomes. Prevention applies cognitive reckoning to identify potential threats.

Situational awareness tells you what you need to know right now. Situational awareness comes close to mimicking human capabilities in decision making.

2.8.5 Cognitive Computing

Cognitive computing is a subset of AI that deals with cognitive behaviors associated with intelligence as opposed to the perception-action cycle. Typically, cognitive computing deals with symbolic and conceptual information rather than just pure data or sensor streams. The objective is to seek interdependencies between large independent data sets to seek additional insight to aid in high-level decision. The potential for cognitive computing is to extract information from complex situations in a timely manner and with lower processing requirements.

Cognitive computing is not a machine-learning method but is an architecture of multiple AI subsystems that work together.

2.9 Summary

The goal of the NCMS is to provide 'knowledge superiority' over potential adversaries, shorten decision-making cycles and to develop and execute an appropriate strategy that may include rapid and accurate weapon engagement. The system enables the commander to execute the best course of action based on the current understanding of an evolving event.

Providing the commander, with timely and appropriate information and recommendations requires extensive use of cognitive functions. This can be challenging to operators particularly when in high stress and highly variable environments. A key goal of the C2 component in the NCMS is to automate elements of cognitive processes to relieve stress levels on operators and to extract relevant actionable intelligence derived from available from all relevant information sources to provide the commander with confidence-based decision support.

The emergence of big-data provides significant opportunities to improve the performance and capability of the NCMS but this comes with challenges in being able to extract timely, relevant information. Computational Intelligence has the potential to extract the required information to aid in the optimization of sensors and systems and complete the execution of the kill-chain whilst minimizing end-user fatigue.

3 Cognitive Sensors and Systems

As discussed in Section 2.6.1, the goal of cognitive sensing is to mimic the perception-action cycle using fast time cognition to adapt sensor parameters based on the sensed, or otherwise known environment. This is undertaken to maximize the probability of success for a given mission objective as defined by the command centre.

This section reviews the cognitive aspects of a ship borne sensors and the weapons suite. This suite includes radar, Electro-Optical/Infra-Red (EO/IR), and Electronic Support Measures (ESM) sensors, Gunnery Weapons, Precision-Guided Munitions, Anti-Submarine Weapons (ASW), Countermeasure Dispenser System (CDS) and Non Destructive Weapons. An overview of these systems as found on the RCN Halifax class patrol frigate is presented in Figure 15 [54].

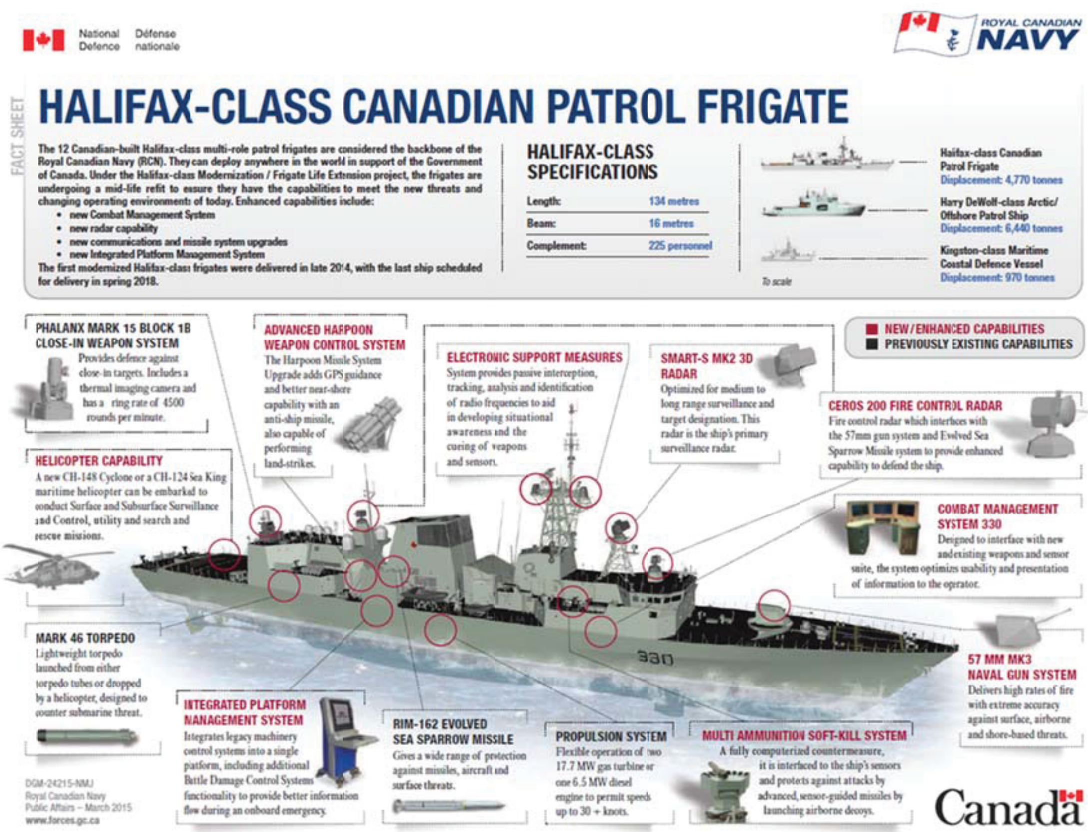

Figure 15 An overview of Sensor and Weapon systems as found on the RCN Halifax class patrol frigate

Consideration is given to both active and passive sensors. An active sensor is a device with a transmitter that sends out a signal that is bounced off a target, with data gathered by the sensor upon their reflection. Passive sensors are receiving only and simply detect and respond to third party signals.

3.1 Review of Naval Vessel Sensors

The NCMS ingests data from a wide variety of both local and remote sensors. These sensors can be categorized as imaging sensors, weather and geo-sensors, and vessel health sensors.

Imaging sensors provide details of the location of a target and include radar, sonar, electro-optical (EO), EO/IR and visible cameras. These sensor are complementary in nature and when combined provide subsurface, surface and air domain awareness. Weather sensors are used to measure wind speed and direction, humidity, aerosol particulate, luminance, tidal, sea-state. Geo sensors include Global Position Systems (GPS), gyrocompasses, inertial navigation systems, and compasses. Health sensors measure the health of the vessel, its engine, machinery and systems. Examples of external data sources include Automatic Identification System (AIS) that is broadcast from all commercial vessels and details their identity, position and intent. Commercial airliners also broadcast similar information through Automatic Dependent Surveillance – broadcast ADS-B.

Examples of imaging sensor systems that are found on naval combatant vessels are presented in the following sub-sections [55]. Details of the other sensing systems whilst very relevant to the NCMS are not discussed further in this report.

3.1.1 Radar Sensors

Radars are the primary sensor for identifying the whereabouts of surface and airborne entities. Radar provides location but cannot provide positive identification. The range of the radar is dependent on many factors, in general, the lower the radar operating frequency the greater the range, but this comes at the cost of resolution and accuracy. Conversely radars operating at a higher frequency are more subject range degradation due to precipitation. A common feature with naval radars is that they have a minimum range and close in surveillance is supplemented using various EO/IR cameras.

The primary radar and sensor on a modern surface combatant vessel is the Active Phased Array multifunction Radar (APAR). The APAR radar supports multi-mission capabilities such as swarm defence, anti-piracy, UAV control and weapon support for active missiles. These different types of targets put different requirements on the radar; air defence require long range, high diving missiles require elevation coverage, sea skimmers require fast reaction time, hovering helicopters require spectral information, whilst UAVs require excellent clutter suppression, etc. [56].

3.1.2 Sonar Sensors

Modern naval vessels can carry a variety of active and passive sonar systems for detection of underwater targets. Hull mounted passive sonar's are primary used for submarine detection whilst active sonar detects mines and torpedoes. For greater range and higher resolution the vessel can also deploy a towed array sonar system. The shipboard helicopter will also carry dipping sonar for detection of submarines.

3.1.3 Electro Optical (EO), Infrared and Visible Cameras.

These sensors provide the close in surveillance around the vessel and when deployed on autonomous or semi-autonomous vehicles can provide a remote view. The EO is limited to day operations where it has greater range and in have excellent imaging quality compared to IR, however, performance is severely afflicted by poor weather. IR functions in both day and night but image quality is less than EO when operating in clear weather, in general these systems are grouped together in an EO/IR system. Visible cameras provide high fidelity static and video images.

Typical capabilities of various classifications of IR thermal imagers used for naval operations are listed below and an example of vessel mounted Obzerv ARGC-2400 Range-Gated Camera presented in Figure 16.

- IR Thermal Imager
  - Long Range Night Vision to about 20 km
  - Detection Only
- Light Intensifiers
  - Short range night vision extension of daylight surveillance to about 600m
- Active non-gated Imager
  - Short to medium range night vision
  - Classification and identification to about 3 km
- Active Range-gated Imager
  - Medium to very long range active night vision
  - Classification and identification to about 10 km
  - Detection to about 25 km

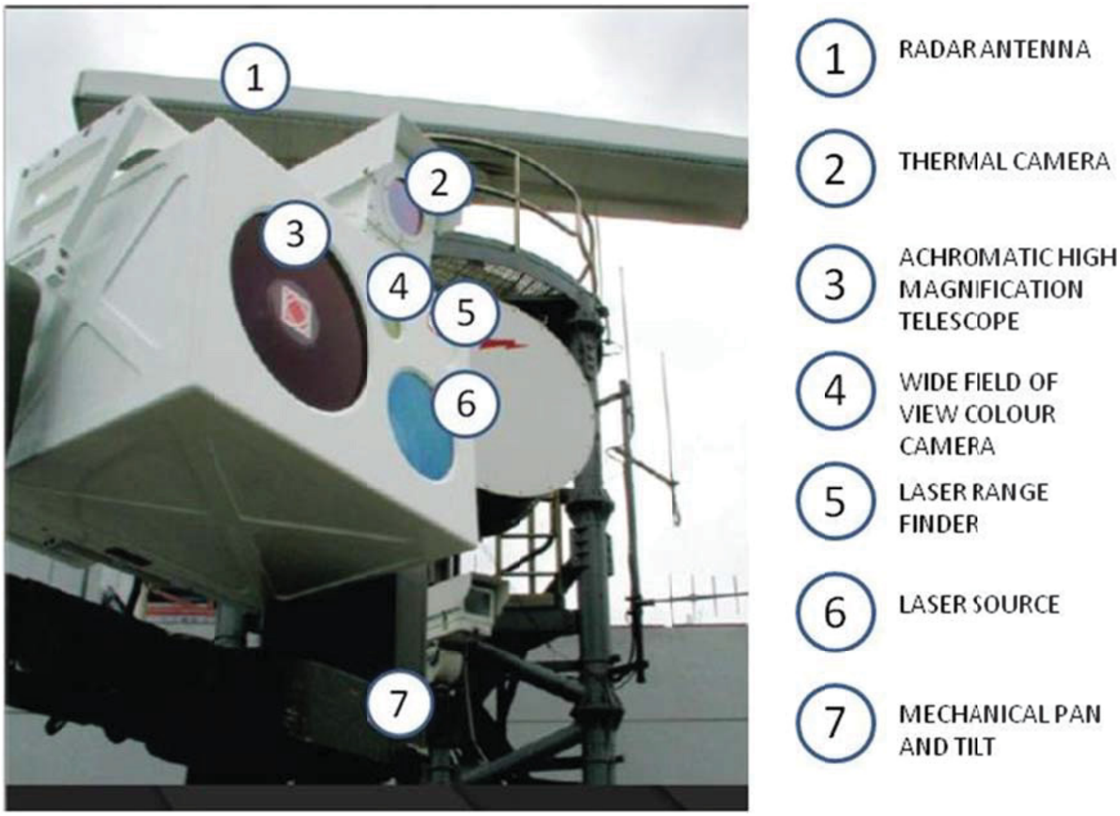

Figure 16 Vessel mounted Obzerv ARGC-2400 Range-Gated Camera

An excellent tutorial introducing EO/IR cameras for the defence industry is available in [57]. The article also shows how EO/IR can also used to detect the launch of a missile.

3.1.4 Electronic Support Measures/Electronic Counter Measures

Electronic Support Measures (ESM) is a segment of electronic warfare (EW) involving actions taken to analyze sources of radiated electromagnetic energy for the purposes of identifying immediate threats or to support longer-term operational planning. ESM provides a source of information required for undertaking EW including the denial of the EM spectrum to an adversary this is known as an Electronic Attack (EA). EW can also be used to guarantee unimpeded access to the EM spectrum portion to friendly forces this is known as Electronic Protection (EP).

3.1.5 Navigation System

Navigation system consists of a large number of integrated systems required to navigate the vessel. These include both S and X-band navigation radars with automatic radar plotting aid, electronic navigation charts and electronic chart display system, GPS, inertial navigation system, AIS, log, echo sounder, and anemometer. Data from these systems are also used to support the NCMS.

3.1.6 Communication System

Effective and secure communication links are a fundamental requirement for navies that rely heavily on radio and satellite technologies to meet increasing demand for bandwidth. Navy vessels use fully integrated communication systems to provide strategic and tactical, internal and external (Ship-to-Ship, Ship-to-Shore and Ship-to-Air) services.

On-board communication systems consist of a comprehensive suite of secure multi-channel, multi-mode, surface and space communications covering the EM spectrum from Very Low Frequency (VLF) to Extremely High Frequencies (EHF). These communication systems were one of the earlier adopters of sense-and-adapt processing which is the core of Software Defined Radios (SDR)

SDR technology is well established with fielded systems providing multiple waveforms and multilevel information security for voice and data communications. SDR provides all radio frequency (RF) to-baseband and baseband-to-RF conversion functions required for line-of-sight (LOS), beyond LOS and satellite communications systems.

SDR technology is considered outside the terms of reference for this report. Product information for the U.S. Navy's AN/USC-61 (C) Digital Modular Radio (DMR) supplied by General Dynamics can be found in the reference [58].

3.1.7 Aviation Capability

The ship borne helicopter supports surface and subsurface surveillance and control, utility and search and rescue missions. It also provides tactical transport for national and international security efforts. Aviation capability can also be augmented with tactical UAVs

3.1.8 On-board Autonomous Vehicles

This includes underwater, surface and airborne assets that are under the control of the host vessel. Autonomous vehicles are the host platform for a number of sensors that include cameras, radar, sonar etc., that support the following type of missions [59]:

- Intelligence, Surveillance and Reconnaissance (ISR) missions
- Over-the-horizon-targeting
- probe & sector search
- battle damage assessment

Autonomous Vehicles can also be used to host various weapon systems for countering surface, air, ground and subsurface threats [60].

3.2 Review of On-board Weapon Systems

The weapon systems on board a warship are capable of engaging airborne targets, surface targets, low flying (sea skimming) missiles and submarines at medium-to long ranges. They also include weapons for engaging with close-in threats and provide point defence.

3.2.1 Gunnery Weapons

This is a general term for various missiles and guns that are used for engaging with all types of threats. Typically these include land attack capable cruise missiles, long-range surface-to-air missiles and Close-In Weapon Systems (CIWS). The CIWS consist of both rapid fire guns and short range missile systems.

3.2.2 Precision-Guided Munitions

A Precision-Guided Munitions (PGM) such as smart weapon, smart munitions, smart bomb are guided munitions intended to precisely hit a specific target, to minimize collateral damage and increase lethality against intended targets.

An example of a precision weapon system is the U.S. Tomahawk, GPS-enabled, Block IV cruise missile that includes a two-way satellite data-link that enables the missile to be retargeted in flight to preprogrammed, alternate targets.

Tomahawk can be launched from a ship or submarine and can fly into heavily defended airspace more than 1,000 miles away to conduct precise strikes on high-value targets with minimal collateral damage [61].

3.2.3 Anti-Submarine Weapons

Anti-Submarine Weapons (ASW) includes vertical launch light weight torpedoes capable of sustained run at high speed with operator selectable vertical and horizontal search patterns. The ship-borne helicopter is also capable of carrying torpedoes to achieve stand-off advantage.

3.2.4 Countermeasure Dispenser System

The Countermeasure Dispenser System (CDS) is capable of deploying advanced Air and Missile Defense (AMD) countermeasures including super rapid blooming off board chaff and multiple types of anti-torpedo decoys.

3.2.5 Non-Lethal Weapons

Navy vessels also have access to an array of non-lethal weapons used to deter aggression and maintaining freedom of the seas [62]. Examples include acoustic hailing devices, enhanced underwater loudhailer, water cannon etc.

3.3 Cognitive Sensors

As depicted in Figure 17 [63], early active sensors, such as radar and sonar, were cognitive in the sense that they generally required a person-in-the-loop to optimize performance based on observed data. The goal of modern sensor development has been to replace the person-in-the-loop. This has led to the development of various techniques that adapt the sensor and tracking parameters to both the mission and operating conditions.

Figure 17 Operator controlling a MPN-13 & MPN-14 ASR/PAR Mobile Radar; circa 1970

The first sensors were manually operated but recently sensors have become adaptive and automatically modify their parameters to the sensed environment based on scripted commands. Cognition is the next level of evolution where the sensor adapts to the environment. Cognition, as defined in [64], utilizes intelligent signal processing, which builds on learning through interactions of the sensor with the surrounding environment as well as feedback, in the case of an active sensor, from the receiver to the transmitter. This learnt behaviour may include either self acquired endogenous knowledge or exogenous knowledge obtained from trusted third party sources. For example, if a target is being observed by other means or is known to be a low value target then resources can be diverted to higher priority targets. Likewise, data related to environmental conditions obtained elsewhere can be used to aid in the optimization of the sensor.

Cognitive techniques allow a sensor to adapt to a changing threat and clutter environment by optimizing performance. A pictorial representation of the Cognitive Cycle is illustrated in Figure 18. Sense relates to collecting and processing of data, and learn is the understanding of the environment based on the sensed data relative to the mission profile. This data may include exogenous knowledge to aid in the detection and tracking process. Decide relates to determining the optimization of the sensor algorithms and act is the modification of the sensor parameters (waveform, detector, tracker etc.) to meet the mission objective. The primary objective of the cognitive system is to allocate sensor resources to sense the unknown with a secondary objective to confirm the known. It can be noted that the Cognitive Cycle is similar in context to the standard OODA decision cycle of observe, orient, decide, and act.

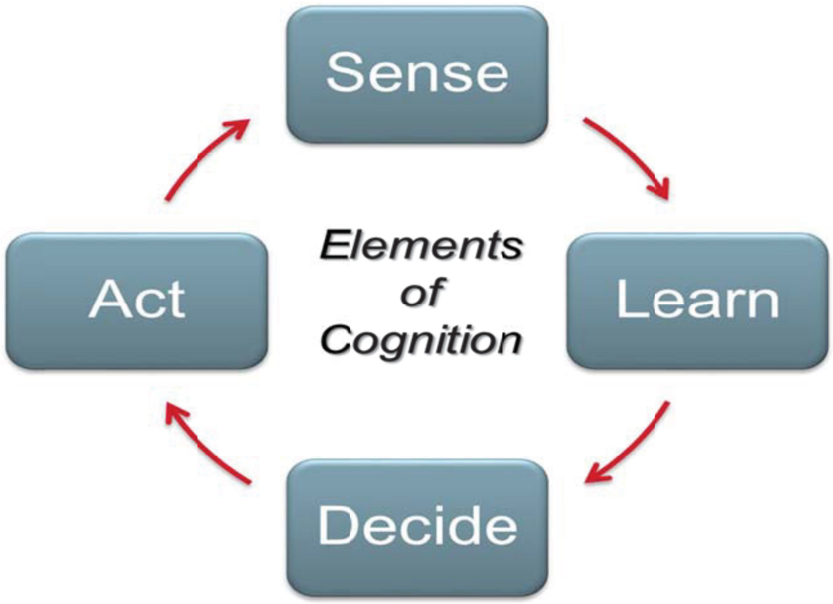

Figure 18 The Cognitive Cycle

The framework of a cognitive sensor model is based on the perceptual hierarchy of sense-learn-decide-act, as presented in Figure 19. This framework uses fast-time or sub-conscious cognition at the sensor level to sense-and-adapt to the local environment. Flow-down of mission specific commands from the NCMS system is top-down via the executive hierarchy using slow-time or conscious cognition.

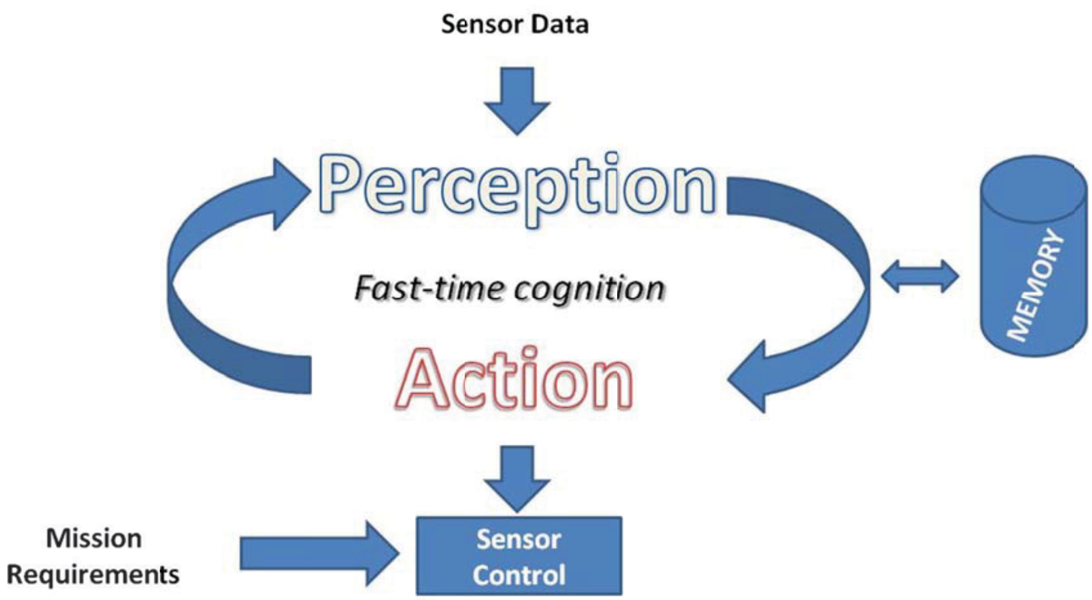

Figure 19 Framework: a cognitive sensor model

The framework is applicable to both active and passive sensors. The difference being that for passive sensors the model is only applicable to the receiver.

3.4 Application to Radar

The core components of cognitive radar are illustrated in Figure 20. The optimizer senses the environment and adapts the transmitter, receiver and processing parameters with the objective of maximizing the wanted signal, whilst simultaneously minimizing the unwanted. The correlator isolates and associates time sequential responses with common attributes to maximize the probability of track whilst minimizing the probability of a missed track or a false track.

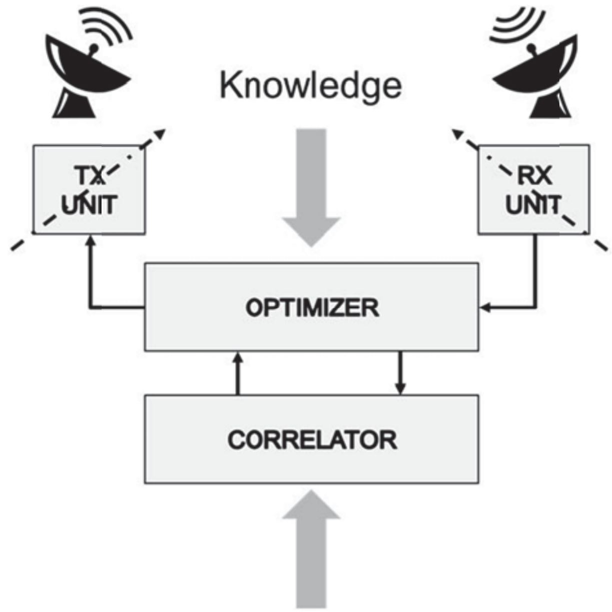

Figure 20 Elements of Cognitive Radar

It can be observed that the cognitive architecture is open and receptive to use data from trusted sources to generate intelligence and knowledge which augment the optimization process. This differs from adaptive radar where the closed, self-contained architecture that adjusts parameters to predetermined settings based on self-sensed data only.

Cognitive radar builds on the principals of cognitive radio's Dynamic Spectrum Access (DSA). DSA is a spectrum-sharing scheme that allows radiating systems to operate as secondary users on a Non-Interference and Non-Protected Basis (NIB & NPB). DSA enables significant improvement in the efficient use of the RF spectrum and maximizes the number of users of the spectrum compared to traditional fixed spectrum access. DSA also opens up the feasibility of spectrum sharing between radar and communication users.

Adaptivity enables a radar to be programmed to simultaneously undertake multiple tasks such as search, track, and fire control. As discussed in [65] the Radar Resource Manager (RRM) is especially important in overload situations when the radar does not have sufficient time to schedule all requested looks. In this case, the radar scheduler must decide which tasks should be prioritized and which should be delayed, dropped or parsed to another sensor or system. For example when operating in a self-defence mode priority will be given to inbound targets on a trajectory towards the vessel that are not reporting as friendly.

3.5 Cognitive Sensing

Cognitive Sensing, as illustrated in Figure 21, uses sensors as a collective with knowledge and resources shared between entities. This is a dynamic process that is both mission and task dependent. Knowledge obtained from either endogenous or exogenous sources is used to optimally configure the sensor and adjust parameters, in real-time. The approach uses a systems-of-system design principal with the objective that the collective value of the sensing system is greater than just the sum of the individual sensors.

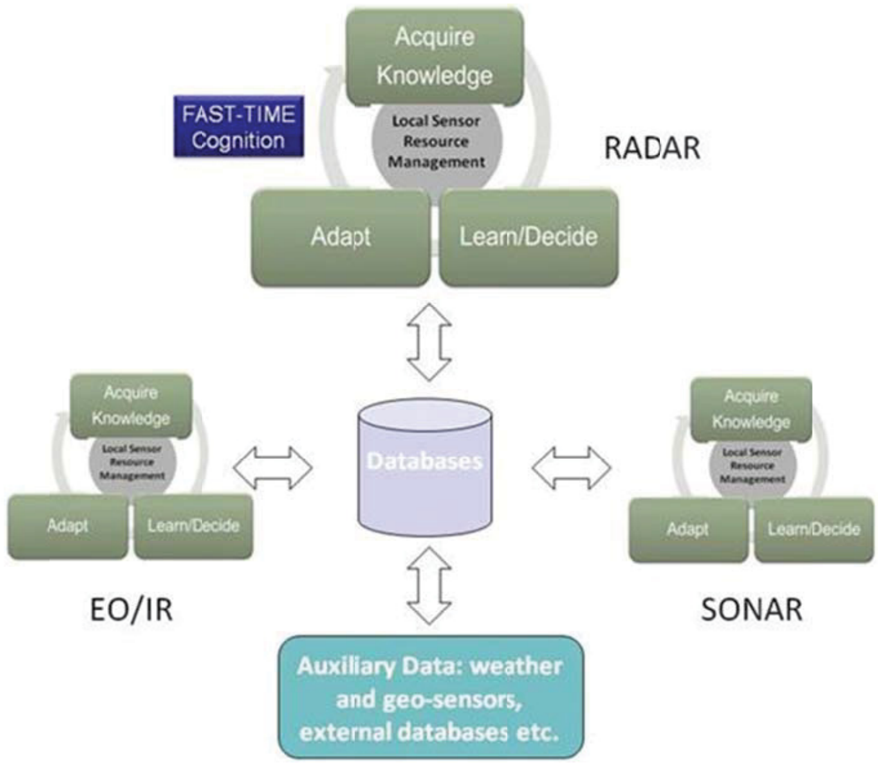

Figure 21 Example of a Cognitive Sensing Architecture where the sensor configuration and parameters are modified based on knowledge gained from other collaborative sensors and systems

3.6 Adaptive Systems vs. Cognitive Systems

In terms of sensing, an adaptive sensor is a system that adapts to the environment such that the overall performance of the system is improved. This includes reacting to changes to an otherwise stable environment as a result of disturbances in the electromagnetic spectrum (EM), in the weather, and target dynamics, etc.

Adaptive sensors and Cognitive sensors both meet the above definition. Most modern sensors are adaptive but cognitive sensors are still very much in their infancy. Adaptive sensors utilize feed-back loops to modify system parameters. They can also uses machine learning to undertake time-sequential tasks such as conditional programming (if, then, else) and statistical reasoning, to adapt sensor parameters, or simple decision aids, based on a pre-defined rule set. This predictive approach to adapting system parameters assumes that all scenarios are known in advance. Adaptive Systems generally operate at the entity level and output through a hierarchy.

Cognitive enabled systems are an evolution development where systems are not only capable of sensing the environment but can undertake an appropriate response without prior programming. That is cognitive systems can be optimally configured without prior knowledge of the threat or environment. The systems can 'think' for itself and is no longer bound to undertake reasoning in a sequential format.

A key enabling feature of cognitive systems is that they use information from the whole suite of sensors and systems rather than operating as an individual entity. That is a cognitive system is a system-of–systems approach, where the systems pool resources and capabilities to create a new, more complex system with functionality and performance that is more than simply the sum of the constituent systems.

3.7 Sensor Resource Manager

Sensor hardware has reached a level of maturity where there is little expectation of significant improvement in the core design. Therefore advances in performance will be gained primarily in optimizing signal processing to the active mission and current environment. This can be achieved by dynamically allocating processing resources and incorporating knowledge obtained from other systems to generate a capability that is greater than just the sum-of-the-parts. Machine learning (computational intelligence) is the enabling technology for achieving this using a cognitive multi-sensor resource management system known as the Sensor Resource Manager (SRM).

The SRM treats sensors as a collective rather than individual entities with the objective that resources and sensors are used collectively to maximize the probability of mission success.

The SRM, illustrated in Figure 22, provides a common interface to the various resource managers in the system. The SRM primary missions are the:

· Dynamic flow down of mission objectives to the various resource managers including tasking, assignment, parsing and prioritization

· Dynamic allocation of processing resources to the various resource managers

· Distribution of external derived sensor parameters to be used within the various resource managers. Self-sensed environmental data will remain the prerogative of the various resource managers.

The following sections describe the functionality of the SRM in more detail.

Sensor systems typically operate under resource constraints that prevent the simultaneous use of all resources all of the time. One goal of the Sensor Resource Manager (SRM) is to control the degrees of freedom in an agile sensor system to satisfy operational constraints and achieve operational objectives [66]. SRM becomes critical when it is not feasible to collect and process all the data all the time.

SRM controls one or more sensors to support tracking and fusion. The SRM allocates resources appropriately in order to gain as much information as possible. The SRM oversees a network of sensors that observe a common environment; each sensor can be set to operate in one of several modes and/or viewing geometries. The objective of the SRM is to maximize the overall rate of information gain. The rate of improvement in kinematic tracking and classification accuracy of all tracks in the area of interest [67]

The SRM has the potential to improve the effectiveness and efficiency of sensors in generating domain awareness by clustering sensors in a collaborative network. In this network, the SRM performs the functions of tasking and assignment of resources. In addition, in overload situations the SRM can parse lower priority targets to secondary sensors and systems. A graphical representation of SRM is presented in Figure 22.

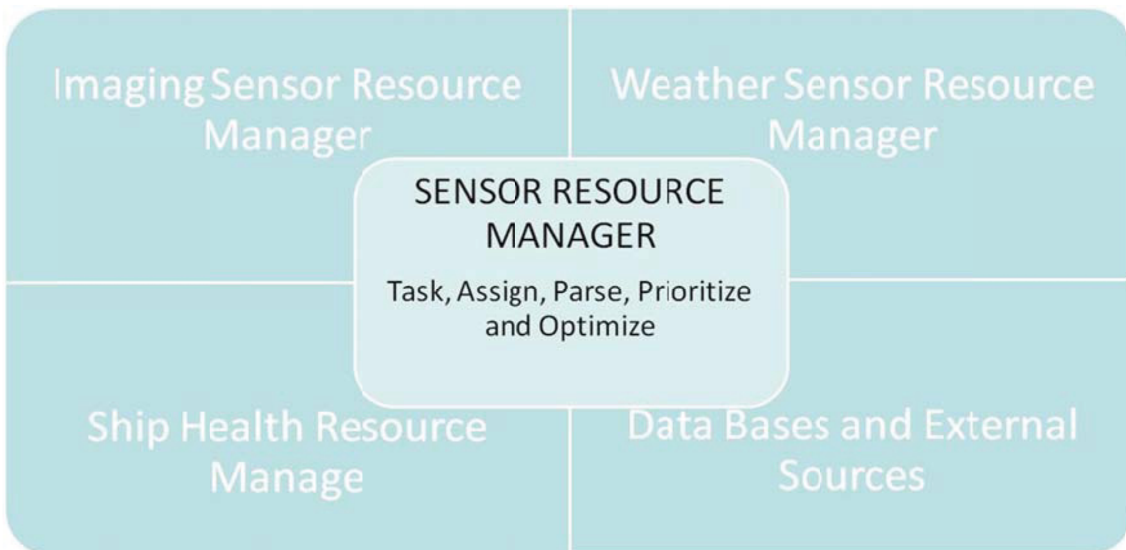

Figure 22 Sensor Resource Manager

Another function of the SRM is to optimize the collection and processing of data by appropriately modifying system parameters based on the sensed environment and mission. In this aspect the SRM is an extension of the classical radar resource manger (RRM) in that it incorporates data obtained from other sensors and systems such as the onboard environmental sensors. The system can also use trusted third party data to assign priorities to entities that are not self identifying.

SRM is a critical factor in gaining domain awareness at the lowest cost. Sensor assets differ significantly in number, location and capability over time. The SRM can be used to determine on which object a sensor should collect measurements during subsequent observation periods for largest gain in relative information. The SRM can use either endogenous or exogenous knowledge related to the environment or target to optimize the performance of a sensor.

The SRM consists of the Sensor Resource Analyzer and the Sensor Tasking Algorithm (Tasker). The Tasker maintains timing constraints, resolution and geometric differences between sensors, relative to the tasking requirements. The Tasker does this using the computational intelligence approach of multi-objective optimization, which involves evolutionary methods [68].

SRM can also be effective in minimizing the probability of an adversary jamming a sensor by only having that sensor active at the appropriate time in the evolution of the mission. This is referred to as 'operation on request' and relies on the SMM cuing the primary mission sensor based on knowledge obtained from other systems. Operation-on-request limits an adversary's ability to gain knowledge of the EM spectrum of the sensor that would allow them to develop EA capabilities.

The growth of industry interest in autonomous vessels is driving this development [69]. The referenced paper describes a futuristic multi-sensor architecture with an adaptive multi-sensor management system for the control and navigation of autonomous maritime vessels in all weather conditions. A block diagram of the envisaged system taken from the paper is presented in Figure 23. The system augments data from onboard imaging sensors (radar, sonar, cameras etc.,), environmental sensors with AIS data and other external information sources. The adaptive multi-sensor management block utilizes non-imaging sensor data to derive an assessment of the prevailing weather conditions. It then uses this assessment to adaptively manage the imaging sensors. The system uses computational intelligence to implement cognitive functions to generate various outputs including navigational situation awareness, weather situation awareness and a need-to-learn awareness.

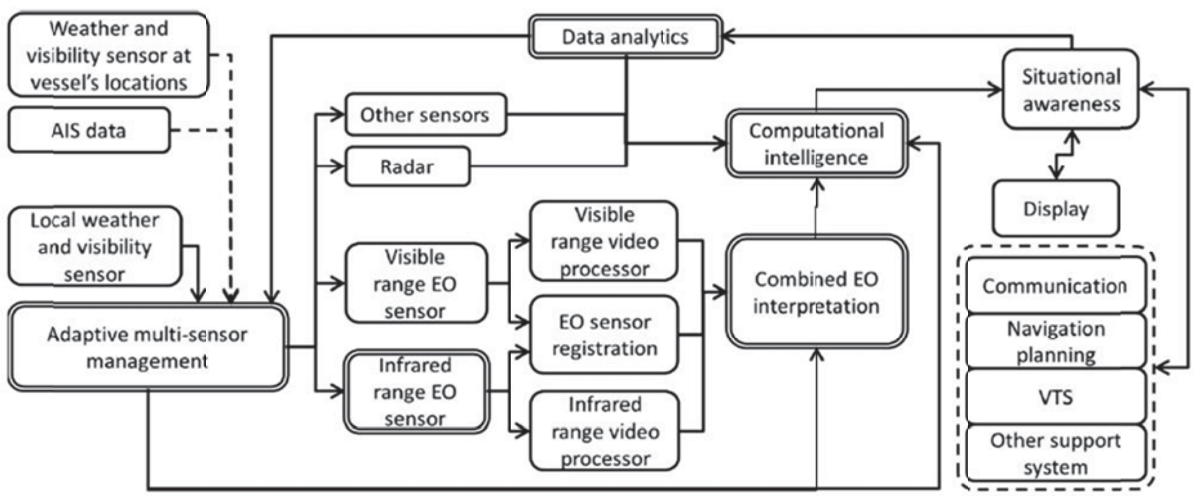

Figure 23 Envision Futuristic Adaptive Multi-sensor Management Architecture for an Autonomous Maritime Vehicle – blocks with double line boundaries are considered critical to the system.

3.8 Summary

Adaptive sensing can be applied to sensors that have the ability to modify their parameters in near real-time. Cognitive sensing is a new paradigm that uses a community of sensor and information systems as a collective, with knowledge and resources shared between entities such the collective output is of greater value that the sum of the individual outputs.

Cognition at the sensor level is defined by the perceptual hierarchy of ‘sense-learn-decide-act’. The requirement to undertake this in near-real-time requires that the perception-action cycle is undertaken using fast-time or sub-conscious cognition techniques.

Cognition techniques can be applied to an individual sensor or a cluster of sensors to learn, remember, understand and take action. Resources to undertake cognition processes can be dynamically allocated using the SRM.

Cognition applied to sensor systems can help anticipate a threat using forward prediction techniques to task sensors appropriately ahead of an event. This can include appropriate parameterization as well as the allocation of additional processing and memory resources such that performance is optimized to match an evolving task. Similarly, cognition can also be used to predict the threat environment to achieve superior clutter, interference and noise cancellation.

Cognition adds capability by expanding the ‘knowledge archive’ based on experience that can also be shared with others. The knowledge may be obtained from either endogenous or exogenous sources.

The SRM can cross cue sensors for confirmation and classification and also supports ‘operation-on-request. The sensor resource manager allocates priorities and assigns secondary targets to alternative systems in the event of sensory overload.

4 Cognitive Naval Combat Management System

NCMS are software-intensive systems that are designed to rapidly adapt to the evolving naval battle environment. The NCMS undertakes four primary actions;

- Situational Awareness: To be aware of the battle environment at sea including surface, subsurface and air. Data is collected through sensors including radars, electro–optical systems and sonar.
- Intelligence: Converts information into actionable intelligence by interpretation, collation and evaluation.
- Planning and decision-making: This facilitates the development of an actionable plan for decision-making and implementation in a rapidly changing complex battle environment.
- Weapon systems command and control: The NCMS directs weapon sensors and systems against the identified threat.
- Archiving and Documentation: This supports post operation analysis

The NCMS enables seamless data transfer to and from sensors, weapons and navigation and communication systems. NCMS provides information fusion with in-built high grade security and decision support aids and presents various tactical pictures to the command team. The NCMS has decision support features for threat evaluation, target indication and weapon designation which are fully integrated with onboard fire control and weapon systems.

The system is designed to be both self-contained and also be a node in a larger Network-Centric Warfare (NCW) system bases on 'Power-to-the Edge' doctrine that is more autonomous than hierarchical.

4.1 Power-to-the-Edge

Power-to-the-edge is information and organization management philosophy first articulated by the U.S. Department of Defense and is the guiding principle behind today's NCW. Power to the edge involves the empowerment of individuals at the edge of an organization (where the organization interacts with its operating environment to have an impact or effect on that environment) or, in the case of systems, edge devices. Empowerment involves expanding access to information and the elimination of unnecessary constraints. For example, empowerment involves providing access to available information and expertise and the elimination of procedural constraints previously needed to de-conflict elements of the force in the absence of quality information [70].

Power to the edge starts with a series of premises on how the environment is sensed, the physical domain is where events take place and are perceived by sensors and individuals. Data emerging from the physical domain is transmitted through an *information domain*. Data is subsequently received and processed by a *cognitive domain* where it is assessed and acted upon.

Power to the edge incorporates the following goals and principles:

- Achieving situational awareness rather than creating a single operational picture
- Self-synchronizing operations instead of autonomous operations
- Information "pull" rather than broadcast information "push"
- Collaborative efforts rather than individual efforts
- Communities of Interest (COIs) rather than stovepipes
- "Task, post, process, use" rather than "task, process, exploit, disseminate"
- Handling information once rather than handling multiple data calls
- Sharing data rather than maintaining private data
- Persistent, continuous information assurance rather than perimeter, one-time security
- Bandwidth on demand rather than bandwidth limitations
- IP-based transport rather than circuit-based transport
- Net-Ready Key Performance Parameter (KPP) rather than interoperability KPP
- Enterprise services rather than separate infrastructures
- COTS based, net-centric capabilities rather than customized, platform-centric IT

The philosophy of power to the edge is aimed at achieving organizational agility. Such agility has six attributes:

- **Robustness:** the ability to maintain effectiveness across a range of tasks, situations, and conditions
- **Resilience:** the ability to recover from or adjust to misfortune, damage, or a destabilizing perturbation in the environment
- **Responsiveness:** the ability to react to a change in the environment in a timely manner
- **Flexibility:** the ability to employ multiple ways to succeed and the capacity to move seamlessly between them
- **Innovation:** the ability to do new things and the ability to do old things in new ways
- **Adaptation:** the ability to change work processes and the ability to change the organization

4.2 Cooperative Engagement Capability

The Cooperative Engagement Capability (CEC) is a U.S. Navy initiative designed to bring Network Centric Operations (NCO) and Network Centric Warfare (NCW) to the battle space. The CEC is a logical extension of the previous system centric, Common Operating Environment (COE) [71]. The COE was designed and built in the early 1980's, with the goal of eliminating incompatibility between U.S. Department of Defense (DoD) systems The COE providing a structure for collaborative software development and execution. The goal being to see earlier, comprehend earlier and strike sooner.

The objective of CEC is to combine the Global Information Grid (GIG) concept with a high performance sensor grid and a high performance engagement grid. This is achieved by integrating information, sensor and weapon data from multiple sources including cooperating, air land and sea, platforms. As illustrated in Figure 24 [72], CEC fuses high quality tracking data from participating sensors and distributes them to all other participants in a filtered and combined state. This results in all participants having access to a superior universal COP. The CEC approach results in significantly earlier detection and more consistent tracking of targets. This enables targets to be engaged at an earlier point in time [73].

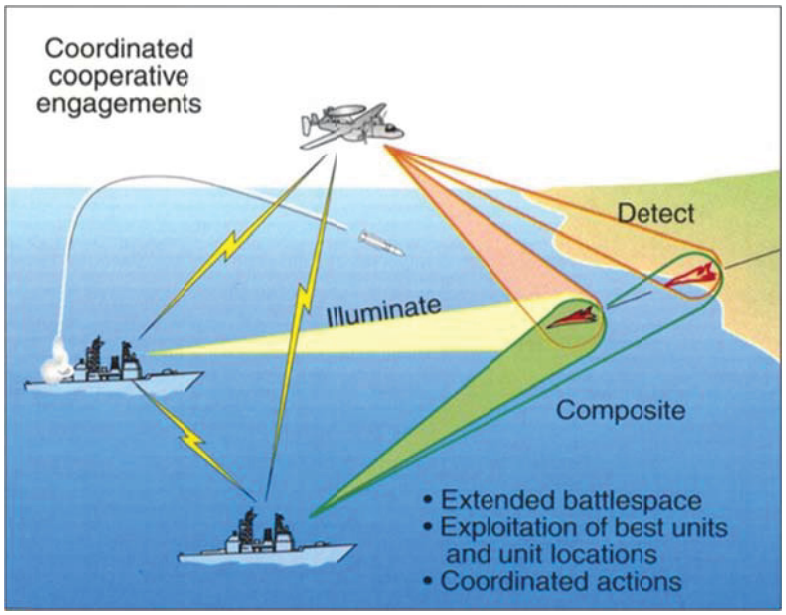

Figure 24 The principal CEC functions include composite tracking and identification, precision cueing, and coordinated cooperative engagements.

The principles of CEC can also be applied to small scale battle groups or a single vessel with autonomous and semi-autonomous vehicles.

The application of cognition within the NCMS is a critical component in the CEC that enables cooperating assets to share information and take coordinated action. The SRM can also be applied to CEC by allocating resources and tasking across platforms. This can be very advantageous in 'operation on request' scenarios.

Details relating to the U.S. Navy CEC are presented in Section 4.4.4.

4.3 Common Attributes of NCMS Software Architecture

The following sub-sections provide an overview of the common features and desirable properties of the software architecture associated with a NCMS.

4.3.1 Software Architecture

Core to the implementation of a NCMS is the Software Architecture (SA). The SA defines the fundamental structure of a software system and its evolution and maintenance. The structure comprises software elements, relations among them and properties of both elements.

For ease of development, evolution and maintenance the NCMS should be developed based on an Open Systems Architecture (OSA) framework. An OSA approach integrates business and technical practices that yield systems consisting of severable modules which can be readily upgraded or replaced, or expanded with the addition of new capabilities.

A system constructed in this manner allows vendor-independent acquisition of capabilities, including the intentional creation of interoperable, enterprise-wide, reusable components. Successful OSA acquisitions result in reduced total ownership cost and can be quickly customized, modified and extended throughout the product life cycle in response to changing user requirements [74].

Fundamental to the OSA is the concept of a Service Oriented Architecture (SOA) which is a style of software design where services are provided to the other components by application components through a communication protocol over a network. The basic principles of SOA are independent of vendors, products and technologies. Each function of an SOA is treated as a discrete unit that can be accessed remotely and acted upon and updated independently. Each function has a specified outcome, is self contained and can be considered a black-box to the user. The SOA defines the protocols that pass and parse messages using description metadata. The metadata describes both the functional characteristics of the service and quality-of-service characteristics.

The SOA allows users to combine large chunks of functionality to form applications which are built from existing services and combining them in an ad hoc manner. A service presents a simple interface to the requester who no longer requires knowledge of the details of how the function works. Users can also access these independent services without any knowledge of their internal implementation [75].

A fully distributed architecture is inherently redundant with no single point of failure. Modular design and scalability assure compatibility with a broad range of existing systems and platforms from unmanned vehicles, small patrol boats to frigates and from command centers to maritime patrol aircraft and helicopters.

4.3.2 Network Topology

Core to the establishment of a NCMS is the decision on the topology of the system. For example, should the system consist of centralized or decentralized processors which in turn determine how the nodes in the system are connected?

For the NCMS, topology will be considered in terms of the information flow. Nodes in the individual computers or programs node and in general anything that has an IP address. Links between nodes indicate that those nodes are sharing information regularly in the system.

Four common topologies, centralized, ring, hierarchical, and decentralized are illustrated in Figure 25 and are compared below [76].

- **Centralized**: In these systems all functions and information is centralized into one server with many clients connecting directly to the server to send and receive information.
- **Ring:** Consists of a cluster of machines arranged in a ring to act as a distributed server. Communication between the nodes coordinates state-sharing, producing a group of nodes that provide identical function but have failover and load-balancing capabilities. Ring systems are generally built assuming the machines are all close on the network and owned by a single organization.
- **Hierarchical:** These systems flow down authority from the primary server to second level servers and from here to third-level servers.
- **Decentralized:** in this topology all peers communicate symmetrically and have equal roles.

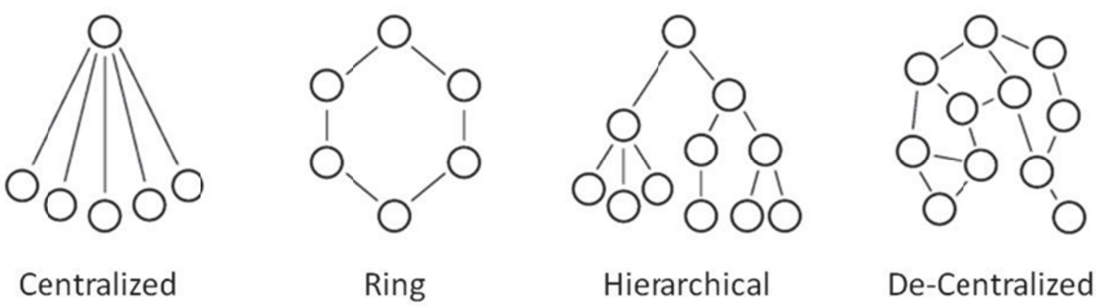

Figure 25 Network Topologies

Distributed systems often have a more complex organization than any one simple topology. Real-world systems often combine several topologies into one system, making a hybrid topology. Nodes typically play multiple roles in such a system. For example, a node might have a centralized interaction with one part of the system, while being part of a hierarchy in another part. Examples of hybrid topologies are presented in Figure 26.

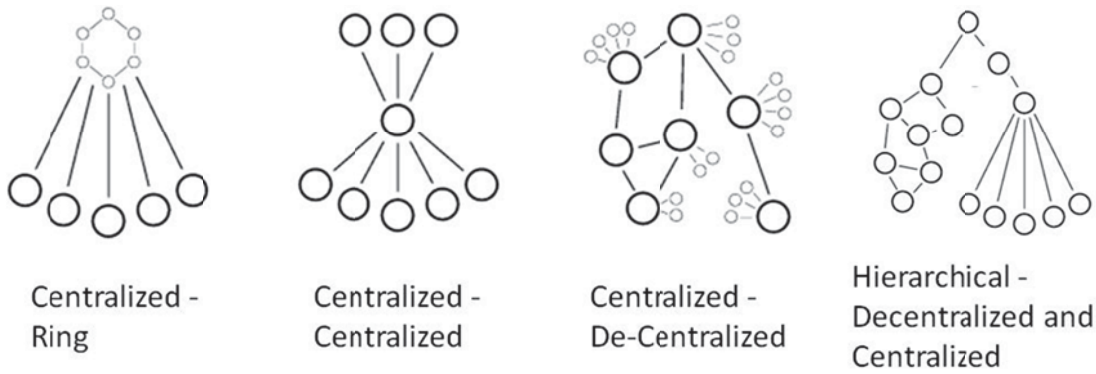

Figure 26 Hybrid Network Topologies

4.3.3 Distributed Networks

Regardless of the specific topology selected there are significant advantages in establishing a distributed network. This is a general term for a collection of autonomous computers linked by a network that appears to an end user of the system as a single computer. A distributed network approach to the NCMS allows easy integration of existing and future systems using a variety of commercial computers and operator displays.

Computers within the network are autonomous and therefore work independently. Resources, such as processing power and memory, can be readily shared within the network even though the computers within the network are at different locations. Core features of a distributed network are [77];

- **Economics**: a collection of microprocessors offer a better price/performance than mainframes.
- **Speed**: a distributed system may have a total computing power than a mainframe. Enhanced performance through load distributing.
- **Inherent distribution**: Some applications are inherently distributed.
- **Reliability**: If one machine crashes, the system as a whole can still survive. Higher availability and improved reliability.
- **Incremental growth**: Computing power can be added in small increments. Modular expandability
- **Data sharing**: allow many users to access a common database
- **Resource Sharing**: expensive peripherals can be readily shared
- **Communication**: enhance human-to-human communication, e.g., email, chat
- **Flexibility**: spread the workload over the available machines.

4.3.4 Software Development Methodology

In selecting software development methodology consideration must be given to the end goals.

Tactical processing must occur in real time at high volume and low latency. It must also address the general requirements of;

- **Maintainability:** Can software fixes and corrections be made easily?
- **Extensibility:** Does the software architecture easily support growth in functionality, processors, interfaces, and languages?
- **Understandability/visibility/comprehensibility**: Is the software system conceptually simple, or are its operations complex and obtuse?
- **Reliability:** Can the software system give predictable performance?
- **Testability:** Can the software be easily tested, and are there convenient measurement points?

The software must have a robust design to accommodate the unpredictable nature of tactical processing loads and potential equipment faults. It must function in a less than complete processing environment, not be susceptible to critical single points of failure and be loosely coupled so that functions can be readily removed or added. Also, because of the frequent revision and improvement of COTS products the software and processing elements must be easily updated, and a change to one must not generally affect the other.

The above can be archived using a software architecture based on Information Oriented Design (IOD) that works with information inside a computer program as opposed to working with just data. Information Oriented Software (IOS) relies on data structures specifically designed to hold information and relies on frameworks that support those data structures. IOS development focuses on the conceptual needs of users and customers rather than the data storage models and object models [78].

As illustrated in Figure 27, the IOD design approach decouples complex, highly interrelated functions and instead features independent functions with access to a common information source.

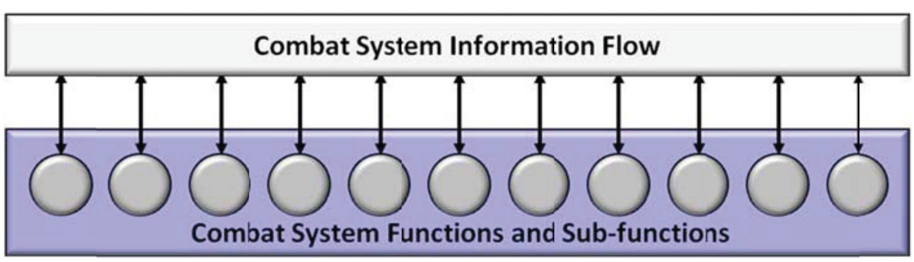

Figure 27 Information-Oriented Software Design: Independent functions with access to a common information source

With the IOD, each function is assigned unique responsibilities to produce unique system information which is then broadcast as a message throughout the system. Each function is offered access to the system information flow from which it will produce its own duties. Incorporated within the design is the ability for each function to deal with incomplete information.

Another enabling feature of an IOD design is that information needs to be only updated on notification of change. In addition, the IOD removes the logical complications of sequential function coordination and communication. If a function is not available then the only impact on the system is the loss of that particular information in the system wide database. Finally, testing and development of individual functions can be accomplished in isolation.

Functional independence enables physical independence in the form of distributed processor architectures. This enables massive computing power to be focused, at any given time, on particular critical functions. It also enables growth and change that are completely independent of other system processes.

The addition of a new system function requires only the definition of the information it will add to the system information. Existing functions need to be changed only if the additional information is desired to improve the quality of the current output. By definition, the new function has access to all system information and will be informed when any portion is updated.

New processes may be added to the system to analyze or extract system information on a completely independent basis. Information display functions may similarly be added with total independence.

4.4 Review of evolution of NCMS and associated systems

The following sections review examples of that demonstrate the evolution of NCMS and associated systems as developed by the U.S. Navy. The section starts with the U.S. Navy AGIS system that was the first implementation of the NCMS whose development was initiated at the dawn of the digital age. The section is followed by a summary overview of a sequence of major technology development that concludes with the implementation of the U.S. Navy Ship Self Defence System that heralded the start of the information age. The section is followed by a brief review of current state-of-the-art NCMS as offered by the international defence industry. Following this section the concept of Holistic Cognitive Enabled (CE)-NCMS is introduced that incorporated engineering developments associated with the birth of the age of machine learning and artificial intelligence. This is commonly referred to as the knowledge age.

4.4.1 NCMS in the Digital Age: The AEGIS Combat Management System.

The first NCMS to be developed and operational deployed was the U.S. Navy's AEGIS Combat System (ACS). The ACS, illustrated in Figure 28, [79] was developed in response to the evolving anti-ship missile threat. U.S. Navy recognizing that their reaction time, firepower, and operational availability did not match this new threat.

Engineering development of the AEGIS system started in 1964 at the dawn of the digital age. The system was developed based on a centralized network topology and simple logical, sequential, command and control structure based on hard computing principals. The AEGIS was designed to support multi-mission threats, specifically; anti-air, anti-surface and anti-submarine warfare

The first AEGIS ship, the USS Ticonderoga, was commissioned in 1983 and was deployed six months later. The AEGIS was designed provide the mission planning capabilities for both domestic and North Atlantic Treaty Organization (NATO) supported operations.

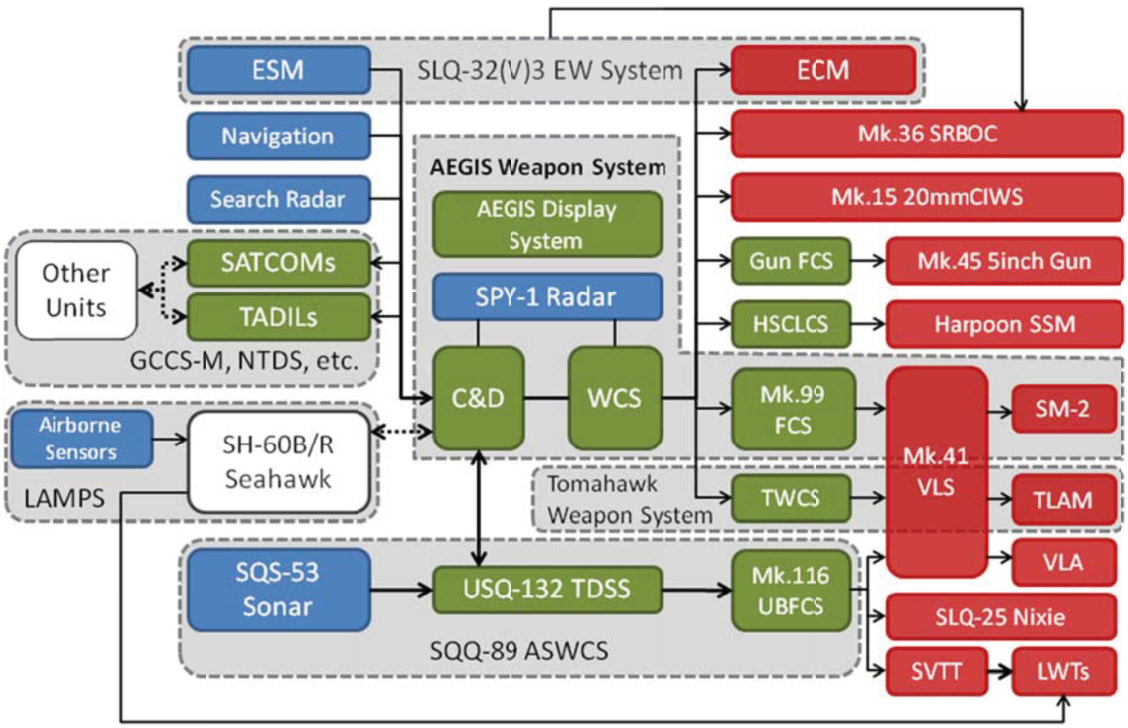

Figure 28 Aegis Combat System

The ACS provides area defense for a battle group as well as a clear air picture for more effective deployment of air assets. The ACS enables fighter aircraft to concentrate more on the outer air battle while cruisers and destroyers assume a greater responsibility for battle group area defense. The missile launching system, the computer programs, the radar and the displays are fully integrated to work together.

The ACS combines a centralized, automated, C2 system with a WCS to provide a unified weapon system, from detection to kill. At the core of the ACS is the computer-based, Command-and-Decision-Support (C&DS) system that provides operators with actionable intelligence. The C&DS integrates the sensors with response systems such that the ACS can simultaneous address a multitude of threats.

The ACS can be deployed on both destroyers and cruiser class vessels. The C2 system on the Destroyers has two operator seats while cruisers have four. An example of the operator control centre for the ACS deployed on the cruiser USS Vincennes, typical of early Aegis platforms 1988, is presented in Figure 29 [80].

The ACS comprises of a suite of products that supports maritime, air, land and joint planning activities. This includes a complete range of planning and execution functions that support operations at strategic and operational echelons. Core to the system designed is its ability to seamlessly integrate Commercial Off-The-Shelf (COTS) software packages and to economically expand its core functionality.

Figure 29 Operator Control Centre for Aegis System USS Vincennes, typical of early Aegis platforms 1988

The AEGIS Weapon System Mk 7 incorporates a Cooperative Engagement Capability (CEC) and an open architecture combat system using commercially developed processors and display equipment. The Mk7 system is made up of the following elements [81]:

- AN/SPY-1 Radar
- Command and Decision (C&D) System
- Weapons Control System (WCS)
- Fire Control System (FCS)
- Guided Missile Launching System (GMLS) Mk 26 or Vertical Launching System (VLS) Mk 41
- Standard Guided Missile (SGM)

- AEGIS Display System (ADS)
- Operational Readiness Test System (ORTS)
- AEGIS Combat Training System (ACTS)

Of the nine elements, seven have sophisticated computer programs for operation, control, and interface. These are the AN/SPY-1, C&D, WCS, FCS, ADS, ORTS, and ACTS. Operators manage and control the C&D, WCS, and SPY programs with doctrine statements that define automatic actions for targets meeting specific conditions. These statements allow the operator to define parameters that control the computer program for the tactical situation [82].

- **AN/SPY-1 Radar System:** This is the primary search and track radar for AEGIS-equipped vessels. It is a multifunction, phased array radar, capable of three-dimensional surveillance, while simultaneously providing fire control tracking for hundreds of air and surface targets in clear and ECM environments. In addition to search-and-track, it provides midcourse guidance to the SGM.
- **Command and Decision (C&D) System:** This is a manned computer and display system that coordinates and controls the AEGIS mission**.**
- **Weapons Control System (WCS):** This system schedules, controls, and assesses all air, surface, and subsurface engagements. It is the interface between the C&D and the FCS of the delivery system.
- **Fire Control System (FCS):** The FCS provides illumination control for SGM engagements. The FCS consists of four I/J-Band fire control radar sets. These four sets permit the simultaneously illumination of multiple targets.
- **AEGIS Display System (ADS):** This is a computer-controlled display system that provides information and visuals of the tactical environment. The commanders can observe and control a graphic representation of selected tracks, coastal maps, weapons release zones, and specific warfare environments.
- **Operational Readiness Test System (ORTS)**: This is a computer-controlled test-and-monitor system that performs automatic fault detection, fault isolation, status monitoring and system reconfiguration. When a fault occurs, the ORTS will automatically evaluate the situation and displays the highest level of system impact.
- **AEGIS Combat Training System (ACTS):** ACTS enables shipboard personnel to conduct highly integrated, multifaceted, warfare training scenarios. It also provides the capability to record and print out specific training events for self-evaluation.

4.4.1.1 Early AEGIS deployment and Lessons Learnt

One of the first deployments of the AEGIS equipped vessels under battle conditions was in the spring of 1987 when the U.S. government committed naval forces to the convoying of U.S. flag tankers operating in the Persian Gulf.

On the 3rd of July 1988 the USS Vincennes shot down Iran Air Flight 655 resulting in 290 civilian deaths. A formal military investigation subsequently determined that the Aegis system on board was completely operational and had the Commanding Officer (CO) used the information generated by the Aegis C&D system as the sole source of his tactical information, the CO might not have engaged [83].

Additionally, the investigation noted that psychological effects resulted in the operators subconsciously manipulating the data to accord with a predefined scenario greatly contributed to the false identification of the civil aircraft as a threat. The investigation found that the ACS did not contribute to the incident, but did aid in the investigation by means of recorded target data. The Navy's self-investigation attributed the discrepancy between the known facts and Commanders' actions to 'scenario fulfillment', where the Commander made "an unconscious attempt to make available evidence fit a preconceived scenario" [84].

Recommendation from the post incident report included research is undertaken into the impact of human stress on command operations and in particular to incorporate measures of human effectiveness into battle simulation techniques to assess the effect of peak overloads and stress on human players. In can be noted that a contributing factor to stress of personnel onboard the USS Vincennes were memories of the USS Stark incident that occurred just months earlier. In this case an Iraqi jet aircraft fired missiles at the American frigate killing 37 navy personnel and injuring 21. In this case the Commander was held at fault for not firing at the attacking aircraft and was subsequently relieved of command.

Another pertinent recommendation from the USS Vincennes incident report was that the ACS be modified to provide better assistance in aiding rapid decision making. It also recommended separating critical information from other non-critical information and that the critical information is displayed on a single display such that the commanding officer and his main assistants did not have to shift attention back and forth between displays.

4.4.2 Distributed Common Ground System- Navy (DCGS-N)

The Distributed Common Ground System-Navy (DCGS-N) program is the U.S. Navy's primary intelligence, surveillance, reconnaissance and targeting (ISR&T) support capability. The DCGS-N was developed for both shore based command centres and deployment at sea. The DCGS-N tools are noted as being critical for the operational commander's battle space awareness and net centric operations [85].

In today's modern battle space, intelligence is the driver of operations. The need for sharing accurate intelligence data is critical to national security. U.S. military forces deployed throughout the world and operating in joint environments require access to time-sensitive, intelligence, ISR data.

DCGS-N addresses the need to facilitate battle space visualization, and thus provide enhanced situational awareness. This is the key to maximizing combat effectiveness in the future. At the heart of DCGS is the DCGS Integration Backbone (DIB), which provide users access to worldwide, real-time actionable intelligence and information [86].

Enabling design features of DCGS are:

- Platform independent, open standards based architecture enabling the easy integration and use of commercial applications
- Information system interoperability
- Networked system providing a global command and control enterprise
- Robust security and attributable safeguards
- Software applications providing real-time control of ISR assets
- Software Development Kit enabling quick integration of 3rd party applications and services

4.4.3 US Navy Tactical Cloud

The U.S. Navy Tactical Cloud (NTC) program was designed to bring big data capabilities to the military environment. NTC is a set of services focused on providing an end-to-end ecosystem for ingesting, storing, processing and accessing data from multiple (possibly disparate) sources in a package suitable for deployment to the tactical edge. NTC is intended to provide the means to take the tools that were previously available only to shore-based operators and make them available to the forward-deployed warfighter. The NTC is designed to support data collection, analysis, and presentation capabilities, even in the absence of robust connectivity to resources ashore [87].

The Tactical Cloud Reference Implementation (TCRI) is a software platform designed to provide a common framework to manage operational data while also performing analysis on this data using automated algorithms and analytics. The objective is to interface with a large number of defense ISR sensor systems to deliver a unified operational picture that enables data-based decision making in both connected and disconnected environments. By design, the TCRI largely functions automatically, with little user input, and only provides information the user designates as relevant [88].

The U.S. Navy has reported using data from the NTC to allow aircraft and ships to access a range of targeting information to launch weapons against surface targets. The NTC ingests and processes data from a wide variety of sources including targeting information obtained from satellites, aircraft, ships, submarines and the weapons themselves [89].

4.4.4 The U.S. Navy's Cooperative Engagement Capability

The U.S. Navy's CEC is a sensor network with integrated fire control capability that is intended to significantly improve battle force air and missile defense capabilities by combining data from multiple battle force air search sensors on CEC-equipped units into a single, real-time, composite track picture. This is an enabling capability for implementing NCW.

CEC is a real-time sensor netting system that enables high quality situational awareness and integrated fire control capability. It is designed to enhance the Anti-Air Warfare (AAW) capability of U.S. Navy ships, U.S. Navy aircraft and U.S. Marine Corps (USMC) Composite Tracking Network (CTN) units by the netting of geographically dispersed sensors to provide a single integrated air picture, thus enabling Integrated fire control to destroy increasingly capable threats such as cruise missiles and aircraft [90].

CEC's two major system functions consist of a Cooperative Engagement Processor (CEP) for sensor networking and a Data Distribution System (DDS) for real-time communications amongst cooperating units (CU). Sensor data from individual units are transmitted to other units in the network via the real-time, high quality, anti-jam capable, line-of-sight DDS. Each CEC equipped unit uses identical processing algorithms that result in each unit having the same display of air tracks. CEC gives an individual ship the added capability to engage anti-air weapons at threats within its engagement envelope based on remote sensor data provided by the CEC sensor network. The CEC system makes it possible for multiple surface ships, aircraft and USMC land units to form an air defense network by sharing radar target measurements in real-time.

CEC is a key element in the future U.S. Navy's Integrated Fire Control – Counter Air capability (NIFC-CA) [91]. The NIFC-CA architecture utilizes airborne platforms that enable the Navy to see beyond-the-horizon and share information quickly and accurately. This use of netted assets to see beyond the horizon and guide a weapon to the target means that simpler, lower cost weapons can be utilized [92].

This networked employment of systems capitalizes on technology to create long range over-the-horizon cooperative engagement. For example, an airborne E-2D Hawkeye linking multiple ship’s together in spotter/shooter roles, or an F-35 providing targeting data to an Aegis destroyers SM-6 missile [93].

4.4.5 NCMS in the Information Age: Ship Self Defence System

The U.S. Navy Ship Self-Defense System (SSDS) represents the latest development in NCMS. A successful at-sea demonstration of the SSDS was conducted with in June 1993. The production contract was awarded to Raytheon in Nov, 2012 [94].

SSDS employs a local area network that uses open computer architecture and standard Navy displays to integrate a surface ship’s sensors and weapons systems to provide an automated detect-track-engage sequence for ship self defense [95]. It is an open, distributed combat management system for surface ships designed to expedite the detect-to-engage sequence to defend against Anti-Ship Cruise Missiles (ASCM), SSDS links and automates standalone sensors and weapon systems to provide the required combat reaction. It utilizes sequential hard and soft computing to aid it decision support process. A fiber optic Local Area Network (LAN) connects ship sensors and weapon systems which [96]:

- Coordinates sensor integration
- Identifies and evaluates potential threats
- Assesses readiness of ship defenses
- Executes specific tactical procedures

While SSDS incorporates a high degree of automation through computerized embedded doctrine, the system also allows the commanding officer to maintain positive control over selected doctrine and weapons release.

SSDS consists of a distributed network of software and COTS hardware that integrates radar systems with anti-air weapons including both hard-kill (missile systems and rapid fire gun systems) and soft-kill (decoys). SSDS includes embedded doctrine to provide an integrated detect-through-engage capability. Although SSDS does not improve capability of individual sensors, it enhances target tracking by integrating the inputs from the several sensors to form a composite track. For example, SSDS correlates target detections from individual radars, the ESM system and the IFF system, combining these to build composite tracks on targets while identifying and prioritizing threats. Similarly, SSDS does not improve capability of individual weapons, but expedites the assignment of weapons for threat engagement and provides a recommend engage display for operators. When in automatic mode the SSDS initiates weapons firing, ECM transmission, chaff or, decoy deployment, or some combination of these [97].

4.4.5.1 SSDS Architecture

The SSDS was designed to provide self-protection and combat system capability to non Aegis ships in the U.S. Navy. The system is the navy's first, distributed-processing, combat system that integrates already developed weapon and sensor systems using a networked set of commercial computers and operator displays. Specifically, the SSDS is an open architecture, distributed-processing system build within a COTS environment [98].

One of the key features of the SSDS has been the introduction of a systems-of-systems approach to the design and the physical decoupling of the complex interactions between the multitudes of sub-systems. This has been achieved using a distributed architecture that is based on information flow rather than data and incorporates IOD and IOS structures.

As illustrated in Figure 30, the SSDS physical architecture consists of a LAN that connects to the various functional elements via LAN Access Units (LAUs). These units provide the interface to the functional elements and may undertake some tactical processing. LAUs may be placed anywhere on the ship.

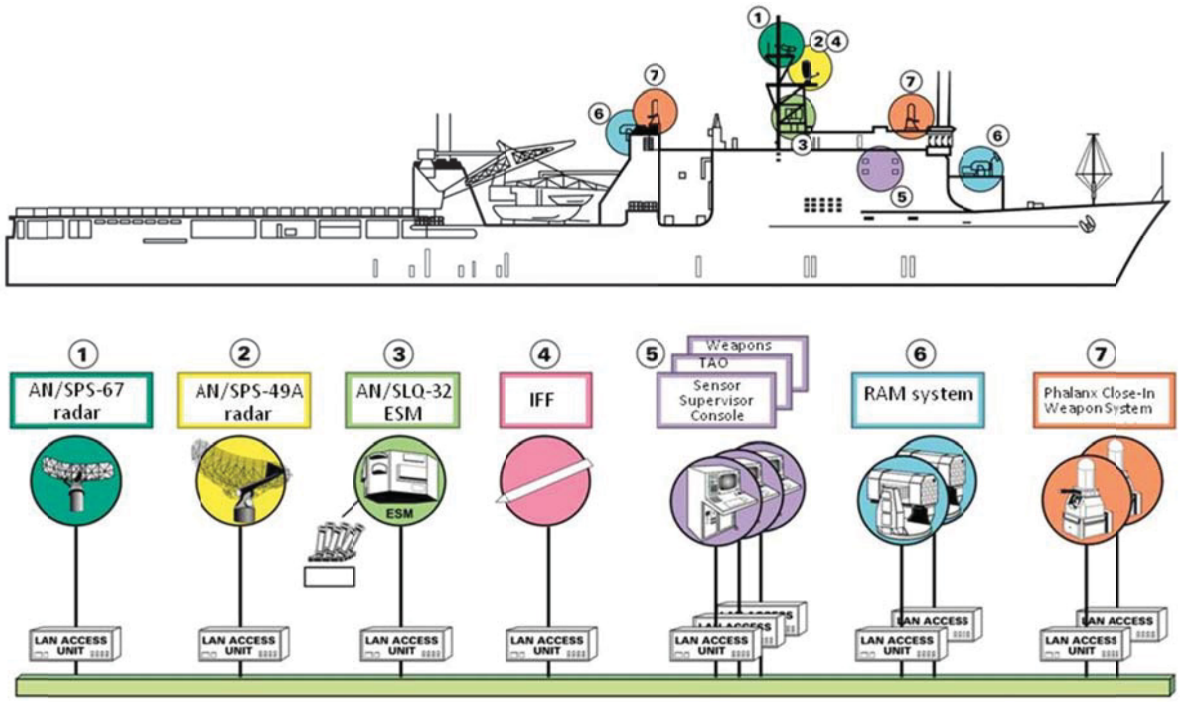

Figure 30 The LSD 41/49 combat system consists of sensor systems, SSDS components, and weapon systems, all connected to the fiber-optic LAN via similar LAUs.

4.5 Summary of Operational NCMS

The following sections provide a summary of international vendors NCMS systems. The primary source of data was copied from SP Guide to Naval Forces [99]. Unfortunately details on the architecture and other technical information are generally not in the public domain. Ancillary information has been added from the referenced web sites. Annex A contains various brochures associated with the discussed systems.

4.5.1 Lockheed Martin Canada CMS 330 NCMS

The Canadian developed Combat Management System 330 (CMS 330) was developed by Lockheed Martin Canada. It is the newest system used by the RCN on its fleet of modernized HALIFAX Class ships and will be implemented on the new Arctic and Offshore Patrol Ships currently under construction. The system was also recently exported to New Zealand and Chile [100].

CMS 330 is designed for smaller navies and platforms with sophisticated weapon and sensor systems that must deliver maximum performance and be capable of operating in a multi-national coalition task group or standalone environment. The system is a derivative of a Lockheed Martin Canada legacy product that was originally developed in Canada in the 1980's for the original build of the RCN HALIFAX Class ships

4.5.2 Thales Netherlands: Tacticos

Tacticos is a single NCMS for combat and maritime security operations. With its certified openness and scalability of the underlying architecture, Thales delivers a modular Combat Management System, matched to multiple mission profiles and to a variety of vessel types. Open standards technology and a massive amount of subsystems interface implementations make Tacticos the core of the mission solution [101]. The latest version enables the navies to:

- Set up networks in coalitions with secure Internet access with ease.
- Rapidly recognise traffic trends and anomalous behaviour.
- Identifies relations between contacts of interest emitting Automatic Identification System (AIS) and Automatic Dependant Surveillance-Broadcast (ADS-B).
- Compact and light-weight consoles which can be fitted in large and small naval vessels.
- 3D net-centric training integrated in Tacticos.

The system operates through the Combat Information Center (CIC) or OpsRoom. Tacticos technology is used on board more than 160 ships (from small patrol craft to full-size frigates and destroyers) operated by 20 navies. Which include the U.S. Navy as well as navies in Asia, Europe, and the Gulf region, Latin America, the Middle East and North Africa.

Tacticos is offered in two configurations:

- Compact Sensor & Control System (CSCS). The Compact Sensor & Control System caters for the small ship market providing command and control and even AIS if required. It can be integrated with fire control systems in order to achieve full combat system capabilities. It is based on open-standards and architecture and uses COTS technology.
- Commander C3. This is Marine Command, Control, and Communications System for non-Combatant applications. It provides seamless near real-time sharing of the Common Operating Picture (contact data, messages, and geo-referenced map overlays) between vessels, helicopters, and shore installations. Commander C3 also provides gateway interfaces to achieve interoperability with major naval data link standards. The system is ideal for both civilian and military users who require an effective, affordable solution to address the technical and interoperability challenges associated with cooperation and coordination of various maritime agencies.

A system block diagram of the Tacticos NCMS is presented in Figure 31. The image was down loaded from [102]

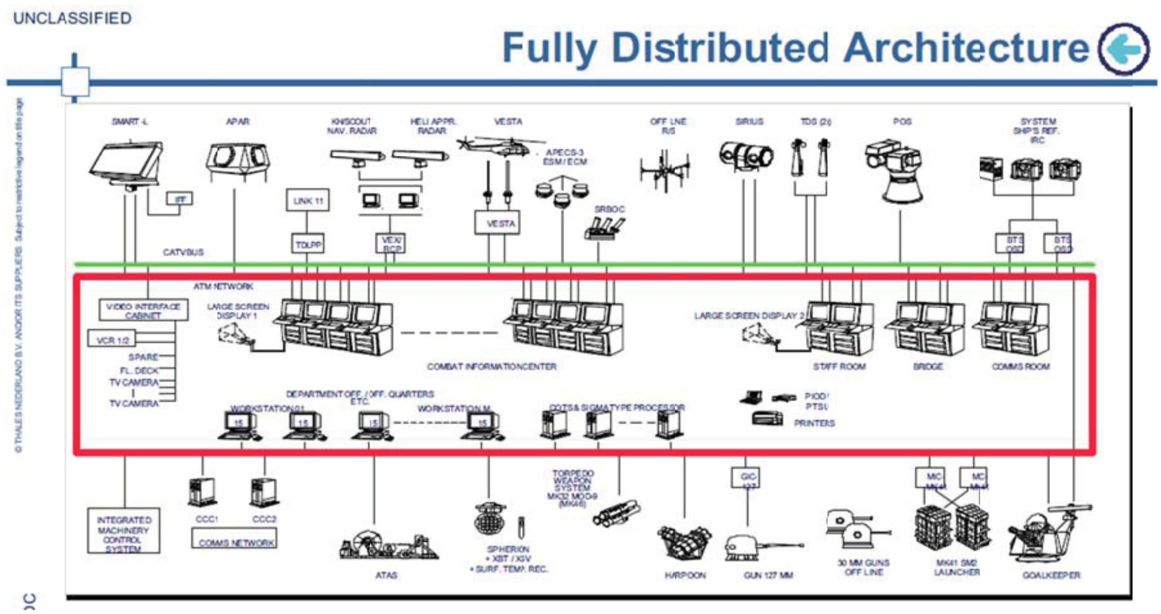

Figure 31 System Block Diagram of the Tacticos NCMS

4.5.3 SAAB 9LV NCMS

A Saab 9LV NCMS system comes with all the operational capability and functionality required by the ship's Command which is well suited for all types of platforms ranging from small patrol vessels up to large frigates [103]. Saab claims to be able to integrate any sub-system selected by the customer.

Due to effective situational awareness and rapid precision tactical response in all warfare domains, 9LV provides the ship and the command team with efficient operational capabilities in support of all mission types, both in the open ocean as well as in littoral regions. It can also meet asymmetric threats, as well as modern and estimated future threat types. It provides a range of options for integration of the user interfaces of equipment/sub-systems, for example, through hosted vendor clients, web services, thin clients or fully-integrated human machine interfaces. It also provides touch-input display with soft keys. It can easily be integrated with other sub-systems like weapon systems. A Saab 9LV CMS system comes with all the operational capability and functionality required by the ship's command. There are more than 200 systems installed worldwide.

A brochure for the SAAB 9LV NCMS is included in Annex A

4.5.4 Lockheed Martin COMBATSS-21

The ship's battle management system, called COMBATSS-21, is produced by Lockheed Martin and derived from the U.S. Navy's latest Aegis surface combatants [104]. The COMBATSS-21

Combat Management System is the backbone of the Freedom-variant self-defence suite and integrates the radar, electro-optical infrared cameras, gun fire control system, countermeasures and short-range anti-air missiles. COMBATSS-21 provides a flexible, reliable next-generation defence system for the LCS. Its mission capabilities include intelligence, surveillance and reconnaissance; mine warfare; surface warfare; special operations; anti-submarine warfare; maritime interdiction/interception operations; homeland defence and anti-terrorism/force protection.

The system provides a scalable, services-based framework. Custom software 'adapters' called boundary components are the key to the flexibility of the architecture to support a wide range of sensors, communication, and weapon interfaces. Boundary components simplify integration of system elements and provide flexibility to accommodate future change. The componentised and layered architecture enables upgrades and changes to any part of the system with minimal impact to the remaining software. Customer defined sensors, communication and weapons are easily integrated and isolated from core components of the command and control system. New components can easily be incorporated to address the unique needs of the customer. Because of its modern architecture, COMBATSS-21 can be hosted on configurations ranging from a single commercial processor running a commercial operating system to more distributed configurations. This makes it readily adaptable to a wide variety of shipboard applications from patrol craft to large deck ships. Its proven software meets requirements for a low-risk, affordable solution that can be easily upgraded to meet evolving threats and environments throughout the ship's life-cycle.

A brochure for Lockheed Martin COMBATSS-21 NCMS is included in Annex A of this document.

4.5.5 DCNS POLARIS® NCMS

POLARIS® is a sea-proven compact solution designed to fulfil the need of navies and coast guards. The system features surveillance and protection capabilities for littoral or exclusive economical zones operations. POLARIS® is particularly well adapted to offshore patrol vessel, fast attack craft, fast patrol boat and landing platform dock/landing helicopter dock. Other features are [105]:

- It can handle an extensive correlation of intelligence data, efficient identification procedures, and enhanced coordination to support sea policing and fighting asymmetric threats,
- It is a robust and versatile CMS which can easily be adapted for upgrade programmes on all kinds of ships. POLARIS® operates surface-to-surface missile systems as well as defence missile systems. Combined with MATRICS, POLARIS® automatically identifies and points out abnormal behaviour patterns.
- It has extended connectivity and interoperability with multiple nodes.
- It can be linked to:
    - Helicopters, Special Forces and unmanned systems.

- Sensors for search and also for enemy carrying out electronic warfare.
- Weapon systems.

4.5.6 Elbit ENTCS 2000 NCMS

Elbit ENTCS 2000 NCMS is designed to assure 'knowledge superiority' over potential enemies, shorten decision-making cycles and execute rapid and accurate weapon engagement in the task force. Simultaneously it ensures optimum response to changing events. Based on open, fully distributed architecture and COTS building blocks, the system has enhanced redundancy and no single point of failure. Modular design and scalability assure compatibility with a broad range of existing systems and platforms, from small patrol boats to frigates and from command centres to maritime patrol aircraft and helicopters [106].

A brochure for Elbit ENTCS NCMS is included in Annex A of this document.

4.5.7 BAE Systems CMS-1 NCMS

BAE Systems is the sole supplier and integrator of NCMS for the UK Royal Navy's surface and sub-surface fleet. Their experience in command and information systems includes interfaces to a wide range of combat system equipment and leading European and U.S. weapon systems. The CMS family supports planning, tactical picture compilation, decision-making and weapon control to meet multiple emergent threats in blue water and littoral operations. CMS-1 is the heart of the combat system, providing situational awareness and weapon control from its intuitive consoles [107].

CMS-1 was developed for the UK Royal Navy's Type 45 Destroyers and will support it in service with the Royal Navy for at least the next three decades. A plan of through-life technology refresh and capability upgrades will ensure that CMS-1 continues to meet operational requirements in the future. CMS-1 supports NATO and other coalition operations, and there is a constant effort to evolve programmes to enhance the network enabled capabilities of its sensors and command systems on a number of additional naval ships.

4.5.8 L&T Shipbuilding (India) ITacS - CMS

L&T ITacS - CMS (Integrated Tactical System) is a NCMS that brings together L&T's experience of designing, integrating and deploying various Naval weapon systems, Radar systems and C4I solutions [108].

The ITacS - CMS provides an integrated solution to facilitate net-centric warfare and seamless integration between operator, real world tactical scenario and available resources. With this, ITacS - CMS achieves successful planning and execution of different types of tactical and surveillance missions.

The ITacS - CMS provides an assimilated situation awareness display and acts as a decision support system for different command-levels. The situation awareness display enables to analyse current threats and field situation to formulate appropriate strategies in order to reduce the response time and to improve the effectiveness of co-ordination. It provides information to ensure seamless sharing of Mission parameters and Intelligence data.

The ITacS - CMS solution is modular and contains multiple components. The components interact through defined interfaces with various sensors, weapons and other classes of the command structure. All the components may be configured to work within a very small deployment or may be configured to work as a distributed system by exploiting the open architecture communication middleware.

The system includes

- Surface and sub-surface application
- Surveillance, multi-sensor data fusion, situation assessment, threat evaluation and weapon assignment/control capability
- Mission planning and intelligent data management features
- Open system architecture
- Excellent real-time performance over dual redundant communication backbone with publish/subscribe paradigm of data network for seamless integration of sensors and house holding data.

4.5.9 Selex ES ATHENA

ATHENA (Architecture & Technologies Handling Electronic Naval Applications) is the Selex ES solution for advanced Combat Management Systems (CMS) from patrol vessels up to aircraft carriers, as well as for refurbishment or refitting programs. ATHENA performs Threat Evaluation and Weapon Assignment (TEWA) in accordance with operational doctrine as well as Force TEWA (FTEWA) at force level to coordinate hard-kill resources [109]. Details of the system can be obtained from the brochure included in Annex A.

Selex ES has developed a family of NCMS solutions named ATHENA with variants to suit various roles. Details are:

- ATHENA is state-of-the-art CMS solution, to perform any type of combat mission applied across any class of surface vessels. It is designed to easily integrate every type of sensor, weapon or support system. It provides the command team with the strategic and tactical situation awareness, and effectively manages all deployed force assets and own ship's resources to accomplish naval objectives and missions.
- ATHENA-P is the NCMS developed to provide C2 capabilities on vessels without missiles guidance (i.e. mine hunters, and fast patrol boats, and patrol vessels for paramilitary organisations).
- ATHENA-C is the NCMS developed to address the requirements for all classes of combat vessels (fast attack craft, corvettes, frigates, destroyers and aircraft carriers).

A brochure for Selex ES ATHENA NCMS included in Annex A of this document.

4.6 Summary of current state-of-the-art of NCMS

The previous sections have provided a top level overview of a number of related U.S. Navy programs associated as well a broad selection of international NCMS. These systems represent the state-of-the-art and will be used as building blocks for developing a holistic NCMS design that fits the requirements of the RCN.

RCN assets typically operate as single units or in small coalition battle groups. Cooperative engagement can consists of host vessel with a number of autonomous/semi autonomous vehicles providing composite tracking and identification, precision cueing, and coordinated cooperative engagements. RCN vessels must also be capable of undertaking multi-missions that include both combat and non combat roles.

Traditional NCMS, as introduced by the U.S. Navy have focused on specific high-value missions such as missile defence. Today's technology permits a more holistic approach that can include concepts such as the internet-of-things or as in the case of a navy vessel the internet-of-the-vessel where all sensors and systems on the vessel such as fire alarms can be included in the NCMS. Also given the multifunction role of RCN vessels it is important that the NCMS incorporated capability to gather and prepare evidentiary reports that can be used in civilian courts of law.

NCMS should be based on open, fully distributed architecture based on COTS building blocks that employs IOD and IOS structures. The system must include redundancy with no single point of failure. Modular design and scalability assure compatibility with a broad range of existing systems and platforms, from unmanned vehicles, small patrol boats to frigates and from command centers to Maritime Patrol Aircraft and helicopters. The modular design also permits capability to be readily added or modified as required.

4.7 Futuristic NCMS of the Knowledge Age: A Holistic Cognitive Enabled NCMS

The knowledge age brings bid-data and cognitive computing cognitive sensing to the NCMS.

The goal of a Holistic Cognitive Enabled NCMS (CE-NCMS) is to support the commander by undertaking those tasks that can be better undertaken using AI such that the commander can focus on those decisions requiring human intervention. The Holistic CE-NCMS mines large amounts of information to extract relevant actionable intelligence to aid the commander in developing an actionable strategy and making appropriate and timely decisions.

The Holistic CE-NCMS would support all missions without compromise and incorporates all ship board sensors and systems as a collective of systems. A goal of the system is to tailor the system output to the individual operator needs and skill level.

The addition of cognition has the potential to anticipate threats and provide additional time to cue sensors and response assets. Within the command centre, the executive hierarchy uses slow-time or conscious cognition to analyze the data and make informed decisions. For example, dispatching responders, requesting additional support, or advising commanders of a new and evolving mission. The analyzed data is then flowed down to the sensor systems so the sensors can be optimized based on the dynamic and evolving needs.

Computation Intelligence should be included at all levels within the system to help accelerate cognitive tasks. This includes fast-time or subconscious cognition for optimizing and adapting sensors to the prevailing threat and environment and slow-time of conscious cognition within the C2 system for cognitive functions such as data assessment, planning and decision support. The objective is to provide the commander and his team with timely, knowledge superiority to defeat an adversary by disrupting the kill chain and by completing own.

As discussed in Section 2.5.3, the NCMS requires a starting definition of the mission with expected outcomes and a default set of initial parameters that can be flowed down to the sensors and subsystems. This enables rapid convergence to an optimal solution. Therefore it is recommended that the NCMS include a set of basic predefined missions. These predefined mission objectives and parameters should be readily definable and new missions added to the library based gained knowledge.

Access to big-data can be a key discriminating factor in gaining knowledge superiority over an adversary. However bandwidth remains a critical limiting factor in how remote vessels such as deployed navy vessels can access this data. Therefore it is recommended that vessels maintain an archived data set that covers the mission area. The big-data set is maintained at land-based Naval Operations Centres (NOC). The NOC accesses and processes the bid-data updates and provides prioritized data to support requests from the deployed vessels NCMS. Transmitted data will generally be limited to updating changes in the archived data set and thereby minimize bandwidth utilization. This will be a continuous process.

It is predicted that in the future deployed naval vessels will act as a mother ship to a host of autonomous and semi-autonomous systems. Therefore the architecture should be readily expandable to support remote control and data retrieval from these systems.

4.8 Key Features of Holistic NCMS

The NCMS is a complex system-of-systems that consists of a collection of task-oriented and dedicated systems that pool their resources and capabilities together to provide more functionality and performance than simply the sum of the constituent systems.

A representative pictorial representation of the information flow of a Holistic-NCMS is presented in Figure 32. It can be observed that the NCMS can be pre-initiated to a particular mission profile using the Mission Select option. The C2 system interfaces to the sensor suite via the SRM and to the response suite via the Response Control System. This decouples the sensors and response systems such as weaponry from the C2 system. Credibility of external big-data is ensured by accessing the RCN tactical cloud. To minimize bandwidth utilization, updates to the vessel C2 system are provide on a prioritized basis and focused on information changes and not raw data. Information flow is summarized by the following six functions.

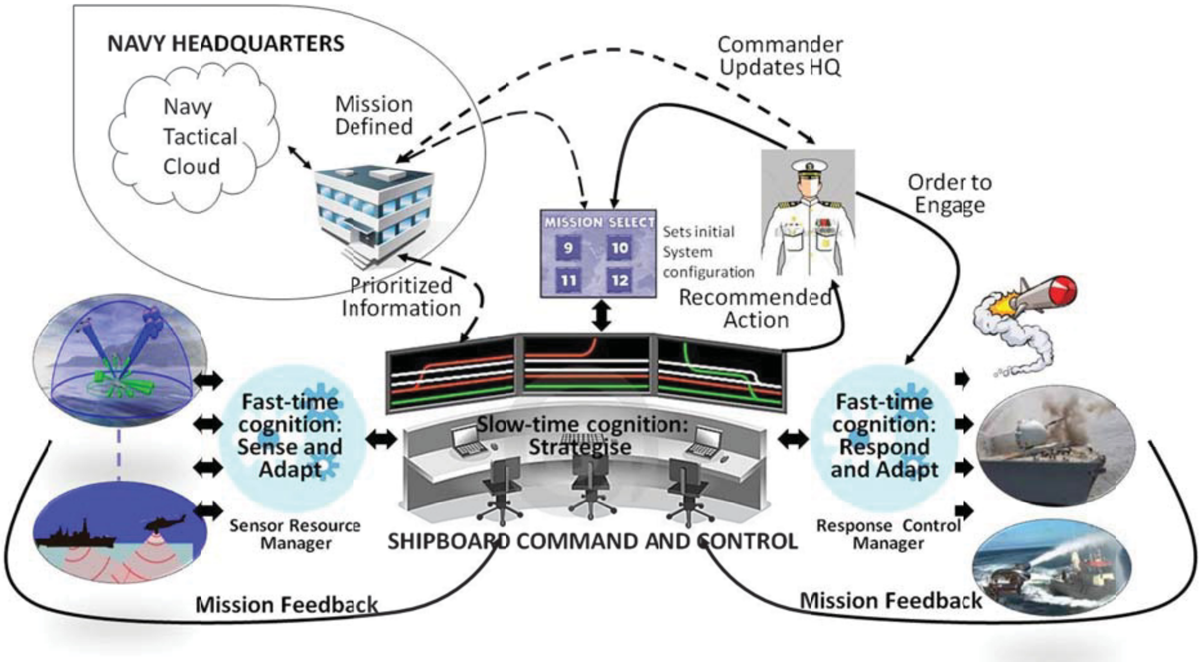

Figure 32 NCMS Information flow.

Function 1 – Mission Definition: Initially the mission is defined at navy headquarters. This information is communicated to the ships commander and to the shipboard NCMS. Once defined the mission select provides the starting parameters for the NCMS. This includes defining the mission outcomes and deliverables, scope of the effort, objectives and identifies the data sets that are going to be used.

Function 2 - Situational Awareness: Understand the operating environment in the area of interest. This includes the host platform, sea surface, subsurface and air. Requirements are flowed down to the sensors via the sensor resource manager that assigns resources appropriately. This is a continuous process that takes place though out the evolving mission. Outputs from the sensors are forwarded to the C2 via the SRM.

Function 3 - Intelligence: Converts the above information using various algorithms into actionable intelligence. This is achieved by interpretation, collation, evaluation and prediction thereby producing a COP of the area of interest as well as the host vessel. Additional information can be acquired through tasking of sensors, simulation and modeling or from the RCN tactical cloud.

Function 4 - **Planning and Decision-making:** These tools help commanders to rapidly develop an actionable strategies in a dynamically changing, complex, environment. Planning and decision making also refines the mission parameters.

Function 5 - Simulation and Modelling: Real-time simulation and modelling of the evolving mission scenario. Modeling of adversaries' kill-chain is used to discover weaknesses and vulnerabilities. Modelling of own kill-chain is used to discover vulnerabilities and recommended remedial actions. Integration of commercial maritime simulation software for training and prediction.

Function 6 - Operational Readiness: Provides real-time testing and monitoring of the health of the overall system. Output feeds available to other functions such that in event of a partial system failure alternative action can be taken. Internet-of-the-vessel provides details of the health of the platform and any failures, such as battle damage, that might impact the outcome of the mission.

Function 7 - Response Systems Engagement: The NCMS provides the commander with the recommended course of action and directs the response system to undertake the appropriate engagement. This may include lethal response or a non lethal response such as an avoidance manoeuvre. Other response relate to maintaining the health of the vessel. The authority to initiate the response resides with the Commander or delegate.

Function 8 - Feed-back: This provides an assessment of the consequences of the action taken to aid in further planning and decision-making as well as post mission analysis.

Function 9 – Archiving: Collection of evidentiary information to support legal prosecution of unlawful maritime acts.

Function 10 – Training/Gaming, Professional Development: Ability to conduct complex, real world, training exercises. Replay of past events to learn from mistakes, Red Blue Training, Certification etc.

The C2 system interfaces to human operators. Therefore the effectiveness of the overall system is influenced by the characteristics of the commander and associated support team. For example, gaming and training can be used to determine the capabilities and preferences of the individual users. This can allow the C2 system to maximize the capability of these users is such things as how recommended actions are presented [110].

The operational readiness function can be used to determine which operators are available and their health such that the C2 system can adapt to accommodate. Bio-metrics have the potential for not only secure log-in but also for monitoring factors such as attention and stress levels that were noted as being key factors the USS Vincennes shooting down Iran Air Flight 655 resulting in 290 civilian deaths as discussed in Section 4.4.1.1.

In consideration of the above, the NCMS system must be structured and operated to reduce variables and define alternatives for commanders, while concurrently avoiding an information overload at the decision-making level. It is also important that a historical summary is also maintained advising the commander of the events that led to the current state [111].

4.8.1 Architecture of an Holistic NCMS System

It is recommended that the architecture of the future NCMS is developed based on a distributed network incorporating an open architecture. Other architecture recommendations are summarized in Table 2.

Table 2 System Architecture Considerations

OSA	Enable readily integration of legacy and new hardware and software.
IOD	Decouples complex, highly interrelated functions and instead features independent functions with access to a common information source.
IOS	Development focuses on the conceptual needs of users and customers rather than the data storage models and object models
Topology	Distributed, potentially hybrid. Provides resilience to signal node failure. Allows resources (memory, processing power) to be dynamically shared. Focus is on data and information flow
LAUs	Are the nodes on the system that interface physical systems and sub-systems to the LAN and LAU's include common fire-walls that maintain enclaves that provide high levels of security from cyber attacks. May also so include some basic processing of data.
LAN	Interconnects the computers within the local system
WLAN	Interconnects external elements (NTC, UAV, CEC) into the LAN WLAN may also provide redundancy to the LAN. .

4.8.2 Design for Cyber Security

Protection from cyber attack is a two prong approach that includes both traditional firewalls, which try to keep any intruder from getting in and secondly when they do get in compartmentalize the system so that they have limited access.

The proposed System-of-System approach ensures clean interfaces where firewall protection at the input to each enclave can limit damage to an individual enclave. The open architecture approach of building plug-and-play modules inherently isolates each component of the system so that a hacker cannot easily access multiple sub-systems. This is known as defense in depth.

4.8.3 Subsystems of the Holistic NCMS

The NCMS consists of a number of sub-systems as illustrated in Figure 33. It is recommended that the functionality of the NCMS builds on previous iterations.

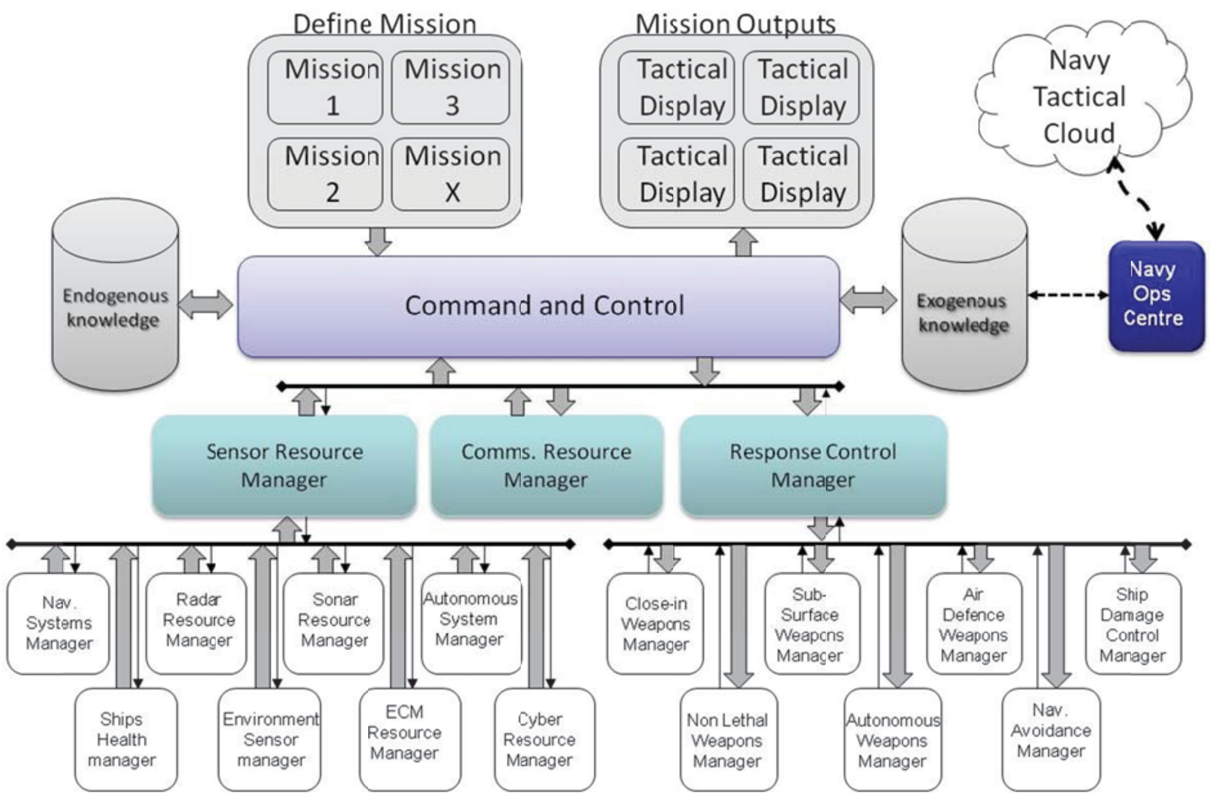

Figure 33 Architecture of Holistic CE-NCMS

4.9 Role of Cognition in Holistic CE-NCMS

Within the Holistic CE-NCMS cognition takes one of two forms. Slow-time, or conscious cognition, supports strategic planning and analysis functions within the C2 system. Fast-time or sub-conscious cognition is used at the sensor level to optimize parameters based on the sensed environment.

4.9.1 Conscious Cognition

Conscious Cognition is closely associated with tasks related to strategic planning.

The C2 system is a decision making aid that predominantly uses slow-time or conscious cognition to convert data into actionable intelligence. This decision-making is defined as a high-level cognitive process based on perception, attention, and memory. As noted in Chapter 2, the human conscious reasoning capability is largely sequential and short term memory has a very limited capacity to retain more than a few elements of data at any given time. Consequently, operators have a great deal of difficulty assessing multiple relationships concurrently. The objective of the C2 system is to relieve the operator of this burden by using automated cognitive processes to analyse multiple relationships in real-time. This permits analysis of cross relationships and the extraction of the maximum amount of relevant knowledge to aid timely decision making.

4.9.2 Sub-Conscious Cognition

Sub-Conscious Cognition is closely associated with tasks related to system optimization.

Sub-conscious, or fast time, cognition is defined by the perception-action cycle and is applicable to sensor systems with the capability to use data from the previous update to optimize the system parameters for the current collection cycle. This can lead to a significant improvement in the quality of the data collected particularly when target is masked by clutter or interference.

Within the sensor domain cognition can play an important role in Non Cooperative Target Recognition (NCTR). Cognition can be applied to micro Doppler, sparse sensing, feature extraction and Inverse Synthetic Aperture Radar. Cognition has the potential to reduce the NCTR process to reduce database requirements.

4.10 Evidentiary Data Collection

The RCN plays an important role in maritime policing and enforcement. As such, RCN vessels collaborate with provincial, federal and international partners. In support of this it is recommended that the NCMS collects and archives evidentiary information that can be used openly in a court of law. It is also recommended that the RCN not only have the ability to participate in international collaboration with other Navy's but also with government, non-military, vessels and aircraft.

4.11 Embedded Trainer

The inclusion of an embedded trainer enables the creation of simulation scenarios via the scripting of targets of interest and other entities for use in a training or simulation environment. Operators can create detailed scenarios using different entity types. Simulation and Training features include the ability to create detailed scenarios combining, real-time distribution and playback of scenarios via Distributed Interactive Simulation (DIS), as well as interactive manual control of simulated entities. This includes user interaction with simulated targets to introduce real-time changes to tracks during scenario playback, and the capability for unscripted entities to be dynamically injected at any time during playback. Scenarios can be played back locally or output to any DIS-compliant system. As a training tool, assets can be planned and tested against realistic scenarios allowing for evaluation of response times and force composition.

Real-time modelling and simulation can be used to model the predicted coverage area for a target of interest and to highlight vulnerabilities. Real-time modeling and simulation of adversaries' kill-chain, with updates during evolving mission, help identify vulnerabilities that can be exploited and strengths that should be avoided.

Research in human cognition and decision making has shown that seemingly insignificant aspects of how information is presented can have surprising effects on people's perceptions and behaviours [112]. Therefore the embedded trainer can be used to determine the capabilities, personal nuances and preferences of individual operators such that NCMS can tailor the manner in which it presents information.

4.12 Summary

This section has provided an outline of the components required for a High-level Cognitive Naval Combat Management System. Various network topologies were introduced based on the concept of a distributed architecture that ensures robustness in the event of a partial system failure. The enhancement to the NCMS by the inclusion of bid-data was demonstrated with examples of the U.S. Tactical Cloud presented.

Examples have been presented showing the evolution of NCMS from the initial U.S Navy's AEGIS system, through to the U.S. DCGS-N and to the latest SSDS. The SSDS is based on an on open, fully distributed architecture based on COTS building blocks. A review of industry furnished NCMS was provided that demonstrates the current state-of-the-art.

Finally a discussion of the key features of a futuristic Holistic CE- NCMS was presented. The next section discusses key research and development activities that are required in order to reach this objective.

Application of cognition will provide operators with timely, relevant, recommended action(s) that maximize the probability of successful completion of mission in complex dynamic environments.

5 Recommendations for Future R&D

Naval vessels provide the physical hardware that hosts sense and respond assets. Software processes mine the sensed data to extract information that, when used in association with other sources, can reveal knowledge that leads to an appropriate response being taken. The challenge remains; see first, understand first and act first.

Another challenge is predicting what tomorrow's threat will be and how to detect it using today's sensors. The answer lays in advances in signal processing and utilizing all data in a collaborative sensor network. For example it may be feasible to sense the presence of a hypersonic manoeuvrable by its disturbance to the electromagnetic environment. Data is currently available from an assortment of onboard systems that when used collectively may provide the ability to extract the required information.

Problems inherent to a C2 system has been noted by the U.S. Navy are reported in [113]. It is not the intent of this report to restate deficiencies that are general and already known but rather focus on the innovations identified in the proposed Holistic CE-NCMS.

Research recommendations are primarily focused on the two key enabling technologies identified in this report:

- The use of a SRM to implement a system-of-systems approach to the sensor suite.
- The impact of big-data.

The enabling technologies behind these innovations are high speed networks and the emergence of machine learning and computational intelligence (also known as AI). The driving force behind these developments are commercially interest however, it is widely regarded that militaries who achieve dominance in computational intelligence or AI will be the dominant force of tomorrow. The third area of research related to human interactions with the NCMS and the impact of machine learning and AI and how this objective/subjective relationship can be used to benefit mission success.

The United States has put AI at the centre of its quest to maintain its military dominance. As a part of its Third Offset Strategy announced in 2014, the Pentagon has reportedly dedicated $18 billion (U.S.) for its Future Years Defense Program, a substantial portion of which has been allocated for robotics, autonomous systems and human-machine collaboration [114]. However the key source of funding in developing sensor networks and cognitive systems remains the commercial sector and in particular the race for developing self-driving cars that as of June 2017 had received an investment of over $80 billion (U.S.) [115].

At first glance the synergy between autonomous vehicles and NCMS may not be obvious. However, the technology required to control an autonomous vehicle is every bit as complex as that required to control a naval weapons suite and much can be gained from research already undertaken in this field particularly in the use of a SRM and the real-time exploitation of big-data. These are the key factors in maintaining the relevancy of NCMS.

A critical area of research is related to maintaining relevancy of the warship in a rapidly changing environment. The hardware components of the NCMS including sensors and weapon system as well as the host platform are designed on a long term refresh cycle of 25 years or more. Software is racing ahead, hardware not so much. The challenge remains that hardware system lag this rapid development with systems typically designed on a replacement cycle of 15 or more years.

The challenge in today's rapidly changing technology environment is now to keep these hardware assets relevant. The key to this is the software components of the NCMS that is the C2 system, Sensor Resource Manager and the Response Manager.

Rapid advances in processing power, coupled with access to vast amounts of data and smart new algorithms are helping computers carry many tasks once restricted to humans. Recent develops in machine learning and computational intelligence has led to the potential for many of the traditional cognitive tasks undertaken my humans to be now undertaken by computers.

Research into the addition of placidity into the system design may also allows software resources to be reallocated and new algorithms introduced to process data in ways yet to be imagined. Placidity can also be used to reallocate resources and responsibility in the event of a partial system failure such that target information may be maintained using other means.

Core to the success of a mission is a clear and comprehensive understanding of the mission. Incomplete understanding of the mission and an adversary's capability can lead to mission failure. Access to big-data and the analysis of the inter-relationships between information sources can lead to better judgement. Cognition allows for incomplete mission objectives and understanding of the environment. Cognitive enabled systems can learn from experience and refine mission goals in the process of execution. Whilst research in cognitive processing and big data will largely be driven by the commercial sector the application to the naval environment needs to be investigated. Information sources will continue to grow and algorithms to mine knowledge will continue to evolve. For example changes in database architectures that allow for more rapid non-sequential searches continue to improve.

Naval mission are undertaken in a dynamic environment. What is normal or suspect behaviour today is dynamic. Using cognition to continuously monitor activities is an on-going effort – to remain static is to lose. Militaries are facing an unknown future threat occurring in an envisioned world of today. Systems must be agile to allow reprogramming and data analysis such that today's systems are relevant tomorrow.

Big data in the form of ocean remote sensing continue to grow at an exponential rate [116] and knowledge gained in the understanding of the real-time ocean dynamics and how a vessel reacts could provide a critical advantage over an adversary.

5.1 Research in Sensor Resource Management

An excellent introduction to sensor resource management can be found in [117].

SRM technology was introduced and shown as a means to collectively manage multiple sensors to support tracking and fusion. The SRM treats multiple, diverse, sensors as a collective unit and employs a systems-of-systems design to maximize the value of the sensed data. The SRM also allocates resources appropriately to gain as much information as possible concerning targets of interest.

The ongoing research in to the development of autonomous vehicles is yielding rapid development in the area of SRM that is directly applicable to a future Holistic CE-NCMS. Key areas where further research is required for NCMS are:

5.1.1 R&D into the Application of High Level Information Fusion to effectively manage sensors

Dr. *Rami* Abielmona, Vice-President of Research & Engineering at Larus Technologies Corporation, has proposed an investigation into the use of High Level Information Fusion (HLIF) as a means to implement an effective Sensor Resource Management. The plan is to investigate the application of HLIF (Level 4 - Process Refinement) techniques and algorithms to the problem of optimizing and managing sensors. Level 4 of an HLIF system concerns itself with modifying the lower level processes in the system to improve metrics of interest. This level involves performance assessment, which, based on a given desired set of system states and/or responses, combines information to estimate a system's measures of performances (MOPs) and measures of effectiveness (MOEs). The goal is to learn and establish trends that are occurring in the real-world and reconfiguring asset deployments and/or fusion processes so as to gain optimal performance from the deployed assets, with minimal operator intervention. The Process Refinement aspect of this module aims to identify such trends and recommend possible dynamic reconfigurations of the system to optimize its performance.

Conceptually speaking, the Process Refinement step should manage the system in its entirety: from controlling hardware resources (e.g., sensors, processors, storage, etc.) to adjusting the processing flows to optimize the behaviour of the system so as to best achieve the mission goals set out by the end user/organization. It is therefore apparent that the Process Refinement stage encompasses a broad spectrum of techniques and algorithms that operate at very different logical levels. In this regard, an implemented full-fledged Process Refinement would provide the system a form of awareness of its own capabilities and how they relate and interact with the observed environment. The Process Refinement part dedicated to sensors and data sources is often called Sensor/Perception Management and it can be defined as "a process that seeks to manage, or coordinate, the use of a set of sensors in a dynamic, uncertain environment, to improve the performance of the system". In other words, a Sensor/Perception Management process should be able to, given the current state of affairs of the observed environment, translate mission plans or human directives into sensing actions aimed to acquire needed additional or missing information in order to improve situational awareness and fulfill the system objectives.

5.1.2 Agile System of Systems Design for ISR Navy

Dr. Thia (Kiruba) Kirubarajan, Professor, Department of Electrical & Computer Engineering at McMaster University, has proposed research into the development of an 'Agile System of

Systems Design for ISR' tailored to the navy's requirement. Most surveillance systems consist of a single sensor while a few may have multiple sensors on a single platform. However, there are systems that consist of a number of subsystems with multiple platforms with multiple sensors. For example, continent-wide (e.g., North American Aerospace Defence Command or NORAD) surveillance systems consist of many heterogeneous sensors distributed over a large geographical area. The sensors and the subsystems (with multiple sensors) may report to different fusion nodes, which combine the data before reporting the fused results to another higher-level fusion node. With the advances in sensor, communication and computing technologies, future surveillance systems will be even more complex, networked and geographically distributed. In these networked surveillance systems, there are many challenges including data flow control, fusion of correlated information, feedback or fused results, bandwidth management, fusion at different levels of data.

Before such complex networked systems can be developed and deployed, conceptual design studies and trade-off analyses have to be conducted to ensure that these future systems will be able to meet performance and cost requirements. To address this issue, it is proposed that an optimal architecture designs for different types of systems be developed. The design would include multimodal sensors and fusion nodes at different levels for networked surveillance systems. Representative maritime and air surveillance scenarios with ground, air, space, ship and underwater based sensors will be used for realistic design options for future systems. This will involve not only architectural design, but also developing new algorithms to solve specific problems such as data flow control, bandwidth management, global track handover across geographically distributed, non-overlapping heterogeneous sensors, latency, bias, and correlation.

In order to design efficient systems that yield optimal performance while meeting complexity and cost requirements, effective performance metrics are needed. In sensor management, typically track level metrics such as prediction errors are minimized. In a networked system, this may not be sufficient because track-level metrics quantify only one aspect of the utility of the surveillance systems. Additional system-level metrics suitable for networked systems that can quantify information flow, recognition and identification (R&I) effectiveness, robustness to failures, etc., are needed. This is similar to previous work on tracker-level performance metrics under taken at McMaster [118]. It is proposed to develop a comprehensive set of metrics especially for networked surveillance systems. Finally, it is recommended that research is undertaken to address fault-tolerant fusion architectures and algorithms for large-scale hierarchical (or networked) surveillance systems, where, as in any networked system, resilience to failures in some parts of the system is critical. This will involve the development of adaptive communication and fusion algorithms that can gracefully degrade in performance instead of resulting in total collapse when faced with communication link and/or processing node failures in the system.

5.1.3 Networking and Information Flow Control Issues for ISR

Dr. Thia Kirubarajan has proposed that research also be undertaken in 'Networking and Information Flow Control Issues for ISR'. With multiple heterogeneous sensors distributed across a network in a hierarchical manner, it is important to manage the network, retention/storage of information (e.g., measurements, tracks, decisions, uncertainties) and the flow of information across various trackers and fusion nodes. While the most desirable way to maintain a common picture among the various players in the network is to broadcast every piece of information, this cannot be done in view of limited bandwidth and processing capabilities. The challenge is to determine the storage and transmission of information with optimal answers to “who, what, when, to whom” in mind.

In this project, it is propose to address a number of problems related to networking and information flow control in ISR systems. One issue in networked systems will be unreliable channels with limited capacity. When deciding what to transmit from one tracker to another, the inherent limitations of the channel and the processing power of tracker/fusion engine at the receiving end have to be taken into consideration. In addition, using the network information and the history of the flow of information and their quality, it is possible to reduce redundancies and avoid double-counting of information. A preliminary work on information flow control in distributed systems using Markov Decision Processes (MDP) was presented in [119].

It is proposed that this work is extended to consider more realistic issues like unreliable channel, limited capacity, data redundancy, order priority and shortest and robust routing. In order for an information flow management algorithm that is tightly integrated with tracking and fusion (i.e., not as an architectural choice) to be effective, it is necessary to consider these issues as part of the overall optimization of tracking results. Data storage is another issue in distributed fusion systems where the amount of information generated at any time can be overwhelming. Because of network latency issues, due to which out-of-sequence data can be received at some fusion node, and because of the need to reduce network load, an efficient data storage mechanism is needed. This is also necessary in view of the need to maintain reliability in case of node failures. We propose to extend the work in [120] to multi-agent MDP issues so that node failures are addressed properly and global information flow is minimized. The network resource management algorithm needs to work in tandem with the tracking algorithm at each platform and consider its accuracy and data needs as well as the network load, in order to determine the transmission of information across trackers. In this project, analytically quantify the performance of local and global optimization algorithms where it is necessary to decide how to optimally distribute the computation in a distributed implementation across nodes would be developed. There are other information flow related issues like statistical data authentication where one has to decide whether the data received from another tracker across the network is reliable. That is, it is necessary to build information on the quality of each tracker/fusion node over time across the network. This will be an extension of the tracker in [121] where a quality measure is used to improve tracking results in a single tracker. Based on previous tracking and fusion results and their statistical consistency, a quality measure will be developed for each resource in a collaborative manner. This information will be use in data authentication, fusion weighting and information flow control. Finally, ensuring reliability and detection/prediction and failures in network resources are essential in deciding the information flow across the network. The statistical models of failures across the network will be factored in explicitly when optimizing the network flow in this project. All these algorithms have military as well as homeland defence/civilian applications.

5.1.4 Sensor, Data and Computational Resource Management

Dr. Thia Kirubarajan has also proposes a research topic related to Sensor, Data and Computational Resource Management. As the number of sensors increases, size of database expands and computational power becomes limited, it is necessary to optimize the usage of these resources in order to maximize tracking performance. Sensor selection, placement and parameter optimization have been tried as ways to manage resources [122]. In addition, processor scheduling has been attempted as well [123]. Typically, sensor management has been considered separately on each platform, possibly with feedback from its own tracker. Recently, collaborative sensor management, where multiple sensor resources coordinate resource usage by sharing information across platforms, has been proposed. However, current collaborative management algorithms work only with a single sensor type. A more challenging and realistic problem is the sensor management, collaborative or otherwise, not only with different types of sensors but also with databases and computational nodes. That is, an integrated approach to total resource management that will consider different types of sensors, knowledge databases and computational options is needed. This will be the key objective of this sub-topic in this proposal. In order to achieve this, multi-objective functions that characterize expected performances (in different categories) and the corresponding constraints will have to be developed. Efficient search techniques with quantifiable accuracies are needed in the end. Also, long-term horizons have to be considered in formulating the resource management problem since most current approaches are myopic with only short-term planning. Because of the desire to incorporate database resources in tracking, data mining algorithms have to be included in the formulation. That is, resource usage will be based on the information contained in the databases. This is analogous to considering kinematic or feature information content of radar in planning their usage. In addition to standard radar and sonobuoys for sensor management, simulated scenarios with multistatic radars, passive sensors and dipping sonar will be used to test the new sensor management algorithms. Terrain, video and ESM data sources will be used as feature sets. Computational and communication limitations will be explicitly factored in while formulating the optimization problems.

5.1.5 Multi-Band Systems

The author has proposed that research be undertaken into the feasibility of developing radars that have the potential to operate over multiple bands. It is noted that cognition sensing and spectrum utilization go hand-in-hand. Key for future sensor growth is to be able to operate over multiple frequency designations. For example, the goal is to develop radar hardware that is capable of operating throughout the microwave band using common antennas, amplifiers and programmable filters. New generation metamaterials may provide opportunity for this development [124]. This capability would significantly enhance the capability of the NCMC to detect, track, classify and engage a target by allowing the radar to dynamically select the optimal frequency-band based on the current condition and threat evolution.

5.1.6 Recognition and Identification with Large Amounts of Heterogeneous Data

Dr. Thia Kirubarajan has proposed that research be undertaken in the field of Recognition and Identification. While the output from the tracker is a list of state estimates and corresponding confidences, the output from a fusion center may be at different levels: object, situation assessment, impact assessment, process refinement, or cognitive refinement levels [125]. In order to aid the higher levels of fusion and to benefit from both soft and hard heterogeneous data at different levels, it is important to recognize and identify objects and classify them appropriately. R&I plays a crucial role in situation assessment based on the lower level signal and track data. As discussed in section 2.7.1, fusion of soft and hard data is inevitable in modern surveillance systems and even the hard data may be at different levels and forms (e.g., signal, radar imagery, video imagery, track outputs, and local R&I). These issues pose major challenges to a multisensor global R&I module that needs to consume heterogeneous data at different levels to generate a global R&I output.

5.1.7 Tracking and Fusion with Augmented Reality

Dr. Thia Kirubarajan has also proposed the topic of tracking and fusion with augmented reality. A recent trend in sensory systems is augmented reality (AR) where real data from sensors (e.g., video) is combined with computer generated synthetic data (e.g., maps, terrain, traffic flow data). In the context of tracking and fusion systems, it is possible to track objects within the field of view of a human operator using data from physical sensors and synthetic computer-generated data. This has applications in head-mounted displays, tracking from a mobile platform with multiple cameras and other sensors, wide-area motion imagery (WAMI), and persistent surveillance. It also has civilian applications in autonomous vehicles and tele-surgery. While a few papers with preliminary ideas focusing on video-only tracking are available in the literature to the best of our knowledge a completely automated robust multisensor-multitarget tracking solution is not yet available. There is renewed attention on augmented reality because of recent advances in mobile computing, Microsoft Hololens (https:// microsoft.com/microsoft-hololens/en-us), and Oculus (https://oculus.com/). Thus, it is of interest to develop tracking and fusion solutions using data from not only video cameras but also other sensors, to improve tracking accuracy, fusion capability, and ultimately operator perception and interaction.

Augmented reality can be seen as a complementary addition to intelligent guidance and tracking systems. Although it is essential to have accurate estimates of the position and orientation of the camera based on inertial navigation system (INS), gyroscope, and computer vision processing, there is also a need to understand the environment in real time. Computer vision algorithms can only provide partial information in such critical situations as surveillance and command and control (C2). Computer vision algorithms can be combined with soft/hard data and multitarget tracking algorithms, so that anomalies can be detected in real time and the operator can respond to them instantly. This level of understanding from the environment is of great interest for security and surveillance applications and can be implemented with low cost AR systems. HSI aspects are important for fusion with AR as well. We can leverage the research proposed under Section 2 to improve fusion in AR systems under Bayesian and non-Bayesian frameworks. Even with high-end head-mounted display systems, there are challenges presented by field-of-view registration errors due to INS/gyroscope imperfections, motion blur due to sudden head or device motion, fusion of 2-D and 3-D data, out-of-sequence data (incorrectly time-ordered data), occlusions, multi-resolution data, and so on.

5.1.8 Robust State Estimation in Uncertain Environments

Dr. Thia Kirubarajan also proposes that research be undertaken into robust state estimation in uncertain environments. The objective of state estimation is to mitigate the effects of noise in sensor measurements and extract the fixed or time-varying parameters of an object of interest using certain system and measurement models. Noise mitigation is necessary not only because no sensor is perfect, but also because our knowledge or model assumptions about any unknown system and its parameters are imprecise. The estimator considers the model uncertainties and noise statistics in order to optimally estimate the parameters of the subject of interest to some optimality criterion. While state estimation typically considers only the effects of system (or model) noise and measurement noise, in estimating the state of a moving object over time, target tracking considers additional measurement-origin uncertainties due to missing detections, false alarms, and interference from other objects of interest. In target tracking, the objective of state estimation is then to mitigate the effects of model and sensor noise and those of measurement-origin uncertainties.

With the emergence of affordable sensors (e.g., cameras, sonobuoys, satellite receivers), sensor processing with the objective of state estimation and target tracking has become common. The ubiquitous and affordable nature of these sensors results in additional uncertainties that have not been addressed properly in the literature to date. In sensor processing where expensive radar systems with only one or a handful of sensors are used, systemic errors such as sensor biases, clutter, electronic countermeasures, and other interference have been effectively modeled and addressed. But, given the large number of heterogeneous sensors available, these additional sources of uncertainties have not been modeled or addressed optimally. This situation provides the motivation for the proposed work.

The core requirement of any surveillance system is its ability to optimally estimate the unknown states and types of an unknown number of targets in the presence of uncertainties due to sensor imperfections, environmental conditions, and target counteractions. At the same time as recent technological advances have driven improvements in sensor capabilities, the nature of threats or targets has also been evolving. Today's targets (e.g., autonomous underwater vehicles or AUV) have gained greater capabilities, with increasing stealth, low observability, high manoeuvrability, swarm coordination, improved countermeasures, survivability under extreme environmental conditions, and sophisticated autonomy. In order to counter these challenges, today's surveillance systems must be able to process large quantities of false alarms, take advantage of environmental factors such as multipath, counter intentional distractions posed by targets, discern patterns of behavior, and operate autonomously themselves. In this respect, today's surveillance systems are required to go far beyond connecting the dots on a radar or sonar screen. They have become part of a decision-making chain with some degree of learning, intelligence, and autonomy. This observation is what motivates the section of the work.

5.1.9 Cross-Seeding of Sensors

This research area has been proposed by the author of this report and relates to the potential for cross-seeding of sensors. Cross-seeding refers to when data from one sensor is used to improve the performance of another. For example it is well know that radar accuracy is primarily determined by the resolution of the radar system but can be degraded by adverse atmospheric conditions. The question for researchers is; if we know, in real-time what the atmospheric conditions are can this information be used to compensate for any degradation in system performance? For example, a CFAR thresholding system that's modified based on information received from other sensors.

5.1.10 System Placidity

This research area has been proposed by the author of this report and relates to being able to mimic the brain ability to respond, adapt, and continually change. That is, to develop a system that is malleable and modifiable [126]. Investigation into how cognition can be used to introduce placidity within the NCMS to re-assign resources and re-configure systems to maintain a basic capability in event of overload or failure of any single part within the chain. This is viewed by the author as being an enabling technology of the Sensor Resource Manager.

5.2 Impact of Big Data and High Level Information Fusion

Big-data continues to grow. Access to data is typically on a fee-per-use base. Models need to be developed to identify primary information sources with back-up sources identified. Access to big-data also requires the continuous verification of trusted data sources and the quality of the information provided. Utilizing commercial cloud computing infrastructure rather than maintaining data centres offer the potential for cost savings and ease of access that needs to be investigated. For example, utilizing processing resources on the ‘cloud’ can significantly reduce bandwidth requirements when knowledge is transferred rather than data. This can be a significant advantage when considering the bandwidth limitation of ship-shore-ship long-range communication systems used to transmit data via satellite with high-frequency sky-wave propagation as a backup.

Long-term challenge is matching the fidelity of data matches the required fidelity of the mission. In general, higher fidelity but more localized data is required as a mission progresses. The higher the fidelity the greater the cost of acquiring it. This can have significant implications when obtaining data from the cloud where cost is generally on a pay-per-go basis. Data fidelity is particularly important during the decision making and targeting stage where it is imperative to know the pedigree of the data, who generated it and when was it last refreshed.

The internet of things can be applied to the monitor the health of the vessel. Research should also be undertaken into evaluating the benefit of including the health and capability of operators in the internet of things. This knowledge could be used evaluate the alertness of the operator and to tailor outputs that match their known capabilities. For example if an operator s fluent in multiple languages then it may be appropriate to pass knowledge to the operator in the native language in which it was obtained in priority over the translated text.

Discussions with Maria Rey (Vice President and Chief Science Officer, Space Strategies Consulting Lt) she note that in terms of the Canadian Navy and what it should do in the areas of big data and cloud computing that she highly recommends R&D into the development of multipurpose, distributed, adaptable, web-enabled, cloud-based, service oriented architectural frameworks that remain "evergreen" to evolving technologies by being able to integrate advanced analytics and other services in support of decision making. Such a system must also be interoperable with OGDs and Allies and therefore support multi-level security. As discussed in some of the following sub-sections this was a common theme with researchers.

Specific research areas related big-data and information fusion systems have been suggested by local industry are listed below.

5.2.1 R&D for exploitation of open unstructured data in C2 fusion systems

Dr. Elisa Shahbazian, President Ooda Technologies, has recommended that research be undertaken in the field exploitation of open unstructured data in C2 fusion systems. The establishment of situation understanding from physics-based sensors has been developed over the last 30-40 years and is considered a mature technology. However, the ability to augment the situation assessment and understanding with actionable knowledge extracted from unstructured data in real-time is novel and not yet proven in defence and security applications.

It is recommended that research be under taken to evaluate technologies used by the big IT giants like Amazon, Google, etc. That has successfully leveraged such unstructured data in their decision making algorithms.

5.2.2 R&D in exploitation of advanced analytics

Dr. Elisa Shahbazian has also suggested that a beneficial area of research in the exploitation of advanced analytics within the NCMS. This research includes data mining, machine learning, artificial intelligence, etc., to compile situation understanding, situation forecasting and resource management, automating and providing enhanced advanced analytics enabled decision support capability

5.2.3 R&D in flexible distributed, web-enabled, cloud-based framework

Dr. Elisa Shahbazian recommends that researches investigate the development of a flexible distributed, web-enabled, cloud-based framework. The framework would have the capability to evolve by incrementally integrating services that perform advanced analytics methods supporting the decision making needs of the RCN, whilst providing multi-level security access supporting coalition partners.

5.2.4 R&D in the use of Artificial Intelligence to reduce mission management costs (Larus Technologies):

Dr. Rami Abielmona has suggested that research in the form of an investigation be undertaken into the use of Artificial Intelligence to reduce mission management costs. Artificial Intelligence (AI) has the promise of significantly reducing the costs associated with mission management through the automated and autonomous submission of collection taskings. This results in a reduction in the time required to generate actionable intelligence through the High-Level Information Fusion (HLIF)-driven data collection and management process. Human efforts are extensively spent to review large numbers of combinations of sensors and Areas of Interest (AOIs) and to manually evaluate feasible and expertise-driven scenarios for such surveillance missions. Future Holistic CE-NCMS will increase the efficiency of human operators, and effectively disseminate information to the proper authorities and downstream systems. The major cost savings will be realized due to the elimination of the majority of the manual steps of the Tasking, Collection, Processing, Exploitation, Dissemination (TCPED) cycle, with the end goal being the automatic cueing and tasking of sensors and assets for a more efficient and timely generation of actionable intelligence to process, exploit and disseminate.

5.2.5 R&D in the effective use of Big-Data using High-Level Information Fusion

Dr. Rami Abielmona has also recommended that research be undertaken into the effective use of Big-Data using HLIF to accurately and effectively monitor a maritime area. In order to achieve this the vast depth and breadth of incoming data must be properly collected, interpreted and disseminated. Often referred to as the “Big Data Problem”, this state is best handled through the creation and maintenance of a real-time representative model of the world. Early solutions attempted to resolve this challenge through low level Information Fusion (IF) modules that used complex mathematical formulations or brute force number crunching; however, these solutions were inadequate because the complexity created by the 4-dimensional vector (variety, volume, velocity and veracity) quickly increased to the point where low level IF modules were overwhelmed. Low level IF was only capable of performing fusion when the data itself was limited in volume, involved few types (low variety), did not frequently change in mission-critical applications (low speed) and was somewhat trustworthy (high veracity). As data complexity continued to grow exponentially researchers realized that at some point a new approach to the Big Data Problem would be needed. That point is today, where we see data expressed in terabytes when it comes to its size, in millions per second when it comes to speed, in tens, if not hundreds of types when it comes to diversity and in jams and interferences per second when it comes to trustworthiness. A new computational paradigm is required.

To address the challenges of Big Data, High-Level Information Fusion (HLIF), which in the Data Fusion Information Group (DFIG) model is defined as Fusion Level 2 (Situation Assessment) and above, has become the focus of research and development efforts. HLIF uses a mixture of numeric and symbolic reasoning techniques running in a distributed fashion, over a secure underlying backbone and a multi-layered multi-caveat security model while presenting internal functionality through an efficient user interface. HLIF allows the system to learn from experience, capture human expertise and guidance, analyze contextually and semantically, lower computational complexity, automatically adapt to changing threats and situations, and display inferential chains and fusion processes graphically. Instead of attempting to keep up with the ever increasing complexity of the 4-dimensional data streams, HLIF, aided by AI/ML allows one to model and therefore, better understand the data stream sources and better adapt to the dynamic structures that exist within the data.

5.2.6 Scalable Tracking and Fusion Using GPU, Hardware, and the Cloud:

Dr. Thia Kirubarajan has proposed a project related to 'Scalable Tracking and Fusion Using GPU, Hardware, and the Cloud'. He notes that recently there have been significant developments in the tracking and fusion literature, ranging from special algorithms for extended targets to algorithms to fuse social-network data with ship-generated automatic identification system (AIS) data [127]. Unlike standard target tracking algorithms, extended target tracking and multipath-aided tracking (where a single target is assumed to be able to generate multiple detections) are NP-hard optimization problems. In contrast, the standard algorithms assume point targets that generate one detection per frame, at most. Because of the non-polynomial time complexity of extended/multipath-aided target tracking algorithms, they are applicable only in scenarios with one or two targets. Beyond that, computational complexity makes extended/multipath-aided target tracking algorithms infeasible.

Similarly, in the fusion of social network data with AIS data, the amount of data and the computational cost of preprocessing social network data are very high. In these problems, single CPU-based desktop computers cannot handle the computational load. A potential solution is to use multiple real or virtual computers to distribute the load and achieve real-time feasibility [128], or to use massively parallel GPU units [129]. Existing cloud and GPU solutions typically treat this as a tasking or task scheduling problem rather than developing new GPU-capable algorithms or re-deriving GPU-specific versions of existing algorithms. In contrast, in the image and video processing literature there are numerous works taking advantage of GPU.

The intention is to develop new algorithms and re-derive complete multisensor-multitarget tracking algorithms (i.e., from detection to fusion; not just a filter module) that are specifically designed for the cloud and GPU architecture, from the ground up. Problems like extended target tracking and occluded target tracking will benefit significantly from scalable theoretical derivations and practical implementations. Although tracking algorithms have already been implemented in hardware, it is possible to improve performance using higher level synthesis techniques and the corresponding higher-level languages (e.g., C/C++, OpenGL). It is proposed to address this issue by the development of GPU, hardware and cloud-friendly algorithms based on Bayesian estimation and fusion, random finite sets and point process models.

5.2.7 Adaptive Maritime Surveillance Using Multimodal Sensors

Dr. Thia Kirubarajan suggests that another area of research would be in 'Adaptive Maritime Surveillance Using Multimodal Sensors'. He notes that due to the vast maritime border and the rich maritime economic zone surrounding it, maritime surveillance using defense mission systems would be of significant interest to Canada. Maritime surveillance using data from radar and automatic identification system (AIS) has been addressed by researcher. The effects of global warming have made arctic surveillance to monitor maritime and underwater traffic a high priority. Because of the nature of its remoteness, it is important to reduce human involvement in such surveillance systems. While this is especially true for arctic surveillance, it is important to reduce operator overload in general maritime systems as well. This provides the motivation to develop new sensor architectures, data processing algorithms and software implementations with emerging sensors. Recently, bistatic and multistatic sensor configurations, where signal transmitters and receivers are not co-located as in the case of standard monostatic sensors, have been considered for maritime and underwater surveillance. However, many real issues related to multistatic tracking (e.g., multipath issues, accurate signal propagation models in tracking, environmental factors, bistatic and multistatic bias issues, bias in heterogeneous bistatic sensors, uncertain transmitter/receiver locations, uncertainty in navaids) have not been addressed well in the literature. Also, target (e.g., ships, torpedoes) classification using bistatic and multistatic data has not been addressed before. We can develop systematic Bayesian and non-Bayesian frameworks for classifying objects using kinematic and feature data. In addition, performance metrics to evaluate target classification will be developed.

Further, tracking of multiple extended targets, especially in the presence of wake, has not been addressed as well. This is a critical issue in maritime surveillance due to ship size, sea state and target manoeuvres. First, measurements from wake are typically considered as clutter and used in the data association and filtering stages of the tracking algorithms accordingly. However, wake measurements carry valuable information about target state, manoeuvres and size and this information is lost by treating wake measurements as false alarms. Algorithms can be developed to handle the general problem of multiple extended target tracking in the presence of wake under different sea state conditions. This will significantly improve target state estimation and classification results. Multipath information with sonar and multistatic sensors has not used before to improve tracking results. This is especially difficult because of the limited observability in sonar tracking systems. With proper modeling for multipath signal propagation, it is possible to improve the observability of the system so that the unknown target state can be estimated more reliably even in the absence of ownship (platform) manoeuvres. This problem becomes more challenging with bistatic or multistatic sensors whose state may not be known exactly due to sea state and wave-induced drift due to waves. It is proposed that observability conditions and performance bounds be developed to quantify achievable accuracies, in addition to developing estimators that can specifically address these issues.

5.3 Modelling and Simulation

It is proposed by the author that research be undertaken in the area of real-time modelling and simulation to model the predicted coverage area for a target of interest using the available sensors and systems and to highlight vulnerabilities in own kill-chain. Real-time modeling and simulation of adversary's kill-chain, with updates during evolving mission, help identify vulnerabilities that can be exploited and strengths that should be avoided. The modelling would take into account the loss of one sensor and the reallocation of resources to another to minimize the void.

On this topic Maria Rey commented that modelling and simulation related to the exploitation of advanced data analytics is an important topic to pursue in order to improve situational awareness, forecasting, resource management and decision making. She also noted that it is critically that improved sensor performance and phenomenology modelling is developed.

5.4 Human Factors

Research into the impact of human stress on command operations and in particular to incorporate measures of human effectiveness into battle simulation techniques to assess the effect of information overload and stress on human players. Since individuals react to stress in different ways the research should investigate how stress impacts an individual and how the C2 system can help relieve that stress on a tailored individual bases.

It was noted in discussions with Maria Rey (Vice President and Chief Science Officer, Space Strategies Consulting Lt) that involving the operator, from the perspective of allowing a system to adapt to (including compensate for) the abilities and mental state of an operator is a worthwhile topic, and stated that she was aware of considerable ongoing research in this topic. However, she was uncertain of exactly what meaningful contribution could be made in this area other than to emphasize issue of trust in AI vs. human decision-making.

Big-data couples with the processing power of modern computers and machine learning techniques can produce very convincing results. However there may be a tendency for operators to place inordinate significance upon the results. Military operations are characterised as be highly uncertain and unpredictable, involving considerable subjective evaluation. Ongoing research into the role and relationship between subjective and objective decision making where subjective is primary undertaken by a machine and objective by an operator.

NCMS systems should be designed with sufficient flexibility to accommodate the needs of different human beings and operations. Emphasis in system design should favor the commander requirements rather than the technology employed.

Thales Canada has undertaken research in the area of Judgmental bootstrapping (using more flexible modeling methods, such as decision trees) and has shown this to be valuable in a decision support context, even in time-pressured decision making situations. This form of support may be achieved by monitoring operator assessments in real time, comparing them with the inferred decision policy, and generating alerts in cases of mismatch. This nonintrusive “shadowing” process constitutes a promising future avenue for improving human–machine system effectiveness without putting the user in the back seat and without imposing an additional burden on the operator [130]

5.4.1 Human-System Integration and Soft/Hard Fusion for Surveillance Systems

Dr. Thia Kirubarajan proposes an investigation in Human-System Integration and Soft/Hard Fusion for Surveillance Systems. The proposed approach incorporates human-systems integration (HSI); this approach will go beyond presenting information to users through a graphical user interface (GUI), evaluating the effectiveness of the information on the screen, and assessing the users’ response. We also plan to develop new mathematical algorithms that respond to human input by modifying the internal steps of the underlying tracking, fusion, and R&I components. This will leverage our expertise on core algorithm development and differentiate us from most HSI research initiatives. One major hurdle in the adoption of automated data fusion techniques in real surveillance systems is trust: operators do not trust automated systems in mission critical situations. However, with multiple sensors generating large amounts of uncertain data at high rates, it is not possible for humans to process the data without the help of an automated system. Thus human operators, with cognition as their unique capability, and automated systems, with raw processing power as their advantage, need to co-exist and leverage each other's abilities to yield agile surveillance in the data-to-decision processing chain. Effective presentation of actionable information is the critical solution to this problem. Toward this end, HSI issues can be addressed in maritime domain awareness systems, using simulated and real scenarios with learning and adaptation capabilities. This work on HSI in maritime fusion systems will be used to fine-tune the user interface and adapt it to facilitate effective HSI development for maritime domain awareness.

Human operators' trust in an automated system is affected by their awareness of corner cases or scenarios: extreme situations where an automated system fails, but a human operator can make the right decision due to cognition and years of experience. To address this issue, corner (extreme) cases where automated fusion does not work well can identify and evaluate the performance of the humans in those situations. Some sample corner cases are extreme manoeuvres by targets, disappearance and reappearance of targets due to occlusion, and move-stop-move motion. Corner case identification will facilitate the development of new algorithms that work better in such situations and strengthen the trust of operators. In addition to sensor data and databases, another valuable piece of information is occasional human input, which is often helpful, albeit with unquantifiable accuracy, in threat identification. On the downside, the human input may become "negative information" that corrupts the results of the systematic automated processing of previous data. The reliability of human input needs to be validated automatically, based on the data from other sources. Incorporation of human input will be considered in a manner similar to smoothing (or retrodiction) in state estimation problems where past estimates are updated in view of subsequent data. Research is required to be undertaken to explore the concept of track stitching as a way of incorporating human input. As part of this project, fusion data processing algorithms that respond to decisions by human operators (e.g., track deletion, merging, measurement removal, and overriding fusion decision) will be developed. This will involve deconstructing automated fusion based on human input.

In most surveillance systems, sensors such as radar, sonar, and video that produce numerical data with quantifiable accuracies are used to collect data. As a result, the research and development of fusion systems has focused on the fusion of these well-defined numerical data sets. With the advent of the internet, social media, ad-hoc sensors, and opportunistic information sources, other types of data (e.g., traffic activities, pedestrian movements, social media feeds, and human input) have become available in massive quantities and at low cost. While the availability of new sources of data is a boon to surveillance systems, such data sources pose new challenges as well. In contrast to the well-defined quantitative (or hard) data from traditional sensors, data from these new sources is often unstructured, with unknown or imprecise accuracies. Such data are deemed "soft," and are not often amenable to integration with the traditional hard data in fusion systems. However, due to the potentially significant value of the information in soft data, it is imperative that we fuse it with hard data in order to extract all available information from all available data. Thus, it is of great interest to develop a systematic framework to fuse data from disparate soft and hard sources in order to improve overall surveillance system performance. This provides the motivation for our work to develop a unified fusion framework with application to surveillance systems with soft and hard data sources. It is proposed to develop a unified fusion framework based on random sets, leveraging our expertise in random sets and the preliminary work in the literature on using random sets for fusion problems.

5.4.2 Impact of Remote Commanders

The author suggests that a study be undertaken to investigate the potential impact of remote commanders in a hierarchal command system. As systems move towards NCO the natural tendency will be for senior remote commanders who normally work at the strategic level to become increasingly involved at the tactical level, especially where a mission has strategic significance. This is at odds with the military doctrine of 'power to the edge' that empowers individuals that are closest to the action to make decisions. It is recommended that research be undertaken to evaluate the impact of such interference by remote commanders.

> *Where high-level commanders possess the capability to engage in evaluation at the on-scene commander level, erosion of authority of the on-scene commander will take place. If a number of commanders in the C3 system are capable of interacting, confusion may occur. The senior commander with the most pertinent information should take precedence. Multiplicity of evaluation can provide consistently better results than the evaluation of a single commander. Those in command at all echelons must know what their seniors are thinking, when to act, when to question, and when to give orders. Command and control of the near future will require a rational discipline on the part of informed commanders who work together as a team to accomplish objectives and goals. On-scene commanders must be constantly sensitive to orders from higher authority while maintaining the mental freedom of action necessary when it is required that they act, but being careful not to include action contrary to the national interest. This concept of mental discipline is perhaps the most critical and controversial, area in this new age of command and control* [131].

5.5 Cyber Security

Protection of the Holistic CE-NCMS and its ancillary systems from cyber attack is of paramount importance. Cyber Security is encompassing technology that is applicable to all networked computer systems. It is not the recommendation of this report that any general cyber security research be undertaken specifically to NCMS other that where it relates to protecting against a compromised GPS signal.

5.5.1 GPS Compromised Signal

The author proposes that a study be undertaken to understand the state-of-the-art in determining if a GPS signal has been compromised. This is has been an area of significant concern to the autonomous vehicle developers. Various solutions have been proposed. For example a statistical approach to the problem of attack detection on the multi-sensor integration of autonomous vehicle navigation systems is presented in [132].

6 Summary and Conclusion

This report has presented a general introduction into the concepts of a NCMS and how these systems have evolved over time to match the evolving threat. Core components of the NCMS system have been outlined and the topics of cognition and machine learning introduced. It has been postulated that the implementation of cognition using computation intelligence has the potential to significantly improve the overall performance of the NCMS. That is to provide objective decision support such that the commander has knowledge superiority to facilitate taking subjective actions.

The report has stated that sensor and weapons suites are mature technologies and no significant innovation is expected to occur in the near future. Therefore, advances in the performance of NCMS will be gained primarily by processing data from existing systems and utilizing this data in such a way that the resulting product is greater than just the sum-of-the-parts.

The ability to process larger data sets enables the role of the NCMS to be expanded to include all aspects of the ships operation and to tailor decision support to the preferences and capabilities of the individual operators. This is referred to a Holistic-NCMS.

> *"In today's environment and with all other considerations assumed equal, the commander who has the "best" information (timely and accurate) will prevail in a conflict of military forces. The key phrase in the definition of command and control is "knowledgeable exercise of authority." The commander, who commands without the benefit of information pertinent to the goal or objective, increases the probability of failing to control his resources optimally. Where that goal is both tactical and strategic in nature involving both military and political considerations, the on-scene commander may not have the information pertinent to that goal" [133].*

6.1 Summary Section 2 - Introduction to the Naval Combat Management System

In Section 2, it was shown that today's naval vessels must be in a position to defend against both conventional and asymmetric threats. Conventional threats originate from both conventional sources and sophisticated and costly semi autonomous and autonomous systems. Asymmetric threats however are generally low cost and simple, they are characterised as undertaking unpredictable actions.

It was noted that the NCMS for the RCN surface combatant vessels are required to support vessel operating in isolation as well as operations within a collaborative network of coalition entities. Further, in addition to its military requirements it is desirable that the Canadian NCMS also support general peace time operations.

The NCMS is a cognitive aid that connects the sensor suite to the weapon suite via the C2 system. The primary missions of the NCMS is to provide 'knowledge superiority' over potential enemies, shorten decision-making cycles and execute rapid and accurate weapon engagement, by providing optimum response to changing events. These actions can be described by the kill-chain model. The NCMS is designed to strengthen the kill-chain such that an adversary cannot disrupt the cycle whilst at the same time the NCMS maximizes the probability of disrupting the adversaries' kill-chain. The overall objective is to gain a competitive advantage over an adversary. That is, to enable a commander to take the best action given the current understanding of the situation.

The C2 provides the interface to the command team and from the command team back to the weapons suite. To provide appropriate decision support the NCMS collects data from a wide variety of sensors and systems. This data is correlated and analysed by the C2 system to provide Domain Awareness. In the context of a holistic CE- NCMS this domain awareness may also include the external environment as well as the health of the host vessel and crew.

It was noted that operator fatigue and information overload is one of the most significant challenges in regards to knowledge transfer and knowledge retention. As systems become more complex the pressure on the human cognitive processes increases. The human brain can only process a limited amount of information, at any given time, to generate actionable knowledge. The availability of extremely large amounts of diverse data only exacerbates the problem. Fortunately the emergence of machine learning to replicate the human cognitive tasks may help alleviate the problem of identifying and extracting interrelationships and thereby aid the operator's ability to make timely decisions.

In discussing cognition it was note that both conscious and sub-conscious cognition were applicable to the NCMS. The C2 system predominantly uses slow-time or conscious cognition to convert information into actionable knowledge. Knowledge is obtained when the inter-relationships between the information data is fully comprehended. Sensors however, primarily use sub-conscious, or fast time, cognition that uses data from the previous update to optimize the system parameters for the current collection cycle. This can lead to a significant improvement in the performance of the sensor.

The chapter concludes with an overview of some of the cognitive processes and models involved in the NCMS and how access to big-data provides significant opportunities to improve the performance and capability of the NCMS but this comes with the not insignificant challenge of being able to extract timely, relevant information. Machine Learning is a process that has the potential to extract the required information to aid in the optimization of sensors and systems and complete the execution of the kill-chain.

6.2 Summary Section 3: High-level framework for a cognitive sensors

Section 3 presents an overview of the sensors and weapon suits that can be found on a modern surface combatant. It is shown that today's NCMS must not only control conventional systems but also semi-autonomous and fully autonomous systems. It can be noted that deployment of cognitive autonomous weapons is currently only be limited by policy [134]. This is likely a peace-time constraint and is likely to be overridden in times of hostilities.

The concepts of cognitive sensing were introduced. Cognitive sensing mimics the perception-action cycle using fast time cognition to adapt sensor parameters based on the sensed or otherwise known environment. This is undertaken to maximize the probability of success for a given mission objective as defined by the command centre.

Fast time or sub-conscious cognition is applicable to all sensor systems that have the capability to use data from the previous update to optimize the system parameters for the current collection cycle. This can lead to significant improvements in the quality of the data collected particularly when targets are masked by clutter or interference. Cognition is used within the sensor to optimize performance based on the sensed environment, historical data and current threat.

The cognitive sensing paradigm is introduced and examples were presented that illustrated how sensors and systems treated as a collective system-of-systems have the potential to yield higher value results than just the simple combination of outputs.

SRM technology is introduced and shown as a means to collectively manage multiple sensors to support tracking and fusion. The SRM allocates resources appropriately to gain as much information as possible concerning targets of interest. The SRM has the potential to improve the effectiveness and efficiency of sensors in generating domain awareness by clustering sensors in a collaborative network. In this network, the SRM performs the functions of tasking and assignment of resources. In addition, in overload situations, the SRM can parse lower priority targets to secondary sensors and systems. Similarly the SRM can be used to support 'operation on request' missions. Sensor resource management has the potential to use of cognition by adding placidity to the system design such that in the event of failure of a primary sensor or system the NCMS has the ability reconfigure, in real-time, to optimally use secondary sensors/systems to fill at least part of the void.

The section concludes with a discussion on CEC that integrates information, sensor and weapon data from participants and distributes them to all other participants in a filtered and combined state. The CEC approach results in significantly earlier detection and more consistent tracking of targets that can be engaged at an earlier point in time.

6.3 Summary Section 4: Cognitive Naval Combat Management System

Prior to the advent of modern computers NCMS were operator intensive. The digital age allowed simple conditional programming (if, then, else) to be introduced to adapt sensor parameters as well as assisting operators in making informed decisions using a predictive approach to decision making. This assumed that the mission followed a predictable plan. Complexity dictated that these predictive algorithms were applied at the sub-system level with results flowed up through a hierarchy.

Desirable software architecture features and topology for a next generation NCMS were presented. It was shown that regardless of the specific topology selected there are significant advantages in establishing a distributed network. This is a general term for a collection of autonomous computers linked by a network that appears to an end user of the system as a single computer. A distributed network approach to the NCMS allows easy integration of existing and future systems using a variety of commercial computers and operator displays.

This was primarily undertaken due to availability of non-classified data and also because of the rapid development of the NCMS that saw its birth with the development of the AEGIS system at the start of the digital age and experienced major development with the SSDS during the information age. Lessons learnt from operational deployment with particular reference to operator fatigue and presentation of data was included in the discussion.

The section concludes with the proposed Holistic CE-NCMS. It is shown that using a systems-of-systems approach to pool resources and capabilities that more functionality and performance can be obtained than by simply summing the individual systems. An outline of the core feature of a next generation Holistic NCMS system that benefits from innovation in the area of machine learning and big-data associate with the knowledge age.

6.4 Summary Section 5: Research and Development

The report includes a section on recommended future R&D. and plan to have input from both NCMS suppliers as well as researchers in the area of cognition, big-data, decision support, sensor resource management and real-time simulation and modelling in a cooperative engagement environment.

For sensor resource management I am interested in the concept of adding placidity to the system design – that is in the event of failure of a primary sensor the ability to reconfigure the system, in real-time, such that other secondary sensors/systems can fill the gap or at least part of the gap.

For real-time simulation and modelling, I am interested in modelling an adversary's kill-chain during an evolving engagement to highlight weaknesses and strengths. Similar modelling can also be applied to the host vessels kill-chain to show own weaknesses and strengths during an evolving mission. This can be used to request additional resources/data.

Today's edge in computing networks and knowledge extraction is rapidly becoming a commodity that is available to all users. The future is therefore in the ability to rapidly assimilate new technologies with in current systems.

Responding requires the ability to understand what is happening in the domain, to isolate a threat and to take action. Response assets include standard weapons systems that are directed to their target prior to departing the vessel, semi autonomous weapons that receive updates to their trajectory during , from the vessel or other member of the battle fleet, during its course and fully autonomous weapons that once programmed will a mission hunt and seek their target.

Big-data is a game changer and allows a NCMS to achieve strategically and tactical advantage over an adversary. Key is being able to extracting time appropriate, actionable intelligence. This is achieved using Predictive Analytics. Predictive Analytics though has the potential to overwhelm operators with the sheer quantity and diversity of the data. Therefore Machine learning is introduced to automatically define the evolving mission.

6.5 Conclusion

Whilst it is impossible, with certainty, to predict the outcome of a mission in terms of outcomes and consequences, the application of cognition allows prediction and probabilities. Future combat missions will likely take place at the extremes into what is collectively known as irregular warfare. This can be the asymmetric threat of a weaker adversary facing a stronger opponent or the threat of using Weapons of Mass Destruction (WMD).

Addressing the evolving conventional threat as well as the unpredictable asymmetric threat requires an NCMS that learns and adapts to changing circumstance in the evolution of a mission. It has been shown that cognition, or machine learning is capable of sensing and understanding an environment and without prior knowledge of an adversarial system to derive an understanding of them and to rapidly take appropriate action. These capabilities are greatly enhanced with to big-data. A key enabling feature of the cognitive sensing system is that it uses information from the whole system rather than individual parts.

Real-time simulation and modelling of an adversary's kill-chain during the evolution of an engagement can be used to highlight weaknesses and strengths that can be exploited or avoids. Similar modelling can also be applied to the host vessel's kill-chain to highlight own weaknesses and strengths during an evolving mission.

A key recommendation is that the NCMS development will continue to be an evolutionary process with rapid advances expected in the application of Machine Learning, primarily driven by the commercial sector. The key for future NCMS is to focus on the framework that can be expanded and adapt to emerging requirements. Hardware will remain hardware in form of sensors and weapon system will remain the same. Software will be required to adapt to take on new challenges using the same core sensors and weapon systems.

Vessels designed today must be able to defend against the envisioned threat of tomorrow. The lifespan of a modern warship is between 20 and 30 years. Typically sensors and weapon system may be updated mid way through the service life. This equates to using today's technology to address the tomorrow's threat. One option to remain current is to update the software and associate computers at a more regular interval to utilize advances in algorithmic development and processing power to maintain a competitive edge.

For example, in the commercial world decision support software has already evolved from rule based doctrine systems to systems that are fully cognitive. Cognitive systems having the advantage that they can handle unique, never experienced before scenarios and past knowledge learnt from other cognitive systems. That is, one class of sensors can learn and adapt from another class to maintain knowledge superiority over an adversary.

Annex A

The following documents describe naval combat management systems (NMCS) and have been provided to the Contract Scientific Authority:

- Brochure for the SAAB 9LV NCMS
- Brochure for Lockheed Martin COMBATSS-21 NCMS
- Brochure for Elbit ENTCS NCMS
- Brochure for Selix ATHENA NCMS

List of symbols/abbreviations/acronyms/initialisms

AAW	Anti-air warfare
AI	Artificial Intelligence
AIS	Automatic Identification System
ACS	Aegis Combat System
ACTS	Aegis Combat Training System
ADSA	All Domain Situational Awareness
ADS	Aegis Display System
ADS-B	Automatic Dependent Surveillance – broadcast
AMD	Air and Missile Defense
AOI	Areas of Interest
AR	Augmented Reality
ASCM	Anti-Ship Cruise Missiles
ASW	Anti-Submarine Weapons
AWS	Aegis Weapon System
C2	Command and Control
C3	Command, Control & Communications
CA	Cyber Attack (CA)
C&D	Command and Decision
CE-NCMS	Cognitive Enabled NCMS
CI	Computational Intelligence
CS	Cyber Defence
CDS	Countermeasure Dispenser System
C&DS	Command and Decision Support
CEC	Cooperative Engagement Capability
CE-NCMS	Cognitive Enabled Naval Combat Management System
CEP	Cooperative Engagement Processor
CIWS	Close-In Weapon Systems
CMF	Combined Maritime Forces
CMS	Combat Management Systems

CO	Commanding Officer
COE	Common Operating Environment
COP	Common Operating Picture
COTS	Commercial of the Shelf
CS	Cognitive Systems
CSCS	Compact Sensor & Control System
CTF	Combined Task Force
CU	Cooperating Units
DA	Data Assessment
DCGS	Distributed Common Ground System
DCGS-N	Distributed Common Ground System - Navy
DDS	Data Distribution System
DFIG	Data Fusion Information Group
DIB	DCGS Integration Backbone
DMAIC	Define Measure Analyze Improve Control
DMR	Digital Modular Radio
DND	Department of National Defence
DRDC	Defence Research and Development Canada
DoD	Department of Defence
DSA	Dynamic Spectrum Access
DSS	Decision Support System
EA	Electronic Attack
EHF	Extremely High Frequencies
EM	Electromagnetic
EO	Electro-Optical
EO/IR	Electro-Optical/Infra-Red
EP	Electronic Protection
ESM	Electronic Support Measures
EW	Electronic Warfare
F2T2EA	Find, Fix, Track, Target,Engage, Assess
F5	Find, Fix, Finish, Feedback, Fire

FCS	Fire Control System
GMLS	Guided Missile Launching System
GIG	Global Information Grid
GPS	Global Positioning System
HLIF	High Level Information Fusion
HSI	Human-Systems Integration
IA	Impact Assessment
IaaS	Infrastructure as a service
IFF	Identify Friend or Foe
IOD	Information Oriented Design
IOS	Information Oriented Software
IRGCN	Iranian Revolutionary Guard Corps Many
IRIN	Islamic Republic of Iran Navy
ISR	Intelligence, Surveillance, and Reconnaissance
ISR&T	Intelligence, Surveillance, Reconnaissance and Targeting
LAN	Local Area Network
LAUs	LAN Access Units
LLIF	Low Level Information Fusion
LTTE	Liberation Tigers of Tamil Eelam
M/HALE	medium/high altitude long endurance
MI	Machine Intelligence
MM	Mission Management
NATO	North Atlantic Treaty Organization
NCMS	Naval Combat Management System
NCO	Network Centric Operations
NCW	Network-Centric Warfare
NIB	Non-Interference Basis
NIFC-CA	Navy Integrated Fire Control-Counter Air
NOC	Naval Operations Centres
NPB	Non-Protected Basis
NTC	Navy Tactical Cloud

OA	Object Assessment
ORTS	Operational Readiness Test System
OSA	Open Systems Architecture
PGM	Precision-Guided Munitions
PR	Process Refinement
R&D	Research and Development
R&I	Recognition and Identification
RCN	Royal Canadian Navy
RRM	Radar Resource Manager
SA	Software Arcitecture
SA	Situation Assessment
SDR	Software Defined Radio
SLN	Sri Lankan Navy
SOA	Service Oriented Architecture
SRM	Sensor Resource Manager
SSDS	Ship Self-Defense System (
TCPED	Tasking, Collection, Processing, Exploitation, Dissemination
TCRI	Tactical Cloud Reference Implementation
TEWA	Threat Evaluation and Weapon Assignment
UAVs	Unmanned Autonomous Vehicles
UNCLOS	United Nations Convention on the Law of the Sea
UR	User Refinement
U.S.	United States
USMC	United Sates Marine Corps
USS	United States Ship
VLF	Very Low Frequency
WAMI	Wide-area Motion Imagery
WLAN	Wireless Local Area Network
WCS	Weapon Control System
WMD	Weapons of Mass Destruction

References

[1] C Nemeth et. al., *Engineering Naval Resilience: Expeditionary Command and Control*, Proceedings of the fourth Resilience Engineering Symposium, page 186-192 June 8-10, 2011, Sophia Antipolis, France http://books.openedition.org/pressesmines/1059, retrieved 2017-12-09

[2] Linking Cognitive Data to Design In Navy Command and Control

[3] M.Keane, "C2" Dictionary of Modern Strategy and Tactics,U.S.Naval Insitutute Press, 2005

[4] http://www.navy-marine.forces.gc.ca/en/about/index.page retrieved 2017-12-09.

[5] http://www.navy-marine.forces.gc.ca/en/fleet-units/mcdv-home.page retrieved 2017-12-09.

[6] B. H. Liddell Hart, Strategy, 2d revised edition, New York: Signet, 1974

[7] Brewer, David (2003). The Greek War of Independence: The Struggle for Freedom from Ottoman Oppression and the Birth of the Modern Greek Nation. Overlook Press. p 93

[8] Office of Naval Intelligence *Report on Iranian Naval Forces*, March 1, 2017 10:25 AM, Updated: March 8, 2017 10:54 AM, retrieved 2018-01-15

[9] IRGCN Small Boat Tactics https://www.globalsecurity.org/military/world/iran/navy-doctrine-2.htm retrieved 2018-01-15

[10] https://www.iiss.org/en/militarybalanceblog/blogsections/2015-090c/april-6dca/ukraines-navy-8311 retrieved 2018-01-15

[11] https://jamestown.org/program/terrorism-and-piracy-the-dual-threat-to-maritime-shipping retrieved 2018-01-15

[12] https://www.revolvy.com/main/index.php?s=Sea%20Tigers retrieved 2018-01-15

[13] http://www.tamilguardian.com/content/sea-tiger-frogmen-sink-navy-supply-ship retrieved 2018-01-15

[14] https://combinedmaritimeforces.com/about retrieved 2018-01-18.

[15] *Modern Piracy Tactics and Challenges,* Op-ed by Allison Maykuth of Beowulf Defense And Security, http://www.oceanuslive.org/main/viewnews.aspx?uid=00000357

[16] T. Howard and J. de Arimatéia da Cruz, *A Cyber Vulnerability Assessment of the U.S. Navy in the 21st Century* Center for International Maritime Security January 31, 2017 http://cimsec.org/cyber-vulnerability-assessment-u-s-navy-21st-century/30405

[17] Department of the Navy Chief Information Officier 0- Definition of Cyber Security. http://www.doncio.navy.mil/tagresults.aspx?ID=28 retrieved 2018-01-23.

[18] MARAD MSCI Alert 2017-005A-GPS Interference-Black Sea https://www.marad.dot.gov/msci/alert/2017/2017-005a-gps-interference-black-sea

[19] New Ccientist Daily news10 August 2017, Ships fooled in GPS spoofing attack suggest Russian cyberweapon, https://www.newscientist.com/article/2143499-ships-fooled-in-gps-spoofing-attack-suggest-russian-cyberweapon

[20] M. Jones, *Spoofing in the Black Sea: What really happened?* GPS World, October 11, 2017 http://gpsworld.com/spoofing-in-the-black-sea-what-really-happened retrieved 2018-01-17

[21] S. LaGrone U.S. Boat Crew Navigation Error, Not Technology Tampering Led to Seizure of 10 Sailors by Iran, USNI News, January 28, 2016 11:42 AM. https://news.usni.org/2016/01/28/u-s-boat-crew-navigation-error-not-technology-tampering-led-to-seizure-of-10-sailors-by-iran Retrieved 2018-01-17.

[22] Scott Peterson & Payam Faramarzi *Iran hijackedU.S.drone* Cristian Scientist Monitor, December 15, 2011 https://www.csmonitor.com/World/Middle-East/2011/1215/Exclusive-Iran-hijacked-US-drone-says-Iranian-engineer retrieved 2018-01-17

[23] Eric Wertheim, The Naval Institute Guide to Combat Fleets of the World;Their Ships, Aircraft, and Systems, 16th Edition,U.S.Naval Institute, Published:August 15, 2013

[24] http://elbitsystems.com/products/naval-systems/naval-combat-management-systems retrieved 2017-12-18

[25] *https://en.wikipedia.org/wiki/Kill_chain* retrieved 2017-12-18

[26] http://cno.navylive.dodlive.mil/2013/04/23/kill-chain-approach-4 Admiral Greenert Outlines FY14 Budget Priorities to HASC, Be Ready: The Critical Link to Our Success, Kill Chain Approach, Posted on April 23, 2013 by jfmetzger

[27] Human Rights Watch, *Review of the 2012 US Policy on Autonomy in Weapons Systems,* April 15, 2013 8:13PM EDT https://www.hrw.org/news/2013/04/15/review-2012-us-policy-autonomy-weapons-systems retrieved 2018-01-22

[28] M., Benitez *It's About Time: The Pressing Need to Evolve The Kill Chain,* WAR on the Rocks, May 17, 2017 https://warontherocks.com/2017/05/its-about-time-the-pressing-need-to-evolve-the-kill-chain

[29] S. Freedberg Jr. Navy Issues New Cybersecurity Standards – With More To Come, Intel & Cyber, Sea, Breaking Defence, February 22, 2016 https://breakingdefense.com/2016/02/navy-issues-new-cybersecurity-standards-with-more-to-come retrieved 2018-01-18.

[30] Advances in Cognitive Ergonomics, Editors Gavriel Salvendy, Waldemar Karwowski, Chapter 7 A Cognitive and Holistic Approach to Developing Metrics for Decison Support in Command and Control, D. Lafond, F. Vachon, R Rousseau, S. Tremblay, CRC Press, Apr. 19, 2016

[31] Jeffrey T. Hansberger *The Distributed Cognitive Components of C2,* 13th International Command and Control Research and Technology Symposia (ICCRTS 2008), 17-19 Jun 2008, Seattle, WA

[32] U.S. Joint Chiefs of Staff JP2-0 - http://www.dtic.mil/doctrine/new_pubs/jp2_0.pdf

[33] J., Gratch and R W., Hill, *Continuous Planning and Collaboration for Command and Control in Joint Synthetic Battlespaces* in .Proc. of the 8th Conference on Computer Generated Forces and Behavioral Representation, Orlando, FL, May 1999

[34] K. Myers *CPEF -A Continuous Planning and Execution Framework*, AI Magazine Volume 20 Number 4 (1999)

[35] A Cognitive Modeling Approach to Strategy Formation in Dynamic Decision Making, S.,Prezenski1, A., Brechmann, S Wolff and N., Russwinkel in Cognitive Modeling in Dynamic Human-Machine Systems, Frontiers. Psychol., 04 August 2017. https://doi.org/10.3389/fpsyg.2017.01335

[36] *Cognitive Elements of Human Decision Making,* J Pohl, February 2008 DOI10.1007/978-3-540-76829-6_2 In book: Intelligent Decision Making: An AI-Based Approach, pp.41-76 https://www.researchgate.net/publication/225192961_Cognitive_Elements_of_Human_Decision_Making

[37] D. Lafond et.al., Advances in Cognitive Ergonomics, Editors Gavriel Salvendy, Waldemar Karwowski, Chapter 7 *A Cognitive and Holistic Approach to Developing Metrics for Decison Support in Command and Control*, CRC Press, Apr. 19, 2016

[38] C. Gonzalez et al., "The use of microworlds to study dynamic decision making". Computers in human behaviour, 21, (273-286)

[39] Fuster, Joaquin (2004). Upper processing stages of the perception–action cycle. Trends in Cognitive Sciences 2004 8(4) pp.143-145.

[40] Perception-Action Cycle: Models, Architectures, and Hardware (Springer Series in Cognitive and Neural Systems) Feb 2011, by Vassilis Cutsuridis (Editor), Amir Hussain (Editor), John G. Taylor (Editor)

[41] https://www.trentonsystems.com/news/big-data-drives-distributed-common-ground

[42] *https://www.smartinsights.com/goal-setting-evaluation/web-analytics-strategy/top-10-strategies-turn-data-actionable-analytics*

[43] https://elearningindustry.com/information-vs-knowledge-tips-transform-information-knowledge-elearning retrieved 2018-02-12

[44] Erik Blasch, et al., High Level Information Fusion (HLIF): Survey of Models, Issues, and Grand Challenges, September 2012 EEE Aerospace and Electronic Systems Magazine 27(9):4-20 https://www.researchgate.net/publication/260657838_High_Level_Information_Fusion_HLIF_Survey_of_Models_Issues_and_Grand_Challenges

[45] Erik Blasch et al., Top Ten Trends in High-Level Information Fusion https://pdfs.semanticscholar.org/b9fc/065d6698a1492bd6d7d52a339f8cc05240ac.pdf retrieved 2018-02-21

[46]Derek B. Johnson, Are federal agencies ready to bail on data centers? Published in The Business of Federal Technology, Aug 23, 2017 https://fcw.com/articles/2017/08/23/bail-data-centers-cios.aspx retrieved 2018-02-21

[47] Derek B. Johnson, *DOD looks to get aggressive about cloud adoption*, Published in The Business of Federal Technology, Sep 20, 2017 https://fcw.com/articles/2017/09/20/dod-cloud-adoption-risks.aspx retrieved 2018-02-21

[48] https://en.wikipedia.org/wiki/Predictive_analytics retrieved 2017 -12-10

[49] https://en.wikipedia.org/wiki/Predictive_analytics retrieved 2017 -12-10

[50] http://www.sixsigmadaily.com/six-sigma-fundamentals-dmaic retrieved 2017-12-20

[51] https://en.wikipedia.org/wiki/Machine_learning retrieved 2017-12-10

[52] C. Clancy, J. Hecker, E. Stuntebeck & Tim O'Shea *Applications of Machine Learning to Cognitive Radio Networks*, IEEE Wireless Communications, Year: 2007, Volume: 14, Issue: 4,Pages: 47 - 52

[53] R. Wang *Understand The Spectrum Of Seven Artificial Intelligence Outcomes,* Sept 19, 2016. https://www.enterpriseirregulars.com/110009/mondays-musings-understand-spectrum-seven-artificial-intelligence-outcomes retrieved 2018-02-28

[54] http://quotulatiousness.ca/blog/wp-content/uploads/2015/12/Halifax-class-mid-life-upgrades.png retrieved 2018-02-26

[55] Rear Admiral (Retd) Arun Saxena, *Weapon Systems & Sensors for Modern Warships* SP's Naval Forces Issue: 4 / 2012 http://www.spsnavalforces.com/story/?id=220

[56] https://www.thalesgroup.com/en/worldwide/defence/apar-active-phased-array-multifunction-radar retrieved 2018-01-23.

[57] G. M. Kuretsky et al., *A Tutorial on Electro-Optical/Infrared (EO/IR) Theory and Systems* , IDA publication https://www.ida.org/idamedia/Corporate/Files/.../IDA.../ida-document-d-4642.pdf 2018-02-24

[58] Software-Defined Communications For The U.S. Navy https://gdmissionsystems.com/products/communications/radios/digital-modular-radio retrieved 2018-01-31

[59] Autonomous Vehicles - Naval Applications. *down loaded from ficci.in/events/22716/ISP/1-RADM_SRINIVAS_KANUGO.pdf* 2017-12-19

[60] *Autonomous Vehicles In Support Of Naval Operations*, Committee on Autonomous Vehicles in Support of Naval Operations, Naval Studies Board, Division on Engineering and Physical Sciences, The National Academies Press, Washington, D.C., 2005 https://www.nap.edu/download/11379 down loasded 2017-12-19

[61] https://www.raytheon.com/capabilities/products/tomahawk retrieved 2017-12-18

[62] U.S. Navy Non-Lethal Weapons Information fact sheet http://jnlwp.defense.gov/Service-Related-Non-Lethal-Weapons-Information/US-Navy-Non-Lethal-Weapons-Information retrieved 2017-12-11

[63] http://www.rfcafe.com/miscellany/images/radar-operator-01.jpg retrieved 2017-12-12

[64] S. Haykin, *Cognition is the Key to the Next Generation of Radar Systems*, Digital Signal Processing Workshop and 5th IEEE Signal Processing Education Workshop, 2009. DSP/SPE 2009. IEEE 13th

[65] P. Moo, and Z. Ding *Adaptive Radar Resource Management,* Academic Press, 2015

[66] A. O. Hero III & D Cochran, *Sensor Management: Past, Present and Future*. IEEE Sensors Journal (Volume: 11, Issue: 12, Dec. 2011)

[67] D. Khosla and J Guillochon *Distributed sensor resource management and* planning Proceedings Volume 6567, Signal Processing, Sensor Fusion, and Target Recognition XVI; 65670B (2007); doi: 10.1117/12.719929, Defense and Security Symposium, 2007, Orlando, Florida, United States

[68] B. Kovalerchuk and L. Perlovsky (2016) *Sensor Resource Management: Intelligent Multi-objective Modularized Optimization Methodology and Models*. In: Abielmona R., Falcon R., Zincir-Heywood N., Abbass H. (eds) Recent Advances in Computational Intelligence in Defense and Security. Studies in Computational Intelligence, vol 621. Springer, Cham

[69] D. K. Prasad, et al., *Maritime situational awareness using adaptive multi-sensor management under hazy conditions* *https://pdfs.semanticscholar.org/9abc/17f350bc9bacc090aaaad8d5e944e7c7bb90.pdf*,

[70] D. S. Alberts and R E. Hayes, *Power to the Edge, Command.and Control in the Information Age*, Information Age Transformation Series, CCRP Publication Series 2003.

[71] US Navy Fact File CEC - Cooperative Engagement Capability http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=325&ct=2 retrieved 2018-02-21

[72] Johns Hopkins Apl Technical Digest, Volume 16, Number 4 (1995) *www.jhuapl.edu/techdigest/td/td1604/APLteam.pdf*

[73]Federation of American Scientists (FAS), - Cooperative Engagement Capability https://fas.org/man/dod-101/sys/ship/weaps/cec.htm

[74], Open Systems Architecture (OSA) http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=450&ct=2 retrieved 2017-12-10

[75] IBM developers Note, developerWorks > SOA and Web services > Migrating to a service-oriented architecture, Part 1 http://www-128.ibm.com/developerworks/library/ws-migratesoa/ retrieved 2017-12-11

[76] N. Minar *Distributed Systems Topologies*: *Part 1*, 12/14/2001, http://www.openp2p.com/pub/a/p2p/2001/12/14/topologies_one.html retrieved 2018-01-12

[77] https://www.kullabs.com/classes/subjects/units/lessons/notes/note-detail/3952 retrieved 2018-02-01

[78] https://en.wikipedia.org/wiki/Information_oriented_software_development

[79] By Panda 51 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=20987182)

[80] By Service Depicted: NavyCamera Operator: TIM MASTERSON - ID:DNST9304318, Public Domain, https://commons.wikimedia.org/w/index.php?curid=1448384

[81] AEGIS Weapon System Mk 7 https://www.globalsecurity.org/military/systems/ship/systems/aegis-core.htm retrieved 2017-12-19

[82]AEGIS Weapon System Mk 7 https://www.globalsecurity.org/military/systems/ship/systems/aegis-core.htm retrieved 2017-12-19

[83] Investigation Report, US Secretary of Defence, *Formal Investigation into the Circumstances Surrounding the Downing of Iran Air Flight 655 on 3rd July 1988*. Retrieved from www.dtic.mil/dtic/tr/fulltext/u2/a203577.pdf 2018-01-11

[84] J. R. Hammond *The 'Forgotten' US Shootdown of Iranian Airliner Flight 655*- Foriegn Policy Journal, Jul 3, 2017 https://www.foreignpolicyjournal.com/2017/07/03/the-forgotten-us-shootdown-of-iranian-airliner-flight-655%C2%AD/ retrieved 2018-01-11

[85] US Navy Fact Sheet, *Distributed Common Ground System-Navy(DCGS-N)* www.secnav.navy.mil/rda/Documents/dcgs-n+overview+for+asn+rda+nov11-s.pdf retrieved 2017-19-12

[86] Raytheon product information sheet DCGS https://www.raytheon.com/capabilities/products/dcgs/ retrived 2018-01-12

[87] Data Focused Naval Tactical Cloud (DF-NTC), ONR Information Package, June 24, 2014

[88] DelTek, GovWin IQ, Market Analysis Article, *DoD Rolls Into the Combat Cloud*, Published: February 22, 2017 https://iq.govwin.com/neo/marketAnalysis/view/1909?researchTypeId=1 retrieved 2017-12-14

[89] U.S. Naval Institute News *Navy Set to Deploy New Lethal Anti-Surface 'Tactical Cloud' Later this Year,* Sam LaGrone and Megan Eckstein, May 17, 2016 https://news.usni.org/2016/05/17/navy-set-to-deploy-new-lethal-anti-surface-tactical-cloud-later-this-year retrieved 2017-12-14

[90]US Navy Fact File, CEC - Cooperative Engagement Capability http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=325&ct=2 , retrieved 2018-01-15

[91] The Big Picture, Raytheon systems connect the dots for naval defense, https://www.raytheon.com/news/feature/big-picture.html , retrieved 2018-01-15

[92] M., Eckstein *NIFC-CA Advances Could Allow The Navy To Use Cheaper 'Dumb' Weapons* : USNI News February 22, 2017 7:54 PM https://news.usni.org/2017/02/22/nifc-ca-advances-could-allow-the-navy-to-use-cheaper-dumb-weapons

[93] M., Benitez *It's About Time: The Pressing Need to Evolve The Kill Chain,* WAR on the Rocks, May 17, 2017 https://warontherocks.com/2017/05/its-about-time-the-pressing-need-to-evolve-the-kill-chain

[94] https://www.prnewswire.com/news-releases/raytheon-awarded-us-navy-contract-for-ship-self-defense-system-177240981.html retrieved 2018-02-26

[95] Navy Program Ship Self Defence System www.dote.osd.mil/pub/reports/FY2011/pdf/navy/2011ssds.pdf

[96] https://www.raytheon.com/capabilities/products/ssds/

[97] Global Security Org Ship Self Defence System, https://www.globalsecurity.org/military/systems/ship/systems/ssds.htm retrieved 2018-01-11

[98] L. S. Norcutt *Ship Self-Defense System Architecture* Johns Hopkins Apl Technical Digest, Volume 22, Number 4 (2001), www.jhuapl.edu/techdigest/TD/td2204/Norcutt.pdf

[99] Lt General Naresh Chand (Retd), Naval Combat Management Systems, SP's Naval Forces, Issue: 4 / 2014 http://www.spsnavalforces.com/story/?id=333 retrieved 2018-02-22

[100] https://www.lockheedmartin.ca/ca/what-we-do/.../combat-management-system.html retrieved 2018-02-22

[101] https://www.thalesgroup.com/en/tacticos-combat-management-system retrieved 2018-02-22

[102] http://maxdefense.blogspot.ca/2016/09/naval-combat-management-system.html retrieved 2018-02-22

[103] https://saab.com/naval/decision-superiority/combat-management-systems/9lv-cms retrieved 2018-02-22

[104] https://www.lockheedmartin.com/content/dam/.../data/.../COMBATSS-21-brochure.pd.. retrieved 2018-02-22

[105] https://www.naval-group.com/en/produit/combat-systems retrieved 2018-02-22

[106] http://elbitsystems.com/product/naval-combat-management-systems retrieved 2018-02-22

[107] https://www.baesystems.com/en/product/combat-management-systems retrieved 2018-02-22

[108] http://www.larsentoubro.com/heavy-engineering/products-services/defence-aerospace/naval-combat-management-systems retrieved 2018-02-22

[109] www.leonardocompany.com/documents/.../body_mm07892_Athena_LQ_.pdf, retrieved 2018-02-22

[110] M. Safahani et al. *The Role of Simulation in Determining Personnel Suitability,* Journal of Ocean Technology, The Future of Martime Simulation, Vol 11, No 1, 2016

[111] Chapter 20 Command, Control, and Communication https://fas.org/man/dod-101/navy/docs/fun/part20.htm

[112] Colleen Roller , *How Cognitive Fluency Affects Decision Making* in Decision Architecture, Designing for Decision Making, July 2011. www.uxmatters.com/mt/archives/2011/07/how-cognitive-fluency-affects-decision-making.php retrieved 2018-02-26

[113] Fundamentals of Naval Weapons Systems, Chapter 20 *Command, Control, and Communication* https://fas.org/man/dod-101/navy/docs/fun/part20.htm

[114] R S Panwar, *Artificial Intelligence in Military Operations: Technology, Ethics and the Indian Perspective* *https://idsa.in/idsacomments/artificial-intelligence-in-military-operations-india_rspanwar_310118*

[115] Ryan Felton, *A Whopping $80 Billion Has Been Invested So Far In The Self-Driving Car Race* https://jalopnik.com/a-whopping-80-billion-has-been-invested-so-far-in-the-1819504421 retrieved 2018-02-26

[116] : M Holland et al ., *Hydrographic processing considerations in the "Big Data" age: An overview of technology trendsin ocean and coastal surveys* 2016 IOP Conf. Ser.: Earth Environ. Sci. 34 012016 *iopscience.iop.org/article/10.1088/1755-1315/34/1/012016/pdf*

[117] Alfred O. Hero III and Douglas Cochran, *Sensor management: Past, Present, and Future*. IEEE Sensors Journal, 2011 down loaded from https://arxiv.org/pdf/1109.2363

[118] A.A. Gorji, R. Tharmarasa and T. Kirubarajan, *Performance measures for multiple target tracking problems*, Proc. Conference on Information Fusion, Chicago, IL, USA, July 2011.

[119] D. Akselrod, A. Sinha, T. Kirubarajan, M. Farooq and Z. J. Ding, *A distributed multisensor-multitarget tracking testbed for maritime surveillance*, Proc. SPIE Defense and Security Symposium, Orlando, FL, April 2005.

[120] D. Akselrod, A. Sinha, T. Kirubarajan, M. Farooq and Z. J. Ding, *A distributed multisensor-multitarget tracking testbed for maritime surveillance*, Proc. SPIE Defense and Security Symposium, Orlando, FL, April 2005.

[121] A. Sinha, T. Kirubarajan and Y. Bar-Shalom, *Autonomous Ground target tracking by multiple cooperative UAVs,* Proc. IEEE Aerospace Conference, Big Sky, MT, March 2005.

[122] R. Tharmarasa, T. Lang and T. Kirubarajan, "Tracking with poorly localized sensors in multistatic sensor networks", Proc. SPIE Conference on Signal and Data Processing of Small Targets, Vol. 6969, Orlando, FL, March 2008.

[123] S. Sutharsan et al., *An optimization-based parallel particle filter for multitarget tracking* Optics and Photonics 2005, San Diego, California, United States, Proceedings Volume 5913, Signal and Data Processing of Small Targets 2005

[124] Bilotti, Filiberto, Sevgi, Levent *Metamaterials: Definitions, properties, applications, and FDTD-based modeling and simulation (Invited paper),* - International Journal of RF and Microwave Computer-Aided Engineering, Jan 2012. https://www.researchgate.net/publication/262320155_Metamaterials_Definitions_properties_applications_and_FDTD-based_modeling_and_simulation_Invited_paper

[125] E. Azimirad, J. Haddadnia, *The comprehensive review on jdl model in data fusion networks: techniques and methods*, International Journal of Computer Science and Information Security, Vol. 13, No. 1, January 2015.

[126] *Brain plasticity* http://www.learning-knowledge.com/plasticity.html retrieved 2018-02-01

[127] A. Thirumalaisamy, et al., *Fusing social network data with hard data*, Proc. 18th International Conference on Information Fusion, Washington, DC, USA, July 2015.

[128] F. D'Souza, *Modeling and implementing distributed computing with applications in multisensor-multitarget tracking*, Master's Thesis, Electrical and Computer Engineering Department, McMaster University, August 2015.

[129] S. Tager, *GPU-specific Kalman Filtering and retrodiction for large-scale target tracking*, Master's Thesis, Electrical and Computer Engineering Department, McMaster University, August 2015.

[130]Daniel Lafond, et al., *Judgment Analysis in a Dynamic Multitask Environment: Capturing Nonlinear Policies Using Decision Trees, Journal of Cognitive Engineering and Decision Making* 2017, Volume 11, Number 2, June 2017, pp. 122–135, DOI: 10.1177/1555343416661889

[131] Chapter 20 Command, Control, and Communication, https://fas.org/man/dod-101/navy/docs/fun/part20.htm

[132] S., Lee et al., *Attack-Aware Multi-Sensor Integration Algorithm for Autonomous Vehicle Navigation* Systems, 2017 https://arxiv.org/pdf/1709.02456

[133] Weapons and Systems Engineering Deptartment, United States Naval Academy, *Fundamentals of Naval Weapons Systems, Chapter 20 Command, Control, and Communication* https://fas.org/man/dod-101/navy/docs/fun/index.html *retrieved 2018-02-21*

[134] M., Benitez *It's About Time: The Pressing Need to Evolve The Kill Chain,* WAR on the Rocks, May 17, 2017 https://warontherocks.com/2017/05/its-about-time-the-pressing-need-to-evolve-the-kill-chain

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1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.) Anthony M. Ponsford, Consultant, c/o Breckenhill, Inc., 305 Breckenridge Cres., Ottawa ON K2W 1J3	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) CAN UNCLASSIFIED 2b. CONTROLLED GOODS NON-CONTROLLED GOODS DMC A

3. TITLE (The document title and sub-title as indicated on the title page.)

Role of cognition in a future naval combat management system

4. AUTHORS (last name, followed by initials – ranks, titles, etc., not to be used)

Ponsford, A.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.)	6b. NO. OF REFS (Total references cited.)
September 2018	107	134

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

Contract Report

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

DRDC – Ottawa Research Centre
Defence Research and Development Canada
3701 Carling Avenue
Ottawa, Ontario K1A 0Z4, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
DRDC-RDDC-2018-C070	

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

naval sensors; naval weapons; sensor resource management; cognition

13. ABSTRACT/RESUME (When available in the document, the French version of the abstract must be included here.)

This report provides a non-technical introduction to Naval Combat Management Systems (NCMS) and concludes with the proposal for a Holistic-NCMS designed to meet the future requirements of the Royal Canadian Navy.

NCMS is a cognitive aid that naval forces use to manage their resources. The NCMS connects the sensor suite to the weapon systems via the Command and Control (C2) system. The C2 system ingests and processes sensor data to supports operator cognitive tasks including planning, re-planning, sense-making and situational assessment. The core functions of the NCMS are to observe, analyze and take action.

The NCMS supports objective reasoning to facilitate a commander to take subjective actions. The overall objective is to gain a competitive advantage over an adversary. That is, to enable a commander to take the best action given their current understanding of the situation. The NCMS manages conventional systems, semi-autonomous and fully autonomous systems. The NCMS is required to function as a standalone entity and work within a collaborative network of coalition forces.

The sensor and weapons suites are mature technologies and no significant innovation is expected to occur in the near future. Therefore, advances in the performance of NCMS will be gained primarily by processing data from existing systems and utilizing this data in such a way that the resulting product is greater than just the sum-of-the-parts.

The report proposes a new Holistic-NCMS that is based on a system-of-systems approach to sensor resource management. This approach utilizes recent advances in networking and computational intelligence. This report discusses the emergence of cognitive computing as the enabling technology.

Cognitive computing can be used within the sensor suite to optimize performance based on the known environment, current threat and historical data. The Sensor Resource Manager (SRM) uses data from across the sensor suite as well as external sources to achieve this goal. Cognitive computing also plays a critical role in the C2 system where it has the capability of exploiting big-data to enhance timely informed decision support, planning and engagement

The proposed SRM dynamically allocates resources and tasking across sensor suite. The SRM adds placidity to the system such that in the event of sensor failure, the system optimally reallocates resources and tasking to fill the void.

The Holistic-NCMS incorporates real-time simulation and modelling of an adversary's kill-chain during an evolving engagement to highlight weaknesses and strengths that can be exploited or avoided. Similar modelling is also be applied to the host vessel's kill-chain to highlight own weaknesses and strengths during an evolving mission.

The report includes a section on recommended future R&D that has been compiled using input from both NCMS suppliers as well as researchers in the area of cognitive computing and cognition, big-data, decision support, sensor resource management, and real-time simulation and modelling

Le présent rapport consiste en une introduction non technique aux systèmes de gestion du combat naval (SGCN) et offre en guise de conclusion une proposition de SGCN holistique conçu pour répondre aux besoins futurs de la Marine royale canadienne.

Le SGCN est une aide cognitive que les forces navales utilisent pour gérer leurs ressources. Le SGCN relie la suite de capteurs aux systèmes d'armes par l'entremise du système de commandement et de contrôle (C2). Le système de C2 ingère et traite les données des capteurs en appui de l'exécution des tâches cognitives des opérateurs, y compris la planification, la replanification, la détermination du sens et l'évaluation de la situation. Les fonctions essentielles du SGCN consistent à observer, analyser et prendre les mesures nécessaires.

Le SGCN étaye le raisonnement objectif pour faciliter au commandant la prise de mesures subjectives. L'objectif global est d'obtenir un avantage concurrentiel face à l'adversaire. C'est-à-dire permettre au commandant de prendre la meilleure mesure en fonction de sa compréhension actuelle de la situation. Le SGCN gère des systèmes conventionnels, des systèmes semi-autonomes et des systèmes entièrement autonomes. Le SGCN est appelé à fonctionner en tant qu'entité autonome et au sein d'un réseau collaboratif de forces de la coalition.

Les suites de capteurs et d'armes sont des technologies matures, et on ne s'attend pas à ce que des innovations importantes fassent leur apparition dans un avenir rapproché. Par conséquent, les avancées du rendement du SGCN seront principalement le fruit du traitement de données provenant de systèmes existants, ainsi que de l'utilisation de ces données de façon telle que la valeur du produit fini soit plus grande que celle de la somme des pièces en jeu.

Le rapport propose un nouveau SGCN holistique fondé sur une approche de système des systèmes pour la gestion des ressources des capteurs. Cette approche fait appel aux avancées récentes dans les domaines du réseautage et de l'intelligence informatique. Le rapport discute de l'émergence de l'informatique cognitive en tant que technologie habilitante.

L'informatique cognitive peut servir au sein de la suite de capteurs à optimiser le rendement en fonction de l'environnement connu, de la menace actuelle et des données historiques. Le gestionnaire des ressources des capteurs (GRC) utilise les données provenant de toute la suite des capteurs ainsi que de sources externes pour atteindre ce but. L'informatique cognitive joue aussi un rôle essentiel dans le système de C2, oû elle a la capacité d'exploiter des mégadonnées pour améliorer en temps voulu et de façon éclairée l'appui à la prise de décisions, la planification et l'engagement.

Le GRC proposé alloue dynamiquement les ressources et les tâches dans toute la suite de capteurs. Le GRC ajoute de la placidité au système en ce que, dans l'éventualité d'une panne de détecteur, il peut réallouer de façon optimale les ressources et les tâches pour remplir le vide.
Le SGCN holistique intègre une capacité de simulation et de modélisation en temps réel de la chaîne de destruction de l'adversaire durant un engagement en cours afin de mettre en lumière les faiblesses et les forces à exploiter ou à éviter. Une modélisation similaire est aussi appliquée à la chaîne de destruction du navire hôte afin de mettre en lumière ses propres faiblesses et forces durant une mission en cours.

Le rapport comprend une section sur la R et D recommandée produite à partir d'intrants fournis par les fournisseurs du SGCN ainsi que des chercheurs dans les domaines de l'informatique cognitive et de la cognition, des mégadonnées, de l'appui à la prise de décision, de la gestion des ressources des capteurs et de la simulation et modélisation en temps réel.