Defence Research and Development Canada
Recherche et développement pour la défense Canada

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Combat Resource Management (11bm) Applied Research Project (ARP): Final report

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Defence R&D Canada – Valcartier
Technical Report
DRDC Valcartier TR 2009-300
December 2009

Canada

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Abstract

Defence Research & Development Canada (DRDC) has, for several years now, been investigating methods to augment or enhance existing shipboard Command and Control System (CCS) capabilities. As part of this investigation, 11bm Applied Research Project (ARP) focuses on the naval combat resource management in the context of Above Water Warfare (AWW).

The project, a summary of which is presented in this report, has explored concepts concerned with the design, development, implementation, and evaluation of a computer-based, real-time decision support system that could be integrated into the future Canadian platforms to assist operators in conducting tactical Command and Control (C2), particularly for combat resource management.

The project resulted in a list of achievements, which includes scientific publications, algorithms, software tools, and recommendations for follow-on work. It has also provided inputs to several projects, including INCOMMANDS and SISWS Technology Demonstration Projects (TDPs).

Résumé

Recherche et développement pour la défense Canada (RDDC) étudie, depuis plusieurs années, des méthodes pour améliorer et augmenter les capacités des systèmes de commandement et contrôle (C2) à bord des navires de combat. Le projet de recherche appliquée (PRA) 11bm, sur la gestion des ressources de combat dans le cadre de la guerre navale aérienne et de surface, représente un des volets de cette étude.

Ce projet, dont un résumé est présenté dans ce rapport, a exploré des concepts visant la conception, le développement, l'exécution et l'évaluation des systèmes interactifs d'aide à la décision informatisés. Ces concepts pourraient être intégrés aux futures plates-formes navales canadiennes pour aider des opérateurs dans la conduite des tâches reliées au C2 tactique, en particulier la gestion des ressources de combat.

Le projet a résulté en une liste de réalisations qui inclut des publications scientifiques, des algorithmes, des outils logiciels et des recommandations pour des projets futurs. Il a également contribué à plusieurs projets majeurrs, incluant les démonstrateurs technologiques INCOMMANDS et SISWS.

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Executive summary

Combat Resource Management (11bm) Applied Research Project (ARP): Final report

A. Benaskeur; DRDC Valcartier TR 2009-300; Defence R&D Canada – Valcartier; December 2009.

Advances in threat technology, the increasing difficulty and diversity of open-ocean and littoral (*i.e.*, near land) scenarios, and the volume and imperfect nature of data to be processed under time-critical conditions pose significant challenges for future shipboard Command and Control Systems (CCSs). Among other functionalities, the CCS provides capabilities to allow operators to evaluate the threat level of the different objects within the Volume Of Interest (VOI), and use the shipboard combat resources, when required, to response to them.

Management of tactical shipboard combat resources, as a part of military naval Command and Control (C^2) process, provides a real world application that involves both human and software decision-makers. To defend itself, a platform, such as a Halifax Class Frigate, uses different systems and modules that interact directly or indirectly together. Therefore, it is very necessary to propose ways to allocate and coordinate the use of the different systems in order to increase the ship's defensive effectiveness against potential threats.

To achieve this requirement, the 11bm Applied Research Project (ARP) was defined to focus on the naval combat resource management in the context of Above Water Warfare (AWW), by exploring concepts concerned with the design, development, implementation, and evaluation of a computer-based, real-time decision support system that could be integrated into the future Canadian platforms to assist operators in conducting tactical C^2. More specifically, this project addressed the following problems: combat resource allocation problem, combat resource coordination problem, tactics generation and evaluation, and Operations Room Officer (ORO) plan integration.

The project results in a list of achievements, which includes:

1. DRDC technical reports
2. Open-literature scientific publications
3. PhD and Master Theses
4. Software tools
5. Knowledge about several technologies that can be used to tackle resource management problems, and
6. Finally, inputs to DRDC and Department of National Defence (DND) major projects, such as INCOMMANDS and SISWS Technology Demonstration Projects (TPDs), and Halifax Modernization Command and Control System (HMCCS) acquisition project.

These achievements are summarized in this report. Note that this report is not intended to provide all the details about these achievements. Reference to the appropriate documents, which provide further details, is given.

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Sommaire

Combat Resource Management (11bm) Applied Research Project (ARP): Final report

A. Benaskeur ; DRDC Valcartier TR 2009-300 ; Recherche et Développement pour la Défense Canada – Valcartier ; decembre 2009.

Les progrès réalisés en technologie de la menace, la difficulté et la diversité croissantes des scénarios en haute mer et près du littoral, ainsi que le volume et la nature imparfaite des données à traiter dans des temps critiques représentent des défis significatifs pour les futurs systèmes de commandement et contrôle embarqués. En plus d'autres fonctionnalités, un système de commandement et contrôle doit permettre aux opérateurs d'évaluer efficacement le niveau de menace des différents objets dans une zone d'intérêt et, au besoin, d'employer les ressources de combat à bord du navire pour répondre aux menaces.

La gestion des ressources tactiques de combat embarquées, comme partie du processus C2 naval militaire, définit un domaine application qui implique à la fois des décideurs humains et logiciels. Pour se défendre, une plate-forme, telle qu'une frégate de classe Halifax, utilise différents systèmes et modules qui interagissent directement ou indirectement ensemble. Par conséquent, il devient nécessaire de proposer des manières d'allouer et coordonner l'utilisation des différents systèmes afin d'augmenter l'efficacité de défense du navire face aux menaces potentielles.

Pour ce faire, le projet de recherche appliquée 11bm a été défini avec, comme problème cible, la gestion des ressources navales de combat dans le cadre de la guerre aérienne et de surface. Le projet a exploré des concepts visant la conception, le développement, l'exécution et l'évaluation de systèmes d'aide à la décision informatisés. Ces derniers pourraient être intégrés dans les futures plates-formes canadiennes pour aider des opérateurs dans la conduite des opérations liées au C2 tactique, et plus particulièrement la gestion des ressources de combat.

Plus spécifiquement, ce projet a abordé les problèmes suivants : l'allocation des ressources de combat, la coordination des ressources de combat, la génération et l'évaluation des tactiques, et l'intégration des plans pour l'officier de la salle des opérations (ORO, en anglais).

Le projet a résulté en un ensemble de réalisations, incluant :

1. Des rapports techniques de la RDDC
2. Des publications scientifiques dans la littérature ouverte
3. Des mémoires de maîtrise et thèses de doctorat
4. Des outils logiciels
5. La maîtrise de plusieurs technologies potentiellement exploitables pour aborder les problèmes liés à la gestion des ressources de combat.
6. Des contributions à des projets de la RDDC et du MDN, tels que les démonstrateurs technologiques INCOMMANDS et SISWS, et le projet d'acquisition HMCCS.

Ces réalisations sont brièvement décrites dans le présent rapport, sans toutefois présenter tous les aspects. Des références aux documents appropriés sont données pour plus de détails.

Table of contents

1 Introduction

Advances in threat technology, the increasing difficulty and diversity of open-ocean and littoral (*i.e.*, near land) scenarios, and the volume and imperfect nature of data to be processed under time-critical conditions pose significant challenges for future shipboard Command and Control Systems (CCSs). Among other functionalities, the CCS provides capabilities to allow operators to evaluate the threat level of the different objects within the Volume of Interest (VOI), and when deemed necessary, use the shipboard combat resources to response to them. However, current operational systems generally provide little support for tactical decision making in complex, highly dynamic scenarios where time for decision-making and action execution is at a premium. The need for such support is all the more pressing given the current emphasis on littoral warfare, including asymmetrical threats, that results in reduced reaction time and the need to deal quickly and correctly with complex Rules Of Engagement (ROE) designed to increase the efficiency of the ship operations and avoid undesirable consequences.

Management of tactical shipboard combat resources, as a part of military naval Command and Control (C^2) process, provides a real world application that involves both human and software decision-makers. To defend itself, a platform, such as a Halifax Class Frigate, uses different systems and modules that interact directly or indirectly together. Therefore, it is very necessary to propose ways to allocate and coordinate the use of the different systems in order to increase the ship's defensive effectiveness against potential threats.

Defence Research & Development Canada (DRDC) has for several years now been investigating methods to augment or enhance existing shipboard CCS capabilities. As part of this investigation, 11bm Applied Research Project (ARP) focuses on the naval combat resource management in the context of Above Water Warfare (AWW), by exploring concepts concerned with the design, development, implementation, and evaluation of a computer-based, real-time decision support system that could be integrated into the future Canadian platforms to assist operators in conducting tactical C^2, particularly for combat resource management. More specifically, this project addressed the following problems, which are described in more details in Chapter 2.

1. Combat Resource Allocation Problem
2. Combat Resource Coordination Problem
3. Tactics Generation and Evaluation
4. ORO plan integration

The report is organized as follows. Chapter 2 presents an exhaustive list with short description of the set of problems that have been addressed by the different activities conducted under 11bm. Chapter 3 summarizes the achievements of the project. Conclusions and recommendations are given in Chapter 4.

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2 Problems Addressed

The activities conducted under the 11bm ARP project allowed tackling different problems related to the naval combat resource management, from both technological and human factor perspectives. The following sections give a list of these of problems with short description. More details can be found in the reports related to the respective tasks and activities.

2.1 Combat Resource Allocation

A resource is any substance or (set of) object(s) the cost or available quantity of which induce some constraint on the operations that use it. For instance, hardkill naval engagements require fire control radars. The fire control radars on the Canadian frigates, *i.e.* the STIR, can track and illuminate only one target at a time. Therefore, for the surface-to-missile and the 57 mm gun, only two fire control channels are available, which constrains their allocation process.

Resources are tightly linked with the notions of time and concurrency. There may be complex relations that link the duration of an activity with the amount of resource it uses, consumes and/or produces. Therefore, the combat resource allocation problem boils down to two classes of problems, which are the *resource allocation planning* and the *resource allocation scheduling*. The border between the two is often very fuzzy and very dependent on the targeted problem. The following definitions aim at making this border as crisp as possible for the problem of interest.

2.1.1 Resource Allocation Planning

Resource allocation planning is about assignment of resources to activities, where the start and end times of each activity are given. In dynamic contexts, this represents a continuing process of analyzing relevant information from the present and the past, and the assessment of probable future developments so that an allocation strategy may be determined that enables the overall system to meet its stated objectives. In the military context, this often referred to as the Weapon-Target Assignment (WTA) [1]. The problem consists of optimally assigning weapons to targets so that the total expected survival value of the targets after all the engagements is minimized.

The enormous combinatorial complexity of the problem implies that, even with the supercomputers available today, optimal solutions cannot be obtained in real-time. Good heuristics must therefore be developed to solve the problem [2]. In summary, in the naval resource management problems, allocation planning consists of selecting which weapons should engage which threat, independently of the order in which the different engagements will actually take place.

2.1.2 Resource Allocation Scheduling

Resource allocation scheduling consists in assignment of start and end times to activities, where each activity requires given resources with given capacities. In pure scheduling problems, activities are already chosen (or given), leaving only the problem of determining a feasible order. In naval operations, scheduling determines when a specific defensive action (a specific weapon against (a) specific threats(s)) will take place. Schedule constraints specify when an action should start or end based on duration, predecessors, resource availability, or intended interception time.

It is, however, very important to mention that the allocation of tactical combat resources in naval engagements involves both classes of problems:

1. Reasoning about limited time and scarce resources is at the very core of the tactical resource management problem, such as in purely scheduling problems.
2. Resource management problem also involves choices. This problem cannot just be confined to a task ordering, but includes choices about which resources to use for each task (action). For a given task, several alternative resources may be available that have differing cost and/or durations, such as in pure allocation planning problems.

Therefore, naval resource allocation problem is about allocation of both resources and start and end times to activities. This defines a *joint resource allocation planning & scheduling problem*. Note that, besides the two above described fundamental problems, a set of different problems needs to be addressed within the combat resource management context. These problems are either imposed by the nature of the primary problem to be solved and/or the environment in which it must be solved, or by the approaches chosen to solve it.

2.1.3 Application to Hardkill/Softkill Allocation

Resource allocation planning and scheduling algorithms were developed and applied to the dynamic allocation of Hardkill and Softkill weapons on-board a single ship. These algorithms, that include Cue Generation, Partly Planner, Holistic Re-engagement Planner, Holistic Tabu Planner, are described in more details in Section 3.2.1.

2.2 Combat Resource Coordination

Given the differing nature of the existing units and their combat resources, the effectiveness of a defensive plan depends on all the involved units/resources, as well as the environment and threats properties. Even though the optimality of the individual plans is assumed, there still are coordination/cooperation problems that need to be solved in order to guarantee the viability and effectiveness of the entire defence strategy. These problems are inherent to distributed environments, such as combat resource management for naval Task Groups, and concern interactions within the decentralized problem solving process. Examples of common types of interactions include:

1. Cooperation - Cooperation defines joint operation or action, that is the process of working together toward a common goal; sharing effort, expertise, and resources to achieve some mutually desirable outcome. This is about synergy.

2. Coordination - Coordination is the process of managing interactions and dependencies between activities. With strictly independent activities, where there is no interaction or dependency, there is obviously no need of coordination. Therefore coordination can be viewed as a regulation process of diverse interacting and/or inter-dependent tasks within an integrated operation. The interaction and the dependency are seldom direct, but through shared resources, which act as constraints on the different activities. This is why most of coordination problems can be viewed as Constraint Satisfaction Problems (CSP).
3. Negotiation - Negotiate is the process by which the different parties involved come to an agreement acceptable to all of them.

In naval context, these interaction problems may occur on-board a single ship, as well as within a set of cooperating platforms (*e.g.*, Task Group, Coalition, etc.). Below are given more detailed definitions and examples of the practical coordination and cooperation that were tackled within this project.

2.2.1 Hardkill & Softkill Coordination

It is possible to observe different interactions between the different resources, even on-board a single platform. These interactions may be positive (to be re-enforced), negative (to be removed, or at least minimized), or simply neutral. Two examples of possible interactions between hardkill and softkill weapons, that may require some sort of coordination/cooperation, are given.

An example of positive interaction is given by the combination *Jamming + Chaff*. If, the probability of success for the *Chaff* alone on a threat is p_1, and for the *Jamming* is p_2, then the use of the two together gives an efficiency p_3 such as

$$1 - p_3 < (1 - p_1)(1 - p_2) \quad \equiv \quad p_3 > 1 - (1 - p_1)(1 - p_2)$$

This efficiency is superior to using the two weapons separately. So there is a synergy between the two weapons. We talk about super-additivity of effects.

On the negative interactions side, when a Separate Tracking and Illuminating Radar (STIR) or Close-In Weapon System (CIWS) radar is trying to guide a hardkill weapon through a *Chaff* cloud, its range might be greatly diminished. In fact, the *Chaff* cloud scrambles the radars. We talk about sub-additivity of effects.

Hardkill and Softkill coordination techniques have been investigated in this project and a set of capabilities have been implemented and evaluated, as described in Section 3.2.1.

2.2.2 Engagement & Ship Position Coordination

During engagements, the survivability can be greatly increased if the ownship is appropriately positioned with respect to threats and the environment. The position and the manoeuvres of the ship play a key role in the ship's defensive plan. Therefore, the ship navigation needs to be coordinated with the weapon deployment in order to increase the ship's survivability. Examples of problems related to the coordination of ship navigation and positioning are listed below.

Blind Zones – Since the effectiveness of a particular weapon varies depending on the orientation of the ownship with respect to the threats faced, a key element of the coordination process is to manoeuvre the ownship to most effectively use all the weapons available, that is, to reduce the constraints due to the weapons blind zones. Figure 1 shows a division of the environment surrounding the ship into sectors on the basis of the hardkill and softkill combat resources available in each sector. These sectors will have to move along with the ownship, and maintain the same relative orientation with respect to the ownship.

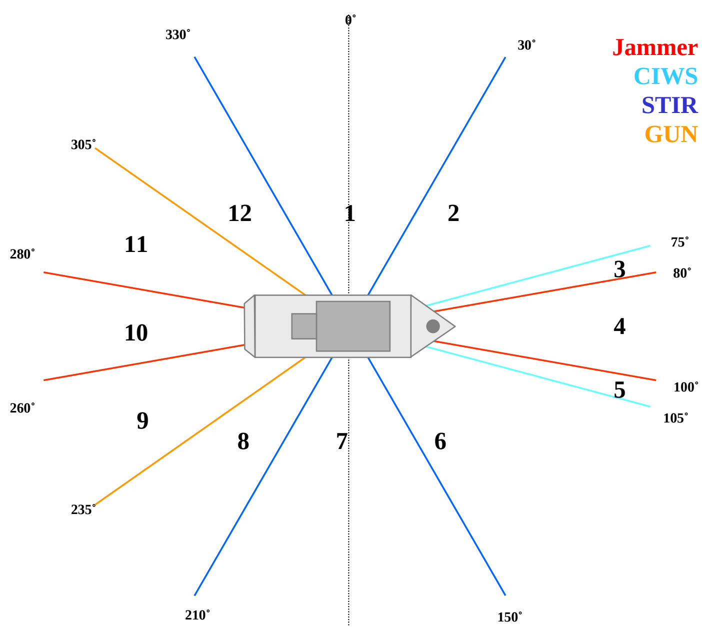

Figure 1: *Resource Blind Zones*

No Fire Zones – These are due to the presence of other non-hostile platforms, such as protected units, friendly ships, neutral vessels, etc. Even though most the activities focused on the single ship configuration, taking into account the no-fire zones will help facilitate the generalization of the developed capabilities to the multi-ship/area defence operations.

Signature Reduction – Various constraints can be placed on the ship movement. One example is given by the ship's exposed Radar Cross Section (RCS). This constraint imposes to the ownship a movement that reduces the RCS exposed to incoming threats, since the capability of threats to lock onto the ship is directly related to the RCS of the ship they see. Thus, the selection of appropriate ship positions helps make it considerably harder for threats to lock and keep a lock on the ship. A simple and convenient way to consider the exposed RCS of the ownship is to sub-divide the environment surrounding the ship into number of sectors, as in the case of blind zones.

The subdivision is based here on the size of the exposed in each sector.

Potential Damage Reduction – In case of potential eminent impact on ownship, the latter can be oriented to reduce this damage. Resources on-board the ship are of varying importance, and the less important may be sacrificed to save the vital ones.

The above-discussed set of constraints was used to coordinate the hardkill and softkill weapons deployment with the ownship movement to maximize their effectiveness.

2.2.3 Multi-Ship Combat Power Coordination

The majority of work performed within this project was oriented towards issues of coordination of resource management processes on a single platform [1], as described in the previous section. Due to the increasing variety of situations it can have to face, a single ship is becoming more and more restricted in actions and responses it can undertake, making it more vulnerable. This restriction can take different forms: the ship resource/human capabilities, the endurance, the reliability, etc. Therefore, to provide an extended capability and higher endurance and reliability, naval forces are more and more often organized into operational groupings for specific missions or tasks, which defined the concept of Task Groups that is becoming the norm in today's naval operations. A Task Group is formed by two or more ships [2], supported by aircraft, helicopters, and/or submarines.

The obvious extension of the coordination problem to the Task Group case is to consider issues of coordination of combat resources through a set of distributed platforms. In this case, the main challenge, compared to the resource coordination on-board a single-ship, becomes the limited communication bandwidth constraint. A comprehensive analysis and investigation of this problem was beyond the scope of this project. However, investigation was performed to use mobile agent technology (see Section 3.1.1 for definition) to reduce bandwidth utilization during plan coordination process.

2.2.4 Engagement & Surveillance Coordination

Target engagement using hardkill weapons cannot start without a target re-acquisition by the Fire Control Radar (FCR) assigned to it. The FCR initiates its search within an area defined mostly by the 2D bearing-elevation information obtained from the surveillance system. Following a specific pattern, the FCR will scan this region of the Volume Of Interest (VOI) until it detects and locks on the target, for which a track is then maintained. The target course and speed contained in this FCR track is then used to compute a Predicted Intercept Point (PIP) inside the weapon engagement envelope. The goal is to provide guidance (for the missile) or the pointing (for the gun) information toward the engaged threat. During this threat re-acquisition [3] phase, the FCR has a search time that depends on several factors, such as: the ownship weapons properties, Command & Control System (CCS) performance, the operator skill/training, the attacking target characteristics, etc.

1. Also referred to as point or self-defence operations.
2. *e.g.*, destroyers, frigates.
3. Also referred to as search and lock-on.

The quality of the information handed-over determines the volume the FCR must scan. The duration of the search and lock-on operation depends on the volume to be scanned and the detection probability of the FCR. This duration is subtracted from the total reaction time available to the decision-maker and necessary to the ship survival. A poor quality tactical picture causes the FCR to search in a large volume, which normally will take more time to re-acquire the target and which may have grave consequences on the ownship reaction time. Therefore, the search and lock-on duration should be limited depending on the available reaction time. This is equivalent to limit the uncertainty contained in the tracks provided by the surveillance system, by executing actions for information gathering (sensor allocation) or information processing (data fusion adaptation).

2.2.5 Hardkill/Softkill Prioritization

Considering the tactical situation involving a ship defending itself against a set of incoming threats, engageability assessment is used to reduce planning complexity and reaction time. This concept of engageability assessment is exploited to prioritize the use of the softkill defence strategy over the hardkill one, when the latter are declared non-feasible. Hence, given the quality $\boldsymbol{Q}$ of the tracks handed-over to the Fire Control Radar, the estimation of the search and lock-on duration $\hat{s}$, and threat/weapons characteristics, the combat resource manager can establish the feasibility of hardkill engagements.

A non-feasibility assessment simplifies the response planning process by discarding all the options that involve hardkill weapons. In such situations, softkill strategies are advocated, and priority is granted to their use against non-engageable targets, since their deployment does not require FCR support and their effectiveness is not affected by the quality of the tactical picture. Such a prioritization of weapons assignment prevents wasting reaction time, by eliminating unfeasible assignments, and helps increase the ship survivability by maximizing the number of engaged threats. However, when hardkill engagements are judged to be feasible, further decisions, involving more criteria, will be required to select between hardkill strategy, softkill strategy, or combination of both [4].

2.2.6 Sensor Management

The objective of any surveillance mission is to gather information about the presence and activity of all potential targets in a volume of interest. Surveillance is the systematic observation of a tactical situation by sensors. The data collected by military surveillance is used by analysts, both human and software, to build a representation of the tactical situation. This representation may describe in detail the environment (terrain, weather and any man-made structures), the spatial coordinates of friendly, enemy or neutral targets, and may include temporal changes if the observation period is sufficiently long in duration. Information gathering process performance can be improved with the application of sensor management. Sensor management is the coordination and control of limited sensing resources to collect the most complete and accurate data observed from a dynamic scene. Sensor management is a key enabling element of tactical surveillance.

4. As addressed by combat resource allocation and coordination activities.

This section will discuss some of the issues that sensor management should address in a tactical surveillance situation, some of the emerging approaches to sensor management, the architecture in which sensor management is applied to control sensing resources, and some of the direct issues associated with information gathering.

Potential issues in tactical surveillance, for which strategies are required, would include:

- If a sensing resource has multiple operating modes, then the sensor management should make use of the most optimal mode for the task being done provided that there is no other overriding reason not to. The performance of certain sensors is dependent on the position and orientation relative to the VOI that they are observing. Although the sensor management system does not have control of the host platform's navigation, it can make a request to the navigation control module to position or orient the platform so that it can improve the quality of the data stream.
- If a sensing resource when in operation is in conflict with another resource (another type of sensor or a weapon) then the management must determine which action or data stream is more important and prevent the other from operating or must allow for some schedule to allow one sensor to be used for a period of time and then the other.
- If a surveillance mission is being undertaken by a group (more than one platform), then the sensor management must be capable of ensuring that the sensors from different platforms and the platforms themselves do not compete with each other but rather cooperate. Two such situations are: the sensors for one platform may have their view of the VOI occluded by another platform, and the sensors from one platform may conflict with those of another.
- While changing sensor mode, the data stream may be halted during the period of transition. The sensor management must address whether it is more important to maintain operation in possibly a sub-optimal mode while maintaining a live data stream or to change to a more optimal mode sacrificing continuity of data.
- While operating active sensing resources to monitor the VOI, it is emitting some form of energy. Is it a high enough level and is it active for a long enough period of time so as to compromise the security of that resource? The sensor management system must trade off the gathering of more complete information over the self security of the resource.
- If a sensing resource is disabled or diminished in capability then the sensor management must alter the sensing allocations and schedule. The sensing load could possibly be redistributed to other sensing resources that are capable of returning a similar data stream.
- If situation changes or a new surveillance request is made to the system, then the sensor management must address when and how to make the necessary changes. The sensor management must determine if the surveillance task being executed should be allowed to finish, should it be suspended, or terminated.

This is not an exhaustive list of issues that sensor management of sensing resources in a tactical surveillance activity will have to address but it shows that sensor management is more than just direct control of sensors.

Conscious of the important role that sensor management has to play in modern Command and Control systems, activities have been conducted, within the 11bm project, to:

1. Characterize the different sensor management problems and the requirements for their solution.
2. Demonstrate the benefits that can be brought by the dynamic management of the available naval sensing resources.

2.3 Tactics Generation and Evaluation

The problem addressed by this activity was to investigate techniques and build a capability that allow the generation of new defence tactics and the evaluation of the existing ones, for possible improvements. Even though the core problem remains the same as the one described previously, that is combat resource allocation and coordination, there is still a major difference. The latter is an off-line planning problem, which removes the real-time constraints and allows the use of computationally heavier approaches.

This activity is concerned with getting the "best" solution taking into consideration different aspects of the problem. On one hand, not only the immediate consequences are concerned, but also the impact of this decision on the whole planning horizon. This is known as "multi-stage" aspect of the problem. On the other hand, to choose a decision, a set of conflicting decision-criteria in the evaluation of alternatives are considered. This defines the multi-criteria (see Section 3.1.2) aspect of the problem.

2.4 ORO Plan Integration

To exercise its role in the detection and tracking of ships, aircraft and submarines within its area of interest, the HALIFAX Class frigate relies on its team of operators in the Operations (Ops) Room. This team consists of 20 or more people, normally coordinated by, and reporting to, the Operations Room Officer (ORO).

OROs' planning responsibilities range from short term, reactive planning to long term, and deliberative planning. There is a grey line between when the implementation of set tactics and procedures stops and reactive planning starts. Short term planning is generally required when the situation dictates a change in the current course of directed action in a manner that was previously unidentified or unaccounted for. For short term planning the ORO will typically employ only those planning tools that are readily available in Ops, such as publications, command instructions such as OPTASK messages, charts and CCS or Global Command and Control System - Maritime (GCCS-M) displays.

It is of no surprise that the cognitive work demands of the ORO are considerable. From the time of preparing for the watch through to its end, the ORO is faced with dozens of decisions, some minor and trivial and others significant in considerations and repercussions. Hence the importance of analyzing aspects of the perceptual, cognitive, meta-cognitive and collaborative work demands on the ORO of a HALIFAX Class frigate in conducting tactical planning and response management within and across the air, surface and subsurface warfare areas. The understanding of ORO demands will support the development of advanced decision aids tools.

3 Summary of Achievements

This section provides a summary of the achievements resulting from the different activities conducted under the 11bm project. These include:

1. Investigation of several cutting-edge technological and human factor approaches, and acquisition of knowledge with respect to their usefulness.
2. Publications in the form of DRDC technical reports, DRDC contract reports, open literature articles, and university theses.
3. Capabilities in the form of simulation environment and algorithms.
4. Input to major projects, such as HMCSS, INCOMMANDS TDP, and SISWS TDP.

These achievements are described in more details in the following sections.

3.1 Investigated Technologies

Different technologies have been investigated to address the naval combat resource management problem. Below is given a list and description of the ones that have been deemed most relevant to the problem.

3.1.1 Agent Technology

Agent has been a central technology within this project. The agent technology aims to conceive entities capable of acting in a rational way via approaches turning around planning, uncertainty reasoning, decision theory, machine learning, vision and perception, etc. However, in many applications, the agent alone is insufficient to do all the tasks, and it is preferable to view it evolving with other agents. This defines multi-agent systems. In this kind of systems, the agents interact together in order to cooperate, compete or more simply, coexist. Agents and multi-agent systems represent a new way of analyzing, designing, and implementing complex systems. The following summarizes the definition of agent as viewed in this project.

An agent is a software component, *situated* in some environment, that is capable of *flexible autonomous* action in order to meet its design objectives [3]. Situatedness means that the agent receives sensory input from its environment and that it can perform actions that change the environment in some way. Autonomy is used in the sense that the system should be able to act rationally without the direct intervention of humans (or other agents), and that it should have control over its own actions and internal state. By flexibility it is meant responsive [5] and pro-activity [6].

The following variants and extensions to the basic paradigm of agent have been explored and used within this project.

5. Agents should respond in timely fashion to changes in their environment.

6. Agents should not simply act in response to their environment; they should be able to exhibit opportunistic, goal-directed behaviour and take the initiative where appropriate

1. **BDI Agents** - The agents, used in this project, model reasoning according to the Belief Desire Intention (BDI) model of Artificial Intelligence (AI). Following the BDI model, intelligent agents are autonomous software components that have explicit goals to achieve or events to handle (Desires). To describe how they should achieve these desires, BDI agents are programmed with a set of plans. Each plan describes how to achieve a goal under varying circumstances. Set to work, the agent pursues its given goals (Desires), adopting the appropriate plans (Intentions) according to its current set of data (Beliefs) about the state of the world.

2. **Mobile Agents** – The mobile agent paradigm consists of small programs that may be dispatched from a local location (computer) and transported to a remote location (computer) for execution. There are several motivations for using the mobile agent approach. Within this project, the two major driving motivations have been the reduction of network traffic [7] and exploitation of asynchronous interaction [8], both during plan coordination in multi-platform configurations.

3. **Multi-Agent Systems** – Multi-Agent Systems are concerned with the behaviour of a collection of autonomous agents aiming at solving a given problem. A Multi-Agent System can be defined as a loosely coupled network of problem solvers that work together to solve problems that are beyond the individual capabilities or knowledge of each problem solver. These problem solvers (agents) are autonomous and may be heterogeneous in nature. The main characteristics of Multi-Agent Systems are: i) each agent has incomplete information (or capabilities) to solve the problem; ii) there is no global system control; iii) data is decentralized; and iv) computation is asynchronous.

   A military C^2 system is a multi-agent organization in which the decision agents are both human and software decision-makers (autonomous agents). The decision agents are geographically dispersed due to the operation environment, the nature of sensors, and physics and speed of the weapons. Thus, both geography and security contribute to the distributed architecture of C^2 systems. Cooperation, coordination and communication between the decision agents are thus crucial in such a distributed C^2 architecture. In this project, the multi-agent technology has been used mainly to decompose the problem into sub-problems and to coordinate the sub- problems solutions using coordination techniques. This technology enables to diminish greatly the planning time for the target real-time application problem, while generating a near-optimal solution.

4. **Holonic Control Systems** – The control and coordination are the major challenges facing the above discussed multi-agent systems. Theoretically, an ideal solution to this control problem is provided by a centralized control strategy. Nevertheless, in real world applications, the hierarchical architecture has received much attention in order to overcome centralized control drawbacks [9]. Typical hierarchical control architecture

7. Since there are usually several information flows between platform computers to perform even a simple task.

8. The local computer sends his agent to a remote computer to perform several tasks, and only when the agent finishes does it retract back to the local computer. A connection does not need to be maintained during the task achievement.

9. Massive computation at the central node; high requirement for inter-node communications; and lacks

is composed of a set of controllers structured in a pyramidal form, where each distinct level addresses a certain class of problems and has a certain level of authority. In such a configuration, the control and coordination mechanisms follow typically a master - slave relationship. Nevertheless, because of the static and deterministic nature of hierarchical control architecture, it is often difficult to make it adaptable to cope with unpredictable changes, essential in highly dynamic and uncertain systems, such as military applications.

The heterarchical (fully distributed) control architecture was proposed to overcome the limitation of the hierarchical control. This is a highly distributed control form implemented by independent, but cooperating, processes without a centralized control. In such architecture, the control decisions are obtained by mutual agreement, through negotiation. The high flexibility, the reliability -in the sense of failure tolerance-, the ease of implementation, and the less computational requirement, are some among the most relevant properties offered by the heterarchical control. Nevertheless, uncertainty, unpredictable target behaviour, and the large-scale nature of the distributed military resource management problem may render the heterarchical approach inefficient. The system behaviour under heterarchical control may, under some conditions, become very unpredictable and almost chaotic, which is unacceptable in military applications. This is why an in between solution, given by the "holonic control" paradigm, represents a good comprise to tackle military applications in general, and the naval resource control and coordination problem particularly. Holonic architectures correspond to a mixture of the heterarchical control and hierarchical control, where higher-level holons [10] act as coordinator for lower level holons. Holonic control structures are the result of a marriage between Koestler's [4] general philosophy (of living organisms and social organizations) and emerging software approaches (distributed artificial intelligence).

5. **Jack Agent-based Language** – The JACK programming language has been used in this project. JACK provides an environment for building, running and integrating commercial-grade multi-agent systems using a component-based approach. The JACK agent extends Java language with agent-oriented concepts, such as agents, capabilities, events, plans, agent's knowledge bases (databases), and resource and concurrency management. The agents used in JACK are *intelligent agents* based on the above described BDI model. Also, JACK agents can exhibit reasoning behaviour under both deliberative (goal directed) and reactive (event driven) stimuli. Each agent has i) a set of beliefs about the world (its data set); ii) a set of events that it will respond to, iii) a set of goals that it may desire to achieve (either at the request of an external agent, as a consequence of an event, or when one or more of its beliefs change), and iv) a set of plans that describe how it can handle the goals or events that may arise. When an agent is instantiated in a system, it will wait until it is

flexibility and robustness, since central node must be kept intact.

10. Holons can be thought of as self-contained wholes looking towards the subordinate level and dependent parts looking upward. Holons have a certain degree of autonomy that allows them to make decisions of limited scope. The decisions that a holon can make are limited to accepting the request being made and executing the request by utilizing available resources. The process used to arrive at a decision is only as complex as necessary for that class of holons and its level within the holarchy.

given a goal to achieve or experiences an event that it must respond to. When such a goal or event arises, it determines what course of action it will take. If the agent already believes that the goal or event has been handled (as may happen when it is asked to do something that it believes has already been achieved), it does nothing. Otherwise, it looks through its existing plans to find the ones that are relevant to the request and applicable to the situation. It select the most appropriate for execution, and if it has any problems executing it, it looks again for others that might apply and keeps cycling through the set of alternatives until it succeeds or all alternatives are exhausted.

3.1.2 Planning

Several planning approaches have been used to address the naval combat resource management problem, as described below.

1. **Reactive Planning** – consists of reflex planner (possibly with internal state) that can be implemented with any variety of representations for condition-action rules. Reactive planners react to the environment, without reasoning about it. This consists of predefining a set of rules to accomplish a certain limited goal. A reactive plan represents a set of tests and reactions able to handle contingencies. Since each response is less carefully analyzed than in the deliberation-based case (see definition below), the response does not need to embody a complete solution to the final goal but can merely be an action to stabilize the situation and allow the time for elaborating a more comprehensive plan.
2. **Deliberative Planning** – consists of designing, before execution, a sequence of steps to achieve a particular goal. Among the strengths of the deliberation is the fact that plans can be built to have a set of desirable global properties regarding the goals to be attained and the resources available. The side effects of the actions to be executed as part of the plan can be carefully taken into account and analyzed before execution begins. These properties are achieved by taking into account complete descriptions of the states of the world as the planner predicts them. Of course, these states may conform to reality only if the environment behaves according to the model that the planner has about it. The more incomplete this model is the more uncertainty in the behaviour of the environment, and the more uncertainty about the actual states that will be encountered during the plan execution.
3. **Anytime Planning** – We used two types of anytime/deliberative planners in our project; Markov Decision Processes [5] (MDPs), and a Tabu algorithm [6]. A Tabu search is a local search approach, while a standard MDP algorithm is optimal. Thus, one can never know in real-time if the solution of the Tabu algorithm is optimal. This algorithm provides better results than a reactive approach but is more complex. Indeed, it may never generate a worst plan than a reactive approach since the initial plan for the Tabu search is the one generated by a reactive approach.

   An optimal solution for an MDP approach is too complex to generate for our real-time application. Thus approximations and heuristics have been developed. We also developed approximation and heuristics to solve the Weapon Target Assignment (WTA) using, among others, piecewise linear programming [7].

4. **Markov Decision Process** – Markov Decision Processes (MDPs) have been recently used in the project. First of all, the optimal acyclic decomposition and approximate on-line decomposition algorithms produced great results [5]. This research opened the door for Multi-agent Task Associated MDPs (MTAMDPs) which plan for each resources and coordinated the plan using an efficient algorithm which considers simultaneous actions and interactions between resources. MDPs prove to be very useful for the resource allocation problem, and can, through the policy iteration approach, provide an anytime solution to the planning problem.

5. **Multi-Criteria Decision Analysis** – Most real world decision-making problems require that multiple and conflicting criteria (points of view) should be taken into account in order to make a decision which reports better the real world situation. In particular, decision making situations often include a full range of social, environmental, technical, economic, and financial criteria. For such situations, reaching the optimal solution that maximizes all the criteria is rarely possible. The best compromise solutions are rather focused on. Several Multi-Criteria Decision Aid (MCDA) methods have been proposed as solving approaches to various types of multi-criteria problems. Those MCDA methods can be divided into two broad categories: Multi-Attribute utility methods and Outranking methods. Methods falling within these two categories consider the decision maker preferences, which are introduced a priori.

   (a) **Multi-attribute utility methods** aggregate local preferences (at each attribute's level) into a unique (utility, value) function which is then optimized.

   (b) **Outranking methods** consist in building binary relations (called outranking relations) in order to represent the decision-maker's preferences (based on the available information). For some outranking methods, discrimination (indifference, preference) thresholds and even veto thresholds, at each criterion level, must be introduced to model the decision-maker's preferences locally. Usually, these relations are neither transitive nor complete. Outranking relations are then exploited in order to formulate a recommendation that can solve the decision problem.

3.1.3 Plan Coordination

Coordination techniques have been used in two aspects of the projects. First, we coordinated the hardkill and softkill weapons [8]. In this work, we concluded that a 'central coordinator' technique is the most efficient considering our real-time environment. Furthermore, we used coordination mechanisms to coordinate a frigate fleet [9]. The most important result demonstrates that the Contract-Net is the most efficient coordination technique considering frigate survival and the number of resource used. [10] proposed a coordination technique based on the decomposition of the problem on the basis of the longest possible engagement, that is, the Jammer. This way, the frigate can elaborate separate plans, which are much less complex than a whole global plan.

3.1.4 Machine Learning

Machine learning [11] has been used in our resource optimization movement algorithms [11, 10, 12]. It has been used to learn the effectiveness of the six different sectors surrounding the frigate. These sectors are defined according to the blind zones of our resources.

3.2 Capabilities

This section presents the capabilities that were developed during the 11bm project.

3.2.1 Algorithms

1. **Cue Generation** – The cue generation (GENCUE) algorithm produces a list of first engagements used by the different others planners (presented below). Therein, an engagement is characterized by a defence resource, an illuminator (in the case of the Surface-to-Air Missile (SAM) or the 57mm gun), a target threat-level, and four time-stamped actions or cues, namely: (1) Search and lock on target; (2) Fire; (3) Target intercept; (4) Kill assessment (*i.e.*, target destroyed or not).

   GENCUE constructs a list of feasible hardkill engagements starting with the weapon that has the earliest target intercept time to the latest. It starts with an initial matrix of feasible time intervals and stops when all time intervals in the matrix are empty. The selection of the latest feasible time to start an engagement is usually good practice in single-target engagements, as the probability of interception for a defensive weapon typically increases when the distance between the target and the ownship decreases. As the algorithm unfolds, a tree is generated, because many different engagements may be possible at a given point through the choice of a particular weapon to fire or a particular threat to shoot at. A new branch is thus generated for each possible engagement; the backward search is then applied in a recursive manner along each branch, until no feasible engagements may be found. The backward search is designed to maximize the number of re-engagements of a target.

2. **Partly Planner** – The Partly Planner uses very low-level reasoning techniques in order to elaborate a response to a situation in a very short reaction time. This is very important in combat resource management context because defending ownship brings a very hard and usually very short time constraint. For this planning mode, the planning agent maintains a list of the objects within the volume of interest. These objects are sorted (from the most to the least threatening) based on several criteria. For this implementation, threat evaluation considers only the Closest Point of Approach (CPA) of the threat to the ownship, and the time for the threat to reach CPA. Then, the planning agent applies some predefined rules for allocating the resources. These predefined rules are

   (a) Allocate a SAM and the 57 mm gun to the most threatening target.

   (b) Allocate a SAM to the second most threatening target.

11. Approach that allow problem solving process to learn from past data and experiences.

(c) Allocate the Close-In Weapon System (CIWS) to all targets that enter into the CIWS range (one target at a time).

The first two rules are inspired by the fact that there are only two STIRs available, which must be used in conjunction with the SAM and the 57 mm gun. Although rules used by the planner are simple, they allow all available resources to be used in an efficient way. Unfortunately, the SAM and the 57 mm gun are only allocated at a given point in time to the two most threatening objects, and all others in the list (if any) are not considered by this specific planner (this is why it is called "Partly"). In the case where a kill assessment indicates that an engaged target has been destroyed, the resources that have been allocated to it become available for the next most threatening object in the list.

3. **Holistic Re-engagement Planner** – As it name indicates, this planner considers all targets within the volume of interest and can re-engage with a SAM. A first list of engagements is obtained with the cue generation algorithm as discussed previously. However, there is a key difference in the SAM engagements from the cues generated for the Partly Planner. Instead of inserting one SAM engagement at the latest possible time, it can use re-engagements of the SAM against a target. If after the kill assessment of the first SAM the target is still alive, a second SAM can be engaged to destroy it. Usually there will be at least one re-engagement for each target. In the planning process, the engagements of the SAM are scheduled backwards in time from the latest time of fire possible. SAMs are added in the Holistic Re-engagement Planner until it is not possible anymore to do the kill assessment of the current SAM and to be able to engage the next one. Another difference from the Partly Planner is that the Holistic Re-engagement Planner considers all targets to make a plan.

   This planner views all the detected threats constituting a complex organization surrounding the ownship. It works as follows: a decision tree is first produced that explicitly considers, in a probabilistic manner, all possible outcomes of a particular action. Such a tree reflects, in fact, a plan with different conditional branches. The conditional branches allow taking into account results of actions. For instance, during the plan execution, one should follow one branch or another depending on the result of an engagement to some threat $\mathcal{T}(i)$. If this engagement has succeeded, then the plan continues by following a branch where it does not consider the target $\mathcal{T}(i)$ anymore. If the engagement has failed, then a branch where other engagements are planned for $\mathcal{T}(i)$ is executed. All these conditional branches reflect contingent plans that are very important since the outcomes of the engagements are uncertain. Notice that without conditional branches, the time horizon of the plan would be very limited and it would be needed to re-plan each time an engagement fails. The latter can take a long time, thus causing problems for the subsequent engagements.

   The Holistic Re-engagement Planner uses the following rules

   (a) the closest targets are engaged first; (threats are ranked based on their distance from ownship, the closest threat has rank 1)
   (b) a SAM has priority over the 57 mm gun to engage a target
   (c) the CIWS engages whenever possible

(d) the number of re-engagements of a target is maximized

4. **Tabu Planner** – Like the Holistic Re-engagement Planner, the Holistic Tabu Planner works with a decision tree to execute the plan, and it considers all targets for the plan. However it does not use the SAM re-engagements, but instead uses Tabu heuristics for improving the quality. An initial tree is first created, and then a Tabu search-based heuristics is used to improve it. The initial tree is improved by a Tabu search [13] through the removal or addition of defence actions, followed by update operations aimed at maintaining the consistency of the plan.

   Tabu search is based on an iterative neighbourhood search method where modifications to the current solution that degrade the solution value are admissible. The latter move allows the method to escape from local optima (as opposed to a pure local search approach). To avoid cycling, a short-term memory, known as the Tabu list, stores previously visited solutions or components of previously visited solutions. It is then forbidden or "Tabu" to come back to these solutions for a certain number of iterations.

3.2.2 Tools

1. **Naval Defence Simulator (NDS)** – A simulator has been developed during this project to allow for large amount of tests of the investigated concept through various scenarios. The Naval Defence Simulator (NDS) shown on Figure 2 allows specific tests to be replicated as many times as desired, which is obviously impossible to match on real-life systems. With low costs compared to real-life demonstrations, this allows to develop, implement, validate and compare a broad range of concepts. Another advantage of having a simulator is that it allows us to focus on particular aspects of the C2 process. In the project, the focus has been on resource allocation and coordination, the situation analysis problem has not been treated. The NDS design and implementation were driven by two major concerns: extendibility and reusability. More details on NDS test-bed can be found in [14, 15].

2. **Tactics Generation and Evaluation Tool** – In order to simulate the naval defence environment, a test bed has been developed (see Figure 3). Threats appear around the ship and are detected (window in top on the right). Then, the decision tree is constructed taking into account the different constraints (window in top on the left). The best compromise strategy is presented in the window in bottom on the left. In bottom on the right, information is given concerning the action or the state of the nature that is pointed. Decision tree, as well as generated threats, can be saved and downloaded. Myopic (single-stage) method and decomposition method were implemented using the weighted sum, lexicographic, TOPSIS [12] and dominance as Multi-Criteria Decision Analysis (MCDA) methods [16, 17].

12. Technique for Order Preference by Similarity to Ideal Solution.

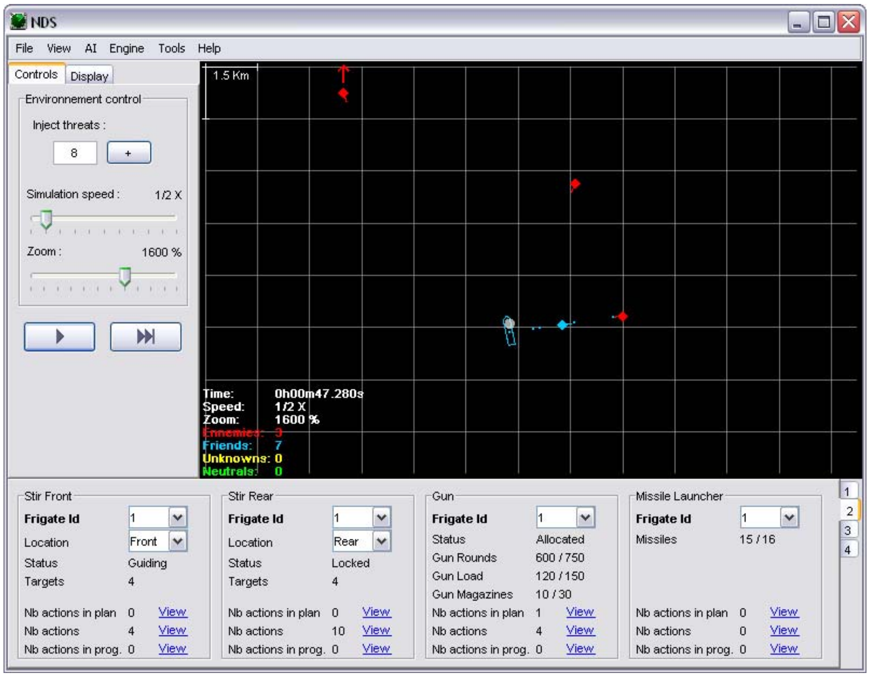

Figure 2: *The Naval Defence Simulator*

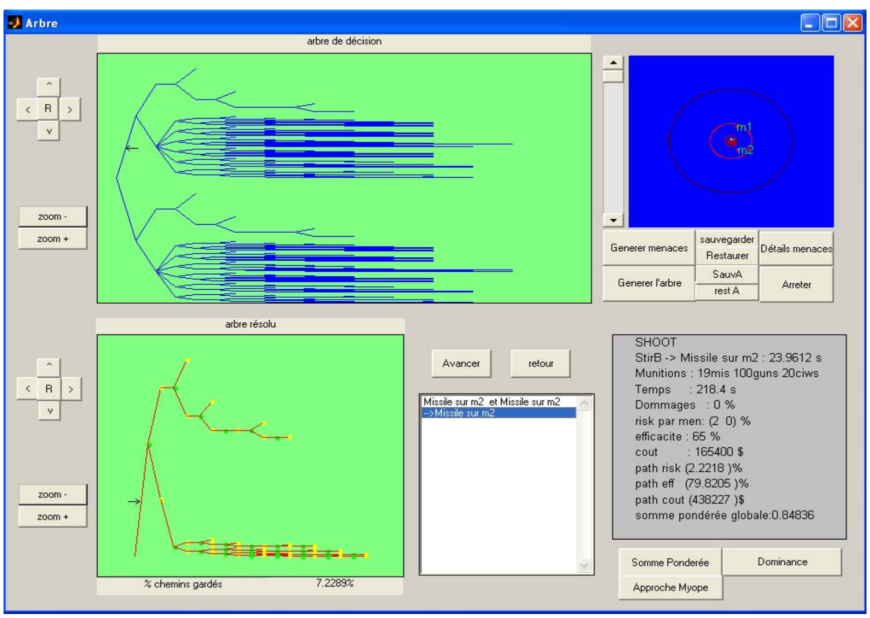

Figure 3: *Tactics Generation and Evaluation Tool*

3.3 Publications

The work conducted under 11bm project generated several publications, ranging from DRDC Technical reports to Master thesis. The following gives an exhaustive list of these publications. Among other information, the section presents the abstract of the different publications. For few publications, these abstracts are modified to avoid redundancy in the text. The modifications concern mainly the introductory text that presents the context.

3.3.1 Technical Reports

Six (6) DRDC Technical reports were produced under 11bm.

1. **Multi-Agent Coordination Techniques for Naval Tactical Combat Resources Management [15]**.

   Abstract – This report presents a review of agent and multi-agent coordination approaches. Theoretical basis of distributed planning in multi-agent systems is introduced and coordination mechanisms are described. Multi-agent approaches are used to address the coordination problems for: 1) hardkill/softkill, 2) weapons deployment/ship navigation, and 3) multi-ship positioning and operations. Results of the implementation and test of different algorithms for these combat resource coordination problems, in naval engagements, are presented and discussed.

2. **Combat resource allocation planning in naval engagements [14]**.

   Abstract – This report presents a review of agent and multi-agent planning approaches. Theoretical basis of agent and multi-agent systems are introduced and planning problems are described. The results of the implementation and test of different algorithms for hardkill and softkill combat resource allocation, in naval engagements, are presented and discussed.

3. **Single Ship Resource Allocation in Above Water Warfare: A Multiple Criteria Dynamic Decision Making Approach [17]**.

   Abstract – This report is concerned with dynamic and multi-criteria decision-making problems in naval engagement context. The objective is to identify best compromise strategies for weapons allocation against a set of incoming threats over a given period of time, in order to maximize the survivability and security of the ship. In this study, the weapon management problem is represented with multiple criteria decision tree and solved using two different solving approaches: 1) the Multiple Criteria Myopic approach (MCM approach), which deals only with the multiple criteria aspect; and 2) the Multiple Criteria Decomposition approach (MCD approach), which considers both the multiple criteria and the dynamic aspect of the decision problem. The empirical results show that the MCD approach is always superior to the MCM approach. This report argues for more research work in order to validate the results with subject matter experts and contribute to the development of tactics for highly complex and dynamic decision-making problems like weapon management of the Halifax Class Frigate facing multiple threats.

4. **Impact of the Tactical Picture Quality on the Fire Control Radar Search-Lock-on Time [18]**

   Abstract – Data fusion is suitable to a broad range of decision support applications. To allow copping with a larger class of problems and contexts, data fusion gains to be adaptive. Adaptation in data fusion corresponds to Level 4 of the JDL model, also referred to as process refinement. The Decision Support Systems (DSS) Section at Defence Research & Development Canada (DRDC) – Valcartier has initiated research activities aiming at developing and demonstrating advanced concepts of adaptive data fusion that could apply to the current Halifax and Iroquois Class Command & Control Systems (CCS), as well as their possible future upgrades, in order to improve their performance against the predicted future threat. This document gives a brief description of the adaptive data fusion concepts. It also presents a new Measure Of Effectiveness (MOE) that serves as an adaptation trigger in the target-tracking problem in the maritime Above Water Warfare (AWW) applications. The proposed MOE uses the search and lock-on time of the Fire Control Radar (FCR) and aims at establishing and quantifying the effect of the quality of the Maritime Tactical Picture (MTP) on the diminution of the battle space size and the reaction time. Besides adaptation of the sensing and processing operation, this MOE allows addressing the trade-off finding problem between the time dedicated to the tracking with surveillance radars versus the time spent in search and lock-on with FCR.

5. **Sensor Management in the Context of the Integration of Sensors and Weapons [19]**.

   Abstract – The sensing resources represent an important source of information on which the Command & Control (C^2) process bases most of its reasoning. Therefore, a major prerequisite to the success of the whole C^2 process is the effective use of these scarce and costly resources. This is the problem of sensor management that has to do with how best to manage, coordinate and organize the use of sensing resources in a manner that synergistically improves the process of data acquisition and ultimately those of perception and comprehension, *i.e.*, the situation awareness of the decision maker. Conscious of the important role sensor management has to play in modern Command and Control systems, the Situation Analysis Support Systems (SASS) Group of the Decision Support Systems (DSS) Section at Defence Research & Development Canada (DRDC) - Valcartier has studied advanced sensor management concepts and applications, to increase the survivability of the current Halifax and Iroquois Class ships, as well as their possible future upgrades. The objective of the reported work is twofold i) to present, in detail, the different sensor management problems and the requirements for their solution ii) to demonstrate, through the target tracking application, the benefits that can be gained by the adaptive management of the available sensors.

3.3.2 Contract Reports

The following Three (2) contract reports were produced as part of the project activities.

1. **Real-Time Planning and Coordinating: Naval Resource Management Process Description [20]**.

   Abstract – This report presents a description of the Naval Resource Management (RM) processes for a single-platform during Naval operations, but is not focussed on any specific set of resources or system architecture. RM was defined and situated in the context of overall Command and Control (C2) operations. Emphasis was placed on demonstrating the unique role played by RM activities in light of Boyd's "Observe-Orient-Decide-Act" (OODA) Loop model of C2, and on the relationship of RM to the functionalities of the Joint Directors of Laboratories (JDL) model of Information Fusion. All of the relevant a priori and dynamic types of information that are needed as inputs to RM processes or produced as a consequence of that processing are listed and briefly described. Figures are presented that show the decomposition of RM into its constituent fundamental processes. The figures also demonstrate some of the relationships and the general flow between processes. Finally, an examination of each of the RM processes provides a brief description of these processes and identifies the input/output information types that are relevant to them.

2. **Real-Time Planning and Coordinating: Final Report [21]**.

   Abstract – This report presents the results of a collaborative project that investigated real-time planning and coordinating techniques for naval Resource Management (RM). A literature review on RM planning and coordinating techniques was conducted. Metrics for the performance evaluation of RM techniques were investigated and developed. Five types of algorithms for RM were identified as the most promising for further development, implementation and performance evaluation: Reflex, Rollout, Reinforcement Learning (specifically Q-Learning), Labelled Real-Time Dynamic Programming (LRTDP), and Markovian Constraint Satisfaction Process (MaCSP) (specifically, a version known as Focused Real-Time Dynamic Planning (FRTDP)). The Ship Air Defence Model (SADM) formed the basis of the test bed used to develop algorithms and conduct performance evaluation. The test scenarios utilized various types of missile threats coming from any azimuth, with varying start times and ranges. Ranking the algorithms from best to worst, for platform survival the order was LRTDP/FRTDP (similar), Reflex, Rollout, and Q-Learning. For planning time, the order was Q-Learning, Rollout, FRTDP, and LRTDP. Recommended enhancements for each of the implemented RM algorithms are provided. Finally, observed defects and anomalies in SADM are reported, and recommendations for modifications and upgrades to SADM to support further RM research are provided.

3. **Tactical Planning and Response Management: Investigating a Cognitive Work Analysis approach to the development of support concepts [22]**.

   Abstract – Cognitive Work Analysis is an emerging framework for designing tools to support cognitively demanding work in complex dynamic environments. To investigate its application in Naval Command and Control, DRDC Atlantic undertook a Cognitive Work Analysis of tactical planning and response management activities aboard the HALIFAX Class frigate, focusing on the job of the Operations Room Officer. Four interview sessions were conducted with Subject Matter Experts using the Critical Decision Method. The data collected was collated into a chronological order and analyzed according to two steps of the analysis framework: a Work Domain Analysis and a Control Task Analysis. The first step mapped the activities described by the experts to an Abstraction-Decomposition Space, itself comprised of an Abstraction Hierarchy and a Part-Whole Decomposition. The second step mapped each activity to a Decision Ladder template. A variety of design seeds were then identified based on these analyses. Each design seed linked knowledge elicitation and work analysis outputs directly to specific design hypotheses for work support. A subset of these seeds was developed further into a tactical planning and response management support concept for presentation to a new set of Subject Matter Experts. Based on the feedback received, the support concept was refined. This report outlines the data collection and analysis activities undertaken. It also details the identification of design seeds from the various analyses conducted and the coalescence of the design seeds into an integrated support concept. Full details of the scenarios described by Subject Matter Experts, the analysis results, the design seeds and the visualization of the support concept are provided in the annexes.

3.3.3 Book Chapters

Two (2) book chapters were published based on the work conducted under 11bm.

1. **Multiple Criteria Dynamic Allocation of Shipboard Weapons [16]**.

   Abstract – This paper is concerned with decision-making in naval operations. Our scenario involves air threats directed toward a ship that has to maximize its survivability by managing its weapons. This dynamic decision-making problem is modeled using multi-criteria decision trees. A dynamic approach is then proposed to solve the problem. This approach is based on the decomposition of the tree and provides the best compromise strategies. The results it yields are compared with those provided by a myopic approach, where the dynamic aspect of the problem is simply ignored.

2. **Resource Allocation in Time-Constrained Environments: The Case of Frigate Positioning in Anti-Air Warfare [12]**.

   Abstract – Maritime environments are known to be very complex environments with tight real-time constraints where it is very difficult to manage resource allocation. This is the case, for example, for a frigate which must position itself in order to use its resources the most effectively possible to increase its chances of survival when the time of air raids comes. Under such very hard constraints, it can often happen that the commander makes errors because of the complexity of the environment or the stress which the situation can generate. We propose here to implement a decision-aid system which suggests the position that the frigate must take. We start by giving a heuristic which evaluates the effectiveness of a position according to the threats found in the environment. Then, we propose an algorithm which treats all the possible rotations and suggests the best regarding a given situation. Finally, we expose the results of our experiments and we comment on them.

3.3.4 Journal Articles

The results of the project activities yielded the three (3) following journal publications.

1. **Target Engageability Improvement through Adaptive Tracking [23]**.

   Abstract – This paper addresses the joint problem of target engageability assessment and engageability improvement in naval Anti-Air Warfare operations. An integrated approach that aims to minimize the detect-to-engage sequence is proposed. It uses an estimation of the search-to-lock-on time of the fire control radar to evaluate the engageability of targets. The latter is then improved through the control of tracking operations. Weapons assignment process and the resulting engagement plan are adjusted based on the results of both the assessment and the improvement of the engageability. A quantitative evaluation of the proposed approach was performed using a simulation and performance evaluation environment developed at Defence Research and Development Canada – Valcartier. Although simple sensors and weapons models used in the presented work, encouraging results were obtained with scenarios involving generic supersonic Anti-Ship Missiles. In such scenarios, the proposed adaptive tracking strategy was able to provide timely engagements compared to a conventional engagement strategy.

2. **A Distributed Intelligent Tactical Sensor Management System [24]**.

   Abstract – In this paper, we report on the project initiated by Defense R&D Canada - Valcartier that is intended as a vehicle to assess holonic control as a means of improving tactical sensor management for distributed military surveillance operations. Three levels of sensor management are considered: sensor, platform, and group. The proposed design is used to develop a simulation using a military scenario in which the holonic control system is employed in the sensor management role. The results of this simulation are presented.

3. **Multiagent Coordination Techniques For Complex Environments: The Case of a Fleet of Combat Ships [25]**.

   Abstract – The use of agent and multiagent techniques to assist humans in their daily routines has been increasing for many years, notably in Command and Control (C2) systems. In this context, we propose using multiagent planning and coordination techniques for resources management in real-time C2 systems. The particular problem we studied is the design of a decision support for Anti-Air Warfare (AAW) on combat ships. In this paper, we refer to the specific case of several combat ships defending against incoming threats and where coordination of their respective resources is a complex problem of capital importance. Efficient coordination mechanisms between the different combat ships are then important to avoid redundancy in engagements and inefficient defence caused by the conflicting actions. To this end, we present four different coordination mechanisms based on task sharing. Three of these mechanisms are communication-based: central coordination, contract Net coordination and ∼Brown coordination, while the last one is zone defence coordination and is based on conventions. Finally, we expose the results obtained while simulating these various mechanisms.

3.3.5 Conference Proceedings

The work performed under 11bm was presented in different scientific events, including conferences, symposia, and workshops. Below is given a list of the most relevant ones.

1. **Fire Control-Based Adaptation in Data Fusion Applications [26].**

   Abstract – In military Command & Control applications, the information quality requirements are very context-dependent and seldom predefined. This leaves much room for adaptation. In this paper, the duration of the search & lock-on operations of the fire control radar is estimated and used as an adaptation trigger. The proposed estimation process aims at establishing a quantitative relationship between the quality of the tactical picture and the reaction time available for decision-making. Based on the target's time of flight, the defensive weapon properties, and the desired range of interception, admissible operational conditions and constraints for the fire control radar are derived to allow the weapon system to achieve its planned interception. These conditions and constraints are re-expressed in terms of tracking quality requirements. Then, adaptation mechanisms are used to select and tune the tracking algorithms and/or manage sensors in order to meet those requirements.

2. **A Q-decomposition and Bounded RTDP Approach to Resource Allocation [27].**

   Abstract – This paper contributes to solve effectively stochastic resource allocation problems known to be NP-Complete. To address this complex resource management problem, a Q-decomposition approach is proposed when the resources which are already shared among the agents, but the actions made by an agent may influence the reward obtained by at least another agent. The Q-decomposition allows to coordinate these reward separated agents and thus permits to reduce the set of states and actions to consider. On the other hand, when the resources are available to all agents, no Q-decomposition is possible and we use heuristic search. In particular, the bounded Real-time Dynamic Programming (bounded RTDP) is used. Bounded RTDP concentrates the planning on significant states only and prunes the action space. The pruning is accomplished by proposing tight upper and lower bounds on the value function.

3. **Tight bounds for a stochastic resource allocation algorithm using marginal revenue [28].**

   Abstract – This paper contributes to solve effectively stochastic resource allocation problems known to be NP-Complete. To address this complex resource management problem, previous works on pruning the action space of real-time heuristic search is extended. The pruning is accomplished by using upper and lower bounds on the value function. This way, if an action in a state has its upper bound lower than the lower bound on the value of this state, this action may be pruned in the set of possible optimal actions for the state. This paper extends this previous work by proposing tight bounds for problems where tasks have to be accomplished using limited resources. The marginal revenue bound proposed in this paper compares favourably with another approach which proposes bounds for pruning the action space.

4. **A Decomposition Real-time Dynamic Programming Approach to Resource Allocation [29]**.

   Abstract – This paper contributes to solve effectively stochastic resource allocation problems known to be NP-Complete. To address this complex resource management problem, the merging of two approaches is made: The Q-decomposition model, which coordinates reward separated agents through an arbitrator, and the Labeled Real-Time Dynamic Programming (LRTDP) approaches are adapted in an effective way. The Q-decomposition permits to reduce the set of states to consider, while LRTDP concentrates the planning on significant states only. As demonstrated by the experiments, combining these two distinct approaches permits to further reduce the planning time to obtain the optimal solution of a resource allocation problem.

5. **An Efficient Model for Dynamic and Constrained Resource Allocation Problems [30]**.

   Abstract – Dynamic constraint satisfaction is a useful tool for representing and solving sequential decision problems with complete knowledge in dynamic world and particularly constrained resource allocation problems. However, when resources are unreliable, this framework becomes limited due to the stochastic outcomes of the assignments chosen. On the contrary, Markov Decision Processes (MDPs) handle stochastic outcomes of unreliable actions, but their complexity explodes when using state-defined constraints. We thus propose an extension of the MDP framework so as to represent constrained and stochastic actions in sequential decision making. The basis of this extension consists in modeling the evolution of a dynamic constraint network by a MDP. We first study the complexity of the problem of finding an optimal policy for this model and then we propose an algorithm for solving it. Comparison to standard MDP shows that this framework noticeably improves policy computation.

6. **R-FRTDP: A Real-Time DP Algorithm with Tight Bounds for a Stochastic Resource Allocation Problem [31]**.

   Abstract – Resource allocation is a widely studied class of problems in Operation Research and Artificial Intelligence. Specially, constrained stochastic resource allocation problems, where the assignment of a constrained resource do not automatically imply the realization of the task. This kind of problems are generally addressed with MDPs. In this paper, we present efficient lower and upper bounds in the context of a constrained stochastic resource allocation problem for a heuristic search algorithm called Focused Real Time Dynamic Programming (FRTDP). Experiments show that this algorithm is relevant for this kind of problems and that the proposed tight bounds reduce the number of backups to perform comparatively to previous existing bounds.

7. **Argumentation-based Decision Support in Naval Command and Control [32]**.

   Abstract – Threat Evaluation and Weapons Assignment (TEWA), a process which is at the heart of tactical naval Command & Control (C2) process, comprises a number of operations that must be performed under time and resource constraints. This article discusses the challenges of decision making in this context, and more particularly the critical issue of target engagement, and shows how this process can be supported by an argumentation-based Decision Support System (DSS). It is shown how the information gathered and analyzed during the execution of the engageability assessment, defined and formalized for the purpose of the paper, can be exploited by an argumentation module. Based on a dialectical model and affording both proactive and reactive interaction modes, the module enables the DSS to anticipate and respond to the operator's objections to its recommendations, and thus substantially enhance the accuracy of its argumentation in a time-constrained decision support context.

8. **The Application of Holonic Control to Tactical Sensor Management [33]**.

   Abstract – In this paper, we report on the project initiated by Defence R&D Canada - Valcartier that is intended as a vehicle to assess holonic control as a means of improving tactical sensor management for distributed military surveillance operations. Three levels of sensor management are considered: sensor, platform, and group. The general holonic architecture and the individual holons at each level are described as well as our next steps towards the implementation of a simulation of a typical scenario.

9. **Adaptation Hierarchy for Data Fusion and Sensor Management Applications [34]**.

   Abstract – By reducing uncertainty in the existing pieces of information and providing means to infer about the missing pieces, data fusion supports the decision-makers in compiling and analyzing a representation of the problem of interest. Data fusion has often been portrayed as a sequential process that simply combines pieces of information in a purely open-loop mode. Nevertheless, to cope with changing objectives, environments and constraints, fusion systems need an active feedback, or adaptation. This article presents part of our research activities that aim at defining, developing, and demonstrating adaptation concepts in data fusion and sensor management. Hierarchy of adaptation and management problems are defined and holonic architecture is identified as suitable control structure. The holonic architecture presents a superior choice in the military settings because it is naturally hierarchical and recursive. A holonic architecture maintains the chain of command, is robust and flexible, and its overall behaviour is predictable.

10. **An Efficient Resource Allocation Approach in Real-time Stochastic Environment [35]**.

    Abstract – We are interested in contributing to solving effectively a particular type of real-time stochastic resource allocation problem. Firstly, one distinction is that certain tasks may create other tasks. Then, positive and negative interactions among the resources are considered, in achieving the tasks, in order to obtain and maintain an efficient coordination. A standard Multiagent Markov Decision Process (MMDP) approach is too prohibitive to solve this type of problem in real-time. To address this complex resource management problem, the merging of an approach which considers the complexity associated to a high number of different resource types (i.e. Multiagent Task Associated Markov Decision Processes (MTAMDP)), with an approach which considers the complexity associated to the creation of task by other tasks (i.e. Acyclic Decomposition) is proposed. The combination of these two approaches produces a near-optimal solution in much less time than a standard MMDP approach.

11. **A Multiagent Task Associated MDP (MTAMDP) Approach to Resource Allocation [36]**.

Abstract – We are interested in contributing to solving effectively a specific type of real-time stochastic resource allocation problem, which is known as NP-Hard, of which the main distinction is the high number of possible interacting actions to execute in a group of tasks. To address this complex resource management problem, we propose an adaptation of the Multiagent Markov Decision Process (MMDP) model which centralizes the computation of interacting resources. This adaptation is called Multiagent Task Associated Markov Decision Process (MTAMDP) and produces a near-optimal policy in a much lower time than a standard MMDP approach. In a MTAMDP, a planning agent computes a policy for each resource, and are coordinated by a central agent. MTAMDPs enables to practically solve our NP-Hard problem.

12. **Threat Evaluation and Weapons Allocation in Network-Centric Warfare [37]**.

    Abstract – The concepts of threat evaluation and weapons allocation (TEWA) in the defence domain have traditionally been considered from the single platform perspective. However, with the current trend in defence towards network-centric warfare, that is the linking of sensors, engagement systems and decision-makers into an effective and responsive whole, it is becoming more appropriate to view these concepts at the force level. One approach to the challenge of developing force level TEWA functionality is to regard TEWA as a dynamic human decision-making process aimed at the successful exploitation of tactical resources (eg sensors and weapons) during the conduct of command and control activities. In this paper, the results of taking this approach to force level TEWA through the application of the applied cognitive work analysis methodology are presented. In particular, a functional abstraction network is described which encapsulates the inferential transformation from sensor data acquisition to inferences about the identification, intent and level of threat for the given entities in the defence environment. Finally, emerging threat evaluation and weapons allocation concepts in network-centric warfare are outlined and an example is given to illustrate the ideas developed within the paper.

13. **Decomposition Techniques for a Loosely-Coupled Resource Allocation Problem [5]**.

    Abstract – We are interested by contributing to stochastic problems of which the main distinction is that some tasks may create other tasks. In particular, we present a first approach which represent the problem by an acyclic graph, and solves each node in a certain order so as to produce an optimal solution. Then, we detail a second algorithm, which solves each task separately, using the first approach, and where an on-line heuristic computes the global actions to execute when the state of a task changes.

14. **Multi-Platform Coordination in Command and Control [38]**.

    Abstract – The use of agent and multi-agent techniques to assist human in its daily routine has been increasing for many years, notably in Command and Control (C2) systems. In this article, we focused on multi-agent coordination techniques for resources management in realtime C2 systems. The particular problem we studied is the design of a decision-support for anti-air warfare on Canadian frigates. In the case of the several frigates defending against incoming threats, multi-agent coordination is a complex problem of capital importance. Better coordination mechanisms are important to avoid redundancy in engagements and inefficient defence caused by conflicting actions. We present different task sharing coordination mechanisms with their evaluation.

15. **An Agent-Based Decision Support System for Naval Anti-Air Warfare: An Exploration Based on Simulation [10]**.

    Abstract – Maritime environments are known to be very complex environments with tight real-time constraints where it is very difficult to manage resource allocation. This is the case, for example, for a frigate which must position itself in order to use its resources the most effectively possible to increase its chances of survival when the time of air raids comes. Under such very hard constraints, it can often happen that the commander makes errors because of the complexity of the environment or the stress which the situation can generate. We propose here to implement a decision-aid system which suggests the position that the frigate must take. We start by giving an heuristic which evaluates the effectiveness of a position according to the threats found in the environment. Then, we propose an algorithm which treats all the possible rotations and suggests the best regarding a given situation. Finally, we expose the results of our experiments and we comment on them.

16. **A Frigate Movement Survival Agent-Based Approach [39]**.

    Abstract – The position of a frigate to face some threats can augment its survival chances and therefore it is important to investigate this aspect in order to determine how a frigate can position itself during an attack. To achieve that, we propose a first method based on the Bayesian movement, performed by a learning agent, which determines the optimal positioning of the frigate by dividing the defense area into six sectors for weapon engagement and then, it makes efficient use of all the weapons available by using the sectors. The second method that we propose is called Radar Cross-Section Reduction (RCSR) movement and, it aims at reducing the exposed surface of the frigate to incoming threats before their locking phase is over. Preliminary results on these two methods are presented and discussed. Finally, an implementation of a meta-level agent which would make efficient use of both complementary methods is suggested.

17. **Sensor Management in Command & Control [40]**.

    Abstract – The sensing resources represent an important source of information on which the Command & Control (C2) process bases most of its reasoning. Therefore, a major prerequisite to the success of the whole C2 process is the effective use of these scarce and costly resources. This is the problem of sensor management that has to do with how best to manage and coordinate the use of sensing resources to improve data acquisition and ultimately perception and comprehension. Conscious of the important role sensor management has to play in modern C2 systems, the Decision Support Systems (DSS) Section at Defence Research & Development Canada - Valcartier is currently studying advanced sensor management concepts and applications, to increase the survivability of the current Halifax and Iroquois Class ships, as well as their possible future upgrades. The objective of the reported part of this study is twofold i) to present the sensor management problem and the requirements for its solution ii) to demonstrate, through a tracking application, the benefits that can be gained by the closed-loop management of the sensors.

18. **A method to optimize ship maneuvers for the coordination of hardkill and softkill weapons within a frigate [11]**.

    Abstract – The coordination of anti-air warfare hardkill and softkill weapon systems is an important aspect of command and control for a Frigate. Since the effectiveness of a particular weapon varies depending on the orientation of the Frigate with respect to the threats faced, a key element of the coordination process is to maneuver the Frigate to most effectively use all the weapons available. This paper shows that the environment surrounding the Frigate can be divided into six fundamental sectors for weapon engagement. The method to determine the general effectiveness of each sector for the threats faced is shown. A naïve Bayes method that determines the optimal positioning of the Frigate to most effectively use the hardkill and softkill weapons is presented. Also discussed are the different types of planners that were investigated for planning engagements for the hardkill and softkill weapon systems. Preliminary results comparing and rating these planners are shown, both with and without the recommended maneuvers.

3.3.6 Theses

Most of the work conducted under 11mb was achieved in collaboration with with Canadian industry and universities. This section gives the list of the graduated students, who contributed the this work, and their achievements.

1. **Techniques For The Allocation Of Resources Under Uncertainty (Pierrick Plamondon, Ph.D), U. Laval**.

   Abstract – Resource allocation is an ubiquitous problem that arises whenever limited resources have to be distributed among multiple autonomous entities (e.g., people, companies, robots, etc). The standard approaches to determine the optimal resource allocation are computationally prohibitive. The goal of this thesis is to propose computationally efficient algorithms for allocating consumable and non-consumable resources among autonomous agents whose preferences for these resources are induced by a stochastic process. Towards this end, we have developed new models of planning problems, based on the framework of Markov Decision Processes (MDPs), where the action sets are explicitly parameterized by the available resources. Given these models, we have designed algorithms based on dynamic programming and real-time heuristic search to formulate allocations of resources for agents evolving in stochastic environments. In particular, we have used the acyclic property of task creation to decompose the problem of resource allocation. We have also proposed an approximative decomposition strategy, where the agents consider positive and negative interactions as well as simultaneous actions among the agents managing the resources. However, the main contributions of this thesis is the adoption of stochastic real-time heuristic search for a resource allocation. To this end, we have developed an approach based on Q-decomposition with tight bounds to diminish drastically the planning time to formulate the optimal policy. These tight bounds enable to prune the action space for the agents. We show analytically and empirically that our proposed approaches lead to drastic (in many cases, exponential) improvements in computational efficiency over standard planning methods. Finally, we have tested real-time heuristic search in the SADM simulator, a simulator for the resource allocation of a platform.

2. **A Method to solve dynamic and multi-criteria decision problems under uncertainty (Anissa Frini, Ph.D), U. Laval**.

   Abstract – The general objective of this thesis is the development of a resolution method for multi-criteria dynamic decision-making problems under uncertainty. In particular, this thesis answers the following questions: is it possible to combine the decomposition of the decision tree when a multi-criteria decision aid method is used to get best compromise strategies? What are conditions that guarantee best compromise strategies via decomposition? How could we select the multi-criteria decision aid method that will be used? What are the resolution method steps? Can we apply the proposed method for concrete applications and which are its advantages and its limits? To answer these questions, a principle of decomposition that generalizes the Bellman decomposition principle to multi-criteria decision trees, is stated. This principle leads to strategies of best compromise when decomposition conditions are verified. A theorem, which specifies these conditions, is stated and proved. When the principle of decomposition is applied, a multi-criteria decision aid method is used in a recursive way for each sub-problem. The choice of this multi-criteria decision aid method is important. It will be made considering not only the decomposition conditions but also some theoretical and pragmatic considerations. Afterwards, the steps of the resolution method are proposed for two cases. At first, the method is presented for quantitative criteria and probabilistic uncertainty. Then, the method is presented for qualitative criteria and possibilistic uncertainty, modeled by possibility distributions. Finally, the proposed method is applied for the defense of a military naval ship. This application aims to generate all feasible defense strategies and to select best compromise ones. Results of the decomposition method are compared with a myopic method, which simply ignores the dynamic aspect of the problem.

3. **Ordonnancement de ressources en temps réel avec contraintes dynamiques dans un environnement non déterministe (Olivier Gagné, Master), U. Laval**.

   Abstract – Military problems are very complex and they can be solved by different artificial intelligence techniques. In this thesis, we address the problem of weapon-targets assignment for a frigate. To defend efficiently the ship, we have to analyze each threat and determine which resource assigns against it. For that purpose, we utilize the engageability assessment to consider different characteristics; useful in the resources assignment. To this end, a mathematical model named Constraint Satisfaction Problem (CSP) is employed. This framework allows formalizing the problem to ensure the constraint consistency and to sort threats in importance order. We tried this algorithm on different types of weapon-target assignment problems. Finally, we demonstrate the advantage of engageability assessment on the weapon-target assignment problem in real time and stochastic environment.

4. **Coordination de plans d'agents Application à la gestion des ressources d'une frégate (Sébastien Paquet, Master), U. Laval**.

   Abstract – In computer science, agents and multi-agent systems have become very popular and are now used for many varied applications. Depending on the target application, the agents can take different architectures. These architectures can be classified as follows: reactive, deliberative and hybrid. In many cases, the agents do not exist alone in their environment and they must be able to coordinate their activities in order to attain a certain goal. They must be able to interact together in such a way that conflicting actions are avoided and, if possible, that favors positive interactions. There are many coordination techniques available, such as the use of an organizational structure, contract allocation, multi-agent planning, negotiation, the use of engagements, etc. However, under certain circumstances, coordination by itself is not sufficient. Sure enough, the agents must not only coordinate well, they have to really act together, in other words, act as a team. The difference between an agent team and a group of cooperating agents is that the team not only acts in order to realize a certain objective, they do it in a certain "mindset", with the knowledge that they are part of a team. This allows a greater cohesion in the team. As an example, an agent might help another if it realizes that the other needs help or if it realizes that the task could be accomplished more efficiently. In this thesis, multi-agent systems and agents teams (both constituted of hybrid agents) are put to use in the design of a resource management system for a Canadian Halifax patrol frigate. Ships of this class feature many weapon control systems which must be coordinated efficiently in order to maximize the chance of survival when a frigate is attacked by anti-ship missiles.

5. **A Frigate Survival Approach based on Real-time Multi-agent Planning (Pierrick Plamondon, Master), U. Laval**.

   Abstract – Nowadays, in computer sciences, intelligent agents are becoming more and more popular. Such systems offer a logical approach to conceive a system where diverse modules interact to solve complex real world problems. Lockheed Martin Canada (LMC) and the Defence Research and Development Canada — Valcartier (DRDC Valcartier) have provided a real world multi-agent application. Our main task for this application is to conceive different multi-agent techniques to improve the defensive effectiveness of a Halifax class Canadian frigate against incoming missile threats. A Halifax class frigate uses different modules that interact together to defend itself and it is necessary to propose ways to optimize the coordination, between them in order to increase their efficiency. In this thesis, we will focus mainly on multi-agent planning. We first present some theoretical bases on planning, different planning approaches, then we investigate how to improve the effectiveness of defence for the frigate using different strategies. Finally, we provide different experimental results. Our experimental results show that 1) using missile re-engagement against incoming threats is more efficient with few threats than with many threats; 2) a central coordinator coordination technique between hardkill and softkill agents is better than with two other coordination techniques; and 3) a Bayesian approach for the frigate positioning enhances the frigate's chance of survival.

6. **Real-time Deliberative Planning (Martin Soucy, Master), U. Laval**.

Abstract – For several years, Defence Research & Development Canada (DRDC) and Lockheed Martin Canada (LMC) have been working together in order to modernize the Command and Control system (C2) present on-board a frigate. The purpose of such a system is to analyze and manage a considerable flow of information in order to carry out the right actions in response to a given situation. Our role within this project is at the decision-making level. We must study the possibilities that agent technology can offer to such a system. In this thesis, we focused our efforts on the implications of real time planning adapted to agents and multi-agent systems. For this purpose, we will first of all present the theoretical elements of real time planning in agent systems and the paradigm of mobile agents. We will then show our results concerning two approaches to carry out the planning of an agent and of a group of frigate agents.

7. **Multi-Platform Coordination and Resource Management in Command and Control (Patrick Beaumont, Master), U. Laval**.

   Abstract – The use of agent and multi-agent techniques to assist humans in their daily routines has been increasing for many years, notably in Command and Control (C2) systems. This thesis is situated in this domain. Precisely, we propose to use multi-agent planning and coordination techniques for resource management in real-time C2 systems. The particular problem we studied is the design of a decision-support for anti-air warfare on Canadian frigates. In the case of several frigates defending against incoming threats, multi-agent coordination is a complex problem of capital importance. Better coordination mechanisms are important to avoid redundancy in engagements and inefficient defence caused by conflicting actions. In this thesis, we present four different coordination mechanisms based on task sharing. Three of these mechanisms are based on communications: central coordination, Contract Net coordination and Brown coordination, while the zone defence coordination is based on social laws. Finally, we expose the results obtained while simulating these various mechanisms.

8. **Real-time planning of ship position in response to anti-ship missile attack (Jean-François Morissette, Master), U. Laval**.

   Abstract – For several years, Recherche et Développement pour la Défense Canada (RDDC) and Lockheed Martin Canada (LMC) have been working together in order to modernize the Command and Control system (C2) present on a frigate. The purpose of such a system is to analyze and manage a considerable flow of information in order to carry out the right actions in response to a given situation. Our role within this project is at the decision-making level. We must study the possibilities that agent technology can offer to such a system. In this thesis, we propose a formal model of interaction between the various resources available on the frigate and the threats it must face. We also propose a technique of positioning and an approach of planning in order to maximize the chances of survival of the frigate. Lastly, we present the results we obtained by means of simulations.

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4 Recommendations for Future Work

This report presents a summary of the problems tackled, the technological approaches investigated, and the achievements realized by the 11bm Applied Research Project (ARP) on combat resource management.

The major significance of this project lies in that it proposes and explores some powerful practical and theoretical ideas into the core of decision support and automation for combat resource management. The foundational ideas come from a variety of areas, including multi-agent systems, agent-based planning, distributed and multi-criteria decision making, man-machine interaction, coordination between agents, cognitive systems engineering and modeling and simulation. The work conducted under 11bm had an important import impact on the technologies/approaches adopted by SISWS TDP for the development of the weapons manager and by INCOMMANDS TDP for the development of CORALS, the combat resource management capability [41, 42].

The project covers several topics and problems, yet many others will require further investigation. The following gives a list of areas/problems where such investigation is required:

1. Constraint-based target engageability assessment.
2. Dynamic tasking and allocation of area of responsibility to defence assets (Task Group) in order to maximize the exploitation of the available reaction-time to defeat air and surface (symmetric/asymmetric) threats (*e.g.*, small boat/aircraft attack).
3. Multi-platform and multi-environment (Navy, Air Force, Army) weapons/weapons and weapons/sensors coordination and cooperation problems (*e.g.*, to support the Army and the Air Force to defeat land-based threats by providing Naval Fire Support).
4. Dynamic information gathering concepts to effectively assess the level of the response success (e.g., kill assessment). Requirements will need to be gathered for surveillance tasks to gain reaction-time and increase the targets engageability and objects discrimination power.
5. Dynamic allocation and coordination of sensing resources to maximize the task-related value of the collected information in order to 1) Increase the reaction-time; 2) Increase the engageability of the threats by providing a higher discrimination power (weapon quality information) in target-dense environments; and 3) Minimize the yet high risk of collateral damages (e.g., in littoral context).
6. Sensors mode control, sensor tasking, and sensor coordination algorithms and solutions in support of adaptive information fusion concepts.
7. Coordination of platforms deployment for a synergetic distributed information gathering.

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List of symbols/abbreviations/acronyms/initialisms

AAW	Anti-Air Warfare
AI	Artificial Intelligence
ARP	Applied Research Project
AWW	Above Water Warfare
BDI	Belief Desire Intention
C2	Command and Control
CCS	Command and Control System
CIWS	Close-In Weapon System
CORALS	COmbat Resource ALlocation Support
CSP	Constraint Satisfaction Problems
CPM	Combat Power Management
DND	Department of National Defence
DRDC	Defence Research and Development Canada
DSS	Decision Support Systems
ESSM	Evolved Sea Sparrow Missile
FCR	Fire Control Radar
FRTDP	Focused Real-Time Dynamic Planning
GCCS-M	Global Command and Control System - Maritime
HMCCS	Halifax Modernization Command and Control System
INCOMMANDS	Innovative Naval Combat Management and Decision Support
LRTDP	Labelled Real-Time Dynamic Programming
MaCSP	Markovian Constraint Satisfaction Process
MCD	Multiple Criteria Decomposition
MCDA	Multi-Criteria Decision Aid
MCM	Multiple Criteria Myopic
MDP	Markov Decision Process
MOE	Measure Of Effectiveness
MTAMDP	Multi-agent Task Associated MDP
MTP	Maritime Tactical Picture
NDS	Naval Defence Simulator
OODA	Observe-Orient-Decide-Act
OPTASK	Operational Tasking
ORO	Operations Room Officer
PRA	Projet de Recherche Appliquée
RCS	Radar Cross Section
RDDC	Recherche et développement pour la défense Canada
RM	Resource Management
ROE	Rules of Engagement
RTDP	Real-time Dynamic Programming
SADM	Ship Air Defense Model

SAM	Surface-to-Air Missile
SASS	Situation Analysis Support Systems
STIR	Separate Tracking and Illuminating Radar
TDP	Technology Demonstration Project
TEWA	Threat Evaluation and Weapon Assignment
VOI	Volume Of Interest
WTA	Weapon-Target Assignment

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(Security classification of title, body of abstract and indexing annotation must be entered when document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Valcartier 2459 Pie-XI Blvd. North Quebec city, Quebec, Canada G3J 1X5	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.) UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Combat Resource Management (11bm) Applied Research Project (ARP): Final report

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

Benaskeur, A.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
December 2009	54	42

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Report

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

Defence R&D Canada – Valcartier
2459 Pie-XI Blvd. North Quebec city, Quebec, Canada G3J 1X5

9a. PROJECT NO. (The applicable research and development project number under which the document was written. Please specify whether project or grant.)	9b. GRANT OR CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
11br	

10a. ORIGINATOR'S DOCUMENT 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 Valcartier TR 2009-300	

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Defence Research & Development Canada (DRDC) has, for several years now, been investigating methods to augment or enhance existing shipboard Command and Control System (CCS) capabilities. As part of this investigation, 11bm Applied Research Project (ARP) focuses on the naval combat resource management in the context of Above Water Warfare (AWW).

The project, a summary of which is presented in this report, has explored concepts concerned with the design, development, implementation, and evaluation of a computer-based, real-time decision support system that could be integrated into the future Canadian platforms to assist operators in conducting tactical Command and Control (C2), particularly for combat resource management.

The project resulted in a list of achievements, which includes scientific publications, algorithms, software tools, and recommendations for follow-on work. It has also provided inputs to several projects, including INCOMMANDS and SISWS Technology Demonstration Projects (TDPs).

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