Recommendations for implementation of the Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) project

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Reference Document
DRDC-RDDC-2017-D101
November 2017

IMPORTANT INFORMATIVE STATEMENTS

Endorsement statement: This publication has been published by the Editorial Office of Defence Research and Development Canada, an agency of the Department of National Defence of Canada. Inquiries can be sent to: Publications.DRDC-RDDC@drdc-rddc.gc.ca.

Abstract

The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) is an initiative intended to revolutionize Canadian Underwater Warfare (UWW) for decades to come. This document details the integrated lines of research required to progress CRACCEN from the proposal stage to a realizable set of deliverables for the Royal Canadian Navy. The lines of research were generated through discussion with the UWW community and an examination of current trends and needs in the underwater domain. The results indicated a need to completely rethink the command and control structure to take into account risk analysis, uncertainty, advanced data fusion, and presentation techniques that allow better exploitation by the command team in the decision making process. These results will guide the CRACCEN effort for the duration of the project.

Résumé

Le CRACCEN, un réseau environnemental de coordination et de contrôle de la zone de reconnaissance du commandement, est une initiative qui vise à révolutionner la guerre sous-marine canadienne pour les décennies à venir. Le présent document décrit les axes de recherche intégrés requis pour faire progresser le CRACCEN de l'étape de la proposition à celle d'un ensemble réalisable de produits livrables pour la Marine royale canadienne. Ces axes de recherche ont été produits à la suite de discussions avec la communauté de la guerre sous-marine et après un examen des tendances et des besoins actuels dans le domaine sous-marin. Les résultats ainsi obtenus ont montré la nécessité de repenser complètement la structure de commandement et contrôle pour tenir compte de l'analyse des risques, de l'incertitude, de la fusion avancée des données et des techniques d'approche qui permettent une meilleure exploitation par l'équipe de commandement dans le processus de prise de décisions. Ces résultats permettront d'orienter les efforts consacrés au CRACCEN pour toute la durée du projet.

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Acknowledgements

The authors would like to thank Mark Stoddard, Sean Kavanaugh, and Edward Ferguson for their input into the project proposal, as well as Dan Hutt and John Osler for their useful comments and support during the project formulation process. In addition, the Canadian Forces Maritime Warfare Centre (CFMWC), the Acoustic Data Analysis Centre (ADAC), and the offices of both MetOc Halifax and MetOc Esquimalt provided invaluable military feedback on the proposed project.

1 Introduction

The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) initiative is the first step toward delivering to the Royal Canadian Navy (RCN) a revolutionary Underwater Warfare (UWW) predictive situational awareness, battlespace management, operational planning, and mission execution system: a system that does not exist today. Automated information collation, environmental prediction, and real-time system modelling will be coupled with novel decision support tools, allowing the command team to focus on the decision-making aspects of mission planning and execution. Making CRACCEN a reality will require the identification or development of a next-generation collaborative interface environment that includes communication technologies to enable effective management and control of the operational battlespace for the unit, task group, and force.

Integrated lines of research effort will create the foundation to the CRACCEN revolution. This document is based on the proposal that was submitted as part of Defence Research and Development Canada's (DRDC's) annual project approval process. Greater detail is provided here to assist in implementation of each proposed Work Breakdown Element (WBE), each of which was further broken down into several specific activity areas.

The long-term CRACCEN vision is to revolutionize the conduct of UWW, rather than merely providing incremental improvements to individual sensors, weapons, and systems. Central to the vision is the need to completely rethink the Command and Control (C2) structure and system (WBE1). Underlying this revolutionary C2 system is a redesigned information flow, advancing data collection, processing, risk analysis, and uncertainty quantization (WBE3); through storage, management, and distribution (WBE2); to data fusion (WBE4); followed by presentation and display (WBE5); to exploitation by the command team in the decision making process (WBE1 and WBE5); and finally to consolidation and integration of the research results (WBE6).

The following sections provide detailed descriptions of the work and possible sourcing strategies for each WBE, while the Appendix contains a detailed list of proposed project deliverables.

2 Work Breakdown Element Overview

2.1 WBE 1: Design Concepts for Revolutionary C2 Systems

The objective of this WBE is to develop CRACCEN design concepts and workflows, and to determine the best methods for users to visualize and interact with the overall system in a re-defined UWW information domain. Research will be organized under three separate activities: requirements exploration, the development of high level design concepts, and the study of detailed design and visualization concepts.

2.1.1 Activity 1: Requirements

This activity involves the identification of requirements and design concepts for the revolutionary CRACCEN system. As a 'revolutionary' system, CRACCEN is more than an evolution of existing tools and processes. CRACCEN is anticipated to overthrow current workflows, personnel roles and responsibilities, and replace stove-piped, individual-focussed software with modernized team-oriented technology. However, without the limitations imposed by an existing system (both human and technological), generating concepts and requirements for CRACCEN becomes more challenging as there are few knowns and many unknowns (which can also be viewed as opportunities).

Current personnel in current roles can speak to their existing requirements, but it is anticipated that personnel roles, and therefore needs, will change significantly once CRACCEN becomes a reality. As such, the target user profiles do not yet exist and traditional user-centred design processes cannot be directly applied. Nevertheless, understanding the current system (i.e., our baseline capability) is important because the existing goals of personnel involved in UWW are one of those few knowns. These goals must still be addressed by the CRACCEN system, though they may be allocated or executed differently, or handled fully or in part by automated processes.

This WBE activity requires devising a methodology to engage RCN UWW Subject Matter Experts (SMEs), RCN clients, emerging technology experts, and other visionaries to conceive of innovative ideas not limited by current constraints (e.g., ship space, wi-fi availability) for an UWW mission planning and C2 system of the future. This methodology is expected to include an 'inspire' phase, where participants are exposed to new and emerging technologies such as collaborative displays and augmented reality, followed by an 'ideation' phase where multi-disciplinary participant clusters brainstorm on possible applications of these technologies to UWW. Key ideas will be evolved through simple prototyping.

2.1.2 Activity 2: High Level Design Concepts

Building on the work of Activity 1 where ideas for CRACCEN's instantiation have been generated, this activity aims to produce an initial concept of operation for CRACCEN, making informed decisions or assumptions about some of the many unknowns in the CRACCEN design landscape. It will identify, at a high level, what CRACCEN will offer, what it will look like, how people will interact with and make use of it, and what information other (future) ship systems will draw from it or provide to it. The activity will produce a series of graphical and textual views and user stories that will be used to: communicate the vision of CRACCEN; align project efforts towards a common goal; orient and focus stakeholder discussions; communicate the limits and boundaries of CRACCEN; and describe how it relates to other RCN capabilities or systems. The initial concept of operation for CRACCEN is expected to evolve over time, based on the research of other WBEs and continued input from UWW SMEs, and will be so updated.

2.1.3 Activity 3: Detailed Design Concepts

This activity involves the application of human computer interaction research and expertise to ensure that the information presented to the user is done in a manner that facilitates understanding (situational awareness), accessibility of relevant information and tools, and intuitive interactions with the system. The correct interface design will contribute to efficient and effective decision making and operator proficiency, while also minimizing errors, information search and assimilation time, freeing up time for more cognitively appropriate tasks that are less easily handled by the system.

This work will deliver concepts for the presentation and consumption of geospatial information layers to support mission planning; visualization of risks and uncertainties; individual and collaborative work in shared workspaces; input and communication of plans in a digital environment; and the suitability and performance of collaborative interface alternatives for CRACCEN.

Information sources and models identified and created through other WBEs must be brought together and displayed to the users in a meaningful way. Decisions will need to be made about what information should be viewed together (e.g., various geographical layers such as weather, underwater cables, biologicals, and sensor coverage, with on/off toggles or transparency adjustments), what information should be displayed in separate windows of the same display (e.g., tabular data vs. geographical data) or instead accessible through menus as needed. Additionally, the applicability of modern technologies to enable 3-dimensional viewing of information to improve situational awareness will be considered and evaluated.

Risk and uncertainty are topics that are touched on by other WBEs in the project, but in the case of this WBE, the focus is on understanding the best ways to convey risk and uncertainty, through interactive graphical representations, diagrams, charts, visual metaphors, and other visualizations. While WBE 3 is concerned with how to determine risk and uncertainty, and WBE 5 is concerned with the impact of these on decision making, this WBE ensures that the risk and uncertainty that have been elsewhere determined are communicated to user in the most effective way.

CRACCEN intends to enable collaborative work and the sharing of ideas and knowledge, whenever appropriate to do so. This activity will lay the groundwork for development of a system that enables all facets of collaboration: synchronous, asynchronous, co-located, and distributed, by considering concepts for how such collaborations within the ship and across ships in a task group could be supported.

CRACCEN will provide the user with a view of their situation, environment, risks, constraints, and restraints. With the system, the user needs to be able to utilize all of this information and build courses of action and mission plans. To do this, they will need mechanisms to input their plans as intuitively and efficiently as possible. Input modalities and methods to consider and evaluate include: mouse, keyboard, pen, touch, gesture, or voice; using menus, glyphs, or digital sketching and recognition, and the application of standardized symbols and techniques.

Early CRACCEN discussions involved the CRACCEN system being instantiated on a large shared horizontal tabletop where team members would work around it, sharing knowledge and ideas. This is a reasonable starting point for concept development, but alternative display technologies exist that each offer their own pros and cons for this application. Alternatives include knowledge walls, Virtual Reality (VR) or Augmented Reality (AR) tabletops or vertical displays, combinations of individual workspaces (e.g., tablets) and shared workspaces (e.g., table or wall) which may on occasion be augmented through VR/AR technology, wearable devices (e.g., for alerting), and other technologies still in their infancy. In order to select the appropriate display technology(ies), it is necessary to understand the tasks and goals that will be supported by the CRACCEN system and the concepts for who will use it and for what purpose, which links backs to the first activities of this WBE.

2.2 WBE 2: Information Backbone

The objective of this WBE is to provide a robust data interchange and classification standard for CRACCEN known as the Information Backbone (IB). The IB will be the main means by which other elements of the integrated Underwater Warfare system will interface with CRACCEN. Research will be organized under three separate activities: information aggregation, cross-resource discovery, and implicit constraints.

2.2.1 Activity 1: Information Aggregation

It is not a trivial task to seamlessly aggregate the diverse information sources [1] required for UWW. Existing resources include processed output from ship and task group sensors, surveillance systems, historical databases, output from simulation or numerical models, and both open-source and classified information. The development of a suitably expandable data model or ontology will be critical to enable the data exploitation possibilities envisioned for CRACCEN. Therefore, this activity will examine the functional requirements imposed by the system and information resources as well as issues related to the aggregation of these resources in support of CRACCEN activities.

Ocean Networks Canada (ONC) has extensive experience with cataloguing diverse datasets in a manner that is intended to ensure their usefulness for decades into the future. It will be beneficial for DRDC experts to leverage ONC's experience and expertise in this area. Other possible collaborators include Marine Environmental Observation Prediction and Response Network (MEOPAR) and the St. Lawrence Global Observatory (SLGO).

2.2.2 Activity 2: Cross-resource Discovery

Automating the discovery of information resources, termed cross-resource discovery, is really about fully exploiting each information resource. By describing the various characteristics of the resource, some obvious (e.g., geospatial extent) and some non-obvious (e.g., the potential to cause an effect), CRACCEN will allow the automated discovery and use of the resource for out-of-context activities.

Building an example using the non-obvious characteristics, consider a Canadian submarine passing in the vicinity of an adversary's territory. An airfield is known to exist near the shore. Intelligence indicates one of the P3 aircraft typically at the airfield, is unaccounted for. At the same time, incoming weather forecasts indicate wind speed increasing over the next 24 hours.

The system's descriptions of the information resources should be capable of building relationships between these resources. The system should know the adversary's P3 is a capable Anti-Submarine Warfare (ASW) platform. As well, the missing P3 indicates a possibility of a patrol flight in progress. The forecasted increase in wind speed should be recognized as important to underwater ambient noise. These factors, and others, should in some manner be accounted for in a decision on whether or not the Canadian submarine should proceed to transit the area, or perhaps delay until the following day when ambient noise levels are higher.

Other examples also exist. For example, ownship noise measurements, regarded as an interfering signal when using a towed array, could be used for earlier detection of ownship mechanical problems. The potential for using the noise measurements for such a detection can be described in the resource's metadata and then potentially exploited by automated processing.

2.2.3 Activity 3: Implicit Constraints

In order to provide the envisioned functionality, the CRACCEN system will be required to handle large volumes of data, which may be drawn from different physical locations for use on a ship at sea with limited bandwidth. Therefore, adaptable data schemes utilizing semantically rich messages (e.g., alerts) will be required to provide the user with the essential information in times of variable or intermittent communications. Similarly, the limited computing power available at sea may require flexible computation algorithms (e.g., anytime algorithms) while taking into account backup methods in the case of severely limited or absent communications capabilities.

This activity will thus examine the combined influence of constraints placed on the IB infrastructure to ensure a responsive information system for CRACCEN. It will investigate the effects of large volumes of data and metadata on system throughput, and also examine methods for ensuring compliance with the unique security laws and policies of the Government of Canada and the Department of National Defence.

2.3 WBE 3: Uncertainty and Battlespace Characterization

The objective of this WBE is to identify suitable battlespace data sources and incorporate them into real-time forecasting and prediction models that will produce operationally relevant sonar performance estimates along with associated uncertainties. The resulting performance predictions are key inputs to the mission planning and decision support modules of CRACCEN. Research will be organized under two separate activities: uncertainty in sonar performance prediction, and applications of Artificial Intelligence (AI).

2.3.1 Activity 1: Uncertainty in Sonar Performance Prediction

In order to calculate detection probability and more sophisticated measures of performance, a sonar performance model requires as inputs environmental information including sea bottom composition, bathymetry, sound speed profile, and surface conditions. However, the environmental information provided will always be only a rough approximation of the environment: there may be limited spatial or temporal resolution (e.g., missing or incomplete data, inappropriate grid size, out-of-date data) that results in an environment that is not truly representative of the expected environment. There is currently no agreed-upon method to understand and quantify how much environmental knowledge is required to provide a sonar performance estimate that is accurate enough to make a satisfactory decision. Neither the environmental knowledge nor sonar performance estimate needs to be perfect, but the mathematical transformation of environmental uncertainty into uncertainty in sonar performance estimates is not well-understood. Furthermore, uncertainty in sonar performance leads naturally to a probabilistic approach to decision-making; again it is not currently known how accurate a sonar performance estimate must be in order to result in a satisfactory decision, and the decision itself need not be perfect in order to achieve mission objectives. The required accuracy is likely to depend on factors such as the specific type of environment being considered and the mission objectives.

At present there is a wide variety of data sources available to provide model inputs, and users often choose data sources based on convenience or habit rather than suitability for the intended purpose. The intent of a review of existing data sources is to get a fuller view of available open- and closed-source data in order to allow the most appropriate data sources to be used, depending upon the specific scenario being modelled. Data sources will include historical databases, real-time measurements, and atmospheric and ocean model forecasts. Relevant parameters to be catalogued will include available spatial and temporal resolution as well as accuracy, and methods of access will be catalogued to enable current or future exploitation. Existing and anticipated future collaborations will be exploited, including:

- the Canadian Integrated Ocean Observing System (CIOOS), which is expected to soon be cataloguing, storing, and making available existing oceanographic datasets collected in Canadian waters;
- the Canadian Operational Network for Coupled Environmental PredicTion Systems (CONCEPTS) collaboration involving DND, Fisheries and Oceans Canada, and Environment and Climate Change Canada, providing operational forecasts of ice and ocean conditions worldwide;
- datasets currently held at Fisheries and Oceans Canada, and Natural Resources Canada, on an ad-hoc basis as required;
- Ocean Networks Canada (ONC), the Marine Environmental Observation Prediction and Response Network (MEOPAR), the St. Lawrence Global Observatory (SLGO), and other non-governmental collaborations that currently provide access to datasets in Canadian waters; and
- classified and unclassified NATO and allied databases.

Once baseline datasets have been identified, they may be found lacking in some areas. Rapid Environmental Assessment (REA) is the activity which examines how to characterize the environment on a variety of different timescales [2]. DRDC's REA research activities were discontinued in 2012; however NATO's Centre for Maritime Research and Experimentation (CMRE) has been continuously active in the field of REA during this time period. CMRE has extensive experience with developing and testing new methods for in situ and remote characterization of the environment for situational awareness, including applications to sonar performance modelling. In order to bring DRDC's subject matter experts up-to-date so they can provide customized advice to the Canadian Forces, the state of the art in REA including recent advances in available techniques will be investigated by collaborating with CMRE. The collaboration may take the form of contracting CMRE to provide a literature review, as well as participating in one or more REA sea trials that take place as part of CMRE's own research program.

Sonar performance models are constantly evolving and it will be necessary to determine whether the latest advances are relevant to RCN scenarios. As computer models increase in complexity, they take longer to run, but increased model accuracy may not result in better decision-making. Therefore, it will be necessary to first identify a suite of models and the conditions under which each model is most appropriate, and then optimize the models to provide calculations in acceptable time frames. It is expected that this work will be done through a combination of in-house work, collaboration with CMRE, and through contracts with industry partners.

Once uncertainty in the environment has been quantified and sonar performance models chosen, the uncertainty needs to be propagated through a model in order to provide an uncertainty in the detection probability (or other performance estimate). There are a number of possible approaches to this problem, including analytical solutions and numerical approaches. Ideally, real-world verification of model estimates would also be available. Several datasets that were acquired as part of previous DRDC Projects and collaborations have been identified as being suitable for exploring the propagation of uncertainty, including:

- the Glider Sensors and Payloads for Tactical Characterization of the Environment 2015 (GLISTEN15) dataset acquired with CMRE;
- the Integrated Multistatic Active Sonar Testbed (IMAST) 2016 dataset acquired as part of the Force ASW Project;
- the future IMAST datasets that are expected to be acquired in 2018 and 2020 as part of the Force ASW Project;
- previous work on propagation of uncertainty in the Bellhop model [3, 4, 5] under the Force ASW Project.

In order to explore acceptable tolerances to sonar performance modelling uncertainties, the Canadian Forces Maritime Warfare Centre (CFMWC) will be engaged to assist in the development of relevant military scenarios to provided a realistic grounding for the work.

Recently among TTCP nations there has been interest in adaptive sensor exploitation, that is, sonar systems that can adapt their pulse transmissions on-the-fly to optimize detection in existing environmental conditions as they arise. The TTCP MAR TP-9 Panel (ASW Technologies and Systems) has proposed an activity called “Cognitive Sonar” which has relevance across this WBE, other aspects of CRACCEN, and future projects in the UWW Program including the proposed Future Sense project.

The work undertaken in this activity will quantify uncertainty in sonar performance prediction due to uncertain knowledge of environmental inputs in order to provide risk estimates. Data sources for baseline environmental knowledge will be identified and evaluated, and knowledge in the fields of REA and sonar performance modelling will be updated. The propagation of uncertainty in environmental knowledge (bottom type, bathymetry, surface, water column, source and receiver position) through to uncertainty in detection probability will be investigated and validated through experimentation. Acceptable tolerances for uncertainty and techniques for acquiring additional environmental knowledge will be explored.

2.3.2 Activity 2: Applications of Artificial Intelligence (AI)

Artificial intelligence has been popularly depicted as having the potential to revolutionize many aspects of warfare; however, there has been a paucity of specific test cases for AI applications in the RCN environment. Two specific examples are proposed for which the technology is mature enough for an operationally relevant test as part of the CRACCEN project.

First, CMRE has been exploring the use of AI in autonomous systems used (among other things) for REA. As part of proposed REA activities within this WBE it will be natural to collaborate with CMRE to observe and possibly contribute to their use of AI in autonomous systems. The collaboration will assist in determining what role such systems may play in the RCN of the future when CRACCEN becomes a reality.

Second, the use of state-of-the art AI techniques such as deep learning networks appears to be well-suited to assist sonar operators in the interpretation of sonar data. Future sensors will result in an overwhelming amount of data that may be presented to the sonar operators, and some automation will be required in order allow operators to focus on contacts of interest. The Acoustic Data Analysis Centre (ADAC) has a rich dataset of annotated sonar data, including raw time series and spectrograms, that have been analyzed in detail according to a specified standard and labelled by contact type. The ADAC dataset would provide a robust test case for AI, as the data were acquired under a variety of environmental conditions, naval platforms, and signal-to-noise ratios, all of which are known to cause problems for more conventional machine learning algorithms [6]. Several academic groups including those at Dalhousie University, University of Toronto, and Université de Montreal, and their corresponding spin-off companies, may be able to contribute by applying their algorithms to a truly challenging dataset. The actual work may take the form of a either a competed contract, or a data challenge as part of the IDEaS program. The security classification of the dataset may limit it to the former, since any sanitization of the dataset to reduce its classification level will reduce the applicability of the technique to real RCN data.

The work under this activity will seek to exploit two distinct applications of AI in support of battlespace characterization: first, the use of AI by autonomous systems for environmental characterization, and second, the use of AI in the interpretation of sonar data.

2.4 WBE 4: Advancing Computational Methods in the UW Domain

The objective of this WBE is to develop the new computational methods and analytical processes required to fully exploit emerging open and classified data sources. Emphasis will be on computational methods required to realize the RCN UWW layered defence concept through the use of large and diverse datasets to enhance detection, classification, and risk assessment at the unit, task group, and force level. Research will be organized into three separate activities: studies of new and emerging data sources, research on computational methods and analytics for UWW, and a UWW data challenge.

2.4.1 Activity 1: New and Emerging Data Sources

Non-traditional data sources with potential to support UWW planning and evaluation will be identified and evaluated.

2.4.2 Activity 2: Computational Methods and Analytics for UWW

New computational methods and analytical processes that leverage the latest advances in data fusion, natural language processing, machine learning, data mining, and risk analysis will be developed and employed to process and exploit traditional and emerging data sources. Collaboration with "big data" researchers from academia (e.g., Dalhousie University), industry (e.g., IBM), and partner nations (e.g., US Office of Naval Research [ONR]) is anticipated to leverage existing outside expertise.

2.4.3 Activity 3: UWW Data Challenge

This activity will plan and execute competitions to engage the data science community to develop cutting-edge solutions to UWW problems. As suitable problems are identified, an appropriate data competition format will be selected and implemented. This activity will also serve to familiarize the data science community with the UWW domain and applicable UWW data sets and to aid in the development of a Centre of Excellence in UWW Data Science though the IDEaS program.

2.5 WBE 5: Human Systems Performance

The objective of this WBE is to develop and validate new CRACCEN decision support concepts through human-in-the-loop experimentation. Research will be organized under two separate activities: Human-in-the-loop experimentation, and development of measurements of performance and effectiveness.

2.5.1 Activity 1: Human-in-the-Loop Experimentation

The purpose of this activity is to understand the relationship between human operators and CRACCEN to ensure the human-machine team works together as a 'joint cognitive system'. The successful integration of humans and machines requires an understanding of the human factors variables that will impact the human-machine system. This activity will conduct Human-in-the-Loop (HIL) research and development related to the following anticipated human factors issues: human understanding of environmental uncertainty, automation, and implications of new information sources on decision-making.

Underwater warfare is characterized by uncertainty requiring operators to make decisions based on risk, or probabilistic information. For instance, in WBE 3 it is noted that uncertainty in sonar performance leads naturally to a probabilistic approach to decision-making. Unfortunately the interpretation of uncertainty, or risk, by human operators is well-documented as being subject to cognitive biases, even when operators are presented with objective numerical values [7]. Part of the HIL experimentation activity will evaluate how uncertainty information should be presented to operators to improve risk-based decision making. For instance, representing risk information visually, as opposed to numerically or verbally, has been shown to neutralize biases making risk-based decision making more accurate [8]. The human-computer interaction and visualization design will happen in conjunction with WBE 1. Work from the NATO Research Task Group under the System Analysis and Studies Panel (SAS-114) on the assessment and communication of risk and uncertainty to support decision making will be leveraged to support this work. DRDC may also extend collaborations with CMRE and DRDC Toronto to investigate issues surrounding this topic.

As CRACCEN moves to revolutionize UWW tasks, decision-making and decision execution are expected to be distributed across human operators and CRACCEN. To do this, various levels of automation will need to be applied. When applied correctly automation should optimize the distribution of work between human operators and CRACCEN to reduce workload and operational stress, while improving situational awareness, confidence and decision-making. Determining what activities should be automated, along with what level and type of automation should be applied will be investigated. Other topics such as trust in automation, adaptive automation, and human centred automation will also be explored. HIL experimentation will be used to investigate optimal levels and types of automation to be implemented in CRACCEN. Potential outside sourcing includes:

- an ongoing NSERC-DND collaboration on Cognitive Shadowing with Dr. Sebastian Tremblay at the Cognition-Distribution-Organization-Technologies (Co-DOT) Laboratory Université Laval and Thales Research and Technology Canada to study adaptive cognitive assistants to aid naval decision making;
- an ongoing SSHRC-DND collaboration on Trust in Automation with Dr. Heather Neyedli at Dalhousie University to study the impact of levels of automation on trust in human-machine teaming;
- a DND-NSERC proposal with Thales, Université Laval and Dalhousie University in FY 2019/2020, which is expected to link the above mentioned work on automation, cognitive assistants and trust.

Finally, CRACCEN has the potential to integrate information sources in new and meaningful ways. Understanding the impact that new information has on UWW decision-making will be evaluated as iterations of CRACCEN information sources are developed. HIL experimentation with operators will be used to evaluate the utility of newly integrated information on the decision-making process. Throughout its development CRACCEN will be evaluated with human-in-the-loop experiments with the intent of improving on and validating CRACCEN concepts. This activity will provide evidence-based assessments of CRACCEN decision support concepts to improve RCN C2 decision-making.

2.5.2 Activity 2: Measures of Performance and Effectiveness

This activity will develop RCN task-specific measures of performance and effectiveness to be used in human-in-the-loop experimentation. These measures will characterize operator behaviour at an individual and team level to determine what impact CRACCEN has on decision-making speed and accuracy, workload demands, stress, trust, communication, situational awareness and overall decision-making effectiveness. Work from TTCP HUM JP2 on the development of maritime command team effectiveness metrics will be leveraged to support this work. Various methodologies may be employed for assessing behaviours, such as eye tracking, physiological and psychological measures. Once identified, performance and effectiveness metrics will be collected to assess the impact of CRACCEN decision support on C2 decision-making. This activity will also explore the feasibility of real-time human factors data capture for ongoing and future evaluations of CRACCEN decision support.

2.6 WBE 6: CRACCEN Integration

The objective of this WBE is to combine the results of all the work performed in the other WBEs into a coherent set of reports, suitable for consumption by the RCN. The work will be organized under four separate but related activities: architecture and design concept, display system requirements and advice, software modules and decision support tools, and prototype development.

2.6.1 Activity 1: Architecture and Design Concept

As described in WBE2, the CRACCEN system architecture must be carefully designed so as to be simultaneously robust and adaptable, which not a simple proposition. Therefore, this activity will produce standards, interface descriptions, system architecture, and a concept of utilization for CRACCEN, ensuring that a prototype CRACCEN can be procured and to put to best use by the RCN.

2.6.2 Activity 2: Display System Requirements and Advice

Given that the CRACCEN project is expected to revolutionize UWW, it is preferable not to be constrained by tradition or habit when imagining the type of display used for future collaborative planning. In fact it may be that users in different roles will require different display formats. The related work in WBE1 will result in a statement of requirement for the display system(s) hardware needed for CRACCEN which will then lead to the acquisition of an S&T system to support research and at-sea experimentation.

2.6.3 Activity 3: Software Modules and Decision Support Tools

Experimentation with software modules, decision aids, and visualizations can begin before the final CRACCEN IB is available, using DRDC's System Test Bed (STB) or the Course of Action Tool (COAT) as an interim solution. By making use of the existing STB or COAT infrastructure, new ideas and developments will be progressed so that they are ready for implementation on the CRACCEN IB when it is finalized. This activity will result in proof-of-concept prototypes, intellectual property, and documentation to allow industry to participate in the eventual incorporation of these capabilities into RCN operational equipment.

2.6.4 Activity 4: Prototype Development

During initial phases of CRACCEN, software and display prototypes will be developed using combinations of DRDC's STB, COAT, and custom-designed software. Once the IB requirements have been determined, a statement of requirements for an initial CRACCEN prototype will be developed. Procurement of the CRACCEN prototype during the later stages of the CRACCEN project will allow for future at-sea experimentation and concept development. Furthermore, explorations with the initial prototype will inform future statements of requirement and will assist in identifying future directions for the UWW program.

3 Summary

An overarching vision has been described for a C2 system called CRACCEN (Command Reconnaissance, Area Coordination and Control Environmental Network), intended to revolutionize underwater warfare in the Royal Canadian Navy. A five-year plan with concrete recommendations for implementation was described. The plan consists of six integrated lines of research (WBEs) that will be required to move toward the RCN's long-term CRACCEN vision: design concepts for revolutionary C2 systems, information backbone, uncertainty and battlespace characterization, advancing computational methods in the underwater domain, human systems performance, and CRACCEN integration.

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Annex A Detailed Deliverables

A.1 WBE 1 Design Concepts for Revolutionary C2 Systems

Deliverable:

1. A scientific letter, "Design methodologies and concepts for CRACCEN," will summarize and contextualize for the RCN the recommended design concepts, information presentation, and interaction methodologies for UWW mission planning and execution.

Sub-deliverables:

a. Report on CRACCEN requirements, as learned through expert engagement and prototype exploration (2019 (initial), 2022 (final)).

b. Report on CRACCEN design concept (2019 (initial), 2023 (final)).

c. Reports on the presentation and consumption of data, information sources, and model outputs to support underwater warfare mission planning (2021 (initial), 2023 (final)).

d. Demonstration of recommended methods for the visualization of data, information sources, and model outputs (2021).

e. Report on display form factor trade-off study for CRACCEN (2021).

f. Demonstration of recommended display and interface technology (2021).

A.2 WBE 2 Information Backbone

Deliverable:

2. A scientific letter, "Contextualization of Information Resources in Support of Underwater Warfare," will summarize and contextualize for the RCN the recommended data models, resource metadata, and system capabilities required to take full advantage of the UW information domain.

Sub-deliverables:

a. Report on standards-based data model design and implementation system (2019).

b. Report on information science issues pertaining to resource metadata required to support cross-resource discovery and aggregation (2020).

c. Demonstration of the discovery of unexpected connections within well-known data sources (2020).

d. Report on system capabilities related to resource discovery and exploitation (2022).

A.3 WBE 3 Uncertainty and Environmental Characterization

Deliverable:

3. A scientific letter, "Uncertainty and Environmental Characterization," will summarize and contextualize for the RCN the recommended environmental models, sonar performance tools, and uses for artificial intelligence that will enable the generation of real-time sonar performance estimates.

Sub-deliverables:

a. Report on the state-of-the art in sonar performance models, rapid environmental assessment techniques, and data sources, with recommendations for adoption by the RCN (2019 (initial), 2023 (final)).

b. Report on theoretical approaches to propagation of environmental uncertainty and exploration of mission-specific acceptable tolerances in sonar performance predictions (2020 (initial), 2022 (final)).

c. Report on experimental results intended to validate theoretical approaches and demonstrate the propagation of uncertain environmental knowledge into sonar performance predictions in one or more specific ASW use cases. (2020 (initial), 2023 (final)).

d. Demonstration the effects of environmental uncertainty on sonar performance prediction (2020).

e. Report on AI in autonomous systems used for environmental characterization (2021 (initial), 2023 (final)).

f. Report on the use of AI on sonar data as a way to reduce operator workload (2020).

g. Demonstration of the use of AI to automate aspects of the sonar operator's workload (2020).

A.4 WBE 4 Advancing Computational Aspects in the UW Domain

Deliverable:

4. A scientific letter, "Advancing Computational Aspects in the UW Domain," will summarize and contextualize the recommended data sources, computational methods, and analytics to improve the RCN's ability to conduct UWW operations.

Sub-deliverables:

a. Report on new and emerging classified, open, and commercial data sources to support future UWW planning and evaluation (2019).

b. Report on new computational methods and automation for data and information processing and exploitation. (2020 (initial), 2023 (final)).

c. Report on analytical processes and information visualization for UWW (2020 (initial), 2023 (final)).

d. Demonstration of analytical processes and information visualization for UWW (2020).

e. Report on UWW data science competition (2023).

A.5 WBE 5 Human Systems Performance

Deliverable:

5. A scientific letter, "Human Systems Performance," summarizing and contextualizing the recommended decision metrics, human performance measurements, plan adaptation, and decision support tools required to enable RCN personnel to plan and execute missions.

Sub-deliverables:

a. Report on decision quality metrics and human performance measurements in systems undergoing revolutionary change (2020).

b. Report on concepts for plan execution monitoring and adaption (2022).

c. Report(s) on study to assess new concepts for decision support related to uncertainty, automation, and/or information utilization (2021 (initial), 2023 (final)).

d. Report on feasibility of system-embedded human factors measurements (2021).

e. Demonstration of new decision support concepts and system embedded human factors measurements (2021).

A.6 WBE 6 CRACCEN Integration

Deliverables:

6. The WBE 6 deliverables include:

a. Statement of work describing the requirements to procure a prototype CRACCEN system. It will include an interface standard, systems architecture, and concept of use (2022).

b. Statement of requirements for a system display and interface. This will lead to a procurement of said devices, to be used to further research and to elicit feedback from the client. A demonstration of the procured system will be held (2021).

c. Software modules and decision support tools, implemented in the STB. These modules will be generated will include sonar performance predictions, data visualizations, decision support tools. (Throughout project).

d. A project proposal for a new UWW project that will seek to capitalize on and extend the capabilities of CRACCEN (2022).

e. A Prototype CRACCEN will be developed though contracting to industry. This system will allow for further research and development of CRACCEN (2023).

List of Symbols/Abbreviations/Acronyms/Initialisms

ADAC	Acoustic Data Analysis Centre
AI	Artificial Intelligence
AR	Augmented Reality
ASW	Anti-submarine Warfare
C2	Command and Control
CFMWC	Canadian Forces Maritime Warfare Centre
CIOOS	Canadian Integrated Ocean Observing System
CMRE	Centre for Maritime Research and Experimentation
COAT	Course of Action Tool
Co-DOT	Cognition-Distribution-Organization-Technologies
CONCEPTS	Canadian Operational Network for Coupled Environmental PredicTion Systems
CRACCEN	Command Reconnaissance Area Control and Coordination Environmental Network
DND	Department of National Defence
DRDC	Defence Research and Development Canada
GLISTEN15	Glider Sensors and Payloads for Tactical Characterization of the Environment 2015
HIL	Human-in-the-loop
IB	Information Backbone
IDEaS	Innovation for Defence Excellence and Security
IMAST	Integrated Multistatic Active Sonar Testbed
MEOPAR	Marine Environmental Observation Prediction and Response Network
MetOc	Meteorology and Oceanography
NATO	North Atlantic Treaty Organization
NSERC	National Sciences and Engineering Research Council
ONC	Ocean Networks Canada
RCN	Royal Canadian Navy
REA	Rapid Environmental Assessment
SAS	System Analysis and Studies
SLGO	St. Lawrence Global Observatory

SME	Subject Matter Expert
SSHRC	Social Sciences and Humanities Research Council
STB	System Test Bed
TTCP	The Technical Cooperation Programme
UW	Underwater
UWW	Underwater Warfare
VR	Virtual Reality
WBE	Work Breakdown Element

DOCUMENT CONTROL DATA

(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Designated)

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.) DRDC – Atlantic Research Centre Defence Research and Development Canada 9 Grove Street P.O. Box 1012 Dartmouth, Nova Scotia B2Y 3Z7 Canada	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) CAN UNCLASSIFIED 2b. CONTROLLED GOODS (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC DECEMBER 2013

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.)

Recommendations for implementation of the Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) project

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

Tollefsen, C.; Hunter, A.; Randall, T.; Isenor, A.W.

5. DATE OF PUBLICATION (Month and year of publication of document.) November 2017	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 30	6b. NO. OF REFS (Total cited in document.) 8

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.)

Reference Document

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

DRDC – Atlantic Research Centre
Defence Research and Development Canada
9 Grove Street
P.O. Box 1012
Dartmouth, Nova Scotia B2Y 3Z7
Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
10a. 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.) DRDC-RDDC-2017-D101	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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The Command Reconnaissance Area Coordination and Control Environmental Network (CRACCEN) is an initiative intended to revolutionize Canadian Underwater Warfare (UWW) for decades to come. This document details the integrated lines of research required to progress CRACCEN from the proposal stage to a realizable set of deliverables for the Royal Canadian Navy. The lines of research were generated through discussion with the UWW community and an examination of current trends and needs in the underwater domain. The results indicated a need to completely rethink the command and control structure to take into account risk analysis, uncertainty, advanced data fusion, and presentation techniques that allow better exploitation by the command team in the decision making process. These results will guide the CRACCEN effort for the duration of the project.

Le CRACCEN, un réseau environnemental de coordination et de contrôle de la zone de reconnaissance du commandement, est une initiative qui vise à révolutionner la guerre sous-marine canadienne pour les décennies à venir. Le présent document décrit les axes de recherche intégrés requis pour faire progresser le CRACCEN de l’étape de la proposition à celle d’un ensemble réalisable de produits livrables pour la Marine royale canadienne. Ces axes de recherche ont été produits à la suite de discussions avec la communauté de la guerre sous-marine et après un examen des tendances et des besoins actuels dans le domaine sous-marin. Les résultats ainsi obtenus ont montré la nécessité de repenser complètement la structure de commandement et contrôle pour tenir compte de l’analyse des risques, de l’incertitude, de la fusion avancée des données et des techniques d’approche qui permettent une meilleure exploitation par l’équipe de commandement dans le processus de prise de décisions. Ces résultats permettront d’orienter les efforts consacrés au CRACCEN pour toute la durée du projet.

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Command and Control (C2); Rapid Environmental Assessment (REA); Decision making; Human systems; information; artificial intelligence; CRACCEN (Command Reconnaissance Area Coordination and Control Environmental Network