Defence Research and Development Canada
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# Scoping Study on DRDC Toronto Future Research Regarding Naval Mine Countermeasures

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*CFEME*

**Defence R&D Canada**
Technical Report
DRDC Toronto TR 2011-178
June 2012

Canada

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# Abstract

Canada currently possesses limited to modest Mine Counter Measure (MCM) capability that includes Maritime Coastal Defence Vessels (MCDVs) used for coastal surveillance and patrol, and Clearance Diving Units for identification and disposal of sea mines. In recognition of its MCM capability deficiencies, Canada has been actively involved in defining a programme for integrating unmanned underwater vehicles (UUVs) in current MCM operations through collaboration with other Allied nations. The objective of the Underwater Intervention in shallow (SW)/very shallow water (VSW) Operations Applied Research Project (ARP), conducted since 2008, is to improve Canadian Forces (CF) capability to conduct MCM, combat diving and Special Operations Force operations in shallow and very shallow water, by increasing capacity of underwater systems, operators, and divers, reducing risk and equipment burden on the diver, and extending speed and accuracy in conduct of these operations. This report summarizes current deficiencies as observed by the CF and Defence Research and Development Canada researchers during a North American Treaty Organization (NATO) certification Exercise NOBLE MARINER 11, and proposes areas for future research for the above ARP. The insights gained from this analysis will also be used to provide Canada and its allies with adaptive and easy-to-interpret feedback on their operational practices and plans as they conduct MCM operations.



# Résumé

Le Canada possède une capacité, de restreinte à modeste, en matière de lutte contre les mines (LCM) qui comprend les navires de défense côtière (NDC) utilisés pour surveiller les eaux côtières et y patrouiller, et les unités de plongée d'inspection pour l'identification et l'élimination de mines marines. En reconnaissance de ses lacunes pour lutter contre les mines, le Canada a participé activement à l'élaboration d'un programme visant à intégrer les engins télépilotés sous-marins (UUV) aux opérations actuelles de LCM avec la collaboration d'autres pays alliés. En 2008, le Canada a mis en œuvre un projet de recherche appliqué (PRA) sur les opérations d'intervention sous-marine en eau peu profonde (SW)/très peu profonde (VSW) qui vise à améliorer la capacité des Forces canadiennes (FC) à exécuter les opérations de LCM, de plongée de combat, de même que les opérations liées aux Forces d'opérations spéciales en eau peu profonde et très peu profonde, en augmentant la capacité des systèmes sous-marins, des opérateurs et des plongeurs tout en réduisant les risques et le fardeau de l'équipement pour le plongeur et en augmentant la rapidité et la précision liées à l'exécution de ces opérations. Ce rapport résume les lacunes actuelles observées par les FC et les chercheurs de Recherche et développement pour la défense Canada lors de l'exercice de certification NOBLE MARINER 11 de l'Organisation du Traité de l'Atlantique Nord (OTAN), et propose des domaines de recherche futurs pour le projet susmentionné. Les connaissances acquises lors de cette analyse serviront aussi à fournir au Canada, et à ses alliés, une rétroaction constructive et facile à interpréter sur les plans et pratiques opérationnels lors de l'exécution d'opérations de LCM.

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# Executive summary

## Scoping Study on DRDC Toronto Future Research Regarding Naval Mine Countermeasures:

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**Introduction or background:** Canada has been actively involved in defining a programme for integrating UUVs in current MCM operations through collaboration with other Allied nations. In line with this effort, the Underwater Intervention in Shallow Water/Very Shallow Water (SW/VSW) Operations Applied Research Project was proposed in 2008 with the objective to improve CF capability to conduct MCM, combat diving and Special Operations Force operations in shallow and very shallow water, by increasing capacity of underwater systems, operators, and divers, reducing risk and equipment burden on the diver, and extending speed and accuracy in conduct of these operations.

It was determined that the initial step in of this work was the analysis of current MCM process in the operational context through direct observation and discussion with MCM operators and staff in a realistic operational environment. The NATO certification Exercise NOBLE MARINER 11 (NOMR11) was identified as a suitable venue for exposing CF personnel and DRDC Toronto analysts to MCM operations and enabling them to gain a more holistic understanding of the MCM process. Consequently, eight DRDC Toronto and Canadian Forces Environmental Medicine Establishment (CFEME) personnel were deployed to the individual component units (i.e. mine hunters) and the Commander Task Group (CTG) ship during the Exercise. The primary goal of this effort was to identify any operational issues/deficiencies in the MCM processes that may impact situational awareness and operational effectiveness.

**Results:** The team's experiences from various ships were consolidated into a comprehensive list of deficiencies. Based on the acquired knowledge and through team discussion, areas for future work suited to DRDC expertise and capabilities were identified for each deficiency and are described in this report. These include: a) sonar operators; b) diving operations; c) unmanned underwater vehicles; d) underwater communications; e) C2 communications; and f) planning and risk calculation software. In addition, the CF officers' experience and the dialogue with personnel participating in the exercise also contributed additional information about non-observed deficiencies, in the areas of: g) effects of underwater explosions on divers; h) alternative methods for mine disposal/neutralization; i) alternative technologies for mine detection; and j) mine jamming capabilities.

**Significance:** The insights gained from this analysis will be used to assist in focusing further research for the 11ci project and to provide Canada and its allies with adaptive and easy-to-interpret feedback on their operational practices and plans as they conduct MCM operations.

**Future plans:** Future work will focus on investigation and the development of technologies and techniques that will improve diver effectiveness in MCM operations, including the defeat of underwater IEDs, specifically in two areas: Human Factors for Automatic Target Recognition

(ATR) and Autonomous Underwater Vehicles (AUVs) coordination for mine hunting, and UUV/diver interaction. Opportunities will be sought to collaborate with DRDC Atlantic (and other national and international partners) in order to examine interactions between divers or operators with autonomous systems, where DRDC Atlantic will provide the technology and the context, while DRDC Toronto will investigate human factors considerations with regards to various relevant topics.

# Sommaire

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**Introduction ou contexte :** Le Canada a participé activement à l'élaboration d'un programme visant à intégrer les engins télépilotés sous-marins (UUV) aux opérations actuelles de LCM avec la collaboration d'autres pays alliés. Dans le même ordre d'idées, le Canada a proposé en 2008 un projet de recherche appliqué (PRA) sur les opérations d'intervention sous-marine en eau peu profonde (SW)/très peu profonde (VSW) en vue d'améliorer la capacité des Forces canadiennes (FC) à exécuter les opérations de LCM, de plongée de combat, de même que les opérations liées aux Forces d'opérations spéciales en eau peu profonde et très peu profonde, en augmentant la capacité des systèmes sous-marins, des opérateurs et des plongeurs tout en réduisant les risques et le fardeau de l'équipement pour le plongeur et en augmentant la rapidité et la précision liées à l'exécution de ces opérations.

Il a été convenu que la première étape de ce travail consisterait à analyser les processus actuels de LCM ayant trait aux opérations au moyen d'observations directes et de discussions avec les opérateurs et les employés de LCM au sein d'un milieu opérationnel réaliste. Il a été déterminé que l'exercice de certification NOBLE MARINER 11 (NOMR11) de l'OTAN serait une façon convenable d'exposer les FC et les analystes du RDDC Toronto aux opérations de LCM pour leur permettre d'acquérir une compréhension plus globale des processus de LCM. Par conséquent, huit employés de RDDC de Toronto et du Centre de médecine environnementale des Forces canadiennes (CMEFC) ont été affectés aux unités de chaque composante (c'est-à-dire les chasseurs de mines) et sur le navire du Commandant de groupe opérationnel durant l'exercice. Cette mission vise à identifier les problèmes opérationnels ou les lacunes liés aux processus de LCM susceptibles d'entraîner des répercussions sur la connaissance de la situation et l'efficacité opérationnelle.

**Résultats :** Nous avons regroupé les expériences de l'équipe de divers navires afin de créer une liste exhaustive de lacunes. En se fondant sur les connaissances acquises et les discussions de l'équipe, nous avons identifié des domaines de recherche futurs - adaptés à l'expertise et aux capacités de RDDC – pour chacune des lacunes. Ces domaines sont décrits dans le présent rapport et comprennent : a) les opérateurs de sonars; b) les opérations de plongée; c) les engins télépilotés sous-marins; d) les communications sous-marines; e) C2 communications; et f) un logiciel pour la planification et le calcul du risque. En outre, l'expérience des officiers des FC et les dialogues menés auprès des participants à l'exercice ont aussi permis d'obtenir des renseignements additionnels au sujet des lacunes non-observées dans les domaines suivants : g) les répercussions des explosions sous-marines sur les plongeurs; h) les méthodes alternatives pour le déminage ou la neutralisation des mines; i) les technologies alternatives pour détecter des mines; et j) la capacité de brouillage des mines.

**Importance :** Les connaissances acquises lors de cette analyse contribueront aux recherches futures pour le projet 11ci et fourniront au Canada, et à ses alliés, une rétroaction constructive et facile à interpréter sur les plans et pratiques opérationnels lors de l'exécution d'opérations de LCM.

**Perspectives :** Les travaux futurs porteront sur la tenue d'enquêtes et le développement de technologies et de techniques susceptibles d'améliorer l'efficacité des opérations de LCM, y compris la destruction d'EEI sous-marins, en particulier dans deux domaines : la coordination des facteurs humains pour la reconnaissance automatique de cibles et de véhicules sous-marins autonomes (VSA) pour effectuer la chasse aux mines, et l'interaction entre le plongeur et le véhicule sous-marin sans équipage. Nous chercherons des moyens pour collaborer avec DRDC Atlantique (et d'autres partenaires nationaux et internationaux) afin d'examiner les interactions entre les plongeurs ou les opérateurs de systèmes autonomes. RDDC Atlantique fournira la technologie et le contexte alors que RDDC Toronto mènera une enquête sur les considérations relatives aux facteurs humains par rapport à divers sujets pertinents.

# Table of contents

# Acknowledgements

This report is based almost entirely on the experiences gained by the research team during their participation in NOMR11. This opportunity and its successful execution were made possible by the efforts and assistance of many people, but particular mention should be made to Standing NATO Mine Countermeasures Group 1 (SNMCMG1) for agreeing to embark the research team. CTG SNMCMG1, Cdr H. Lammers of the Royal Dutch Navy and in particular, his Principle Staff Officer, Lt Cdr Richard K. Anderson of the Royal Danish Navy, were instrumental in enabling and organizing our participation. As well, support from MCC Northwood staff, primarily Cmdre Belliveau of the Royal Canadian Navy, and Lt Cdr Laurent Rioux of the French Navy, were critical in allowing this opportunity.

Additionally, we would also like to extend a special Thank-you to the Commanding Officers and crews of the Mine Countermeasure Vessels (MCMVs) of SNMCMG1, ORP KONTRADMIRAL XAWERY CZERNIKI, BNS NARCIS, FGS DATTELN and HMS BROCKLESBY, that hosted and welcomed the Research team into their respective “homes” during their time at sea. Not only did they go out of their way to provide their valuable time and expertise throughout the exercise, but did so enthusiastically, a testament to their dedication and professionalism.

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# 1 Introduction

## 1.1 Background

Sea mines are a recognized maritime threat arising from the availability of a wide variety of commercially-made mines and waterborne Improvised Explosive Devices (IEDs), as well as the existence of significant historical stockpiles. They are inexpensive to produce, easy to lay and readily available, while difficult to detect, time consuming and resource draining to counter. Traditionally accessible only to major naval forces, they have increasingly become a weapon of choice for smaller nations as well as non-state/terrorist organizations. Even a stated intent or claim that an area has been mined can have similar adverse consequences to that of a real threat.

> "While traditionally considered that a direct state-on-state military offensive mining threat to Canada is low, the emerging global security trends illustrate the potential for irregular attacks on Canada from terrorists (be they non-state, state sponsored, or even our own disenchanted diasporas) and criminals, may be increasing. This makes the use of such weapons an attractive option for potentially hostile regimes or terrorist organisations wishing to act against Canada, to indirectly threaten the United States, or merely to illustrate an ability to act globally… The geographic isolation of North America from other continents by the oceanic barriers and the relatively low historic incidence in Canada of conventional sea mining has led some to disregard the potential risk. However, the political and social impact of just one sinking of a merchantman or warship in continental US/Canadian waters is incalculable. Canada shares many of its vital waterways with the United States and through its inexorable security ties is fully engaged in the common defence of North America."

[Director General Maritime Force Development (2011)
*Concept for Naval Mine Countermeasures*
Para 3-6]

With increasing awareness of a mine threat to national and international waters, many of the allied nations, along with Canada, are making significant investments in developing their Mine Countermeasures (MCM) capabilities[1] (for example, The European Defence Agency [EDA] has recently launched a multinational initiative to examine future MCM capabilities required by 11 European nations). As defined by the North Atlantic Treaty Organization (NATO), MCM can constitute any of the following:

a. Preventing the enemy from laying mines.

b. Forcing or enticing the enemy to lay mines in waters which our ships need not or do not use.

[1] **Annex A** summarizes past and current research by various organizations.

c. Causing the mines to explode without loss, or with acceptable loss to allied shipping, by the use of mine countermeasures forces.

d. Causing the mines to become ineffective by removing them to a safe place or by preventing the firing mechanism from operating.

e. Reducing the danger to allied shipping by confining ships to routes in which enemy mines are scarce or non-existent, either because mines have not been laid in any quantity or because their number has been reduced by the actions of mine countermeasures forces.

f. Altering the characteristics of ships, either permanently or temporarily, so that they do not or are less liable to actuate mines (NATO Standardization Agency, 2002).

MCM operations are generally conducted in four stages: detection, classification, identification and neutralisation[2]. The detection[3] phase typically utilizes sonar (e.g. hull-mounted, variable depth or side-scan) which can be fitted to a number of vessel types (e.g. ships, boats, remotely operated vehicles (ROVs) or UUV. They are used to search the water column and seabed in order to detect potential foreign objects (route survey data of the area searched, if available, can be used to identify which contacts were or were not there when the original survey was conducted). Classification techniques are then employed for each new object encountered (e.g. higher frequency sonar). Depending on the environmental conditions, the type of mine anticipated (based on the known mine threat) and the sonar operator's skill in interpreting the display, contacts are then classified as either mine or non-mine like. Once objects are classified as mine-like, additional sensors (e.g. optical sensors or clearance divers) are deployed to visually identify the contact.

MCM operations in ports and harbours in particular are extremely time-critical, due to high costs incurred by any disruption to shipping (Law et al., 2004). Presently, NATO's ability to respond to a mine threat in ports is slow, laborious and dangerous. This is due to many factors, such as shipping movements, very shallow water, turbidity, confined space, mine burial due to muddy/silty conditions, and high clutter density (Bovio, 2006; Law, Bovio and Bezemer, 2004). Sonar operators are faced with challenges such as lack of bottom mapping data to compare with the current picture when identifying objects, or knowledge of anticipated mine types in the area (Simmons and Naigle, 2000). Clearance divers are constantly put at high risk when deployed to identify, neutralize or recover mines. In Canada, these challenges are compounded by equipment deficiencies (such as lack of remote active MCM equipment) and outdated self-protective measures. Canada currently possesses modest MCM capability that includes Maritime Coastal Defence Vessels (MCDVs) used for coastal surveillance and patrol and Clearance Diving Units for identification and disposal of sea mines (CF Director General Maritime Force Development, 2011)[4].

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[2] Neutralisation can include many different techniques, e.g. removal, recovery, disposal in-situ, over pressurisation or other none/explosive methods.
[3] The discovery by any means of the presence of a person, object or phenomenon of potential military significance.
[4] At no point in this document is either mechanical or influence mine sweeping considered.

The Standing NATO Mine Countermeasures Group 1 (SNMCMG 1) is one of NATO's two specialists MCM Groups that conducts exercises on a regular basis to assess its Command Staffs on their abilities to complete their mandated missions and on their training and preparation of personnel to conduct MCM operations, such as humanitarian and disaster relief. It is a permanently established, multinational, sea going force of MCM vessels, on task continuously, giving NATO the ability to respond to a wide range of missions anywhere in the world. The role of Group 1 is to provide a continuous Maritime MCM capability for operations in peacetime, as well as during periods of conflict.

The NATO Response Force rotation 17 (NRF17) conducted a maritime exercise, NOBLE MARINER 11 (NOMR 11), between 28 February – 10 March 2011, in the Mediterranean Sea and Atlantic Ocean. The Command staffs of both Standing NATO Maritime Group 1 (SNMG 1) and SNMCMG 1 were assessed on their preparedness to provide security and assistance in an operation to stabilize a situation or crisis. The Maritime Component Commander for this exercise, Spanish Maritime Forces (SPMARFOR) was also responsible for the certification of the two Groups.

## 1.2 Purpose and Scope

The exercise was identified by DRDC Toronto's Experimental Diving and Undersea Group (EDUG) Commander (11ci project lead) as an ideal opportunity to observe and collect information about current NATO MCM operations in a realistic environment and identify any potential deficiencies in the process. Eight DRDC Toronto and Canadian Forces Environmental Medicine Establishment (CFEME) personnel were deployed to the individual component units (i.e. mine hunters), and the Commander Task Group (CTG) ship. The primary goal of this effort was to identify any operational issues in the MCM processes that may impact situational awareness and operational effectiveness. Of particular interest were those related to human factors in man-machine integration, as this was in line with the project's objectives, and DRDC Toronto's expertise and capabilities; however, other deficiencies were also noted. The insights gained from this analysis were to be used to assist in focusing further research for the 11ci project and to provide Canada and its allies with adaptive and easy-to-interpret feedback on their operational practices and plans as they conduct MCM operations.

Section 2 of this report will describe past and current research and outcomes under project 11ci, Underwater Intervention in SW/VSW Operations, and the research gaps identified in the 2010 Diving Research and Development (DRAD) meeting for the EDUG and the proposed way ahead. Section 3 will provide further details about exercise NOBLE MARINER (NOMR 11). Sections 4 and 5 will discuss the methodology used to collect data, observed and potential deficiencies and areas for future work. Finally, Section 6 will summarize proposed research efforts by DRDC Toronto based on the experiences from the exercise and the priority topic areas identified in the DRAD meeting.

# 2 Underwater Intervention in SW/VSW Operations (11ci)

Canada has been actively involved in defining a programme for developing MCM capability and improving the efficiency of MCM operations through collaboration with other Allied nations. In line with this effort, the Underwater Intervention in SW/VSW Operations ARP (11ci) was proposed in 2008 with the objective to improve CF capability to conduct MCM, combat diving and Special Operations Force operations in shallow and very shallow water by increasing capacity of underwater systems, operators, and divers, reducing risk and equipment burden on the diver, and extending speed and accuracy in conduct of these operations. The goal of the project was to develop a comprehensive delivery platform to demonstrate optimized human and machine interoperability in navigation, route survey, seabed search, detection, classification, target identification, reacquisition and neutralisation, in collaboration with national (DRDC Atlantic, Suffield and Toronto) and international (Australia, Britain, and New Zealand [ABCANZ]), TTCP13 partners. Four research areas have been identified for further study:

- Improving CF capability for shallow and very shallow water diving operations through reduced requirements for decompression stops with the development and validation of decompression tables using novel gasses (e.g. Trimix) and techniques;
- Development of effective approaches to interaction/interoperability between divers and UUVs;
- Development of tools to assess and mitigate personnel risks associated with diving in moderately contaminated waters encountered in ports; and
- Assessment and validation of equipment requirements (breathing equipment, navigation and communications) for very shallow water.

Most of the work to date has been focused on investigation and development of technologies and techniques that will improve diver effectiveness in MCM operations. Currently, CFEME/DRDC Toronto is conducting research in development and validation of decompression tables for Trimix gas. The pilot study completed in 2006 demonstrated the decompression savings offered in the shallow water region and the tables are undergoing a validation process. EDUG is also conducting immunology and decompression studies and investigating immunological-inflammatory responses to decompression stress. Recently, the Human Systems Integration section produced a report on human factors issues when operating UUVs after an extensive literature search, consultation and discussions with subject matter experts (SMEs), and visits to industry and academia partners, and commenced a study investigating Automated Target Recognition (ATR) with various levels of automation and their effect on sonar operator trust (Ho, Pavlovic, Arrabito and Abdalla, 2011).

DRDC Atlantic has also been investing efforts in developing collaborative systems for countering mines and undersea threats under Mine and Harbour Defence project (11cf). New ATR algorithms have been developed that can deal with various sea bottom types, can exploit change detection and can be integrated on-board a UUV (Myers and Fawcett, 2010). Work is ongoing to increase UUV autonomy and allow them to plan and re-plan missions in light of dynamic changes in the environment. The on-board ATR and payload autonomy capabilities have been developed with MCM requirements in mind and are almost ready to be transferred to UUVs being procured by the CF in the near future.

## 2.1 Results of the 2010 DRAD Meeting for EDUG

DRDC Toronto and EDUG host an annual DRAD meeting to review the current status of projects and define the way ahead. This meeting is attended by representatives of all CF diving elements, personnel from the scientific community, as well as Department of National Defence (DND) procurement. During the 2010 meeting it was determined that the EDUG program of work needed to be expanded from strictly diving research to a wider ranging undersea theme that would encompass UUV work. The group selected three main themes with possible project concepts:

Next Generation Decompression Methods (Personnel Protection/Performance Enhancement)

- Decompression, markers treatment;
- Pre-breathing procedures, per fluorocarbons;
- Change-in-tables, alternatives to tables;
- Diver conditioning and fitness;
- Alternate decompression method without Recompression Chamber (in-suit decompression/1 Atmosphere suits);
- Effects of pressure on diver physiology (post-dive fatigue causes & solutions); and
- Performance enhancing supplements.

Increased Efficiency in MCM (including underwater IED) disposal)

- Underwater (U/W) dry working environment for ordnance;
- Containment/portable environment for diver to conduct Render Safe Procedures on mines;
- Through-water communications and data transfer;
- Alternate U/W explosives detection methods (e.g. sniffers used in conjunction with Autonomous Underwater Vehicles (AUVs) and UUVs);
- Network U/W & MCM battlespace (via Low Complexity Access Networks [LCAN]), linking all U/W assets, and ability to transmit data, integrating diver into the network);
- Diver aids (e.g. propulsion systems);
- Alternative mine neutralization methods (e.g. Electro-magnetic Pulse [EMP]/defeat electronics);
- U/W visual acuity;
- U/W tele-robotics (methods similar to existing remote surgery developments in medical world, potential also in EOD applications);
- Single diving set;

- Alternative U/W breathing systems (e.g. artificial gill);
- Alternative method for buoyancy control (e.g. chemical reactions); and
- Alternate Gas Supply tables.

Extreme Environments

- Innovative diver heating/cooling methods systems;
- Surface support for extreme environment diving ops (e.g. Arctic, Persian Gulf) should include RCC treatment solutions (divers and submariners);
- Requirement to adjust decompression tables for colder waters;
- Contaminated environments.

Since EDUG was already conducting next generation decompression research through Trimix Table Development and Immuno-Inflammatory Response in Experienced Military Divers, and several NATO Allies were conducting extensive research into extreme environments, it was decided to focus future research efforts on Increased Efficiency in MCM. In order to better define a way ahead, it was determined that the initial step of this work was to fully understand the MCM process in the operational context. This is best accomplished through direct observation and discussion with MCM operators and staff in a realistic operational environment. Consequently, exercise NOMR 11 was identified as a suitable venue for exposing CF personnel and DRDC Toronto analysts to MCM operations and enabling them to gain a more holistic understanding of the MCM process.

# 3 Exercise NOBLE MARINER 11

As previously stated, the exercise NOMR 11 was a NATO certification exercise, conducted to assess the capabilities of SNMG1 and SNMCMG1 command staffs on their abilities to complete assigned missions. The exercise involved all of the NRF rotation 17: Belgium, France, Germany, Italy, Netherlands, Norway, Poland, Portugal, Spain, United Kingdom, and the United States of America. The aim was to exercise the Preparatory Period for NRF rotation 17 and CTGs, with the specific focus on the maritime expeditionary nature of NRF deployments in littoral environments, evaluating and improving interoperability and integrating tactical maritime operations at the Task Force level, and providing the opportunity for Commander SPAMARFOR to validate combat readiness of forces under his command. This large, complex exercise involved about 3,500 NATO personnel, 20 warships, including the Spanish command ship Spanish Naval Vessel (SPS) CASTILLA (Commander Task Force [CTF]), frigates, tankers and 3 MCM vessels, together with 4 submarines and 4 aircraft, complete with an imbedded media organization to exercise command in media relations.

The CTF, like all roles in the NRF, is a rotating role taken by different countries. CTF has control over all assets assigned to NRF, including air, sea and Marine units. For the purposes of EX NOMR 11, exercise control was undertaken by the Maritime Component Commander Northwood, UK. This allowed for a degree of uncertainty for the CTF as they were unaware of how the events would unfold.

The CTGs (8 in all) were responsible for:

- Escort/Show of Force duties (frigates, destroyers; three Task Groups);
- Air – Observation, Anti-surface Warfare, Anti-submarine Warfare, Fast Air Strikes (land and sea based);
- MCM;
- Logistics;
- Amphibious Operations; and
- Subsurface (submarines).

One aspect of the exercise involved a Non-combatant Evacuation Operation (NEO) an amphibious landing to extract civilians from an area of social or political unrest. A naval mine threat was inserted into the Ex Plan that required clearing using a mine hunting element of the Task Force in order to allow amphibious ships into the landing zone. Dummy mines and decoys were laid in the area that the MCM CTG was tasked to clear. This mine hunting mission was the component of the exercise that was of particular interest to the DRDC/CFEME team and they were embedded in participating ships.

The CTF's role in the MCM CTG's deployment was to promulgate MCM priorities via the establishment of areas or routes that are required for the CTF's manoeuvre (through liaison with the Naval Co-operation and Guidance for Shipping (NCAGS) authorities). The CTF maintained the "big picture" so as to effectively deploy the other CTGs within their areas of responsibilities.

The MCM CTG controlled the overall conduct of MCM operations through feedback and status reports of the individual units. The CTG initiated plans and evaluated the MCM efforts as they progressed. They issued tasking messages to the Mine Counter Measures Vessels (MCMVs) and reported regularly to the CTF.

The missions tasked to the CTG and individual units can been summarized as follows:

- Reconnaissance – Making an assessment of the limits of a mined area and if appropriate establishing a diversion route;
- Exploratory – Investigating a sample of a route or an area to determine the presence or absence of mines, after which further operations may be undertaken;
- Clearance – The purpose is to achieve a high probability of sweeping/hunting any mine in an area. The level or probability accepted/required is determined by the CTF (Allied Tactical Publication (ATP) 6(C) Volume II); and
- Leadthrough – Piloting vessels, which are without the appropriate navigation capability, through mined areas. MCMVs may be used to lead, but this should not preclude the use of other units that have suitably qualified personnel, such as pilots, and accurate navigation equipment (ATP 6(C) Volume II).

Overall, the MCM CTG was able to exercise all of the above. Section 5 will summarize the observations and deficiencies identified specifically during those missions.

# 4 Methodology

The DRDC/CFEME analysis team was organized into four teams of two. Each team was composed of one military officer with expertise in ordnance diving/MCM and one scientist or technologist with expertise in human factors research. Military members were deployed to act as subject matter experts in MCM with the main role to explain and comment on procedures and to act as “interpreters” for the civilian analysts. Using this methodology, analysts did not have to interrupt the operators on task for clarification on what has transpired. The analysts consisted of two scientists and two technologists with considerable experience in observation and analysis of military operations and a variety of academic backgrounds including psychology, kinesiology, and engineering. Since MCM involves a combination of both human and more technologically oriented science, it was thought that varied backgrounds within the team would allow for a more comprehensive understanding of the issues at hand. Three of the teams were deployed to MCMVs and one pair was deployed to the CTG staff onboard the ORP KONTRADMIRAL XAWERY CZERNICKI logistic support ship. The MCMVs included BNS NARCIS, a Tripartite-class mine hunter, FGS DATTELN, a Type 332 Frankenthal class mine hunter, and HMS BROCLESBY, a Hunt class mine hunter.

The CFEME Naval officers deployed to the exercise had extensive experience in mine hunting and ordnance diving. The scientists and technologists had previous experience in a variety of military settings other than naval. The officers conducted a number of tutorial sessions on MCM for the civilian analysts and otherwise extensively briefed on procedures and practices to prepare them for the study. The goal of the study was broad: to identify deficiencies and future research areas related to the human factors of MCM. Hence, aside from background education, the research method was limited to opportunistic observation and post-incident interviews while onboard the ships.

The teams were generally given access to all relevant areas of the ships involved and were able to observe most aspects of mine hunting (the one exception was the actual diving which was performed exclusively by ships’ clearance diver teams). Hence, the teams were able to observe mission planning, mine detection (through sonar), mine identification (using UUVs and divers), and mine retrieval. Mine disposal/EOD operations were not observed as there was no designated disposal area for explosive work. Due to exercise conditions, other aspects of the mine warfare battle rhythm, such as initial route surveys or pre-cursor operations, were not observed. The lack of exposure to these events was compensated for through dialogue with the staff and crew on the command ship and the MCMVs. Though anecdotal, the information gathered through discussion allowed the team to formulate a more comprehensive list of perceived deficiencies.

# 5 Observations and Analysis

The following section describes the observed deficiencies as assessed by the DRDC/CFEME team during the exercise. The team's experiences from various ships were consolidated into a comprehensive list of deficiencies. Based on the acquired knowledge and through team discussion, areas for future work suited to DRDC expertise and capabilities were identified and are further described for each deficiency. The CF officers' experience and the dialogue with personnel participating in the exercise contributed additional information about non-observed deficiencies that are also summarized in this section.

## 5.1 Observed Deficiencies and Areas for Future Work

### 5.1.1 Sonar Operators

The MCMVs that participated in NOMR 11 all used forward looking hull-mounted sonar to search for contacts. Although BNS NARCIS was equipped with Self-Propelled Variable Depth Sonar (SPVDS), it could not be used during the exercise due, in part, to the shallow water depth of the operating areas and underwater battlespace management issues due to the participation of a submarine in the exercise, therefore the possible advantages of this system could not be investigated. The SPVDS also uses forward looking sonar but it can be operated at different depths, giving it the advantage of operating below isothermal or halocline layers which may adversely affect a more traditional hull mounted sonar. Ship borne Variable-Depth Sonar (VDS) is also available, however none of the participating vessels were fitted with VDS therefore the possible advantages of this system could not be investigated.

Additionally, although all vessels used a hull mounted type of sonar, some were more capable than others. For example, the modern wideband sonar on HMS BROCKELSBY was able to detect and classify more mines than other vessels. This finding highlights the importance of technological advantage to the success of the mission. However, it should be noted that advancements in this particular technology may not be sufficient during some operations, as there is a wide variety of mine types with different characteristics and many differing environmental conditions that may render any hull mounted sonar almost ineffective.

#### 5.1.1.1 Observed Deficiencies

Mental workload of operators when analyzing sonar data is extremely high, and is increasing with modern systems that can detect ever smaller target strength objects. Extensive experience and expertise in feature detection are essential, but there are also vigilance considerations. Due to the overwhelmingly large amount of data to be viewed over an extended period of time, especially in high clutter density areas, it is very difficult for the operator to maintain attention and therefore potential exists for contacts to be missed. Research has shown that constant attention during prolonged search for few and intermittent targets can only be sustained for about 30 minutes, after which significant vigilance decrements are observed (Wickens and Hollands, 2000). Yet, sonar operators are habitually on watch for up to six hours, following a 1 hour on console/one hour off console routine.

#### 5.1.1.2 Areas for Future Work

A literature review on vigilance and cognitive processing of complex displays may suggest how to improve human performance. The typical "one hour on, one hour off" during a watch rotation is not based on much empirical evidence and considering that analysis of the sonar information is the weak link in the mine hunter routine, this area has much potential for study.

There is currently a lot of work being conducted worldwide in the field of Computer Aided Detection and Computer Aided Classification (CAD/CAC) and ATR designed to aid the operator in these tasks. ATR is used to select potential targets by computing the mine-like features used for classification, or by comparing given survey data with a historical data or previous survey (change detection). The operator is not required to continuously monitor the incoming imagery and/or perform detection and classification in real time, which may significantly reduce mental effort and mission time. However, automation is not always reliable, which brings into question how much trust the operator will put into the system and whether he will use it sparingly or not at all. In addition, it is also worth considering how the bottom classification impacts the operator's reliance on the system. DRDC Toronto has conducted a series of experiments on the human factors of monitoring complex displays, as well as trust in automation; the work could be extended to include sonar displays. DRDC Atlantic is currently leading the effort in developing the ATR algorithms and DRDC Toronto can potentially assume a role in testing these algorithms on human subjects.

As modern Side-Scan Sonar (SSS) and wideband high definition technology replaces the traditional scanning sonar, it is also worth considering what impact this may have on the operator. For example, some of the research questions could include:

a. Will a sonar operator have to process more noise;

b. Will the operator have difficulty maintaining vigilance because more information needs processing;

c. Will experienced sonar operators be able to transfer previous experience; and

d. Could previous experience interfere with operating a new system?

These questions could be answered through experimentation to be conducted at DRDC Toronto in collaboration with DRDC Atlantic.

Another, more technology oriented area of research is data fusion. For vessels that use multiple and/or different types of sonar it may be beneficial to have the capability to fuse the images from both in order to have a better picture of the contact. This is beyond the scope of DRDC Toronto capabilities, but could be of interest to DRDC Atlantic's future research.

### 5.1.2 Diving Operations

During the exercise, minimal diver tasking was observed due to the focus on ship certification. Clearance diving is personnel intensive, resource and time consuming and requires numerous safety measures to be in place, thus UUVs were the preferred option for identifying contacts.

However, when UUVs were disabled or otherwise unavailable, clearance divers were employed. It is worth noting that although UUVs can now be employed for most of the tasks divers used to perform, divers are still an essential tool to maintain operational capability when a UUV is not capable or when in close proximity to underwater infrastructures or submarine cables, where damage is unacceptable, and mine neutralization or movement is required.

#### 5.1.2.1 Observed Deficiencies

Minimal communication with divers prevents exchange of information when divers are investigating contacts. Standard communication method via line signals is accomplished through a line tied to the diver and secured on a surface float or held by a tender. The multiple lines that have to be maintained by the in-water diver also constitute a well recognized hazard.

#### 5.1.2.2 Areas for Future Work

Expanding upon existing technology, such as acoustic or electronic networking, could allow for the ability to track divers underwater and communicate with them more effectively, possibly reducing either the number of dives or the time spent on contact. Further benefit of non-line based diver communications is the removal of this hazard. This area of work may be best suited to EDUG's area of expertise.

As UUVs become more integral to the MCM operations, diver/UUV interaction will need to be considered with more scrutiny. For instance, there is a potential for using a UUV to guide divers to the contact or carry various payloads such as lighting and tools. Currently, there is no concept of operation that involves concurrent operation of UUVs and divers, mainly due to safety reasons such as entanglement or potential of underwater explosion. With improved communications, real time location/situation awareness (SA) devices (on both diver and UUV), and enhancements in avoidance technology, the risk could be mitigated substantially to allow for further investigation of concurrent operations.

### 5.1.3 Unmanned Underwater Vehicles (UUVs)

The MCMVs were equipped with two types of ROVs. HMS BROCKELSBY and BNS NARCIS operated an Atlas Elektronik SeaFox Remotely Operated Vehicle (ROV), while DATTELN employed a Pinguin B3 Minehunter ROV for identifying contacts classified as mine-like or non mine-like. Once a contact was detected and classified as mine-like by the hull-mounted sonar, the ROVs were launched from the vessels and were semi-autonomous and/or manually controlled by an operator onboard via a recoverable fibre optic cable dispensed from the MCMV which also carried optical, sonar and positional data to the ship.

#### 5.1.3.1 Observed Deficiencies

Typical challenges associated with operating an ROV were observed with both types of ROVs. Turbidity and the backscatter of light from the particulates in the water reduced visibility at certain depths and degraded the camera image. There were also some challenges with manoeuvring the vehicles to avoid entanglement with the cable. An incident was observed where the Pinguin B3 could not be immediately recovered due to high turbulence of the water and reduced battery power. In another incident, there was a malfunctioning depth gauge and navigating the vehicle to the contact site was a challenge. Moreover, a faulty positioning system resulted in a contact not being found immediately. Although technological in nature and thus beyond the scope of human factor study, it should be noted that these problems significantly increased search times and affected the outcome and operational efficiency of the mission. In addition, it was observed that navigating and manoeuvring the vehicle required skill and experience, not only in managing the slack to avoid cable entanglement, but also avoiding hitting other objects and debris, while constantly making small positional and attitude adjustments to compensate for water currents or tidal stream.

#### 5.1.3.2 Areas for Future Work

Laser, low light high definition cameras, image enhancement and other technologies have the potential for increasing underwater awareness, which is an important improvement since visual identification is currently the only means of positive identification of underwater contacts by UUV. While divers are capable of tactile identification, visual confirmation remains the preferred method. Other areas of investigation could focus on determining different means of identification acceptable to the NATO Mine Warfare community, such as high definition sonar outputs and explosive “sniffers” that may provide the “proof positive” required for mine identification.

Advances in underwater acoustic communication and vehicle autonomy may allow for faster underwater communications and coordination of multiple vehicles. With theses advances, operator workload and situation awareness challenges common to the other unmanned systems (air and surface) will inevitably arise. In addition, although wireless underwater communication may become faster and more reliable, there could still be delays and lost messages between the vehicle and the operator on the surface, resulting in reduced SA. More research is required to determine exactly what the new challenges will be and how to mitigate them.

As Autonomous Underwater Vehicles (AUVs) become increasingly more automated and intelligent, automation failures may negatively impact the operator’s trust. Complacency issues with the operator being out-of-the-loop during supervisory control and alternatively, spikes in operator workload when trying to troubleshoot problems to avoid mission failure, as well as trust in the system when it fails, will likely become challenges. ATR can potentially be integrated into the AUV platform, serving as an intelligent agent and allowing the vehicle to make decisions between mine and non-mine like objects. Additional research is required to determine the adequate combination of operator role and system autonomy.

With UUVs becoming an integral part of the MCM missions, new tactics will need to be developed that define human machine interoperability. UUVs are particularly suited for tasks such as route survey, load carrying, etc.; however, certain tasks will still have to be performed by humans (e.g. render safe and mine recovery). Depending on the threat environment and the operational scenario, there may be cases when it would be desirable to use divers and UUVs in tandem; alternatively, there may be instances when they need to be de-conflicted either in time or space (The Technical Cooperation Pannel, (TTCP) 2008). Further research is required to identify other MCM tasks suitable for UUVs, as well as in the areas with regards to diver/UUV interoperability.

In cases when destruction of the mine is not desirable (such as in the initial phase of conflict or when damage to surrounding underwater infrastructure is unacceptable), divers are deployed to neutralize or move the mine. This requires very precise handling and currently, UUVs have no such capability. However, advances in tele-robotics for human surgery could potentially be extended to manipulator arms on UUVs to be used for mine disposal.

### 5.1.4 Underwater Communications

Presently, there are minimal means to conduct effective underwater communications for diver and UUV operations. The only means of communicating with divers is through a line (e.g. lifeline or communications wire), which itself can pose a safety hazard. For ROVs, communication is accomplished through the umbilical cable to obtain optical, sonar and positional data. With increasing interest in utilizing AUVs and in particular, for concurrent operations with divers, wireless underwater communication will become vital for safety and mission success. Today, wireless underwater communications are intermittent and unreliable, and extremely difficult to accomplish (Akyildiz, Pompili & Melodia, 2004), but there is increasing research effort in this area.

#### 5.1.4.1 Observed Deficiencies

No wireless underwater communications methods were employed in this Exercise.

#### 5.1.4.2 Areas for Future Work

DRDC Atlantic is currently investigating ultrasonic low-power acoustic communications, optical methods, and electromagnetic communications methods. Ultrasonic low-power acoustic communications requires significantly less power than traditional lower frequency acoustic communications systems and has potential to support systems using energy-limited acoustic modems. Optical methods use light at visible wavelengths to communicate data and have the potential to be a useful method for underwater communication at short ranges when the application requires high data rates and low latency. An added benefit to the MCM community is that optical communication methods are less likely to interact with mine threats. Lastly, electromagnetic communication methods use quasi-static magnetic fields as a wireless channel for signalling, communications, and navigation. The major benefit of electromagnetic methods is that there are no emissions, thereby eliminating the possibility of detection outside of the operating area and limiting its susceptibility to conventional electronic warfare countermeasure.

DRDC Atlantic is also currently working on LCANs with the purpose of providing communications, and possibly bandwidth, to UUVs, divers and submarines. General practice is to try to enable the longest link ranges possible. The alternative unique solution being pursued by DRDC with LCAN is to use very short link ranges (50-100 m) combined with physical carriers that experience extreme absorption. With short range, high absorption or easily scattered communications signals, the nodes of an ad hoc access network require only a 'simple' equalizer. The low complexity equalizer results in real-time decoding, reduces energy consumption, and provides support for multiple hop communications. The absorption also increases the stealth of the network. The goal is to provide connectivity to AUV, surface ships, and submarines. This type of communication system would be a major step in developing interoperability between divers and UUVs. Another method alternative to LCAN that is presently being trialed is tethering UUVs to transceiver buoys for network communications between other submerged UUVs (i.e. swarming).

Another important component in the study of diver/UUV communication is determining what information is actually relevant and needs to be communicated in real time. There is always potential for overwhelming the diver with unnecessary information and thus negating the effectiveness of the interaction.

#### 5.1.5 C2 communications

The C2 structure and reporting process was clearly outlined in Allied Tactical Publications (ATPs). There were six types of MCM messages which were used for this exercise: MCMOPDIR, OPTASK MCM, MCMREP, MCMSITREP, LEADTHROUGH ORDERS and MDA requests. The latest procedural publication contains formatted messages that are intended to be machine read as well as structured messages that are written free form and used when machine reading is not possible. In order to meet the Ex mandate for using only formatted and not structured messages, the NATO MCM community has reduced the number of MCM messages. As a result, there was only one tasking message and one reporting message, OPTASK MCM and MCMREP. Each of the messages was designed to be used at different levels of Command and incorporate as much information as necessary to cover as many circumstances that may arise. Additionally, these messages were also designed to be machine read so that information can be easily extracted and used in other systems or programs. The communication channels for MCMVs is very limited but does generally included HF, VHF and UHF voice circuits and Telegraphic Automatic Relay Equipment (TARE).

##### 5.1.5.1 Observed Deficiencies

Large exercises that rely on both secure web pages through NATO Secret Wide Area Network (NSWAN) and hard copy messages to disseminate information are prone to several problems. Web pages and chats are only available when Satellite Communications (SATCOM) is working properly and the internet is available. Information and updates to the program only available by these means may be lost, not available to units not equipped with NSWAN or SATCOM, or not received in a timely manner due to technical issues. HMS BROCKELSBY was the only MCMV with NSWAN and had only two lines for Internet connectivity that had to be shared among staff.

None of the MCMVs in the exercise had machine reading capability. Consequently, information had to be received and transmitted manually, which is time- and resource-consuming. All incoming messages had to be printed and kept in the log book, while outgoing messages had to be manually typed by the drafting officer. In addition, there were no tactical data links on any of the MCMVs. These systems are beneficial in a multi-threat environment for building and maintaining a Recognized Maritime Picture and early warning of threats. These two factors may have contributed to the loss of SA and redundancies in the reporting from the individual units to both the CTG and the CTF.

The communication instructions and plans were not well adapted to limited MCMV communication capabilities. With the organization being so large and complex, there were concerns about the accountability and responsibility to inform, which resulted in CTF broadcasting all messages regardless of their relevance to individual units. Messages transmitted by broadcast presented problems to smaller units such that they were being overwhelmed by the sheer volume of messages concerning warfare areas or operations that did not impact them. Important information and directions were being missed and the time taken to read all the messages distracted attention from the operation at hand. Long turnaround times in reporting and issuing orders were partially due to the reporting structure through the multiple levels in the chain of command as well as the overwhelming amount of message traffic. There were times when CTF was issuing orders directly to the mine hunting units, circumventing the CTG.

Another factor that impeded communication and affected SA was the limited number of voice circuits. There were three circuits available, HF, VHF and UHF, one of which was dedicated to copying the broadcast for messages. Of the remaining two, only one could be covered at any one time. In addition, UHF communication lines are prone to problems such as latency, signal loss, or message errors. With the limited voice circuits and a lack of tactical data link, it was very difficult to maintain SA and monitor or participate in other warfare areas.

#### 5.1.5.2 Areas for Future Work

SATCOM with secret intranet capabilities or a tactical data link system should be made more widely available on MCMVs to avoid loss of SA and ensure early warning of threats. Information overload was a continuous issue for MCMVs; therefore a more efficient system needs to be developed. One option could be improving automated filters or developing better procedures to reduce the overload. Another option might be to change the messaging system and ensure compatibility and consistency among units and the chain of command. For instance, it may be more efficient to use a bulletin board oriented system so that all messages are displayed and grouped as appropriate. In either case, there are already available technological solutions that could potentially be adapted to the MCM process and requirements.

### 5.1.6 Planning and Risk Calculation Software

MCM Expert was used for mission planning and evaluation and Decision Aid and Risk Evaluation (DARE) was used for risk assessment by both the CTG and the individual units.

#### 5.1.6.1 Observed Deficiencies

MCM Expert and DARE are not being updated for the introduction of new technologies such as UUVs and SSS. SSS image analysis is different than hull-mounted or VDS sonar, and existing bottom classification systems are not compatible with these newer technologies (e.g. SSS, Synthetic Aperture Sonar [SAS], and interferometrics). MCM Expert is becoming an outdated planning tool as it was designed to be used solely forward looking sonar. SSS and SAS systems have their own processing software and there are no available means to integrate this information into the output from MCM Expert. As a result, it is impossible to articulate MCM efforts and results achieved into a common and understandable end-product that Command can use to make risk assessment decisions. Some nations including Canada (DRDC Atlantic) are trying to develop a method for importing SSS information curves into MCM Expert so that it can be used as a planning tool for SSS, however, this will not be progressed within NATO due to lack of funding.

DARE is labour intensive to set up, populate with results and update. It can only produce results once enough MCM effort has been achieved. Usually only one operator updates the information from MCMREPs, as the information could be subject to different interpretations. DARE 2.1 is the final version of this risk assessment software as it is no longer in the program of work for the NATO Undersea Research Centre (NURC).

#### 5.1.6.2 Areas for Future Work

The US Navy uses its own MCM planning and evaluation/risk assessment tool called MEDAL (Mine Warfare Environmental Decision Aid Library). MEDAL provides additional functionalities that are unavailable in MCM Expert and DARE. The program continues to be supported and new versions produced which incorporate new technologies, such as SSS. Australia has also developed a similar tool called Mine Warfare Tactical Command Software (MINTACS). These tools could potentially be adapted to meet CF needs and requirements. This work is already under way at DRDC Atlantic.

## 5.2 Non-observed Deficiencies

### 5.2.1 Effects of Underwater Explosions on Divers

As diving and UUV operations are never conducted concurrently due to safety concerns for the divers, there has been a lack of effort in investigating the effect of underwater explosions on divers. At present, when a UUV is operating in a mine threat area, diving operations are prohibited within a 2 nautical mile radius. Understanding the risk of underwater explosion to divers and development of minimum safety distances would potentially allow the use of divers concurrently and in relatively close proximity to UUVs operating in a mine threat area. Studies have been conducted in Canada, and by other NATO / ABCANZ allies, regarding the effects of underwater explosions on ship and submarine hulls. This work has not extended to the effect on humans, but facilities and expertise exist that could be used to pursue these studies. DRDC Toronto is investigating this issue with the intention of developing a tactical decision aid which will provide the framework for calculating minimum safety distances between divers and UUVs.

### 5.2.2 Alternative Methods for Mine Disposal/Neutralization

Mine neutralization tools are fairly limited and manual, explosive or kinetic in nature. Drop charges from UUVs, one-shot UUVs and some more selective tools when using divers (e.g. limpet mine disposal tools, shaped charges) are the most commonly used methods for mine neutralization. However, there are other potentially useful methods, such as chemical neutralization, or EMPs that could be employed to disrupt the electronic packages within mines. In addition, tele-robotics also has potential with further advances in UUV technology.

### 5.2.3 Alternative Technologies for Mine Detection

Sonar is the standard tool used for mine detection. However, this has limited effectiveness in detecting partially buried or buried mines. Although efforts are made towards developing new technologies with bottom penetrating capabilities, other options, such as chemical sniffers, (under development but similar to concepts used in airport sniffers) should also be investigated. Chemical sniffers can be mounted on UUVs and would be particularly useful for discovering mines of irregular shape, or constructed of non-metallic elements.

### 5.2.4 Mine Jamming Capabilities

Mine jamming is a complimentary MCM technique that could be used if confidence in threat mine type intelligence is high and the mission is critically time constrained. One method of mine jamming employs an influence minesweeper, with gear streamed and operating, transiting through an area with the non-MCMV transiting close to and abeam to the sweep gear. This method produces a sufficiently large magnetic and acoustic influence so that mine reads the signature as too large and therefore not a viable target and switches to inter-look dormant mode. This requires significantly higher magnetic influences and noise than would be typical when conducting normal MCM activity. However, this type of jamming may introduce dangerous levels of influences and jeopardize safety of personnel and equipment. More research has to be completed before this MCM technique can become a realistic option.

# 6 Conclusions and Way Ahead

In the near future, the CF will have new technologies to combat the sea mine threat. These technologies include UUVs with advanced sensors. UUVs have the potential of vastly improving the safety of MCM by removing manned vessels and divers from the *area of threat*. Yet, many questions remain unanswered. For example, how do we define the *area of threat*? At what distance can vessels and divers operate UUVs safely when a known mine is encountered? Today, the CF has no protocol regarding safe distances to operate unmanned systems for MCM tasks.

Future research at DRDC Toronto will investigate the underwater blast effects on the human body in order to help define boundaries of safety. This research will begin by using computer simulation of blasts and the human body to estimate blast effects and may eventually lead to live blast tests. This research will be particularly valuable for developing the Concept of Operations (CONOPS) that exploit the strengths of divers and autonomous systems in a complementary way.

In addition, the continued use of unmanned systems will impose additional human demands to filter and analyze the vast amount of data that is collected. Technologies like ATR which can help to reduce the human demands to analyze data will continue to be critical in the future. To this end, our present work on improving ATR for sea mines has yielded some promising results. While this study failed to improve operator trust in ATR, the results suggest that when ATR reliability is imperfect, the accuracy of ATR can be optimized by lowering the level of automation (Ho, Pavlovic, Arrabito, & Myers, in preparation). This study was only a preliminary study and lacked the ecological validity to make strong conclusions. However, additional human factors research in ATR is required so that stronger recommendations can be provided.

Another human factors challenge that we envision will affect future mission performance is the delay and reliability of transmitted data from UUVs. Advancements in underwater communications and improvements in the methods used to transmit data from UUVs will soon allow for some real-time (or at least near real time) monitoring of AUVs. However, it likely that operators will have to deal with some levels of intermittent, low bandwidth and unreliable communications. It is not known how poor communications affect operators nor is it clear how human factors can be used to mitigate the negative impacts of poor communications. Thus research in this area will be valuable to future underwater operations.

Finally, many research trends for unmanned aerial systems have yet to be investigated for underwater systems. These trends primarily involve methods to monitor and control multiple AUV scenarios, interface developments for the remote operator or dismounted soldier, and methods to improve mission planning for complex AUV operations. Below, we identify six topics that we believe could also be important to future MCM research.

- Human factors issues with UUV swarms – monitoring multiple UUV systems, information overload issues due to controlling and tracking multiple vehicles and sensors.
- Control of multiple autonomous systems, what one operator can handle, and how that correlates with the system's autonomy;

- Augmented reality to support ROV operation – 3 Dimensional (3D) modeling of underwater environments, conveying this model to an ROV operator;
- Interface concepts for supporting navigation and SA – Head Mounted Displays for divers, human factor issues related to new technologies that can enhance diver vision and displays, usability and control issues;
- Underwater diver systems – navigation systems, dive computers, hand-held sonar in diving, alternative forms of input devices that may be more suitable for divers (e.g. data gloves, chordic keyboards) for interfacing with other devices;
- Adapting existing planning and evaluation tools, such as MEDAL, MINTACS, concepts and scenarios for integration of diver systems with the Mine Information Database System (MIDAS), concept demonstration and evaluation;

In sum, the growth of unmanned systems will change the way that MCM is conducted. Methods for MCM today that use manned vessels and divers may be replaced with unmanned systems. While this is promising with respect to human safety, the current practices and the roles of the humans will surely be changed. We anticipate that these changes will bring about new human factors challenges that should be addressed before unmanned systems become fully deployed in future MCM operations.

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# Annex A Review of Past and Current Research on UUV Integration in MCM Operations

Unmanned systems have been internationally recognized as having an immense potential to perform many of the MCM tasks to increase efficiency and reduce risk to personnel in MCM operations (US Navy Office of the Chief of Naval Operations, 2004; US Department of Defence, 2007, 2009). In the past decade, as the UUV technology matured, more and more Navies of the world are realizing the potential contribution of UUVs for missions such as mine reconnaissance, route survey, port surveillance and rapid environmental assessment. Consequently, a number of nations have been engaged in research, development and procurement of systems specifically designed for MCM operations. The US Navy set the first example in 2003 when they deployed the Hydroid Remote Environmental Measuring Units (REMUS) 100 system into the warm, shallow waters of the Northern Arabian Gulf to systematically map the channel into the port of Umm Quasr. The vehicles conducted autonomous wide-area searches, marking this the first time that UUVs were used in a real military operation (Scott, 2010). Since then, more than 10 Navies worldwide have acquired REMUS 100, creating a niche market for the UUVs.

The use of UUVs in conjunction with MCMVs and clearance divers has obvious advantages: significantly faster search rate, reduced danger to divers and parent platform, and ability to carry out sonar searches in confined and very shallow areas (Bovio, 2006; Fish and Hollosi, 2009). Experiments conducted by NURC in La Spezia, Italy in 2004 confirmed that commercial off-the-shelf UUVs (i.e. REMUS) can in fact perform efficient surveys in ports and harbours to detect and classify objects on the seafloor, in conjunction with existing assets (MCMVs and EOD divers). However, there are limitations to commercially available UUVs for military uses as the vehicles were originally designed for scientific research and pipeline survey (e.g., classifying partially buried mines, or IEDs, navigating in confined spaces; Rothenbach, Bovio, Yip and Gabellone, 2004). Some of the technological issues include: the problem of providing adequate power density for mission endurance; the increase in data volume from advanced sensors like SAS requiring either on-board processing or periodic data offload; maturation of automatic target recognition algorithms for classification of seabed objects; and improvement of navigation accuracy for target reacquisition (Fish and Hollosi, 2009). More research, development and experimental programs are being enacted across industry, academia and the defence research community to accommodate the military community. These efforts are aimed at demonstrating a wide range of technologies and techniques with regards to navigation, endurance, autonomy, communications, sensing and sensor resolution (Scott, 2010).

One of the leading organizations in UUV research for military operations is the US Office of Naval Research (ONR) and its primary organization, Naval Research Lab (NRL), with a well-rounded research program in a wide array of unmanned system projects, spanning all domains. Past and current projects funded by ONR include REMUS UUV, SeaFox Unmanned Surface Vehicle (USV), Coyote advanced ceramic UAS, and the RoboLobster amphibious robot. In particular, Hydroid's REMUS vehicle system has been subject to a programme of continuous evolution and system enhancement funded by ONR and is now equipped with state-of-the-art acoustic and Iridium communications, inertial navigation systems and Global Positioning System (GPS) navigation, video cameras, acoustic imaging, and dual-frequency sidescan sonar (Scott, 2010). ONR's Chemical Sensing in the Marine Environment Program has also supported the future goals of EOD MCM teams through developing novel means to detect and locate Unexploded Ordnance (UXO) in marine environments, and to detect, characterize, and quantify explosives and their derivatives in seawater and marine sediments (Fletcher, 2001).

Hydrodynamic field tests, conducted at Space and Naval Warfare Systems Command – Systems Centre Pacific (SSC Pacific) using a specially configured REMUS vehicle, have shown positive results, providing data for the development of detailed models capable of forward and reverse tracking of UXO plumes. The Unmanned Undersea Vehicle Technology project is another research effort that focused on developing the capability to perform missions with UUVs that will allow submarines, surface ships and other Naval Forces to clandestinely expand their sphere of influence while reducing potential vulnerability in the littorals (Wernli, 2000). Furthermore, ONR has also partnered with Bluefin Robotics to explore the coordination of heterogeneous collections of unmanned vehicles for the autonomous execution of goal-oriented missions. This system concept, developed under the umbrella of the Cooperative Autonomy for Distributed Reconnaissance and Exploration, has specifically addressed the undersea search and survey and communications/navigation aid signature capabilities from the US Navy's UUV master plan (Scott, 2010).

In support of multiple acquisition programs for Program Management Office for Explosive Ordnance Disposal, SSC Pacific is maintaining projects aimed at outfitting Fleet forces with UUVs for searching ship hulls for limpet mines or IEDs, and further developing capabilities and product improvements to currently outfitted systems as new technologies are being developed (Nguyen et al., 2009). The Advanced Unmanned Search System (AUSS), an acoustically controlled UUV capable of relaying real time sonar and photographic data to the surface and capable of diving depths to 20,000 feet is one of the systems SSC has developed as a result. The AUSS current research thrusts include robotic intelligence, autonomous navigation on the sea surface and undersea, human presence detection, 3D world modelling and enhanced human-robot interaction. SSC Pacific is also using the Bluefin-9 to support research into co-operative information architectures for unmanned vehicles (Scott, 2010).

Other nations have also established continuous research programs for integrating UUVs into MCM operations. UK's Defence Equipment and Support Organisation's Programmes and Technology Group is currently managing the Littoral UUV (LUUV) Capability Concept Demonstrator programme in collaboration with Atlas Elektronik UK, to explore whether a single two-man portable UUV may significantly improve the tempo and effectiveness of MCM operations while retaining an ability to conduct harbour protection operations. The programme is seeking to further expand the role and functionality of portable UUVs through combining cutting edge UUV technology and military planning and assessment tools during MCM-type operations, and is focusing on development of new operating techniques and capabilities that will enhance underwater situational awareness (Scott, 2010). Similarly, as part of its automation of the battlespace initiative, Australia's Defence Science and Technology Organization (DSTO) is addressing several critical undersea issues using a combination of simulation and field experimentation. To this end, a small test-bed UUV system, Mullaya, has been developed to support field experiments, the testing of critical technologies and techniques, and the demonstration of different concepts of operation (such as multiple vehicle co-operation in integrated air/undersea operations and multiple undersea vehicle operations). DSTO's overarching concept is a large vehicle that delivers, deploys and recovers a number of small expendable UUVs into littoral waters (Scott, 2010). Norwegian Defence Research Establishment (FFI) and the Royal Norwegian Navy (RNoN), in partnership with Kongsberg Maritime, have also instituted a programme of concept development and operational employment for the HUGIN Mine Reconnaissance System (MRS), based on the HUGIN 1000-MR UUV, intended to provide the RNoN with a forward-deployed MCM/REA capability (Scott, 2008).

NURC is an example of an international collaborative endeavour that has been continuously exploring the concept of using UUVs in MCM operations over the past decade. Between 2002 and 2005 the centre has successfully conducted multiple experiments in the ports of La Spezia, Straenraer, Rotterdam and Olpenitz to assess the value of AUVs for MCM operations in ports and to compare their performance with that of existing assets. The experimental programme demonstrated that off the shelf AUV technology, used in conjunction with EOD divers and MCMVs, is capable of significantly improving the speed, efficiency, and safety of operations aimed at countering a terrorist mining threat to NATO's ports (Bovio, 2006). The results have also highlighted limitations of current technologies and outlined future research activities to improve the usability of AUV assets, specifically sensing and AUV navigation technologies. Research at NURC is also addressing ATR algorithms to complement SAS/high-resolution data (these include model-based techniques, adaptive approaches to cope with environmental changes, and on-line learning algorithms) and the use of shape theory to support ATR performance prediction (Scott, 2008). The Planning and Evaluation of MCM Operations using AUVs project developed a methodology to evaluate the capability and predict performance of AUVs as MCM tools. Various REMUS missions demonstrated the potential of the ATR method to assess system (vehicle, sonar and ATR) performance in various environments using real sonar data, but also confirmed the limitations in current seafloor classification and performance of currently existing AUVs and sensors (Pettilot et al, 2006). The same project also looked at adapting MCM Expert (software tool used for planning and evaluation of minehunting operations) and provided recommendations for its use with side-scan sonar as opposed to the traditional hull mounted sonar for which it was designed (Bryan, 2006).

There seems to be a shared vision among allied nations for organic UUV systems to become an integral part of MCM operations as force multipliers in the key roles of Rapid Environmental Assessment (REA) and mine reconnaissance. Autonomous platforms are of particular interest in these research efforts, with specific focus on enhancing communication, navigation and sensor systems, autonomous target recognition, mission planning and assessment, and developing concepts of operation involving multiple unmanned vehicles. Small, rapidly deployable and relatively inexpensive UUVs equipped with a range of acoustic, optical, and magnetic sensors for shallow water operations are foreseen to significantly contribute to improving the capability of conventional assets (US Navy Office of the Chief of Naval Operations, 2004). In line with international efforts, Canada's future active MCM is envisioned to be modularised and deployable utilising autonomous[5] surface and underwater systems capable of operating from any maritime platform; Passive Self Protective Measures (SPM's) will focus on future combatant material design and tactical procedures, capacity for Route Survey (RS) and associated control of shipping (CF Director General Maritime Force Development, 2011).

[5] Autonomous does not exclude the possibility of taking continuous or periodic vehicle control for mission data exchange, mission update or abort.

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# List of abbreviations/acronyms

| | |
|---|---|
| 3D | 3-Dimensional |
| ABCANZ | America, Britain, Canada, Australia, New Zealand |
| ARP | Applied Research Project |
| ATP | Allied Tactical Publication |
| ATR | Automated Target Recognition |
| AUSS | Advanced Unmanned Search System |
| AUV | Autonomous Underwater Vehicle |
| C2 | Command and Control |
| CAD/CAC | Computer Aided Detection and Computer Aided Classification |
| CF | Canadian Forces |
| CFEME | Canadian Forces Environmental Medicine Establishment |
| CONOPS | Concept of Operations |
| CTF | Commander Task Force |
| CTG | Commander Task Group |
| DARE | Decision Aid and Risk Evaluation |
| DND | Department of National Defence |
| DRAD | Diving Research and Development |
| DRDC | Defence Research & Development Canada |
| DRDKIM | Director Research and Development Knowledge and Information Management |
| DSTO | Defence Science and Technology Organization |
| EDA | European Defence Agency |
| EDUG | Experimental Diving and Undersea Group |
| EMP | Electro-magnetic Pulse |
| EOD | Explosive Ordnance Disposal |
| FFI | Norwegian Defence Research Establishment |
| GPS | Global Positioning System |
| HF | High Frequency |
| IED | Improvised Explosive Device |
| JSRC | Joint Sub-Regional Commander |

| | |
|---|---|
| LCAN | Low Complexity Access Networks |
| LUUV | Littoral Unmanned Underwater Vehicle |
| MCDV | Maritime Coastal Defence Vessel |
| MCM | Mine Countermeasures |
| MCMOPDIR | Mine Countermeasure Operation Directive |
| MCMTA | Mine Countermeasures Technical Authority |
| MCMV | Mine Countermeasures Vessel |
| MEDAL | Mine Warfare Environmental Decision Aid Library |
| MIDAS | Mine Information Database System |
| MIE | Mine Investigation and Exploitation |
| MINTACS | Mine Warfare Tactical Command Software |
| MIX | Mixed Initiative Experimental |
| MRS | Mine Reconnaissance System |
| NATO | North Atlantic Treaty Organization |
| NAVWARN | Navigational Warning |
| NCAGS | Naval Co-operation and Guidance for Shipping |
| NEO | Naval Evacuation Operation |
| NMCM | Naval Mine Countermeasures |
| NOMR 11 | NOBLE MARINER11 |
| NRF | NATO Response Force |
| NRL | Naval Research Lab |
| NSWAN | NATO Secret Wide Area Network |
| NURC | NATO Undersea Research Centre |
| ONR | Office of Naval Research |
| OTC | Officer in Tactical Command |
| RC | Regional Commander |
| REA | Rapid Environmental Assessment |
| REMUS | Remote Environmental Measuring Units |
| RNoN | Royal Norwegian Navy |
| ROV | Remotely Operated Vehicles |
| SA | Situation Awareness |
| SAS | Synthetic Aperture Sonar |

| | |
|---|---|
| SATCOM | Satellite Communications |
| SNMCMG1 | Standing NATO Mine Countermeasures Group 1 |
| SNMG1 | Standing NATO Maritime Group 1 |
| SSC | Space and Naval Warfare Systems Command – Systems Centre |
| SPMARFOR | Spanish Maritime Forces |
| SPS | Spanish Naval Vessel |
| SPVDS | Self-Propelled Variable Depth Sonar |
| SSS | Side-Scan Sonar |
| SW/VSW | Shallow Water / Very Shallow Water |
| TARE | Telegraphic Automatic Relay Equipment |
| TTCP | The Technical Cooperation Program |
| UHF | Ultra High Frequency |
| USV | Unmanned Surface Vehicle |
| UUV | Unmanned Underwater Vehicle |
| U/W | Underwater |
| UXO | UneXploded Ordnance |
| VDS | Variable Depth Sonar |
| VHF | Very High Frequency |
| WBE | Work Breakdown Element |

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Scoping Study on DRDC Toronto Future Research Regarding Naval Mine Countermeasures:

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

Pavlovic, N.J.; Smith, D.; Maceda, E.; Ho, G.; Gowan, LCdr S.; Holden, LCdr N.; Beechinor, Lt(N) T.W.; Bures, Lt(N) G.

| | | |
|---|---|---|
| 5. DATE OF PUBLICATION (Month and year of publication of document.)<br><br>June 2012 | 6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)<br><br>46 | 6b. NO. OF REFS (Total cited in document.)<br><br>29 |

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.)

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**Canada currently possesses limited to modest** Mine Counter Measure (MCM) capability that includes Maritime Coastal Defence Vessels (MCDVs) used for coastal surveillance and patrol, and Clearance Diving Units for identification and disposal of sea mines. In recognition of its MCM capability deficiencies, Canada has been actively involved in defining a programme for integrating unmanned underwater vehicles (UUVs) in current MCM operations through collaboration with other Allied nations. The objective of the Underwater Intervention in shallow (SW)/very shallow water (VSW) Operations Applied Research Project (ARP), conducted since 2008, is to improve Canadian Forces (CF) capability to conduct MCM, combat diving and Special Operations Force operations in shallow and very shallow water, by increasing capacity of underwater systems, operators, and divers, reducing risk and equipment burden on the diver, and extending speed and accuracy in conduct of these operations. This report summarizes current deficiencies as observed by the CF and Defence Research and Development Canada researchers during a North American Treaty Organization (NATO) certification Exercise NOBLE MARINER 11, and proposes areas for future research for the above ARP. The insights gained from this analysis will also be used to provide Canada and its allies with adaptive and easy-to-interpret feedback on their operational practices and plans as they conduct MCM operations.

Le Canada possède une **capacité,** de restreinte à modeste, en matière de lutte contre les mines (LCM) qui comprend les navires de défense côtière (NDC) utilisés pour surveiller les eaux côtières et y patrouiller, et les unités de plongée d'inspection pour l'identification et l'élimination de mines marines. En reconnaissance de ses lacunes pour lutter contre les mines, le Canada a participé activement à l'élaboration d'un programme visant à intégrer les engins télépilotés sous-marins (UUV) aux opérations actuelles de LCM avec la collaboration d'autres pays alliés. En 2008, le Canada a mis en œuvre un projet de recherche appliqué (PRA) sur les opérations d'intervention sous-marine en eau peu profonde (SW)/très peu profonde (VSW) qui vise à améliorer la capacité des Forces canadiennes (FC) à exécuter les opérations de LCM, de plongée de combat, de même que les opérations liées aux Forces d'opérations spéciales en eau peu profonde et très peu profonde, en augmentant la capacité des systèmes sous-marins, des opérateurs et des plongeurs tout  en réduisant les risques et le fardeau de l'équipement pour le plongeur et en augmentant la rapidité et la précision liées à l'exécution de ces opérations. Ce rapport résume les lacunes actuelles observées par les FC et les chercheurs de Recherche et développement pour la défense Canada lors de l'exercice de certification NOBLE MARINER 11 de l'Organisation du Traité de l'Atlantique Nord (OTAN), et propose des domaines de recherche futurs pour le projet susmentionné. Les connaissances acquises lors de cette analyse serviront aussi à fournir au Canada, et à ses alliés, une rétroaction constructive et facile à interpréter sur les plans et pratiques opérationnels lors de l'exécution d'opérations de LCM.

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Mine countermeasures, deficiencies, diving operations, ROV, UUV, underwater communications, planning and risk calculation software

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