NATO STO CMRE

2023 ANNUAL REPORT

Science and Technology Organization
Centre for Maritime Research and Experimentation

MISSION

The mission of CMRE is to organize and conduct scientific research and technology development, centred on the maritime domain, delivering innovative and field-tested Science & Technology (S&T) solutions to address defence and security needs of the Alliance.

ORGANIZATION

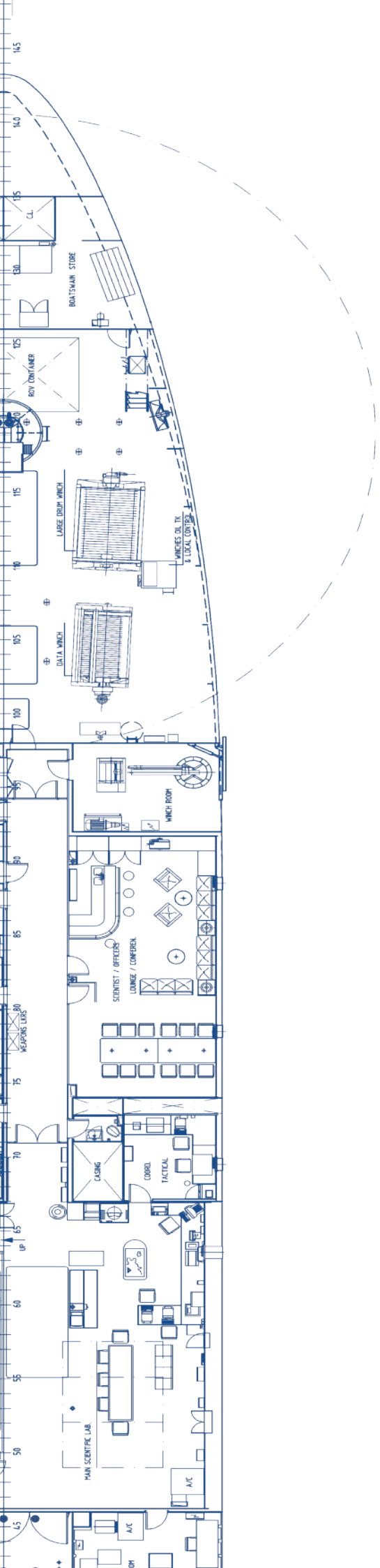
The Centre for Maritime Research and Experimentation (CMRE) is an executive body of the NATO Science and Technology Organization (STO), which operates under North Atlantic Council (NAC) authority through the Military Committee (MC) and the Conference of National Armaments Directors (CNAD).

ABOUT

The Centre for Maritime Research and Experimentation, originally known as SACLANT ASW Research Centre and subsequently as NATO Undersea Research Centre, was commissioned on 02 May 1959.

With over 60 years of knowledge and experience in undersea research, CMRE is a recognized centre of world-class expertise in the maritime domain. The Centre is a collaboration hub for scientists from all NATO Nations to work together to maintain NATO's maritime technological edge.

Today, the scope of the Centre's work encompasses the fields of artificial intelligence, big data analytics, underwater acoustics, oceanography, autonomous systems, and climate change and security studies. Underpinning CMRE's success in maritime research over the years is its global sea-going capability. CMRE provides an outstanding at-sea research environment where internationally recognized scientists and engineers from NATO Nations share their knowledge while delivering results more effectively than would be possible by individual nations. The Centre conducts cutting-edge maritime experimentation and demonstration in extremely challenging conditions from the Mediterranean Sea to the Arctic Ocean.



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FOREWORD

It is with great pleasure and much pride that I write this Foreword to the CMRE 2023 Annual Report. I started as CMRE Director in December 2023, so the majority of the products and services for NATO and the NATO Nations reported herein were delivered under the purview of my predecessor, Dr Catherine Warner. I would like to acknowledge her hard work and success at raising awareness of the CMRE and maintaining the Centre's relevance during her six years as Director.

Reflecting on the CMRE's overall performance during 2023, it is with much pleasure that I can report a significant uptick in the Centre's income. Indeed, total income was at an all-time high of 36.5 MEUR, over 80% of which was provided by NATO Allied Command Transformation (ACT) and the NATO Science and Technology Organization (STO). I would like to take this opportunity to thank NATO ACT senior leadership and the STO and its governance body the Science and Technology Board (STB) for their trust and continuing commitment to the CMRE.

I have been most impressed by the work carried out in the relatively new-to-the-Centre fields of investigation such as: Quantum Technology; the Climate Change and Security programme; and the Protection of Critical Undersea Infrastructure. One of the CMRE's perennial strengths is the ability to bring to life and test new and innovative capabilities at sea, to the benefit of all NATO Nations, and to provide military operators with early exposure to such new systems and capabilities. In this way, opportunities are provided for the development of suitable tactics and procedures, therefore de-risking their introduction into service. Sea trials funded by ACT during 2023 carried out on-board the NATO Research Vessel (NRV) Alliance included: the Anti-submarine Warfare (ASW) COherent Localization Detection (COLD) 23 trial in the Barents Sea; the Nordic Recognized Environmental Picture (NREP) 23 campaign in the Greenland Sea / Svalbard region; and, the Mediterranean ASW Autonomous Network 2023 trial in the Tyrrhenian Sea, which was partially supported by the US Office of Naval Research (ONR). Additionally, ACT funded a very successful at-sea trial of an advanced naval mine countermeasures low frequency high resolution synthetic aperture sonar sensor on-board the Coastal Research Vessel (CRV) *Leonardo*. Finally, CMRE staff organized two highly successful conferences: a Quantum Science and Technology Workshop in Turin, Italy; and a Climate Change and Security Workshop in Lerici, Italy.

On a personal note, I am proud and honoured to serve NATO as the CMRE Director. In endorsing my selection and forwarding it for North Atlantic Council approval, NATO Nations through the STB have entrusted me with leading the talented team of researchers, engineers and technologists to respond to the most pressing science and technology (S&T) challenges of the Alliance. My mission and responsibilities are multi-faceted, but one aspect that is particularly important to me is people. A research laboratory is only as good as the people who work there. As Director, I am committed to attracting and retaining the best scientific and engineering talent to the CMRE, especially young early-career professionals. The scientific community in all NATO Nations must perceive the CMRE as an inspiring place to work and an environment to develop professionally, while carrying out innovative research to meet NATO's research priorities. I am also committed to developing a diverse CMRE workforce and enforcing ethics, compliance, security and safety, such that research is conducted responsibly and ethically, and in accordance with all NATO and host nation policies and regulations.

We have much to look forward to in 2024. Not only does the CMRE have challenging and well-funded S&T research and development programmes in place for 2024, but also there will be the opportunity to shape the CMRE's future capabilities so that it will become the preferred choice for NATO and nations to organize and conduct scientific research and technology development and deliver innovative and field-tested S&T solutions to address the defence and security needs of the Alliance.

2023: CMRE IN CONTEXT

NATO's core role is to keep its one billion people safe. NATO does so through political dialogue and consultations to ensure unity and coherence among NATO Nations, and by making sure that the military plans, forces and capabilities are in place to protect and defend all NATO Nations at sea, in the air, on the ground, in cyberspace and in space.

Russia's war of aggression on of Ukraine has ushered a new era of power competition, emphasizing the critical role of the Alliance in executing its core task of deterrence and collective defence as described in the NATO 2022 Strategic Concept. Russia's aggression, coupled with additional recent security challenges in the East Mediterranean and Red Sea, has demonstrated why the Alliance must drive innovation to maintain its technological edge to meet the challenges of today and tomorrow. Such challenges include climate change, the security of the sea lines of communication (SLOC) and maritime trade routes, and the protection of critical undersea infrastructure.

The 2021 NATO Warfighting Capstone Concept (NWCC) acknowledges that the Alliance's operating environment is evolving beyond more traditional military bounds, with competition among different actors becoming more persistent across all instruments of power. Diverse actors, new weapons and technologies employed in new ways, will continue to be a feature. The NWCC details how NATO and NATO Allies must develop their military instruments of power to maintain an advantage for the next 20 years through a proactive and anticipatory approach to rising security threats based on integrated multi-domain operations (MDO). In a multi-domain world, all domains influence NATO's ability to operate in the maritime domain, and Allied maritime assets contribute significantly to effective MDO.

The NWCC is being operationalized through the NATO Warfare Development Agenda (WDA). The CMRE, through the Maritime Science and Technology (S&T) Programme of Work funded by NATO Allied Command Transformation (ACT) has been able to—and will continue to—contribute significantly to the WDA and NWCC, enabling effective operations through developing and fielding advanced sensors deployed on autonomous platforms and networked together through multi-domain command and control capabilities such as the CMRE Command Control and Communications for Maritime Robotic Exploitation (C3MRE). C3MRE provides an infrastructure for connectivity among a system of heterogeneous autonomous systems in the land, air and maritime domains, supporting adaptive

and cooperative behaviours. Through such capabilities, the Centre is leveraging the opportunities presented by emerging and disruptive technologies to contribute to NATO's digital transformation and maintain the Alliance's technological edge.

The financial security of the Centre took a significant turn for the better in 2023 with a total income all-time high of 36.5 MEUR—a 40% increase on the average CMRE annual income over the previous four years. This encouraging financial performance demonstrates the rising demand for CMRE's products and services that meet customers' requirements and expectations. NATO ACT continues to provide over 80% of the CMRE's annual income by way of the ACT Maritime S&T Programme of Work and funding other projects at the Centre such as software minimum viable products (MVP), modelling and simulation (M&S) services, and operational experimentation. The NATO Science and Technology Organization (STO) funded the Climate Change and Security programme at the CMRE during 2023, becoming the Centre's second largest customer after NATO ACT by income earned.

The higher demand for CMRE products and services during 2023 demonstrates that NATO Nations increasingly appreciate the CMRE's role in complementing and enhancing national research and development efforts. There is much benefit in doing science together under the NATO flag, thereby informing NATO and national S&T programmes and acquisition in order to provide NATO armed forces with the capabilities they need. Indeed, NATO Nations have agreed in principle to use NATO common funds for a very ambitious programme to regenerate and renew the CMRE's research equipment and infrastructure. During 2024, under the leadership and guidance of ACT, the corresponding Capability Programme Plan will be submitted to the NATO Security Investment Programme governance authorities for endorsement and final approval by NATO Nations.

2023 also saw the accession of Finland to NATO as the Alliance's 31st member Nation, and in March 2024 Sweden has become the 32nd NATO Nation. The Director and all CMRE staff welcome Finland and Sweden to NATO, and acknowledge the impressive maritime capabilities that they bring to the Alliance. CMRE staff look forward to working closely with their world-class maritime science and technology research entities.

RESEARCH DIVISION

In 2023, the overall CMRE Programme of Work (PoW) was funded mainly by two customers: NATO Allied Command Transformation (ACT), and the NATO Science Technology Organization (STO).

Since 2012, ACT has provided the majority of funding for CMRE science and technology (S&T) products and services, the requirements for which are specified in the annual ACT Maritime S&T PoW, which encompasses four major programmes:

- Autonomy for Anti-submarine Warfare (AASW).
- Autonomy for Naval Mine Countermeasures (ANMCM).
- Data and Environmental Knowledge and Operational Effectiveness (D-EKOE).
- Maritime Unmanned Systems Enablers (MUSE).

In 2023, CMRE also welcomed the STO through the NATO Office of the Chief Scientists (OCS) as a key new customer, sponsoring a dedicated PoW that:

- Enhanced the CMRE's existing Visiting Researcher Programme;
- Strengthened the existing MUSE Quantum Technologies work; and,
- Launched an additional programme on Climate Change and Security (CCAS).

The majority of the projects and research activities within CMRE's Research Division (RD) are carried out within the overall framework and funding of the above programmes, and the Division is internally structured along similar lines.

Autonomy for AASW and ANMCM Programmes

The specific aim of these programmes is the improvement of the Alliance's ability to exploit autonomous security networks to counter evolving threats in the underwater domain. The AASW and ANMCM programmes are long-term investments by NATO in CMRE, and exploit emerging and disruptive technologies (EDTs)—such as AI, autonomy, data analytics and quantum sensing—to improve future NATO capabilities. CMRE researchers are exploring the use of innovative, highly sensitive, high-resolution and low-noise sensing capabilities and technologies for ASW applications and for naval mine detection, classification and identification.

Research activities within both AASW and ANMCM programmes focus on developing, at-sea testing, and demonstrating to the NATO maritime operational community, advanced concepts for ASW and NMCM operations based on autonomous heterogeneous assets, equipped with active and/or passive sensor packages, operating in networks of unmanned systems,. All assets are designed to work either in autonomous single vehicle or collaborative robotics modes, communicating and persistently operating to detect and localize maritime targets of interest, to include target tracking for ASW, and the classification and identification of naval mine warfare threats. Research is also conducted into exploiting the environmental data collected by the sensors in order to optimize vehicle adaptive behaviour using a cognitive approach. Moreover, as interoperability among Allied armed forces is a key enabler and capability multiplier, CMRE researchers place particular emphasis on the development and the promotion of standardized protocols for collaborative autonomy; for example, by participating in the development of the standardized Collaborative Autonomy Tasking Layer protocol (CATL).

Through Operations Research, AASW and ANMCM scientists advance doctrine development for the employment of maritime unmanned systems for underwater warfare operations and their integration with traditional NATO capabilities. Activities include developing and testing algorithms for planning and evaluating underwater warfare operations carried out by manned and unmanned systems equipped with traditional and modern sensors. CMRE researchers also support Allied Maritime Command with the analysis of the performance of NATO underwater warfare forces during NATO maritime live Exercises.

D-EKOE Programme

The D-EKOE programme aims to improve the Alliance's ability to operate in the maritime domain through a greater understanding of the oceanic environment, while supporting advanced situational awareness concepts with a robust multi-domain orientation. The research activities within this programme leverage EDTs in autonomy, networking, robotics, big data analytics and AI to provide near real-time distributed multi-domain intelligence and surveillance in key regions such as the High North.
The 'CMRE Arctic Science and Technology Strategy'

lays out the rapid environmental assessment (REA) requirements and capabilities to optimize ASW operations by NATO forces in a rapidly transforming Arctic environment. During 2023, dedicated sea trials were conducted in the Greenland Sea/Svalbard region on-board NATO Research Vessel NRV Alliance with data collected using innovative aerial and underwater drones. The benefit of these sea trials is in validating the strategy and enhancing its concept of operations and methodologies, which may be readily employed in other maritime regions within NATO's area of responsibility.

The D-EKOE programme incorporates data science research to address NATO operational requirements for situational awareness by advancing information processing techniques that enable cognitive superiority and decision support through AI and advanced analytics. The research builds and shares coherent situational awareness, with emphasis on the maritime domain, through: all-source information integration and fusion; target tracking; traffic pattern learning; and, anomaly detection and behavioural analysis. The coherent and integrated operational picture resulting from this seabed-to-space approach is the foundation for the effective monitoring and protection of critical underwater infrastructures (CUI). CMRE D-EKOE researchers are making cutting-edge scientific advances in basic research, algorithms and prototype methodologies for fusing sensor data with contextual information, thereby enhancing NATO capabilities for protecting CUIs.

MUSE Prgramme

MUSE is a cross-cutting programme supporting the CMRE AASW, ANMCM and D-EKOE programmes with enabling capabilities for maritime autonomous systems. The work under the MUSE programme includes research into the security and standardization of underwater communications, with an emphasis on interoperability and architectural coherence. MUSE researchers investigate and define the framework in which autonomous underwater systems and missions are cast, with the intent to ensure future NATO forces are equipped with secure, interoperable, and scalable systems benefitting from increased effectiveness and reduced risks and costs.

A strand of the activity under the MUSE programme addresses maritime command and control in harsh environments by developing a 'digital ocean', a synthetic environment for testing, verifying, and validating autonomous maritime systems and missions. Additionally, MUSE programme researchers are very active in the fields of Quantum communications, navigation and computing. The MUSE modelling and simulation team assist ACT staff with the investigation, analysis, and development of solutions to support a range of NATO activities, including training, decision-making, advance planning, operations planning, and concept development and experimentation.

CCAS Programme

An increasingly important strand of CMRE RD activity is concerned with exploring the security implications of climate change (CC) in the maritime domain, and specific CC impacts on: the effectiveness of current and future NATO military capabilities, including sensors, weapons, and platforms; the resilience of infrastructures; and, the operating environment for NATO operations and missions. The results contribute to assessing how climate change might impact NATO's deterrence and defence posture, part of the NATO Climate Change and Security Action Plan.

During 2023, CMRE researchers addressed a number of basic and applied research topics, including:

- Exploring the mechanism of El Nino climate pattern;
- Understanding and monitoring Arctic transformation, with a dedicated sea trial deploying the first elements of the NATO Arctic Underwater Climate Observatory;
- Investigating possible CC impacts on the future performance of ASW sonar systems, underwater acoustic communication systems, and ship and coastal radar systems; and,
- Studying how the system of NATO naval bases might be affected by extreme weather events.

Additionally, CMRE staff organized an international Climate Change and Security Workshop, and—in collaboration with NATO civilian and military academia—designed a new syllabus for a dedicated higher educational course on CCAS.

AUTONOMY FOR ANTI-SUBMARINE WARFARE

MARITIME UNMANNED SYSTEMS FOR ASW

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

NATO established the Centre in 1959 with a single mission area, anti-submarine warfare (ASW). Although CMRE's maritime science and technology programme of work has broadened over the years to include other undersea warfare areas, ASW has remained a perennial focus for the Allies, and has become a higher priority in light of recent geopolitical developments.

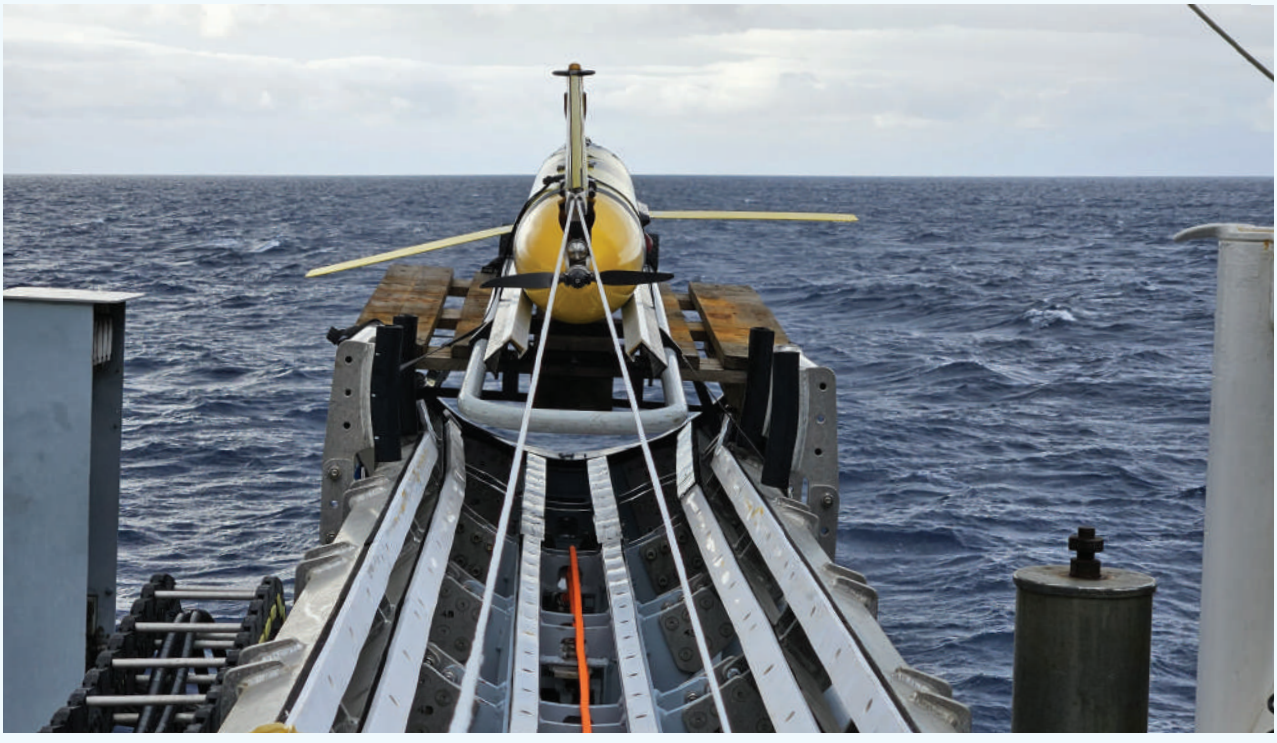
The aim of the Maritime Unmanned Systems for ASW project is to develop and test at sea innovative ASW solutions in which networks of unmanned platforms complement and augment conventional ASW capabilities in the detection, localization, tracking and classification of submarines. To achieve this aim, the project team exploit emerging and disruptive technologies (EDTs) such as advanced heterogeneous sensing (including quantum), autonomy (including collaborative robotics), and artificial intelligence.

The scientific activities carried out under this project have both theoretical and experimental components, as they include the test and validation of the conceived innovative concepts at sea in operationally relevant scenarios.

Results

The main achievements during 2023 were related to the execution of two sea trials: COherent Localization Detection (COLD23) conducted in June off the north-western coast of Bear Island; and, MEDiterranean ASW Autonomous Network (MED-ASWAN23) carried out in October in the Tyrrhenian Sea off the northern coastline of Elba.

- In the COLD23 sea trial, the team deployed a squad of sea bottom nodes in shallow waters. Three nodes were equipped with a suite of low-frequency passive acoustic sensors and quantum magnetometers. In addition, four Ocean Acoustic Seismometers were tested. The main objectives of the trial were to: investigate the space and time coherence of signals received by a planar, sparsely-distributed array of sensors as range to target and environmental conditions varied; and, study of the effects of an Arctic environment on the performance of sensing nodes comprising of sonar and quantum magnetic sensors.
- The MED-ASWAN23 sea trial had similar objectives to COLD23, and included at-sea tests of a network of mobile and static passive ASW ro-



bots. Compared with previous CMRE sea trials, the network architecture was extended to include a larger number of nodes, and the cooperative autonomy among nodes was based on a new approach using behaviour trees, which replaced the more conventional finite-state machines. This new approach is designed to improve the robotic network's robustness, flexibility and reusability in the context of mission planning and execution. Successful target localization and tracking results were obtained from the fusion of contacts shared in real time through underwater acoustic communication from each of the network's heterogeneous sensing nodes. It is concluded that the newly introduced cooperative autonomy concept contributed to an overall improvement of the federated robotic sonar's performance.

Future Goals

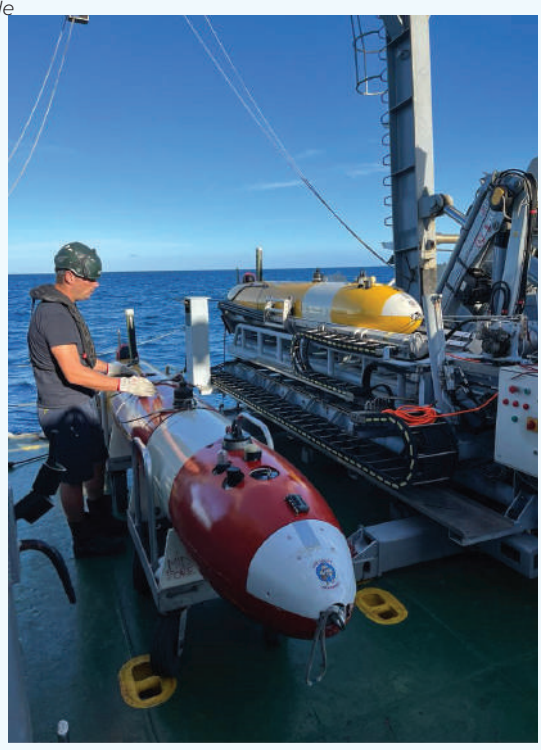
Very rich data sets were collected during both 2023 at-sea trials, which will support:

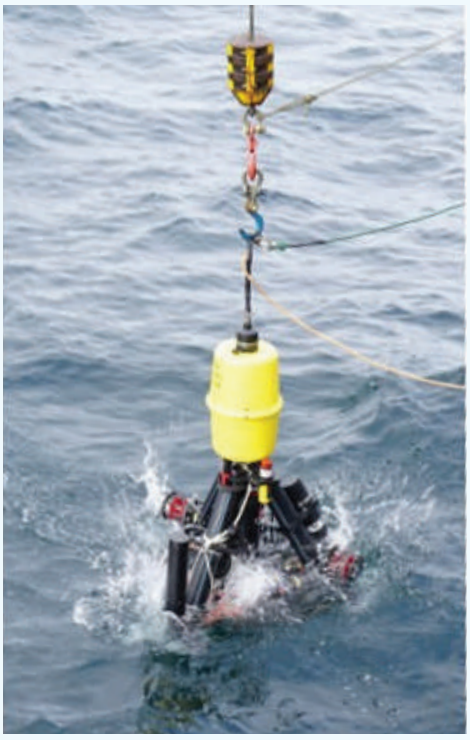
- The development of improved processing algorithms; and,
- The optimization of the configuration of a network of large numbers of heterogeneous smart-sensing platforms sparsely distributed in an area of operational interest. The goal is for the ASW network to maintain overall target localization and tracking performance in changing environmental conditions by autonomously adjusting its geometrical configuration and sensor characteristics.

¬ *An acoustic glider ready to be deployed from the autonomous underwater vehicle (AUV) Launch and Recovery System installed on the aft deck of NATO Research Vessel (NRV) Alliance (MED-ASWN23)*

> *CMRE's mid-size AUVs on the aft deck of NRV Alliance after recovery at the end of a full-day ASW mission (MED-ASWAN23)*

>> *Deployment during COLD23 of a CMRE-designed bottom node*





AUTONOMY FOR ANTI-SUBMARINE WARFARE

ANTI-SUBMARINE WARFARE DECISION SUPPORT

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

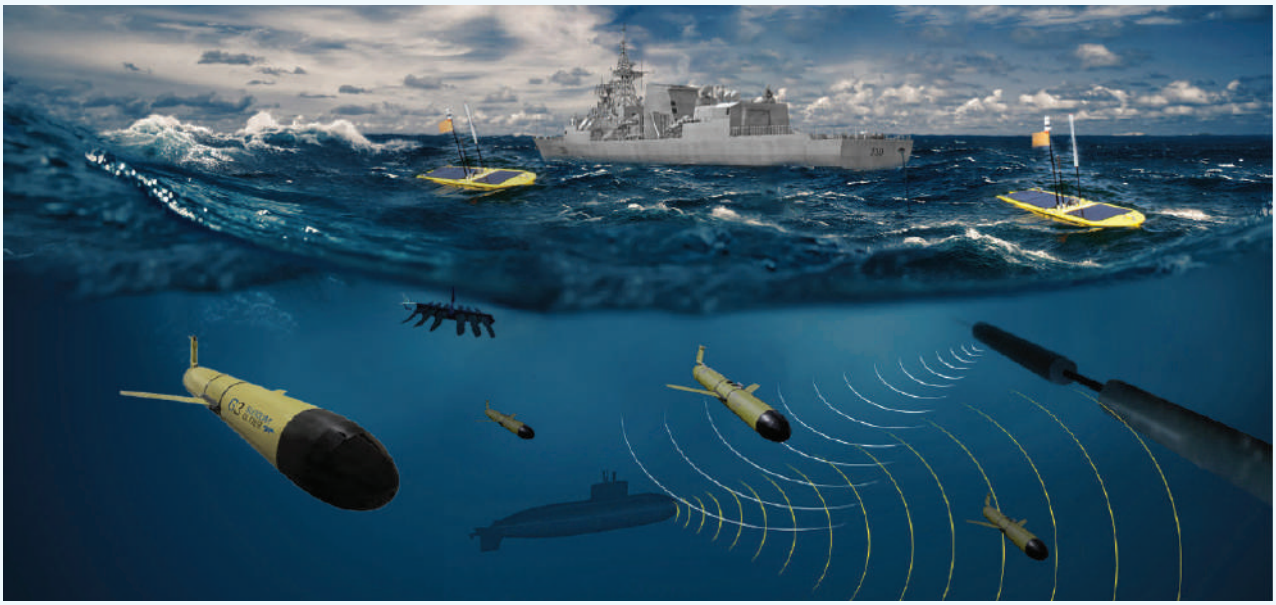
The Anti-submarine Warfare (ASW) Decision Support project is concerned with the future planning and optimization of ASW missions executed by large numbers of heterogeneous unmanned—and manned—platforms, including all categories of platforms available to NATO Nations in addition to those currently operated by the CMRE.
The fast optimization of platform force mixes accounting for logistic and endurance constraints provides valuable insight for future ASW capability solutions. The results obtained may be further transitioned into tactical advice for incorporation into relevant NATO doctrinal publications. Furthermore, inspection of optimized configurations may lead to technical requirement specifications for future platforms in terms of sensor range, platform speed, and endurance.

Results

The linear programming framework has been further improved to include a system of systems approach to account for potential performance increases afforded by cooperating platforms. This is an important consideration since there are several scenarios in which overall performance may be improved through inter-platform cooperation. Cooperative system of systems might include active and passive platforms within a multi-static network, or the coherent processing of multiple passive platforms such as bottom nodes. Consequently, the optimization framework must determine whether to deploy platforms individually, or within a cooperating system of systems, while considering endurance and logistics constraints.
Additional work concerned the outputs required from a future ASW mission planning tool to incorporate planning parameters for unmanned platforms. In particular, the tool determines the precise regions where each platform must be deployed along with an optimum recharging/refuelling schedule. Further analysis determines the optimum locations for recharging/refuelling points to minimize the impact of platform time off task on overall system performance.

Future Goals

The current optimization framework has been tested using generic performance parameters for a wide variety of platform and sensor configurations. Future work will leverage the SEAWASP minimum viable product (MVP) software tool to include a range-dependent acoustic model component, providing for more accurate sonar performance assessment.



Visual representation of a heterogeneous network of unmanned platforms conducting ASW operations.

AUTONOMY FOR ANTI-SUBMARINE WARFARE

SUPPORT TO MARCOM IN-STRIDE DEBRIEFING IN SUPPORT OF TRAINING TEAMS

FUNDING BODY: NATO ALLIED MARITIME COMMAND

Overview

NATO Navies plan and execute several large-scale anti-submarine warfare (ASW) exercises requiring significant effort and coordination from multiple maritime assets and personnel. The expense and resource requirements for these exercises are justified by their valuable training benefit. For this reason, Allied Maritime Command (MARCOM) regularly deploys an In-stride Debriefing in support of Training (IDT) team to support each exercise. The IDT provides timely reconstruction and analysis of events during each programmed serial, determining which contacts originated from a submarine target in order to provide valuable insight into actual submarine hunting performance.

For several years, MARCOM has funded CMRE to augment the IDT analysis with more detailed acoustic analyses. Existing acoustic models, such as the Rapid Acoustic Prediction Service (RAPS) and Submarine Environmental Assessment for Wide Area Sonar Prediction (SEA WASP) tools, are leveraged to determine predicted sonar detection ranges as a function of sonar position and depth along with submarine depth and aspect. The reconstruction of actual ship and submarine disposition allows for a sonar ping-by-ping comparison of predicted sonar range versus actual submarine range, providing insight into the periods during which submarine detection should be expected. Further analysis seeks to determine contributing factors towards detection opportunities—including sonar depth, submarine depth, and submarine aspect. The analysis is summarized in a single plot which may be appended to the IDT analysis report and provided to exercise participants shortly following completion of a serial.

Additional analysis is provided to the MARCOM meteorological and oceanographic (METOC) community in the form of maps of various acoustic layer depths. Mixed layer, sonic layer, and channel depths may be determined throughout the exercise area and provided as GeoTiff files for display on MARCOM mapping software. This visualization provides insight into the complexity of the underwater environment and its potential impact on sonar performance. Further analysis determines predicted sonar range throughout the exercise area, which may be transmitted to participants via military signal.

Results

During 2023, CMRE researchers successfully supported MARCOM with IDT acoustic reconstruction and METOC analysis products during three live NATO ASW Exercises: DYNAMIC MANTA, DYNAMIC MONGOOSE, and DYNAMIC MARINER. Feedback from exercise participants demonstrated that the detailed CMRE analysis products were well received.

Future Goals

Statistical trends in real-world ASW performance have been extracted through analysis of several previous exercises. As additional data are added after each individual exercise analysis, the impact on submarine detection range is assessed from both environmental effects and tactical decisions e.g. submarine depth and aspect. Going forward, this work will provide valuable insights into the continuing ASW decision support work under the ACT programme of work (POW).

AUTONOMY FOR ANTI-SUBMARINE WARFARE

METRICS PROJECT

FUNDING BODY: EU COMMISSION

Overview

The Metrological Evaluation and Testing of Robots in International Competitions (METRICS) project organizes physical and virtual challenge-led robotics competitions in four priority research areas: healthcare, inspection and maintenance (I&M), agri-food, and agile production. In order to assess the reliability of the different competing robots in a rigorous and unbiased way, METRICS has been developing an evaluation framework based on metrological principles.
With a breadth and depth of experience in the organization of robotics competitions, CMRE is a key partner in the project. CMRE is responsible for the marine segment of I&M competitions and is tasked with organizing two physical in-presence events at CMRE, as well as two virtual challenges. The physical competitions involve underwater robots challenged with response tasks in a realistic oil and gas emergency scenario.

Results

From 16 – 21 July 2023, CMRE hosted the second Robotics for Asset Maintenance and Inspection (RAMI) Marine Robot competition at the CMRE sea basin. The competition, a European Robotics League event, brought the CMRE once again to the forefront of student marine robotics. Teams of students met at the CMRE and were challenged to deploy autonomous underwater vehicles (AUV) capable of accomplishing complex I&M tasks in a mock, but realistic, oil and gas plant. Autonomous advanced perception and manipulation skills were required to be successful.
More than 30 judges and observers attended the event, from European and US companies, academia and research institutions, including: from Europe, representatives from ROSEN Group, DLR Institute of Robotics and Mechatronics, Fincantieri SpA, and Leonardo SpA; and, from the US, from the Naval Research Laboratory (NRL), Naval Information Warfare Systems Command, and RoboNation Inc. Additionally, the US Office of Naval Research (ONR) generously supported the event. Local schools from the La Spezia area were also involved in the framework of the CMRE's education and outreach programme, and around 20 students close to high school graduation participated and interacted with the teams.

Future Goals

The METRICS project terminated at the end of 2023. However, RAMI23 re-established CMRE as a global leader in marine robotics and ocean science, and such events are fundamental for building and strengthening the international research community, paving the way for future CMRE collaborations. The intent is to continue organizing AUV competitions at CMRE, including designing and proposing applications of interest, such as tasks in scenarios involving the protection of critical undersea infrastructure. In this respect, several sponsors and institutions—e.g. Institute of Electrical and Electronics Engineers (IEEE) Ocean Engineering Society (OES) and US ONR Global—have shown an interest in supporting such events.

> *Participants and Organizing Committee at the RAMI23 award ceremony and banner of the RAMI23 event.*

>> *A student team deploying their vehicle at RAMI23.*

AUTONOMY FOR NAVAL MINE COUNTERMEASURES

AUTONOMY AND INTEROPERABILITY FOR NAVAL MINE WARFARE

FUNDING BODY: NATO ALLIED MARITIME COMMAND

Overview

This project focuses on the automatic, machine-centric processes that composed together build autonomous capabilities. In particular, the project seeks:

- To build knowledge regarding the extraction of information from data using machine learning and artificial intelligence.
- To prototype and exhibit autonomous functions and systems that yield more efficient naval mine warfare (NMW) prosecution capabilities.
- To help the naval mine countermeasures (MCM) and general maritime unmanned systems (MUS) communities define interoperability building blocks that are necessary for building the flexible, robust and scalable autonomous NMW toolboxes of the future.

Moreover, the project exploits this knowledge in relevant NATO exercises and experiments, such as in the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 2023 and DYNAMIC MESSENGER (DYMS) 2023 exercises, where the CMRE Autonomy and Interoperability for NMW (A&I-NMW) toolbox was demonstrated to, and integrated with, industry and operators from the Alliance and Partners.

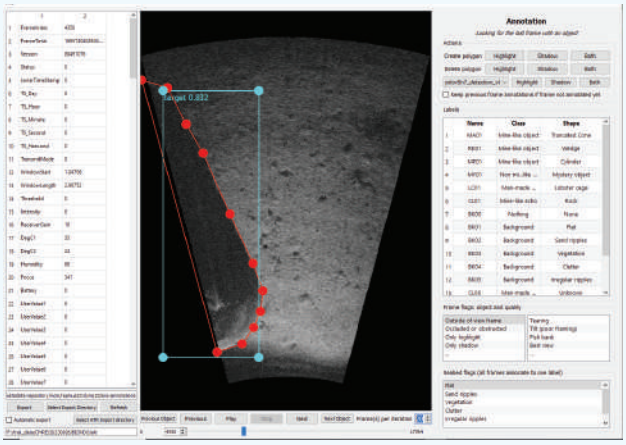
Results

In 2023, an automatic target recognition system (ATR) was designed and trained, specifically looking at the applicability of such strategies during contact identification activities as part of mine clearance missions. This first generation ATR is concerned primarily with the use of short-range, high-resolution multi-beam imaging sonar, a commercial off-the-shelf (COTS) technology that can provide sub-centimetre resolution in some configurations. This ATR has shown good performance using real data, particularly that collected during the REPMUS and DYMS 2023 exercises.
Another important topic in the NMW machine learning toolbox is the derivation of compact target signatures for machine-to-machine teaming. This concept envisions the encoding of compact target signature data independent of specific sensor type to share among unmanned systems, allowing for robust target reacquisition within an autonomous squad of heterogeneous systems.

The interoperability topic for NMW in 2023 has focused on the extensive testing of the Collaborative Autonomous Tasking Layer (CATL), reported in more detail under the MUS Interoperability and Security project in the Maritime Science & Technology Enablers programme.

Future Goals

Future work will refine the concept and implementation of an AI-generated target model and expand this concept to the environment. The expected outputs will inform and guide the target relocalization and reacquisition process. In parallel with this activity, the team will focus on the automatic target identification problem from an algorithmic perspective, and from an autonomous behaviour aspect with the development of through-the-sensor autonomous underwater vehicle (AUV) reactive behaviours. In partnership with the CMRE's Maritime Unmanned Systems Enablers (MUSE) programme, the project team will pursue the development of CATL and its implementation within NATO Standardization Agreement (STANAG) 4718.



An underwater target seen through forward-looking sonar: the image is from an analysis tool developed and used by CMRE researchers to label sonar data for training deep-learning networks

AUTONOMY FOR NAVAL MINE COUNTERMEASURES

NEW SENSING TECHNOLOGIES FOR NAVAL MINE WARFARE

FUNDING BODY: NATO ALLIED MARITIME COMMAND

Overview

As the technology has matured, NATO Navies have started to adopt Autonomous Underwater Vehicles (AUV) to conduct mine countermeasure (MCM) missions. These platforms are often equipped with high frequency sonar sensors such as side-scan sonar (SSS) or synthetic aperture sonar (SAS) providing high-resolution seafloor mapping. However, in complex environments, the detection and classification performance of such high frequency systems decreases drastically, especially for buried or partially buried objects. The scope of this New Sensing Technologies for Naval Mine Warfare (NMW) project is to investigate, develop and assess alternative sensing modalities to overcome the limitations of traditional sensors. One strand of research in particular investigates the use of ultra-wideband SAS to detect, classify and potentially identify mine-like objects in complex seabed environments.

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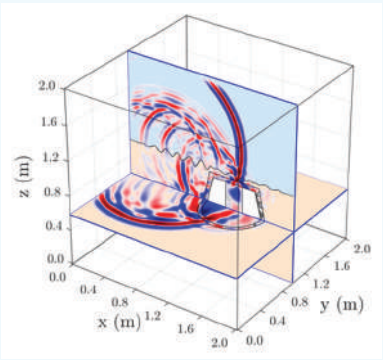
CRV Leonardo during SUNFISH'23 experiment off the coast of Elba



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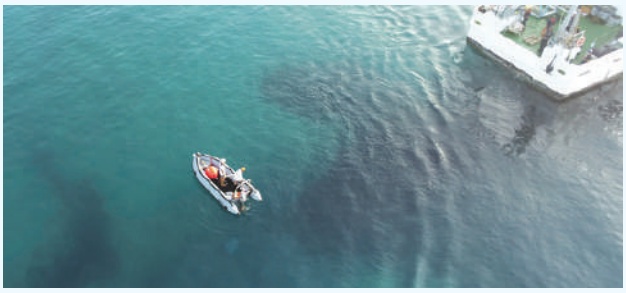
Example of the acoustic response of a target modelled by the 3D viscoelastic wave equation solver



Results

In September 2023, the CMRE project team conducted the SUNFISH'23 experiment off the coast of Elba in the Tuscan Archipelago, where the CMRE's High Resolution Low Frequency Synthetic Aperture Sonar (HRLFSAS) prototype was deployed from the Coastal Research Vessel (CRV) Leonardo to study the impact of complex environments on low-frequency target imaging. Particular focus was directed towards the study of the acoustic behaviour of the sea grass Posidonia and its effect on HRLFSAS performance.
CMRE researchers investigated the benefits of multiple input multiple output (MIMO) SAS systems to support the development of an ultra-wideband SAS (UWSAS) system, which would improve the performance of traditional high-frequency SAS sensors. This work resulted in the development of novel AI-based micro-navigation algorithms.
CMRE researchers developed a 3D viscoelastic wave equation solver model to support the appreciation, understanding and exploitation of low-frequency acoustic responses from prone and buried objects. A staggered finite-difference time domain (FDTD) scheme was adopted to discretize the equations. The intrinsic low-resolution of the scheme, especially close to curvilinear interfaces, was improved with the adoption of a novel nested multi-grid method, where the mesh is locally refined near the interfaces. The synthetic data generated are in excellent agreement with theoretical and analytical benchmark test data.

Future Goals

Future goals include:
The development of a portable UWSAS AUV to demonstrate the advantages of such technology.
Using the wave equation solver model, the generation of a large synthetic target database to train AI-based automatic target recognition (ATR) algorithms.

AUTONOMY FOR NAVAL MINE COUNTERMEASURES

DECISION SUPPORT FOR NAVAL MINE WARFARE

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

Existing NATO mine countermeasures (MCM) planning and evaluation (P&E) tools and doctrine were developed for legacy, crewed minehunting platforms fitted with forward looking sonars. Current generation and future operational minehunting capabilities of the NATO Allies make increasing use of side-looking sensors—such as side-scan sonar (SSS) and synthetic aperture sonar (SAS)—fitted to autonomous underwater vehicles (AUV). The aim of this project is to develop accurate and robust MCM P&E algorithms and procedures for all current and future NATO Naval MCM sonars, with a particular research emphasis placed on implementing organic planning and evaluation capabilities to autonomous platforms in order to enable adaptive behaviour. In 2023, CMRE's MCM staff participated in the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 2023 and DYNAMIC MESSENGER (DYMS) 2023 exercises.

Results

Following a feasibility study in 2022, the project team carried out a further study on the employment of a single hybrid unmanned platform to conduct detection, classification, and identification of naval mine targets in a single minehunting mission. During 2023, the study explored candidate technical solutions for such a platform, including a survey of existing hybrid platforms deployed in NATO (e.g. the NOR HUGIN vehicle) and commercial off-the-shelf (COTS) platforms that could be suitably modified to support the required SAS and identification sensors.

Following a minehunting mission, it is important to evaluate accurately the performance achieved—with a particular focus on determining the risk of undetected mines remaining in the operating area. Previous work in NATO has employed Bayes theory using standard probability measures to determine the most likely number of undetected mines given assumptions on the sonar performance and the number of mine-like contacts (MILCOs) reported. In 2023, CMRE researchers explored the use of an alternative approach termed 'possibility theory' to determine the number of undetected mines. This work has resulted in some promising findings, with more accurate estimates on the number of undetected mines along with better handling of prior assumptions and probability of false alarm.

Finally, CMRE researchers provided analysis support to:

- Teams participating in REPMUS 23 and DYMS 23 exercises.
- Standing NATO Mine Countermeasures Group 2 (SNMCMG2) ships and staffs participating in the ITA MINEX23 exercise.

Future Goals

Employing modern optimization techniques, future work will further refine the planning and evaluation of modern minehunting systems to address all phases of an overall minehunting operation. The possibility theory framework will be extended and applied to the determination of remaining risk to follow-on maritime traffic. A historic analysis of CMRE minehunting performance over previous years will be performed to better understand the impact on planning accuracy of the assumptions made about the characteristics of the probability of target detection against lateral range curve. Such analysis will also seek to quantify the look-to-look dependence of target detection probabilities, allowing for better estimations of coverage and improved planning and evaluation.

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

ASW ENVIRONMENTAL ACOUSTIC SUPPORT IN A RAPIDLY THAWING ARCTIC OCEAN

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

The Arctic Ocean is a fundamental component of the security space in the Euro-Atlantic zone, and the rapid thawing of the Arctic is a major disruptive force for potential conflict. In particular, the re-emergence of Russia's Arctic submarine capability presents a significant threat to the Alliance. New, effective Allied Arctic anti-submarine warfare (ASW) capabilities rely on re-establishing NATO's technological, operational, and strategic advantage in the underwater domain through regenerating knowledge of the Arctic region. The aim of this project is to provide understanding and updated Arctic databases to support sensor design, signal processing, and system configurations for effective NATO ASW operations in the Arctic Ocean, including long-range sonar propagation, and acoustic surveillance and navigation support in icy waters.
CMRE leads an Arctic Joint Research Project involving 14 institutions from eight NATO Nations.

Results

The impact of ice-floe reverberation on sonar-like signals was assessed during the Nordic Recognized Environmental Picture (NREP) 23 trial in the Greenland Sea/Svalbard region in the period 20 June – 11 July 2023, which involved the collaboration of seven institutions from five NATO Nations.
The formation of near surface sound ducts under Arctic leads—large fractures within an expanse of sea ice—was unveiled using high-resolution simulations of Arctic lead dynamics to centimetre scale.
The oceanographic and sea ice dynamics in the Fram Strait was determined with a high-resolution and two-way nested ocean model.
A capability was developed to assess—in tactically useful timescales—sea-ice thickness and bottom roughness using a ground penetrating radar on-board an unmanned aerial system.

Future Goals

Future work will continue to determine and quantify the emergent environmental factors impacting ASW sonar detection ranges in the thawing Arctic.

Remotely operated vehicle under the ice during NREP23.

NATO Research Vessel (NRV) Alliance during the Sea Trial NREP23

Underwater ice keel

^ *Aerial view of an ice-floe inspection*

^^ *CMRE staff at the ice edge during NREP23*

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

CAPABILITIES FOR RAPID ENVIRONMENTAL ASSESSMENT IN BLUE WATERS

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

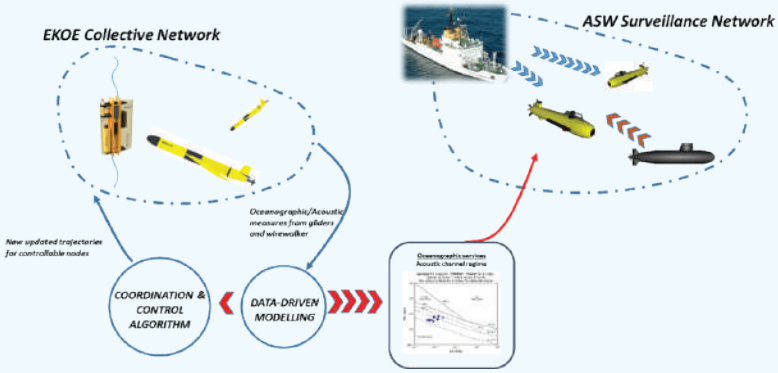
Rapid Environmental Assessment (REA) capabilities provide timely environmental information delivered from on-site sensors and advanced analytics, informing and enhancing Commander's decision-making in order to optimize mission performance. REA in hostile and/or environmentally harsh regions requires autonomous unmanned platforms to carry sensors into areas where it may not be safe nor prudent for manned platforms to operate. Although REA emerged from NATO's post-Cold War orientation towards crisis response operations in littoral waters, the return to deterrence and defence has refocused NATO naval operations back to blue water scenarios, in addition to littoral theatres; however, scaling up littoral REA capabilities to blue water domains remains a technological challenge. This project delivers networking and autonomous capabilities for the timely provision of environmental information to support naval decision making in blue waters.

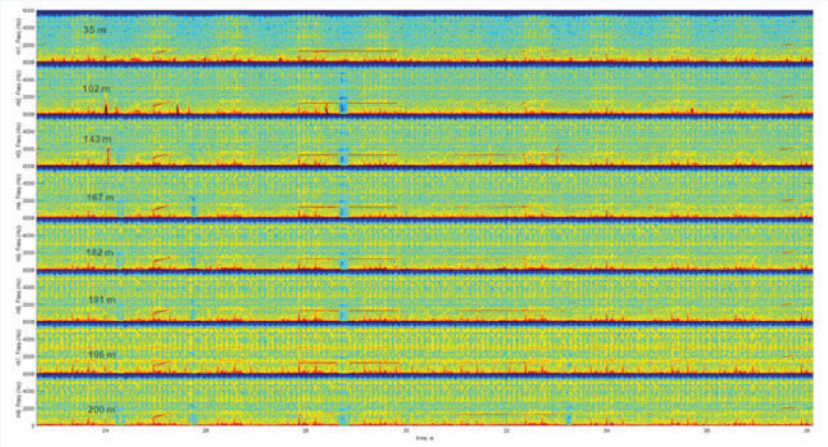
Results

Networking concepts for ocean REA were successfully tested through the deployment of an autonomous network of heterogeneous acoustic sensors during the Nordic Recognized Environmental Picture (NREP) 23 trial in the Greenland Sea/Svalbard region 20 June – 11 July 2023.
To facilitate acoustic monitoring in open waters, a portable and hand-deployable acoustic Slim Vertical Array (p-SLIM) with eight synchronized channels was built, and testing carried out during the NREP23 sea trial. The tests showed some technical issues with the p-SLIM array, the majority of which were successfully addressed by CMRE staff during the NREP23 trial; final technological development of the array was completed by the end of 2023.

Future Goals

To deliver by 2025 a networked and autonomous capability to support the near real-time assessment of sonar performance.





Surface buoy and logarithmic acoustic array p-SLIM.

Schematic of the acoustic environmental network and its integration into the ASW surveillance system.z

Example of dataset collected by the p-SLIM during NREP23; records at different depths of the chirps (inclined red segments) and tones (horizontal red segments) transmitted from the source.

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

DATA KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

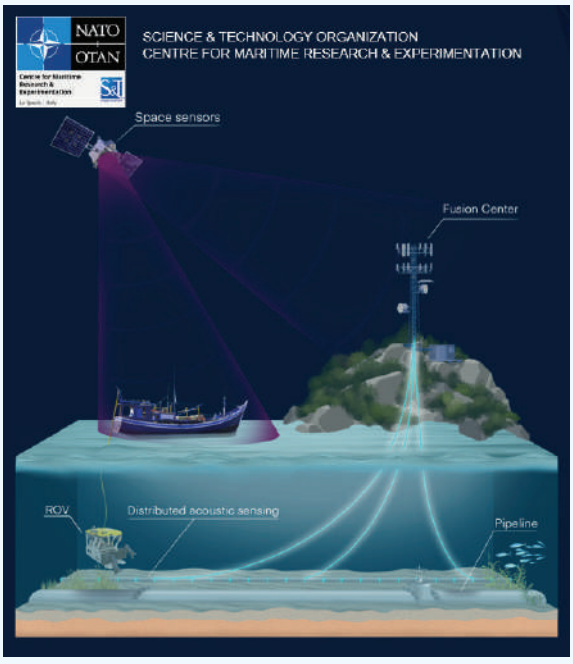
Overview

In November 2023, NATO Secretary General Jens Stoltenberg participated in a meeting with EU Defence Ministers to discuss the protection of Critical Undersea Infrastructure (CUI). Recalling the sabotage to the Nord Stream pipelines in 2022, followed by the damage of the Balticconnector gas pipeline in October 2023, the Secretary General stressed the vulnerability of CUI and the existence of real threats, highlighting the urgent need to improve the resilience of CUI.

The research activities of the Data Knowledge and Operational Effectiveness (DKOE) project aim at enhancing the Alliance's multi-domain seabed-to-space situational awareness (S3A) by developing strategies to process and combine extensive volumes of information, generated by a variety of sources that are used to monitor the very large number of at-sea platforms. Such strategies are based on artificial intelligence and information fusion (AI2F) techniques, which have significant potential to anticipate future behaviours, identify threats, and pinpoint critical situations.

During 2023, CMRE DKOE researchers maintained and strengthened scientific collaborations with several universities and research institutions from NATO Nations, including: the University of Connecticut (USA); the Massachusetts Institute of Technology (USA); the University of the Aegean (GRC); the Norwegian University of Science and Technology (NOR); the University of Florence (ITA); the University of Calabria (ITA); the University of Naples "Federico II" (ITA); the Italian National Research Council (ITA); and, the Polytechnic University of Milan (ITA).

A multi-domain approach to monitoring and protecting CUIs



Results

- Development of novel information fusion techniques for S3A, trajectory classification methodologies for anomaly detection, and graph database approaches for maritime events. Such tools enable the efficient analysis of surface vessel traffic in close proximity to CUIs, and were applied to produce situational assessment after relevant incidents to CUI in 2023, e.g., the damage of the Balticconnector gas pipeline.
- Validation of the mathematical framework that supports the performance prediction of machine-learning classification techniques. The capability of the proposed framework to predict the performance of binary classifiers has been demonstrated using two different datasets: the Modified National Institute of Standards and Technology (MNIST) database, a reference dataset in the machine-learning community; and, a synthetic dataset of extended targets.
- Development of a model-based deep-learning architecture of limited complexity for the long-term prediction of manoeuvring targets. The adopted approach combines mathematical models with data-driven methods to leverage the advantages of both techniques. The system harnesses partial domain knowledge through mathematical modelling and pertinent historical datasets.

Future Goals

Future activity will focus on the further theoretical and methodological advancement of AI2F techniques for S3A, and their application to the problem of monitoring and detecting threats to CUI. The impact and operational relevance of merging multiple sources of information—including electronic intelligence (ELINT) data for maritime surveillance—will be assessed.

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

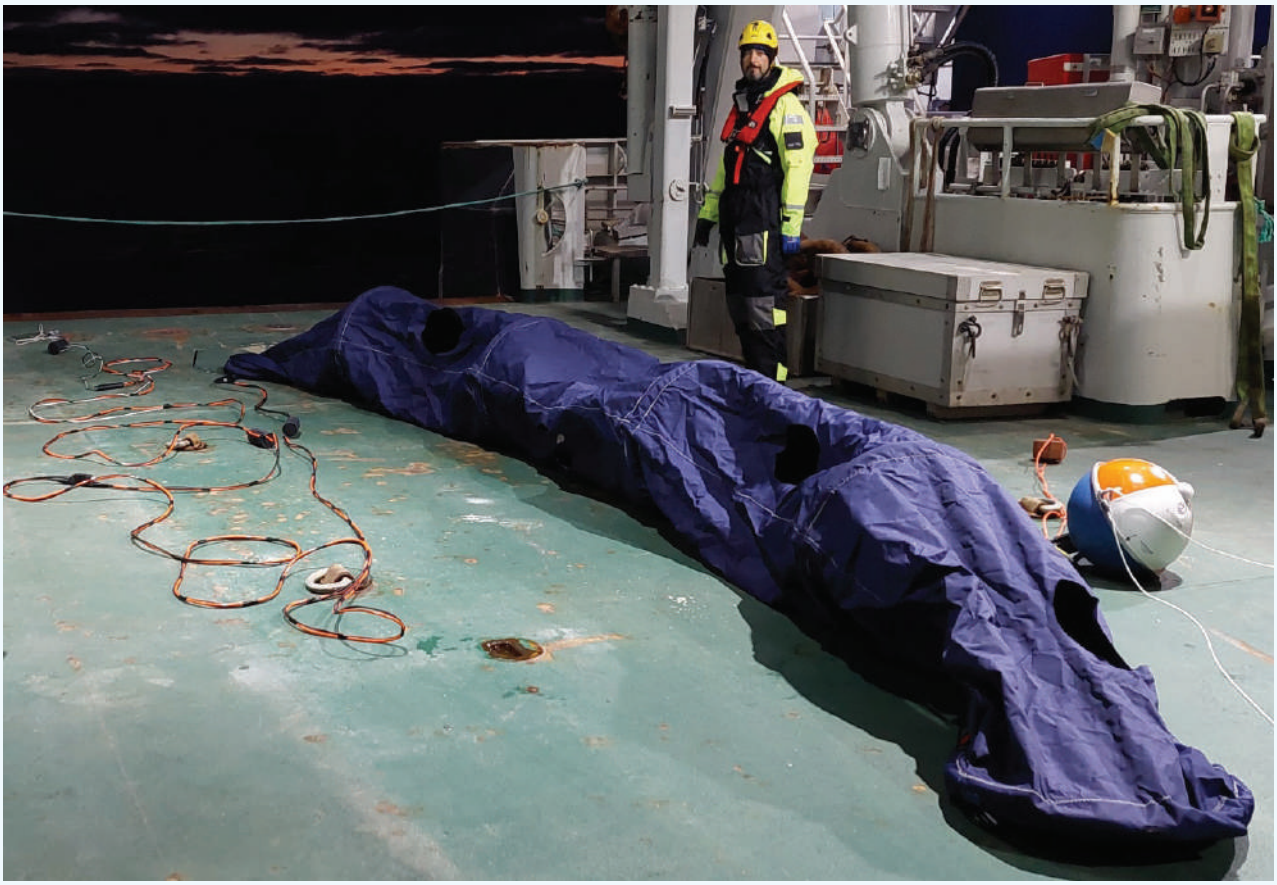
AMBIENT NOISE CHARACTERIZATION USING LAGRANGIAN PLATFORMS

FUNDING BODY: US OFFICE OF NAVAL RESEARCH

Overview

Underwater noise is a central topic in underwater acoustics and acoustic oceanography. It is mainly generated by natural sources—rain, wind, waves, earthquakes, marine mammals, thermal motion, etc.—but can also contain a significant anthropogenic component. For example, ships, sonars, drilling and dredging equipment and seismic air cannons are all sources of noise that contribute locally to anthropogenic environmental noise. Monitoring the characteristics of ambient noise such as level and directionality is important to understand how noise affects marine mammal behaviour and to increase the effectiveness of military underwater warfare operations.

Free drifting (Lagrangian) platforms such as surface drifters and profiling floats are inexpensive and easy-to-deploy instruments that are widely used to collect oceanographic data in large ocean basins. The Ambient Noise Characterization using Lagrangian Platforms (ANOCLAP) project, a three-year (2021–2024) project funded by the US Office of Naval Research (ONR), aims to develop a network of acoustic Lagrangian platforms for the rapid monitoring of ambient noise and measurement of sound velocity profiles, with specific applications for the complex and rapidly changing ice-free sub-Arctic regions. CMRE acoustic drifters and floats will be integrated into an in-situ network, together with other platforms such as gliders and research vessels. The sensing network will be spatially, temporally and functionally distributed, and complemented by improved numerical modelling and remote sensing in order to assess environmental conditions in confined or restricted blue waters in a timely and covert manner. The data collected will support advanced analysis to inform naval decision making by NATO Standing Naval Forces and Navies, especially for anti-submarine warfare (ASW) and underwater communication applications.



Results

Acoustic sensors, single hydrophones and directional compact arrays, have been attached to commercially available surface drifters and profiling floats. Electronics and software were developed to store and process the acoustic data on board and to transmit reduced data sets of anomalous signals and statistical information on ambient noise in real time via satellite. The buoyancy and diving capabilities of the modified Lagrangian instruments were also adapted and optimized in direct collaboration with the commercial manufacturers.

The acoustic drifters and floats were deployed during the Northern Ocean Rapid Surface Evolution (NORSE) sea trials in the Nordic seas. In addition to ambient noise measurements, the drifters were also used to measure acoustic signals at low (<1.5 kHz) and medium frequencies (8–15 KHz) emitted by various sources.

After several hardware and software improvements compared with the prototype used in 2022, a profiling float was successfully deployed during the 2023 NORSE trial to collect oceanographic and acoustic data as deep as 300 m in the water column. The instrument was programmed to collect temperature and salinity data during descent, and directional acoustic data during ascent, when self-noise from valves and pumps is reduced.

Future Goals

The acoustic data collected by the CMRE acoustic drifters and floats in the Nordic seas during 2022 and 2023 will be further analysed in collaboration with NORSE partners to describe the 3D soundscape in the open Nordic seas under strong and rapidly evolving atmospheric forcing.

A CMRE acoustic drifter with array of hydrophones (left), holey-sock drogue (middle) and surface buoy (right) ready to be deployed

Deployment of the CMRE acoustic float equipped with temperature and conductivity (salinity) sensors (on top), and the compact volumetric acoustic sensor (cVAS) with own battery pack (at the bottom).

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

PROMENADE

FUNDING BODY: EU COMMISSION

Overview

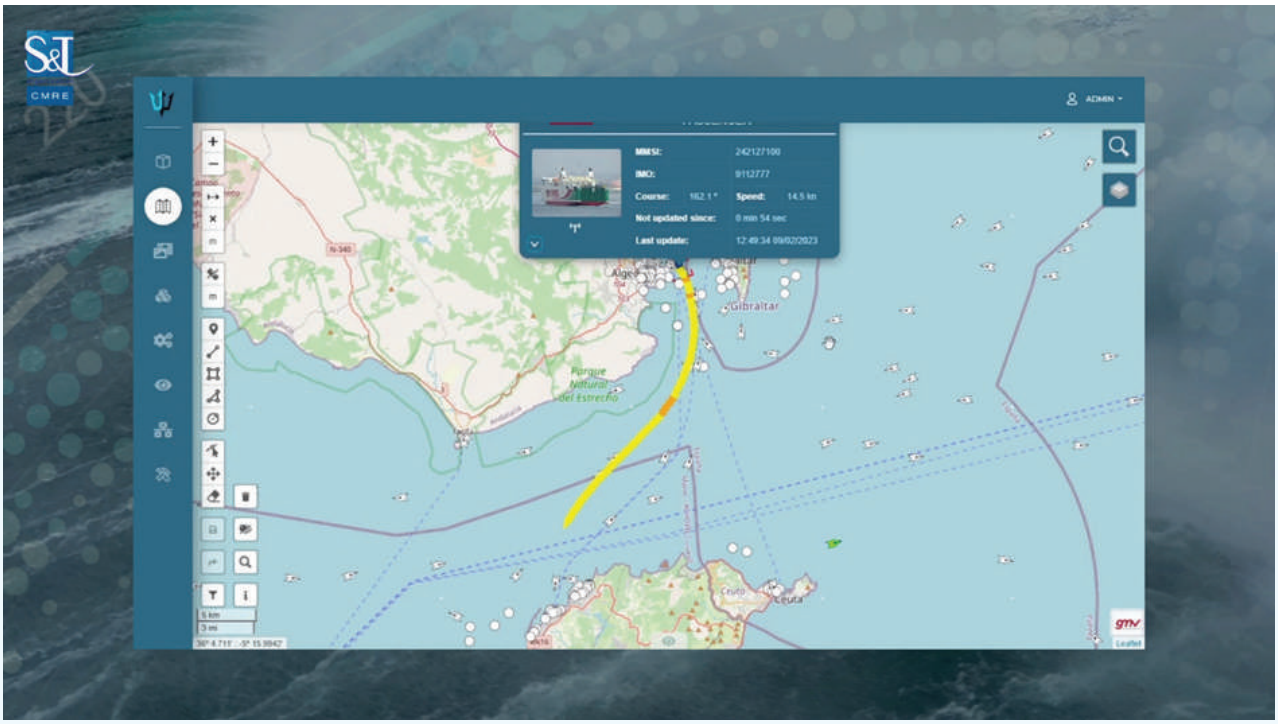
The numerous vessels traversing European waters on a daily basis produce copious amounts of monitoring data through various surveillance systems. Enabling the exchange of this diverse data among decision-makers while avoiding data overload is a significant challenge in attaining effective maritime situational awareness (MSA), and neglecting this aspect may result in errors or misinterpretations of maritime activities.

At the same time, the abundance of maritime data presents substantial opportunities for leveraging Artificial Intelligence (AI) techniques to enhance surveillance and MSA. A key task involves automatically deriving actionable insights from extensive surveillance data. For instance, extracting motion patterns in space and time that can be fed into deep neural networks enables the prediction of vessel trajectories, thereby facilitating MSA.

Running from October 2021 to March 2023 and supported by the EU Horizon 2020 research and innovation programme, the PROMENADE (Improved Maritime Awareness by Means of AI and Big Data Methods) project aimed to facilitate collaborative information exchange among maritime surveillance authorities. Its objective was to enhance maritime vessel tracking, behaviour analysis, and anomaly detection through the application of AI and big data technologies. As part of PROMENADE, CMRE was tasked with designing, implementing, and demonstrating an AI-driven prediction algorithm in real operational scenarios. This algorithm utilized extensive historical data to learn recurring traffic patterns, enabling it to forecast vessel trajectories based on real-time vessel positions.

Results

- Within the PROMENADE project, researchers at CMRE developed, validated and tested in multiple relevant operational scenarios a framework for learning and predicting vessel trajectories. This framework can forecast the future course of a vessel by analysing positional data in real time. It comprises three primary components: a training module, an inference module, and a user interface. These components together create PROMENADE's Advanced Ship Prediction Service, which is able to provide a precise estimation of a vessel's future path, even in presence of complex motion patterns.
- The inference module of the Advanced Ship Prediction Service is a Docker-based micro-service that incorporates the trained model produced by the training component. It receives prediction requests from clients and generates corresponding prediction responses. This component



is fully compliant with the Common Information Sharing Environment (CISE) data model established by the EU, allowing it to exchange data with legacy maritime data systems, services, and processes.

- In 2023, the Advanced Ship Prediction service was successfully demonstrated in all three PROMENADE live trials: the Iberian trial in the Strait of Gibraltar; the Baltic trial in the Baltic Sea; and, the Hellenic trial in the Ionian Sea. In all three demonstrations, the operational scenarios were run with the involvement of real vessels and actors, both in the field and in the control centre. Surveillance data were acquired from different sensors in real-time, and operator alerts successfully generated.

Demonstration of the CMRE-developed Advanced Ship Prediction Service during the Iberian operational trial, 07–09 February 2023

Photos from PROMENADE's Iberian operational trial, performed with real vessels in Almeria (top) and coordinated in real time from Madrid (bottom), 07–09 February 2023

Future Goals

This project ended in 2023

DATA AND ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

LESSONS LEARNED ONTOLOGY DATASET

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION JOINT ANALYSIS AND LESSONS LEARNED CENTRE

Overview

CMRE researches, funded by the NATO Joint Analysis and Lessons Learned Centre (JALLC), have been investigating the application of natural language processing models to facilitate the extraction of lessons from unstructured text data.

The mission of the JALLC is to support the Alliance-wide implementation and sustainment of NATO's Lessons Learned (LL) policy through monitoring and supervising the NATO LL Process within the NATO Command Structure and other NATO bodies. The JALLC is NATO's lead agent for the collection and sharing of lessons, accomplished through management of the NATO LL Portal, and as such the JALLC is investigating potential approaches for automating modelling and reasoning of LL using modern Artificial Intelligence (AI) solutions. In particular, processes for the extraction, assessment, and querying of LL from unstructured text data are complex challenges with significant implications for organizational learning and research, and traditional methods have been resource intensive and often fail to deliver optimal results. However, recent advancements in the field of natural language processing, particularly Large Language Models (LLM), have shown promise in automating and improving these processes.

The advent of open-source LLMs, such as Meta's Large Language Model Meta AI (LLaMa), makes it possible to apply this technology to more sensitive information in classified environments. In order to facilitate this usage, CMRE researchers have investigated its applicability to two difficult tasks: the automated extraction of lessons from text; and, automated assessment of their quality.

Results

- An automated lesson extraction pipeline has been proposed which has shown promising initial results. It performed particularly well in cases where the text contained a single LL, and has demonstrated significant potential in more complex cases. The limitation is that this is a stochastic process, and good results are mixed with weaker ones, which is partially addressed through automated LL scoring.
- A procedure for automated LL scoring has been developed, exploiting the stochastic behaviour of LLMs to obtain a sum of evidence 'for' or 'against' a particular LL being of high or low quality. An LL can be assessed against several criteria. Primarily, at this stage of research, CMRE researchers focused on addressing to what extent a LL adheres to the NATO standard Observation - Discussion - Conclusion - Recommendation (ODCR) format adopted by NATO. As this is a question about the language itself, assessing whether a particular passage satisfies some semantic conditions—e.g. "is the following a succinct, objective observation?"—LLMs are particularly well suited to this task.
- A pipeline for synthetic generation of unstructured reports has been developed and run in tandem with the automated lesson extraction pipeline, which generated a large 10000-elements dataset of synthetic LL. Furthermore, an exploratory investigation has been undertaken for querying lessons learned using current open-source solutions implementing the Retrieval-Augmented Generation method, showing promising results.

Future Goals

During the execution of this project, emphasis has been placed on identifying the most promising avenues for further research. Lesson extraction could likely be improved by fine-tuning an appropriate model and using a multi-step extraction process. Moreover, for the cases when multiple lessons learned can be extracted from the same text, further research into appropriate fusion mechanisms is required.

In the area of the automated assessment of LLs, future areas of work include improved prompting—similar to Chain-of-Thought or Graph-of-Thought techniques—using a Mixture of Experts approach and fine-tuning the assessment model along with explainability analysis through curated datasets.

MARITIME UNMANNED SYSTEMS ENABLERS

MUS INTEROPERABILITY AND SECURITY

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

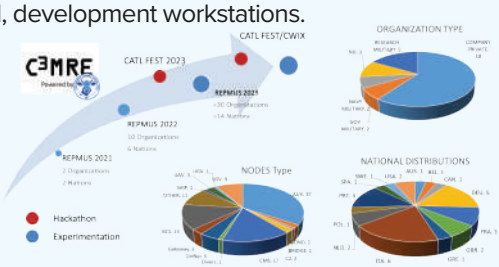
As NATO Nations initiate procurement and integration of unmanned systems in air, land and maritime domains, the proliferation of platform-specific command and control (C2) systems highlights issues related to connecting all these systems together and securely in order to ensure 'day zero' interoperability of NATO forces.

In this context, this project's prime focus is on the command, control and communications (C3) infrastructure to enable force interoperability at all command levels for maritime unmanned systems. NATO Standardization Agreement (STANAG) 4817 is the relevant NATO standardization effort, and CMRE staff are playing an increasingly important role within the STANAG 4817 Custodian Support Team (CST), as part of the command team and for integrating CMRE interoperability studies regarding a federated coalition of autonomous assets. The Cooperative Autonomy Tasking Layer (CATL), produced by the participation of CMRE researchers on the NATO STO Systems Concepts and Integration (SCI) 343 Research Task Group (RTG) 'Enabling Federated, Collaborative Autonomy', is fundamental to the development of STANAG 4817. The CATL is a data model and set of messaging approaches that allow the interoperable exchange of status, target and C2 cues among unmanned systems and their C2 systems.

From this conceptual development, CMRE has produced the Command Control and Communications for Maritime Robotic Exploitation (C3MRE) infrastructure, which implements CATL and STANAG 4817 standards.

Results

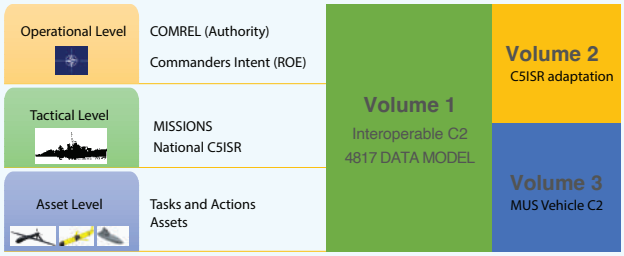
- A refined CATL model was developed within the framework of the SCI-343 RTG.
- CMRE staff promoted CATL within the STANAG 4817 CST and assisted with the development of the STANAG's organizational scope.
- An updated version of C3MRE has been implemented and was made available in March 2023 to partners to start interoperability testing activities. The first event was the CATL Interoperability Festival in April, but the availability of C3MRE continued throughout the whole year. The main milestones in 2023 were the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 23 experiment organized by the PRT Navy and the NATO Maritime Unmanned Systems Initiative (MUSI), and Exercise DYNAMIC MESSENGER (DYMS) 2023.
- C3MRE and associated services were deployed at REPMUS 23 and DYMS 2023 enabling 30 organizations from 15 nations to achieve a common operational picture and share tasking of their assets.
- C3MRE connected together more than 100 nodes (assets) registered on the network. These included: unmanned vehicles from the different NATO-recognized domains—maritime autonomous underwater vehicles (AUV) and unmanned surface vehicles (USV), land unmanned ground vehicles (UGV), and air unmanned aerial vehicles (UAV); oceanographic equipment—gateway buoys, drifters, bottom nodes; ships; divers; C2 systems such as ground control stations (GCS) and combat management systems (CMS); and, development workstations.



Evolution of C3MRE users and nodes over the last three years

Future Goals

- In 2024, CMRE researchers will continue to focus research on C2 for multi-domain autonomous vehicles within the STANAG 4817 CST, with the ambition to publish an initial draft for testing at the scheduled REPMUS 24 exercise. In parallel, CMRE will focus on more advanced aspects of the coordination of highly autonomous systems with the ambition of integration into future STANAG 4817 releases.
- In addition, CMRE staff will continue to support NATO interoperability and standardization activities for autonomous vehicles by investigating tools and methods to analyse and design an acceptable level of security for autonomous vehicles in the context of collaborative missions and operations.



Organizational Scope for STANAG 4817 Main Volumes

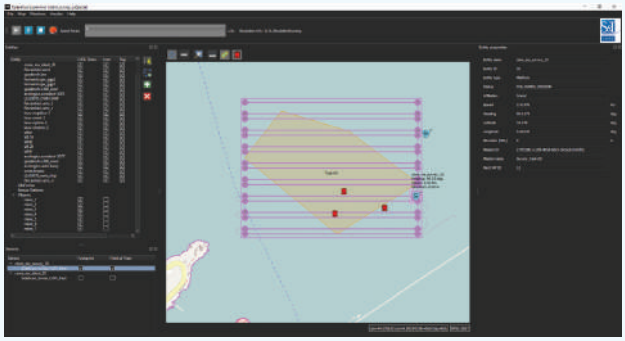
MARITIME UNMANNED SYSTEMS ENABLERS

MODELLING AND SIMULATION FOR EXPERIMENTATION, DIGITAL TWINS AND AUGMENTED/VIRTUAL TRIALS

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

This project is part of a multi-year effort to perform research on the adoption of modelling and simulation (M&S) as a methodology to support the investigation of novel operational concepts and the testing of innovative technologies—concerning maritime autonomous systems in particular—in a safe-to-fail environment. Since 2014, CMRE researchers have developed and federated simulators to run distributed experiments and tests.

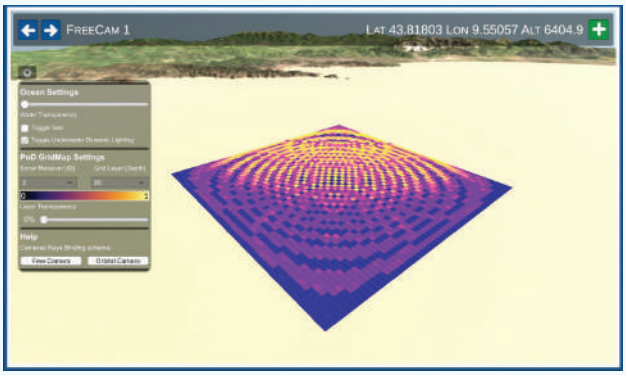


Results

During 2023, an extended version of a digital twin of the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 2023 exercise was delivered. By leveraging the Collaborative Autonomy Tasking Layer (CATL) architecture, a higher level of interconnectivity with the command and control (C2) environment adopted for the exercise was achieved compared with the 2022 prototype: the digital twin was available for interoperability testing by exercise attendees. A set of detailed tests were performed with the Italian Navy and Fincantieri SpA and Leonardo SpA, the industrial partners involved with a Combat Management System (CMS) deployed for REPMUS 23. The figures show the same scenario in the real and digital environment.

Future Goals

Future activities will consolidate the federated simulation capability and further investigate digital twins for the underwater domain, with an objective for 2024 to start an analysis on the impact and the applications of digital twins to support maritime operations on board Navy vessels. The intent is to inform decision-making using advanced simulation and visualization techniques, and to provide interoperability between the real C2 systems and the simulated digital environment; for example, the figure shows a representation in the 3D environment of a sensor's probability of target detection.



Real-life CMS screen, simulated vehicle in blue and simulated detection in red

M&S Operative Supervisor displaying simulated vehicle (blue) and detection (red)

3D view of probability of target detection maps

MARITIME UNMANNED SYSTEMS ENABLERS

UNDERWATER COMMUNICATIONS AND NETWORKS

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

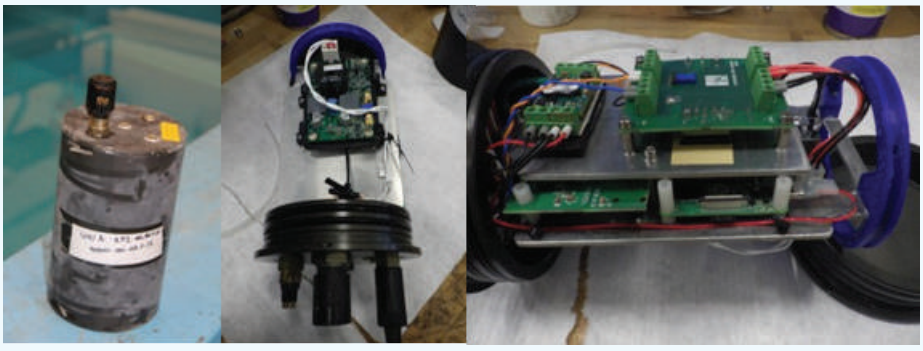
The Underwater Communications and Networks (UWNET) project aims to provide leading edge underwater communications science and technology for the benefit of NATO and the Allies, and to support other CMRE programmes.
The project's key ambitions include conducting relevant research in the field of underwater communications, spawning collaborative efforts to the benefit of NATO and the Nations, and promoting interoperability and standardization of military underwater communications within NATO as a fundamental enabler for the development of multi-national missions with heterogeneous autonomous assets. CMRE is well positioned within the international academic community and is recognized as a leading contributor to research on underwater communications. NATO entities and the maritime operational community are also involved in defining the problem set on which new developments are expected to bring innovative solutions for effective and reliable underwater communications.
The project includes a line of research on underwater quantum key distribution (QKD). Free space QKD—underwater or in the atmosphere, e.g. between two ships—and quantum positioning, navigation, and timing (PNT) are expected to provide the first practical benefits to NATO maritime operations, owing to the ongoing efforts to bring such technology from the laboratory to the sea.

Results

n 2023, CMRE further developed its underwater cognitive modem that now includes a fully capable transmitter module and enables adaptive communications that change waveform in response to the prevailing acoustic environmental conditions.
CMRE, in collaboration with the Nations, delivered a revised version of the CMRE-developed JANUS underwater communications standard, now including additional frequency bands and other minor adjustments.
To promote the interoperability of maritime systems in support of Allied operations, an 'Interoperability Festival' was organized at CMRE during the month of May where usage of JANUS by different equipment providers was addressed. Five institutions/industrial partners from three different Nations exercised JANUS interoperability with the objective of maturing their capabilities. Capitalizing on this activity, the CMRE team actively cooperated with the PRT Navy to explore the usage and integration of new technologies during the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 2023 exercise. Serials dedicated to submarine escape and rescue activities were planned and successfully executed, with an industrial partner deploying the underwater communication equipment implementing the JANUS standard. Submarine escape and rescue can now benefit from standardized digital underwater communications that lead to more automated and faster procedures, saving lives.
CMRE made substantial progress towards solving / simplifying the problem of underwater optical alignment, crucial to achieve an effective employment of the underwater QKD developed in the recent years.

Future Goals

Future research will focus on establishing secure, adaptive and interoperable underwater communications capabilities based on state-of-the-art science and technology. A new series of activities on underwater quantum navigation will kick-off in 2024.



< *CMRE's software-defined cognitive modem*

MARITIME UNMANNED SYSTEMS ENABLERS

ADVANCED QUANTUM TECHNOLOGIES

FUNDING BODY: NATO SCIENCE AND TECHNOLOGY ORGANIZATION AND NATO ALLIED COMMAND TRANSFORMATION

Overview

Next-generation quantum technologies (QT) are among the most nascent and variable technological developments of the 21st century. Consequently, NATO has identified QT as a key emerging technology, whose potential applications might deliver substantial scientific and technological benefits to NATO and the Alliance, but may also cause significant disruption to defence and security, as well as having political and societal impacts. The implications of QT for defence are extensive and include important applications in the fields of computing, communication, sensing and navigation. QT applications within these three fields will have an impact on all NATO military capabilities, and the outcomes of the CMRE's QT Programme will contribute to maintaining NATO's technological edge in responding to the defence and security needs of the Alliance.

CMRE is able to provide a fundamental and unique contribution to the application of QT in the maritime domain, particularly with respect to underwater warfare operations, owing not only to the staff's exceptional expertise in the maritime/underwater domain, but also to the number of highly specialized assets and equipment the CMRE can operate at sea. As a consequence, a significant number of stakeholders from industry and academia are willing to collaborate with CMRE on QT.

Results

In 2023, CMRE staff developed a forward-looking strategy outlining a multi-year plan for the CMRE to become a world-class maritime QT research facility by developing a centre of QT expertise, building research partnerships, conducting technology demonstrations, and exploring key enabling technologies and concepts.

The Quantum Science and Technology Workshop held in Turin, ITA 12 – 15 June 2023 successfully contributed to defining the CMRE QT research programme, and extended the network of industrial partners and academia interested in collaborating with the CMRE in QT research activities.

The CMRE Quantum Lab was founded to carry out experimental research activities in QT. It grew significantly throughout 2023, with new activities and experiments being designed and prepared for execution during 2024.

Future Goals

The strategic end-state for CMRE is to deliver a world-class maritime QT research programme, well connected with governmental, industrial and academic partners, delivering quantum-enabled capabilities aligned with NATO 2030 and STO objectives. In 2024, CMRE will conduct experimental activities, both in the laboratory and at sea, mainly in the field of quantum communications.

Dr. Bryan Wells, NATO Chief Scientist, opening the CMRE Quantum Science and Technology Workshop, Turin, Italy, 13 June 2023

Quantum science and technology workshop. Day-1: Keynote speech by Prof Jan Thomsen, Niels Bohr Institute: 'High Tech Opportunities and Risks'

MARITIME UNMANNED SYSTEMS ENABLERS

MODELLING AND SIMULATION SUPPORT TO INNOVATION HUB

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

This project supports the NATO Allied Command Transformation (ACT) Innovation Hub in developing and operating its synthetic environment for testing and assessment of innovative solutions. Over a multi-year campaign that started in 2019, the implemented synthetic environment has proven its operational value for testing hypothesis and solutions in the maritime domain.
During 2023, activities focussed on designing and developing a disruptive technology experiment (DTEX) to include other domains, such as land, air, space and cyber, to support NATO's ambition to plan and execute integrated multi-domain operations (MDO). The objectives of this MDO DTEX are:

- Explore the individual effects and interaction effects of military and non-military activities.
- Investigate the impact of using emerging and disruptive technologies in the MDO context.
- Provide a forum and an adaptable and safe-to-fail framework to investigate and discuss alternative approaches to address MDO scenarios in NATO.

Starting from the NATO working definition of the MDO concept, the CMRE modelling and simulation (M&S) team together with researchers from the Massachusetts Institute of Technology are designing a computer-assisted wargaming environment to experiment on the concept of MDO. Furthermore, the project team is working on the design and implementation of a scenario involving the interplay of politics, economics, military strategy and human psychology.

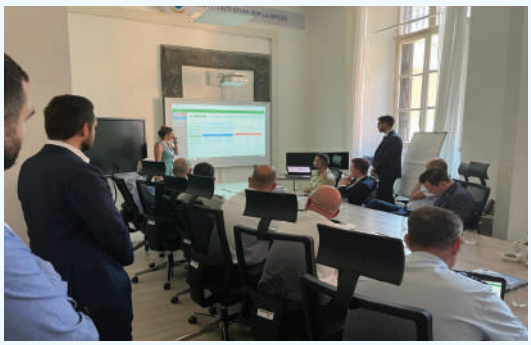
Results

The project team attended the Wargaming Initiative for NATO (WIN) event organized by the Italian MoD in Rome at the end of June 2023. During WIN23, the team showcased the first version of MDO wargame.
The project team organized three test and demonstration events at the Virginia Military Institute (VMI); these sessions with the students provided a valuable framework to test the developments and design of the wargaming environment and scenario.
In December 2023, the project team conducted demonstrations of the MDO DTEX to: participants at the Alliance Warfare Development Conference at HQ SACT, when very valuable feedback was received for future developments; and to the staff and students at NATO Defense College Rome.

Future Goals

The data and insights collected in future executions of the experiment will be analysed to assess the alignment of the decisions taken by the players with the four NATO MDO guiding principles: agility, interconnectivity, unity and creativity. This assessment aims at informing NATO and Nations on future steps for the implementation of the NATO MDO concept.

Wargaming Initiative for NATO 2023 (WIN23) event



MARITIME UNMANNED SYSTEMS ENABLERS

VIRTUAL/AUGMENTED REALITY FOR SITUATIONAL AWARENESS IN HARBOUR PROTECTION

FUNDING BODY: NATO HQ INTERNATIONAL STAFF EMERGING SECURITY CHALLENGES DIVISION - DEFENCE AGAINST TERRORISM PROGRAMME OF WORK

Overview

This project focuses on the design and development of a virtual reality framework for improving the situational and spatial awareness of divers during underwater operations. The prototype tool immerses the user in a full and interactive operational picture of a mission area, thereby supporting the decision-making process. Application areas include underwater explosive ordnance disposal (EOD) and counter improvised explosive device (C-IED) operations, harbour clearing, and critical undersea infrastructure protection.

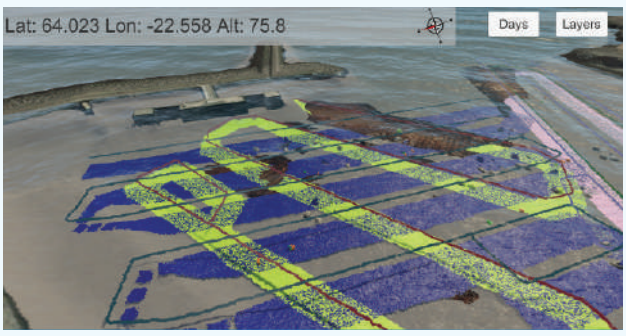
Results

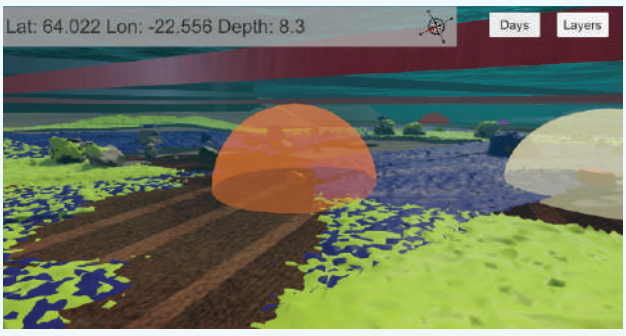
In 2023, the prototype virtual environment was presented to the operational community through the participation of CMRE researchers in different events organized by NATO and the Nations including the annual Icelandic Coastguard-led EOD Exercise NORTHERN CHALLENGE in October 2023, and the Technical Exploitation in Water Environments Seminar and Trials organized by the NATO C-IED Centre of Excellence in November 2023.

Future Goals

The objective for next year is to test and validate the operational value and utility of the prototype solutions in live exercises, supporting operators through the whole mission, from planning, through execution, to post-mission analysis. The project team will focus efforts on improving the usability of the tool to facilitate the injection of real data collected in-situ from real sources following defined military standards. In 2024, there are two larger exercises in which the improved prototype virtual environment will be used to support operators in pre-mission and post-mission analysis: OLIVES NOIRES 2024 in the south of France; and, NORTHERN CHALLENGE 24 in Iceland. In addition, the virtual reality capability will be integrated within the NATO Modelling and Simulation (M&S) Federation.

Two examples of the immersive M&S environment with a collection of different types of data—trajectories of autonomous vehicles, reconstructed meshes, side-scan sonar images, and detections with location uncertainty. On the left, an overview of the operating area, and on the right, a lower-level picture.





MARITIME UNMANNED SYSTEMS ENABLERS

COMPLEX HOLISTIC OUTLINE BASED INTEROPERABLE NETWORK (CHOBIN) FOR UNDERWATER SIMULATION

FUNDING BODY: ITALIAN MINISTRY OF DEFENCE

Overview

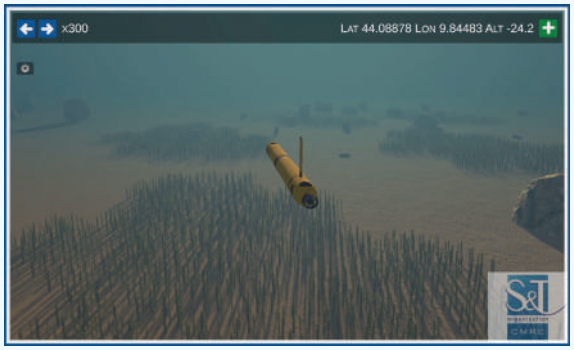
The CHOBIN project will deliver a distributed modelling and simulation (M&S) Digital Twin capability to the ITA Navy Centro di Supporto e Sperimentazione Navale (CSSN) to support the design, development and testing of autonomous maritime technologies. Additional use cases envisioned by the ITA Navy include war-gaming, training and support to planning. CHOBIN will support multi-domain operations, from sea bottom to air, with an emphasis on underwater warfare.
Thanks to the dedication and cooperation of the CSSN customers, the CMRE project team has made excellent progress and maximum shared value is being created through successful collaboration on scientific journal publications and the implementation of a network of CHOBIN stakeholders within the ITA Navy, academia and industrial partners.

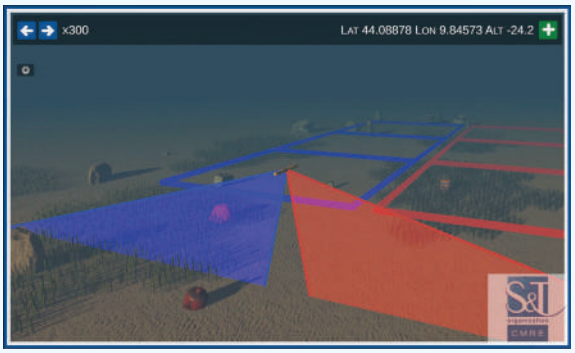
Results

In 2023, the CMRE M&S Team refined the conceptual models drafted in the feasibility study during Phase 1, and carried out the design, development, test and integration of the simulation environment. The ITA Navy and CMRE personnel conducted preliminary executions of the first prototype of the simulation environment in order to complete pre-delivery validation, verification and accreditation.
A first prototype of a digital twin based on the CHOBIN demonstrator was demonstrated with ITA Navy real and digital assets.

Future Goals

In 2024, the CMRE M&S team will deliver the CHOBIN prototype capability to the Italian Navy. As part of this effort, the following aspects will be developed and enhanced: real-time mission key performance indicator (KPI) computation and performance assessment; simulation of collision avoidance scenarios; further improvements on the user interfaces; and, completion of the robotics interoperability interface.
In addition, the CMRE M&S team will support Italian Navy staff during experiments in national and NATO exercises, in expanding the operational community of interest, and in collecting requirements for future CHOBIN iterations.





The digital version of a CSSN autonomous system (mod. X300)

The simulated X300 exploring the sea floor of a harbour with a representation of the coverage of a side-scan sonar.

A verification and validation session

OPERATIONAL EXPERIMENTATION

INTEROPERABILITY TECHNICAL DEMONSTRATION IN EXERCISES

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

In 2023, NATO Allied Command Transformation (ACT) funded CMRE to participate in the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 23 and DYNAMIC MESSENGER (DYMS) 23 exercises. The aims were to demonstrate: firstly, higher technology readiness level (TRL) capabilities for command and control (C2) interoperability in naval mine warfare; and, secondly, collaborative autonomy using prototype CMRE maritime unmanned systems (MUS).

REPMUS23 was the fourth edition of the Portuguese exercise, bringing together 14 nations and seven NATO bodies, industry and academia to test and evaluate MUS. REPMUS23 was immediately followed by Allied Maritime Command (MARCOM) and ACT's DYMS23 exercise, taking the highest TRL MUS capabilities and deploying them into operationally relevant vignettes.

The common architecture, world model and message sets to enable interoperability, collaboration and devolved C2 for MUS is provided by the Collaborative Autonomy Tasking Layer (CATL), developed under CMRE co-leadership in the NATO Science and Technology Organization (STO) Systems Concepts and Integration (SCI) Research Task Group (RTG) 343 'Enabling Federated, Collaborative Autonomy'.

Results

For the 2023 edition, the CMRE Autonomy for Naval Mine Countermeasures (ANMCM) team deployed its CATL-compliant BIONDo autonomous underwater vehicle (AUV) equipped with a 900 kHz forward looking sonar/acoustic camera. Other underwater unmanned vehicles with mine-search capabilities participating in the exercises tasked BIONDo to investigate detected contacts deemed as having minelike characteristics. BIONDo autonomously accepted these tasks and successfully reacquired and positively identified the contacts, demonstrating how heterogeneous multi-national teams of autonomous vehicles could build the non-lethal elements of the MCM kill chain—detection, classification, identification—using CATL.

At the Maritime Operations Centre (MOC) in Tróia, Portugal, CMRE researchers from the Interoperability, Standards and Security project under the CMRE's Maritime Unmanned Systems Enablers (MUSE) programme deployed CATL on their Command Control and Communications for Maritime Robotic Exploitation (C3MRE) service to demonstrate C3 interoperability for MUS. C3MRE allowed exercise participants from 14 NATO Nations and over 30 industrial and academic partners to connect over 100 nodes to a common C3 backbone, allowing operators and commanders to exercise C2 over heterogeneous MUS teams during the exercise serials. Importantly, C3MRE also provided interconnectivity with existing

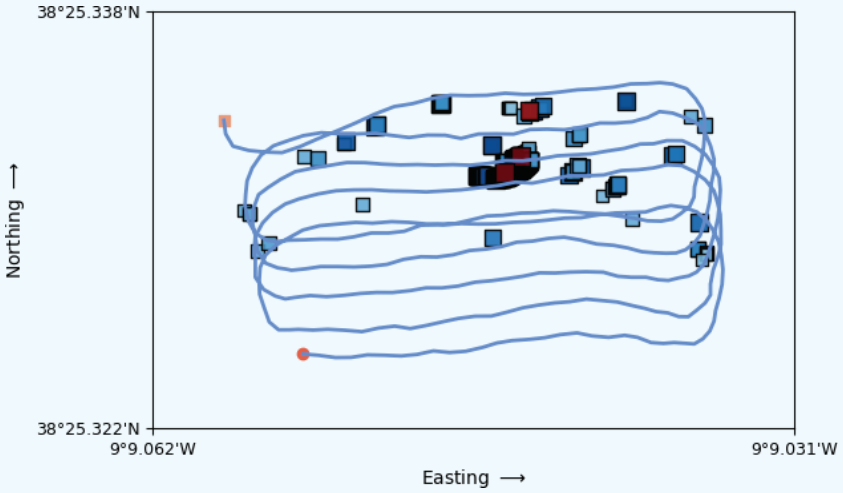


Image of a minelike contact from BIONDo acoustic camera

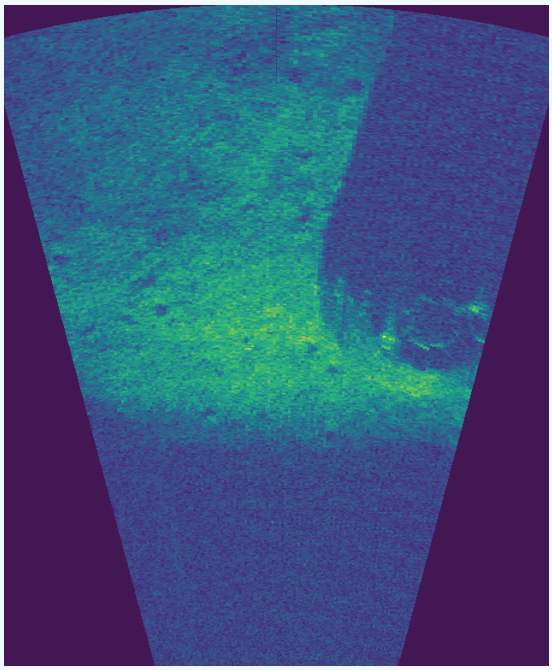
Minelike contact acoustic image analysis

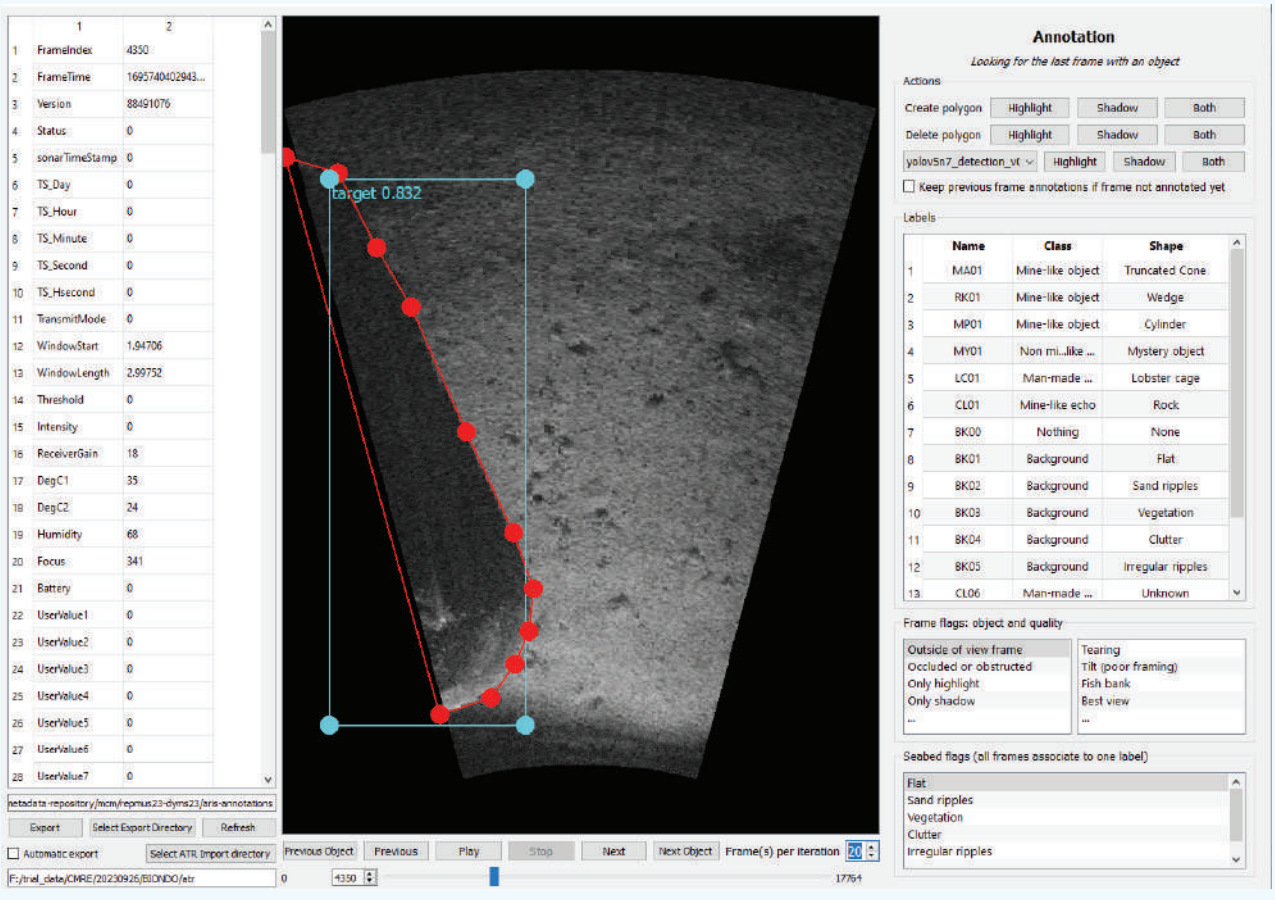
BIONDo AUV track for minelike contact re-acquisition

national C3 capabilities brought to the exercises by USA (CCS-Maritime), GBR (Naval Strike Network), and ESP (NAIAD). CMRE is working closely with these and other NATO Nations to establish a new NATO Standardization Agreement (STANAG) 4817 for a Multi-Domain Control Station.

Future Goals

In 2024, CMRE will participate in REPMUS24 and demonstrate MUS C3 interoperability using the new NATO STANAG 4817 for the first time. C3MRE and CATL will be modified to be completely interoperable with national capabilities compliant with the new standard.





OPERATIONAL EXPERIMENTATION

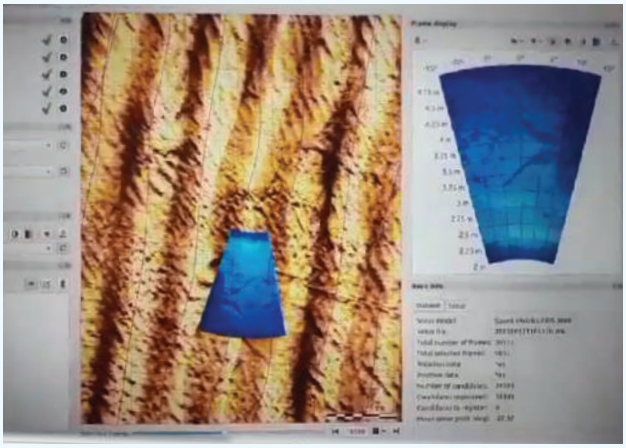
TECHNOLOGICAL DEMONSTRATION FOR CRITICAL UNDERSEA INFRASTRUCTURE DURING EXERCISE DYNAMIC MESSENGER 23

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

Following the recent disruptions to the Nord Stream and Baltic Connector pipelines, NATO has undertaken new initiatives to secure the protection of critical undersea infrastructure (CUI), including establishing a new NATO CUI Coordination Cell at NATO HQ and standing up the new NATO Maritime Centre for the Protection of Critical Undersea Infrastructure at Allied Maritime Command (MARCOM).
Allied Command Transformation (ACT) has been investigating how some of the higher technology readiness level (TRL) unmanned survey and inspection capabilities developed within the Autonomy for Naval Mine Countermeasures (ANMCM) programme at CMRE can address key aspects of monitoring and protecting CUI. ACT funded CMRE to perform a scoping study to recommend new sensing capabilities for its autonomous underwater vehicles (AUV) suitable for the monitoring of CUI. In addition, ACT funded CMRE to participate with the Centre's existing naval mine identification capability—the BIONDo AUV—in Exercise DYNAMIC MESSENGER (DYMS) 23, during which one of the first ever CUI serials in a NATO maritime exercise was executed.

Dummy IED placed on mock CUI (fibre optic cable)



BIONDo FLS imaging the dummy IED

Results

CMREs scoping study identified a potential commercial-off-the shelf (COTS) solution for the effective surveying and monitoring of CUI.
During DYMS23, a collaborative asset tasked the CMRE's BIONDo AUV to re-acquire and inspect a section of a small diameter undersea fibre optic communication cable—representing a CUI—for the possible presence of an improvised explosive device (IED). BIONDo successfully reacquired and inspected the CUI using its forward looking sonar (FLS)/acoustic camera, and in post-mission analysis, the images generated by BIONDo showed both the small diameter cable and the dummy IED.

Future Goals

In 2024, CMRE proposes to automate the monitoring of CUIs by integrating an edge-processing automatic target recognition (ATR) capability on-board the Centre's BIONDo AUV. In addition, to enable CUI protection operations by autonomous assets, CUI survey and inspection functionalities will be incorporated within the Cooperative Autonomy Tasking Layer (CATL) and NATO Standardization Agreement (STANAG) 4817.

OPERATIONAL EXPERIMENTATION

SUPPORT FOR EXERCISE DYNAMIC MESSENGER 23 ANALYSIS TEAM

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

Exercise DYNAMIC MESSENGER (DYMS) 23 was NATO's second consecutive unmanned systems exercise, co-sponsored by Allied Maritime Command (MARCOM) and Allied Command Transformation (ACT). DYMS23 emphasized the development and testing of doctrine and interoperability for the exploitation of maritime unmanned systems (MUS) in maritime operations. The exercise included serials in anti-surface warfare, maritime security, anti-submarine warfare (ASW), naval mine warfare (NMW), amphibious operations, force protection, and critical undersea infrastructure (CUI) monitoring and protection. ACT staff took the lead for the experiment analysis and assessment of the exercise. ACT contracted CMRE to support the assessment of: the overall level of autonomy and maturity of the MUS participating in the exercise; MUS interoperability including data sharing and command, control and communications (C3) connectivity; and, the contribution of MUS to the recognized maritime picture (RMP). In addition, CMRE analysts, with additional funding from MARCOM, conducted an in-depth analysis of the ASW and NMW capabilities, both manned and unmanned, deployed in the exercise.

Results

CMRE analysts employed surveys and exit interviews to collect data to support the assessment of MUS autonomy, C3 connectivity and data sharing, and maturity, and collected observations about the contribution to the RMP from warfare area syndicate leads. Exit interviews were also carried out.

Although there was incomplete feedback in some warfare areas, sufficient information was collected to generate a report summarizing the findings from the exercise. General conclusions were that NATO MUS are reaching important and compelling levels of maturity to contribute to most maritime warfare areas, although several gaps remain, especially with respect to interoperability and the sharing of information to create a single RMP.

In the context of the NATO Standing Naval Force (SNF) ships participating in the exercise, the ability to exploit situational awareness information collected and provided by MUS, and to exercise effective command and control (C2) over MUS, depended on whether the ships had organic MUS assets, and/or MUS C3 capabilities integrated into the ship's combat systems. Virtual ships at the Maritime Operations Centre (MOC) in Tróia, Portugal equipped with national C3 tools—for example, CCS-Maritime (USA), Naval Strike Network (GBR), and NAIAD (ESP)—were able to exploit the MUS sensor's contributions to the RMP and exercise C2 over MUS assets deployed from either the shore or the SNF ships.

The NATO Command Control and Communications for Maritime Robotic Exploitation (C3MRE) platform, deployed by the CMRE for the exercise, successfully integrated into the RMP the information from MUS that were compliant with the NATO Cooperative Autonomy Tasking Layer (CATL) standard.

Future Goals

In 2024, CMRE will continue to be engaged in experiment, analysis and assessment activities, most likely in support of ACT's new Innovation Continuum 24 multi-domain operations (MDO) series of operational experiments (OPEX).

CLIMATE CHANGE AND SECURITY

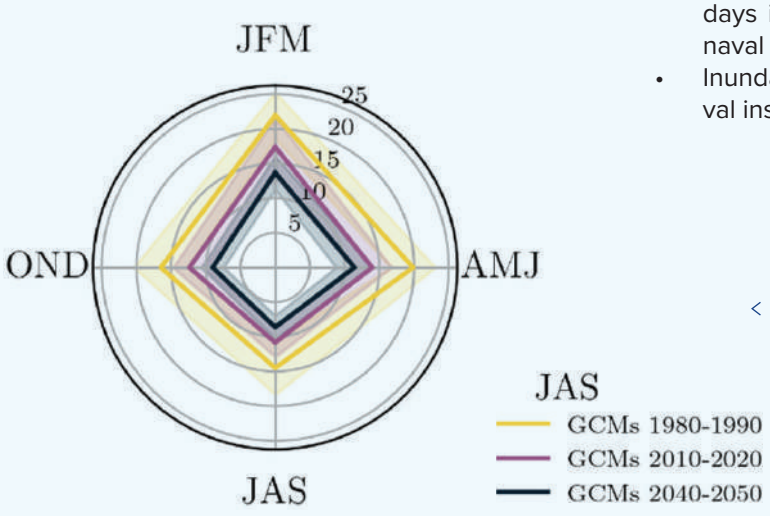
CLIMATE CHANGE AND SECURITY ANALYSIS

FUNDING BODY: NATO SCIENCE AND TECHNOLOGY ORGANIZATION

Overview

Climate change (CC) is a threat multiplier that potentially affects NATO security, operations and missions. CC effects—such as increasing global temperatures, thawing permafrost, desertification, loss of sea ice and glaciers, and the opening up of shipping lanes—will likely shape the geopolitical environment, leading to instability and geostrategic competition, and creating conditions that can be exploited by state and non-state actors that threaten or challenge the Alliance. CC also affects the way NATO armed forces operate, and NATO infrastructure is vulnerable to its effects. Within the Euro-Atlantic area, the High North represents possibly the most concerning epicentre of CC.

During 2023, a new Climate Change and Security (CCAS) Programme was established at the CMRE, which leverages CMRE's extensive experience and expertise on maritime research and Arctic studies. The overarching aim of this Programme is to contribute to NATO's response to CC effects along the four lines described in the NATO Climate Change and Security Action Plan published in June 2021: awareness, adaptation, mitigation and outreach. By developing an understanding of the impact of CC effects on NATO activities, operations and missions, NATO forces can adapt existing capabilities and plans to maintain operational effectiveness while exploring new opportunities to exploit emerging and disruptive technologies to enhance mission success.



Example of CC impact on seasonal mean detection range (km) of a generic active sonar system according to oceanographic conditions provided by an ensemble of three publicly available GCMs for: (i) the 1980–1990 period (yellow line); (ii) the 2010–2020 period (purple line); and, (iii) 2040–2050 period (black line). Shaded areas represent standard deviations.

Results

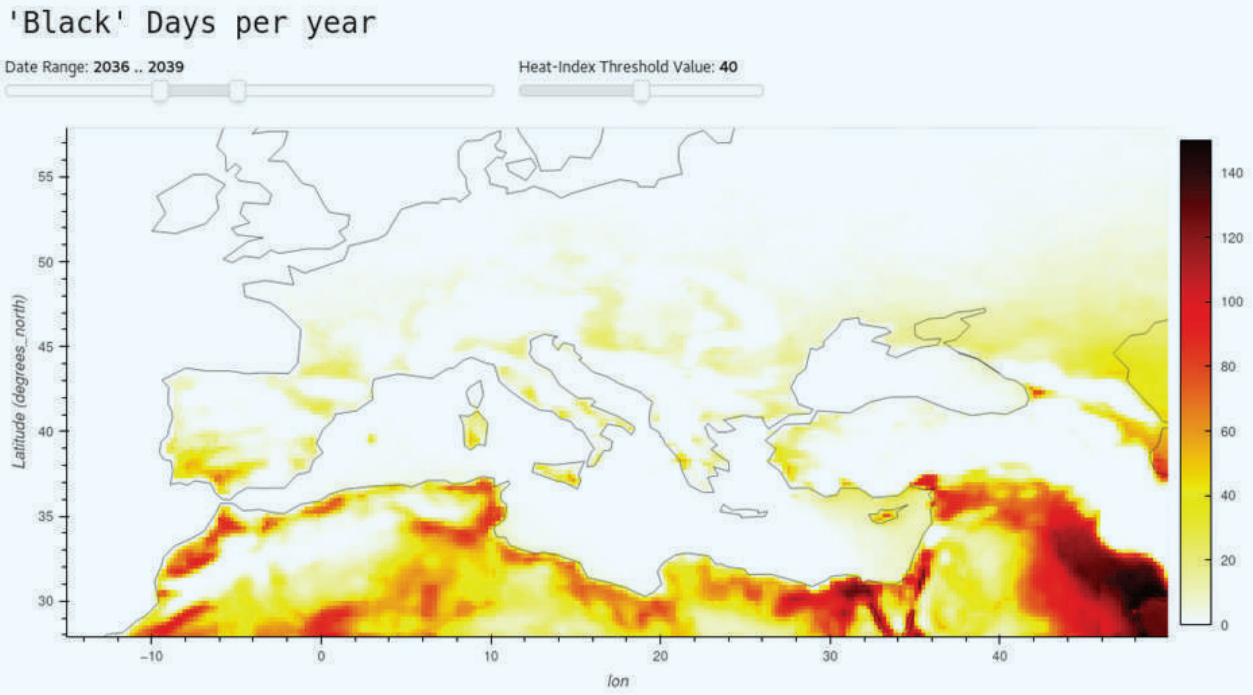
To facilitate tailored studies and results sharing within the CCAS programme, an innovative framework to handle the massive climate datasets and projections was developed and deployed in the NATO Software Factory accredited cloud environment.

The NATO underwater Arctic Climate Observatory (NACO) was deployed during a dedicated sea-trail in July in the northern Norwegian Sea/Fram Strait region. It consists of oceanographic-acoustic sensors on three deep, long-term moorings, which will be recovered, serviced and redeployed in 2024.

A paper was published investigating fundamental climate patterns, focusing on the El Nino-Southern Oscillation, and associated impacts in the security realm.

A number of studies were delivered to assess the impact of CC on military capabilities. These studies included:

- The effect on sonar and underwater acoustic communication performance caused by projected changes to underwater sound speed profiles.
- The future frequency of occurrence of higher sea states that can negatively impact maritime operations and inform future platform design.
- The effect on naval radar performance and electromagnetic communications resulting from projected modifications to atmospheric surface evaporative ducts.
- The evolution in the occurrence of the number of days in a year with high temperatures affecting naval helicopter operations.
- Inundation and extreme weather impacts on naval installations and coastal infrastructures.



The CMRE promoted a series of outreach events during 2023, culminating in the international CCAS Workshop held in October (www.climatechangesecurity.org).
The syllabus of a dedicated higher educational course on CCAS has been designed in collaboration with prestigious academic institutions, including the US Naval Postgraduate School, and the support of NATO Science for Peace and Security (SPS) programme. The first course is scheduled to be run in 2024.

^ *Demonstration of CC analysis tools implemented in the NSF cloud environment: by using the sliding buttons on the top, the user can select period and threshold for visualizing the yearly number of 'Black Days', computed using Heat Index formula applied to projected daily maximum temperature and relative humidity data. In this example, temperature and humidity data came from a single, publicly available Global Climate Model (GCM)*

Future Goals

The research conducted in 2023 will be continued to deepen NATO's knowledge of the impacts of CC on security. Activities in 2024 include: investigating further consequences of CC on sonar performance; analysing ambient noise data collected by the NACO; increasing collaboration with, and support to, other NATO entities dealing with CC—e.g., adapting NATO standards to CC, contributing to the annual NATO Climate Change and Security Impact Assessment; and, delivering a report on the science of CC.

ENGINEERING & IT DIVISION

ENGINEERING DEPARTMENT

Overview

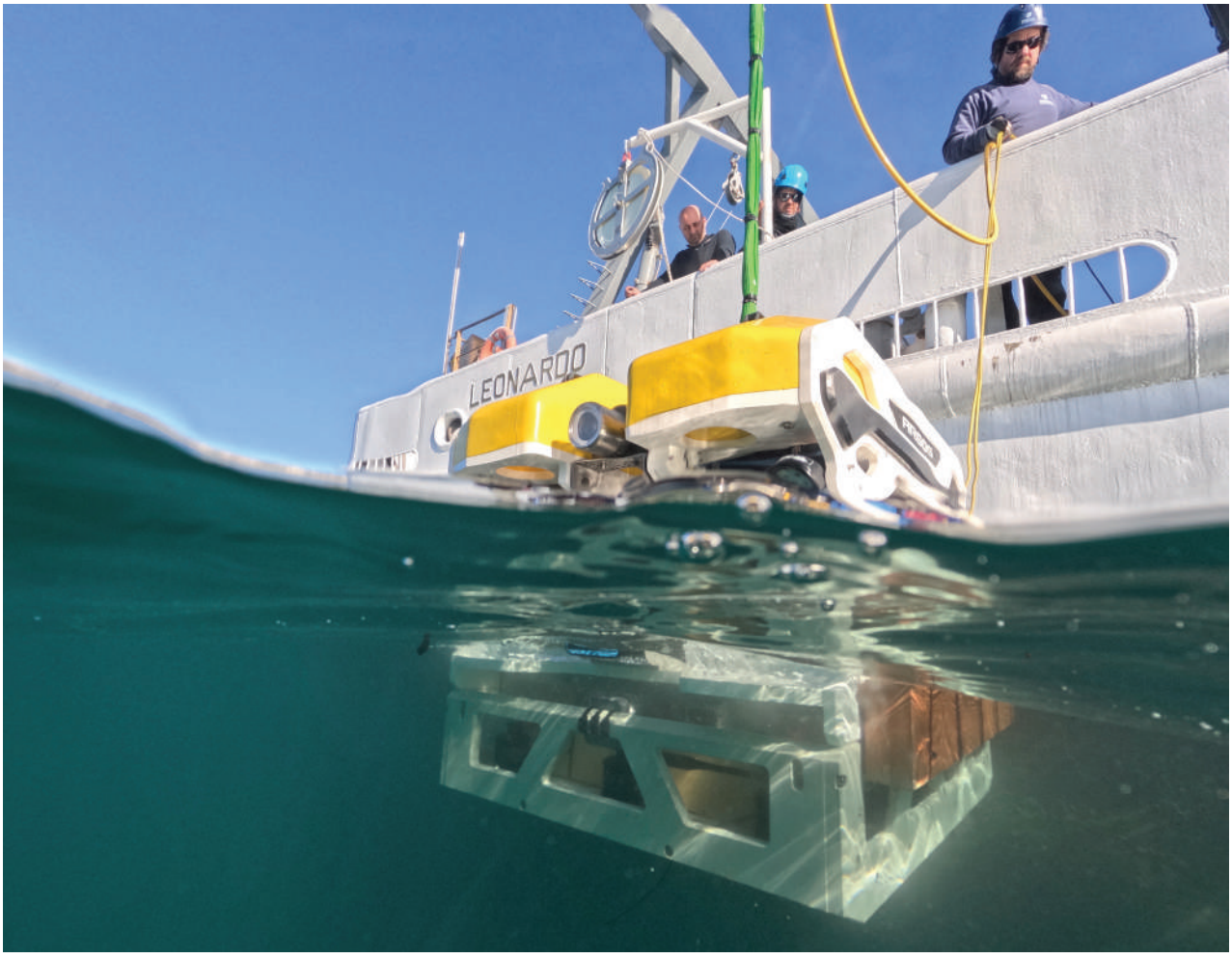
The Engineering Department (ED) supports CMRE's scientific research programmes by enabling the collection of scientific and engineering data in the maritime domain. Additionally, the ED carries out specific customer-funded engineering and testing projects. A team of 33 dedicated engineers, technicians, and artisans address the challenges of taking CMRE's science and technology to sea, through the development and operation of unique experimental systems.

The work of the ED is structured into three types of activities:

- Ongoing maintenance, repair, calibration, and improvement of the existing CMRE-owned equipment in preparation for operations at sea;
- Development of new equipment and instruments, designed and integrated according to specific requirements from either CMRE's research projects or external customers; and,
- Logistical and operational support for at-sea experimentation.

To carry out these activities, the ED multidisciplinary staff is organized within three Sections:

- The Sonar and Marine Sensors Section develops and operates state-of-the-art sonar systems,



Launch of Oceanographic Moorings during NREP23 – CCAS23 Sea Trial. CMRE has a consolidated experience in the design, deployment and operation of moorings, in support of Scientific operations.

CMRE AUVs on board NRV Alliance during MEDASWAN23 Sea Trial. Autonomous Vehicles operations have started at CMRE more than 25 years ago, and involve today a wide range of platforms (underwater – surface – aerial) equipped with multi-purpose scientific payloads

including transmitting and receiving transducers and arrays, and supports knowledge development of the ocean environment through persistent data collection across large geographical areas using traditional and novel, innovative sensors deployed in moorings, towed from ships, or fitted to CMRE's fleet of autonomous vehicles.

- The Embedded Systems Section designs and integrates custom electronic equipment, including: data acquisition, storage, and processing devices; battery and power management systems; underwater and aerial communication links; and, auxiliary equipment for autonomous platforms. Emphasis is placed on miniaturization, energy efficiency, and endurance. Section staff also support custom integration and at-sea operation of surface and underwater vehicles.
- The Ocean Engineering Section provides a wide range of support services, through the electromechanical design, fabrication, integration, testing, at-sea operation, and maintenance of all CMRE engineering equipment, using state-of-the-art machinery and techniques.

Results

During 2023, ED staff successfully provided products and services, within time and budget, to support a broad range of projects within the NATO Allied Command Transformation (ACT) Maritime Science and Technology (S&T) Programme of Work (PoW) and the 2023 Climate Change and Security (CCAS) programme funded by the NATO Science and Technology Organization (STO) through the NATO Office of the Chief Scientist.

Notable highlights include:

- In support of the Autonomy for Anti-Submarine Warfare (AASW) programme, ED staff: improved the data acquisition hardware and the energy management systems of the Bottom Nodes (BONO) fleet; expanded the consistency and continued the integration of the network of commercial off-the-shelf (COTS) platforms such as Ocean Bottom Seismometers (OBS) in the ASW passive acoustic sensing network; and contributed to the accreditation process of two ASW acoustic communication and information system (CIS) networks—MUSNET, a full network at NATO Unclassified level and SECBONO, at a higher Classification Level. Additionally, ED staff maintained, prepared, and deployed the full network of equipment for the COLD23 and MEDASWAN23 at-sea trials. The networks included three BONOs, three OBSs, two Ocean Explorer (OEX-C) autonomous underwater vehicles (AUV) towing advanced hydrophones and vector sensor arrays, two envi-

ronmental/acoustic monitoring buoyancy Glider AUVs, and a full set of communication gateway systems, including buoys and wave glider unmanned surface vehicles (USV).

- In support of the Autonomy for Naval Mine Countermeasures (ANMCM) programme, ED staff prepared the prototype High Resolution Low Frequency Synthetic Aperture Sonar system for the SUNFISH 23 sea trial off Elba Island Italy on-board Coastal Research Vessel (CRV) Leonardo. Specifically, the following aspects were updated and improved on the system: digital, high-power and energy efficient amplifiers for the transmission of arbitrary waveforms; different implementation of impedance matching units for the transducers, allowing more flexibility in the physical arrangement of the staves; and a complete service of all the receiving and transmitting elements, including a calibration trial executed at CMRE premises on the SONAR rail facility. Additionally, updates have been made to the CMRE's IQUA Robotics SPARUS II AUV 'BRUNO', which has a hovering capability and therefore a suitable platform for NMCM contact classification and identification operations. These updates included: new motor controllers in order to reduce noise in the acoustic communication band; a new underwater acoustic communication system for improving interoperability with partners; and, new scientific payload capabilities to support automatic target recognition from acoustic camera images.
- In support of the Data and Environmental Knowledge and Operational Effectiveness (D-EKOE) programme, ED staff designed the mechanical and electronic integration of a COTS sub-bottom profiler in a buoyancy glider AUV, and enhanced the environmental sensing capabilities of air drones and an underwater remotely operated vehicle (ROV) for above and underwater sea-ice floe characterization. Additionally, ED staff prepared and deployed a range of oceanographic data collection instruments for the Nordic Recognized Environmental Picture sea trial held in June – July 2023 in the Arctic Sea, including underway conductivity temperature and depth (CTD) instruments, expendable bathythermographs (XBT), and buoyancy gliders with oceanographic and acoustic sensor payloads.
- Within the Maritime Unmanned Systems Enablers (MUSE) programme, ED staff continued to maintain and operate the CMRE's Littoral Ocean Observatory Network (LOON) permanent test bed deployed in the gulf of La Spezia, comprising of a wide range of acoustic and non-acoustic sensors. Among several new developments, ED staff implemented and operated CMRE's cognitive underwater acoustic communication system and Quantum Key Distribution (QKD) system prototypes.
- To support the CMRE Technical Demonstrations funded by ACT during the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) and NATO DYNAMIC MESSENGER (DYMS) exercises in September 2023 off the coast of Portugal, ED staff prepared for and supported the deployment of CMRE's BIONDo AUV and its support equipment. BIONDo and BRUNO are SPARUS II-based AUVs in CMRE's inventory that have similar capabilities.
- For the Climate Change and Security (CCAS) programme, ED staff designed, maintained and deployed oceanographic and acoustic sensors on long-term deep-water moorings in High North Arctic waters for the Arctic Climate Observatory sea trial held in July 2023. In cooperation with the Norwegian Defence Research Establishment (FFI), ED staff recovered a damaged mooring, floating adrift between the Norwegian and Greenland Sea.

< *One of the CMRE AUV being launched from NRV Alliance during MEDASWAN23 Sea Trial. CMRE has a broad experience in the design and manufacturing of Launch and Recovery Systems (LARS) in support of Autonomous Underwater Vehicles (AUV) operations*

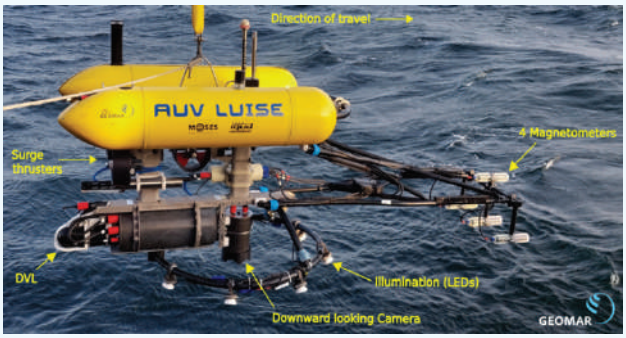
ENGINEERING DEPARTMENT

UNEXPLODED ORDNANCE TEST SITE IMPLEMENTATION, DEMONSTRATION AND MAINTENANCE

FUNDING BODY: US ENVIRONMENTAL SECURITY TECHNOLOGY CERTIFICATION PROGRAM

Overview

The problem of underwater unexploded ordnance (UXO) remediation is, when possible, long and complex using conventional methods, such as divers in the field. Consequently, in the last decade, there has been a proliferation of autonomous underwater and surface vehicle (AUV – ASV) systems designed or adapted to perform this task. The performance evaluation of these systems requires lengthy at-sea testing, in well-defined and controlled underwater conditions, purposely designed and deployed, characterized and documented as accurately as possible. The US Environmental Security Technology Certification Program (ESTCP)—the US Department of Defense (DOD) environmental technology demonstration and validation program—awarded CMRE at the end of 2020 a grant for a project to implement, maintain, manage and monitor a UXO Testbed site, located offshore of the CMRE facilities, in the harbour of La Spezia, Italy.
In 2023, the project entered the operational phase, with the deployment of the UXO targets of interest and clutter objects within the UXO Testbed, and completion of the first use of the Testbed by European Research Institutes demonstrating underwater UXO sensing systems.

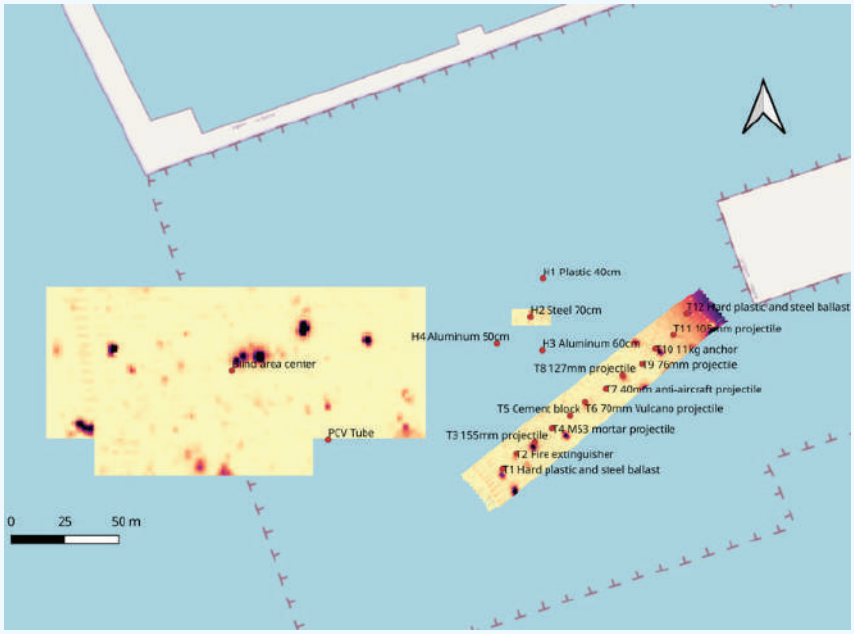


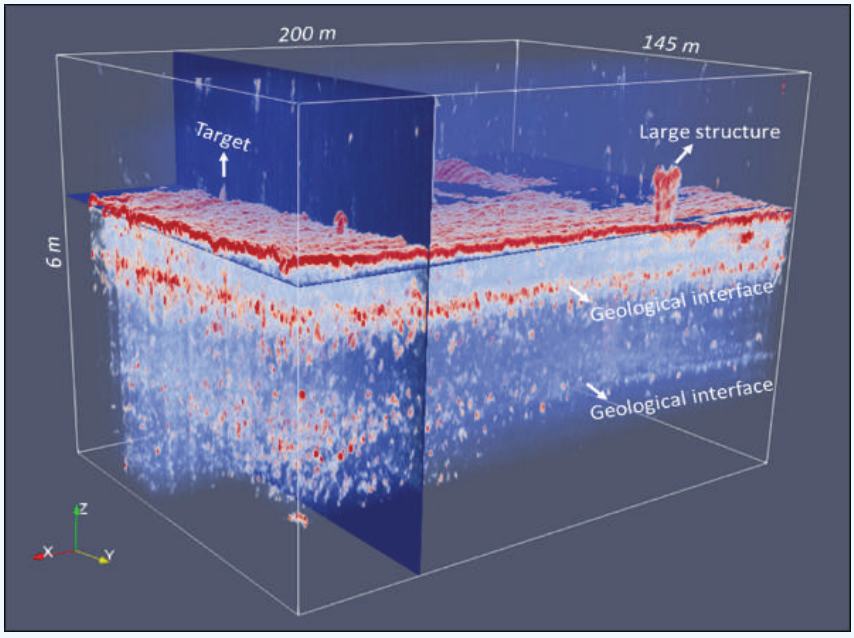
Results

- During the first quarter of 2023, the site was seeded with objects—dummy/replica UXO and artificial clutter—and high-accuracy geolocation surveys performed both during and after the deployment using the instruments and methods identified in the preliminary 2022 engineering tests. Based on these data, a detailed seeding catalogue was delivered to the ESTCP Program Office, and to the Institute of Defense Analyses (IDA), the independent Scoring Authority for the following Demonstration phases.
- A Lessons Learned (LL) Report on Test Site Implementation was delivered to the ESTCP Program Office.
- Successful demonstrations were performed in the CMRE UXO Testbed site by two European Research Institutes: the Helmholtz Centre for Ocean Research (GEOMAR), Kiel, Germany, operating an autonomous underwater vehicle (AUV) equipped with magnetic, acoustic and optical sensors; and, Vlaams Instituut voor de Zee (VLIZ), Flanders, Belgium, operating an acoustic sub-bottom profiling system from a surface support boat. Both these demonstrations were supervised by ESTCP/IDA representatives, with CMRE staff providing logistics support. Preliminary results have been made available by both Institutes, and the final performance assessment of the sensing systems is ongoing by IDA staff.

Future Goals

The CMRE UXO Testbed site will be used by a third demonstrator, the ELWAVE Company from Nantes, France, in February 2024, to evaluate the performance of their innovative in-house Controlled Electric Detection And Ranging CEDAR® sensor system, bio-inspired by active electro-location perception mode of tropical fishes. Notably, the ELWAVE demonstration is financed within the framework of the NATO Defence Innovation Accelerator for the North Atlantic (DIANA) programme of work.v





⌜ *Support boat operating VLIZ sub-bottom profiler*

< *GEOMAR IQUA Robotics GIRONA 500 AUV with magnetic sensors and underwater camera*

^ *Preliminary results of the GEOMAR Survey*

⌜ *VLIZ survey results - 3D acoustic volume*

ENGINEERING DEPARTMENT

ACTIVE TOWED ARRAY SYSTEM AT-SEA TESTS

FUNDING BODY: LEONARDO SISTEMI DIFESA SPA (ITA)

Overview

The Active Towed Array System (ATAS), developed for the Italian Navy by Leonardo Defence Systems, is a variable-depth sonar designed for anti-submarine warfare (ASW) operations in both littoral waters and open oceans. CMRE has supported the development of the Leonardo ATAS by designing and building the prototype of the acoustic receiving array, developing the code for the receiving signal processing chain and the acoustic simulation tools, and supporting the whole campaign of tests at sea with the system deployed from the NATO Research Vessel (NRV) Alliance in 2021 and 2022. After each of these trials, CMRE provided to the customer a comprehensive scientific and engineering report of the system performance, including the lessons identified and the recommendations for system developments and corrective actions.

ATAS on-board NRV Alliance

Loading operations alongside at La Spezia

Results

The final sea acceptance trials of the fully integrated ATAS were successfully executed in January 2023 off the Ligurian Coast near La Spezia, Italy.

- The corrective actions were completed for the issues identified during the 2021 and 2022 ATAS at-sea trials.
- The Trial Plan for 2023 final sea acceptance trials was delivered to Leonardo, including the dedicated scoping study for marine mammal risk mitigation.
- The completed Leonardo ATAS, including its launch and recovery equipment, was integrated on-board NRV Alliance.
- All necessary auxiliary equipment to support the at-sea ATAS trials was prepared and integrated into the trials, including the acoustic recording mooring on-board NRV Alliance, and the towed echo-repeater acoustic system on-board Coastal Research Vessel (CRV) Leonardo.
- A final ATAS performance report was delivered to the customer.

Future Goals

The final sea acceptance trials of the ATAS completes CMRE's activity in support of this project.

ENGINEERING DEPARTMENT

PENN STATE UNIVERSITY NESMA 23 TRIAL SUPPORT

FUNDING BODY: US OFFICE OF NAVAL RESERCH

Overview

Funded by the US Office of Naval Research (ONR), CMRE engineers built a complete technologically advanced towed array system—the 128-element, three-octave research array (THORA), which was delivered to Pennsylvania State University – Applied Research Lab (PSU-ARL) in September 2021. In 2023, ONR funded CMRE staff to participate in the ONR NESMA 2023 pilot experiment embarked on the Research Vessel (RV) Endeavor for the month of May 2023, in support of PSU-ARL for the first at-sea tests of THORA.

Results

Major achievements of this experimental work were:

- Successful engineering tests of THORA, including acoustic calibration, flow noise, and verification of non-acoustic sensor data;
- Coordinated source and towed array measurements between the RV Endeavor and RV Armstrong, over 250 km of ship track;
- Several terabytes (TB) of acoustic data recorded;
- Successful science measurements, including simultaneous measurement of low- to mid-frequency bi-static scattering, refraction from the northeast flank of the Atlantis II seamount, and single-bounce geo-acoustic measurements across the top of a local underwater plateau;
- Contiguous recordings of propagation and scattering from one to 80 km range, and analysis of sub-surface duct propagation and ambient noise directionality around the test region, including marine mammal vocalizations;
- Valuable experience gained by the PSU-ARL/CMRE team in operating a towed array in the challenging Gulf Stream current environment, enhancing planning for NESMA 2024;
- On-site training for PSU-ARL staff by CMRE participants on the deployment and use of the THORA; and,
- A successful at-sea test of the THORA CMRE-designed weak link safety device, which protects against risk of damage to the towing cable, gears and machinery from accidental contact with the seafloor or other submerged objects.

Future Goals

The cooperation between CMRE and ONR in support of PSU-ARL will continue in 2024. In July 2024, CMRE staff will participate in the NESMA 2024 Sea Trial, taking place in the New England Sea Mounts area offshore Boston. CMRE will implement a series of modifications and improvements to the THORA System—including the leading connector and real time data acquisition software—from the lessons learned during the 2023 activity. Beside this technical support, CMRE staff on board will continue to provide PSU personnel with operational training and support the scientific measurement campaign.

ENGINEERING DEPARTMENT

USV-BASED ANTI-SUBMARINE WARFARE

FUNDING BODY: DIRECTION GÉNÉRALE DE L'ARMEMENT (DGA) FRANCE

Overview

The aim of this project is to evaluate the ability of state-of-the-art unmanned surface vehicles (USV) to conduct anti-submarine warfare (ASW) operations. In 2023, CMRE staff collaborated with Alseamar and Exail industrial partners by providing the CMRE's Slim LIne Cardioid Towed Array (SLICTA) for integration with Exail's DRIX USV, and conducted a series of at-sea trials to help DGA assess the potential of the technology for ASW operations.
Overall activities in 2023 consisted of:

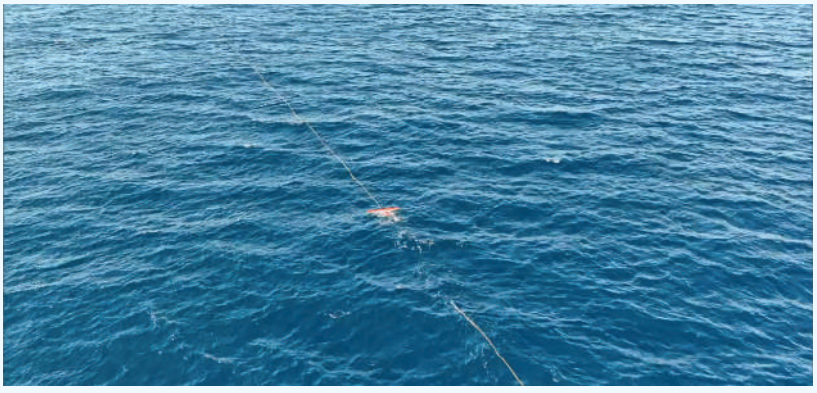
- Integration of the CMRE SLICTA towed array and acquisition canister with Exail's Flipix towfish.
- Integration of CMRE real-time detection and tracking processing suite on-board Exail's Drix USV.
- Engineering trials from Exail's GGIX research vessel, which was the command and control (C2) platform for the trial's activity.
- Sea trials with DGA's transmission and echo-repeater acoustic suite in a realistic operational scenario.

Results

System integration and the engineering trials were completed in September 2023 to validate launch and recovery procedures, and to evaluate the self-noise and operational characteristics of the overall system. Sea trials were conducted in November 2023 with the use of DGA's artificial target, and the ability of the overall system to perform an ASW mission was demonstrated.

Future Goals

"The analysis of the sea trails will be completed in Q1 2024 and the final results discussed with the project partners. A decision will be made on potential follow-on activity."

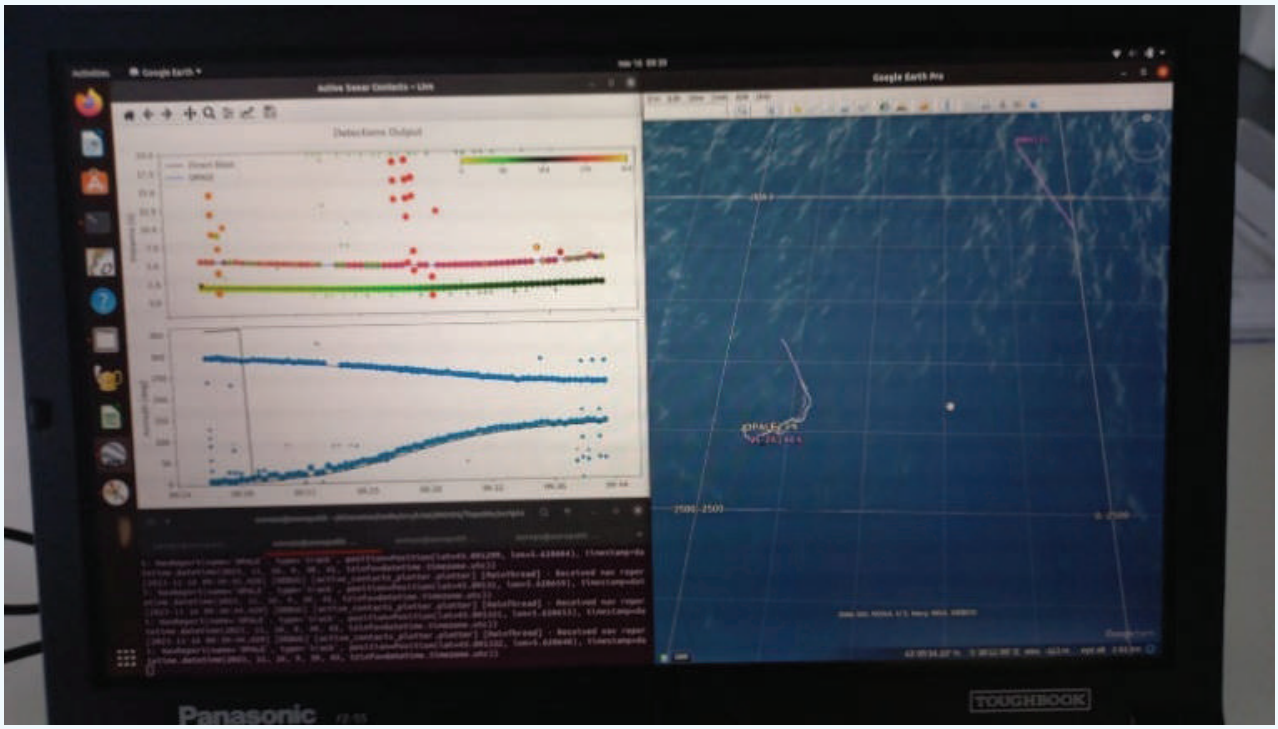


< *Umbilical deployment from Exail GGIX vessel*

⌞ *DRIX USV, tow-body and SLICTA at the surface*

⌝ *Real-time contacts and tracking on-board the GGIX C2 vessel*

> *Real-time contacts and tracking on-board the GGIX C2 vessel*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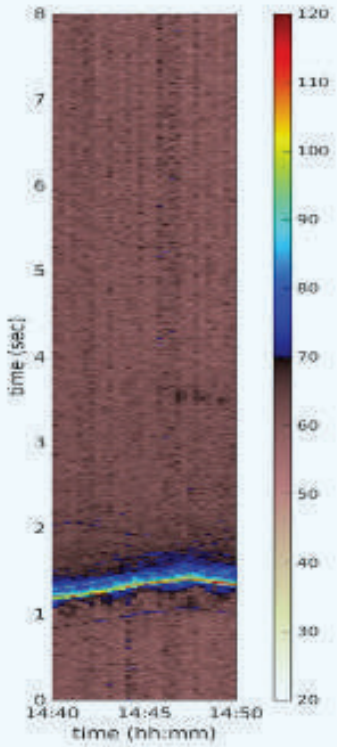
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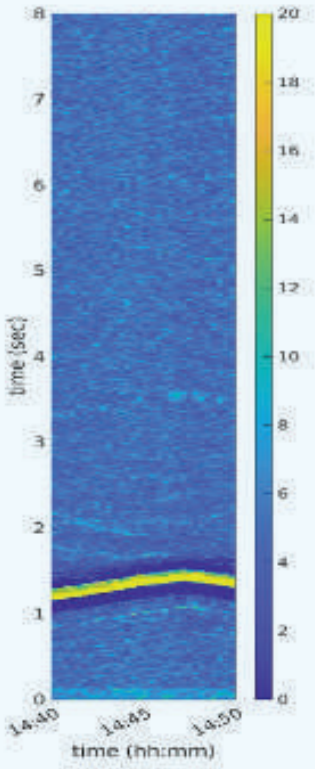
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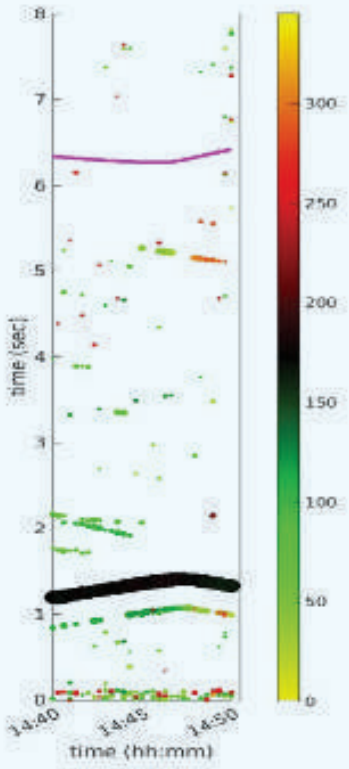
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ENGINEERING & IT DIVISION
INFORMATION TECHNOLOGY DEPARTMENT

Overview

The mission of the Information Technology (IT) Department within the CMRE Engineering and IT Division is to support the Centre's scientific research programmes by designing, testing, operating and maintaining state-of-the-art unclassified and classified communication and information systems (CIS) used by CMRE's scientists and engineers. The work includes the provision of systems and services to enable data collection, sharing and collaboration with external partners and customers. IT Department staff implement artificial intelligence and machine learning algorithms for deployment on embedded platforms and in hosting facilities, and, funded by NATO Allied Command Transformation (ACT), deliver innovation by leading the development of unique software minimal viable products (MVPs) predominantly in the maritime domain.
The work of the IT Department is structured into three types of activities:

- Ongoing support, maintenance, and improvement of existing CMRE-owned CIS systems;
- Direct support to scientific and engineering led projects with expertise in CIS design, implementation, security review, data collection and software development; and,
- Leading and executing customer-funded innovation projects.

The IT Department staff of system architects, engineers and technicians are organized into two Sections:

- The Scientific CIS Section staff operate, maintain and enhance the CMRE scientific networks in support of the Centre's programme of work, in particular the Scientific Network (SciNet) Infrastructure—CMRE's working network for researchers and engineers.
- The Software Development and Data Management Section staff develop and operate state-of-the-art software systems and services, support software development and data management activities within the Centre's programme of work, and lead customer-funded innovation projects.

Results

In 2023, CMRE continued investment in the modernization of the Centre's computing facilities, reflecting a significant effort towards future readiness and resilience. The activation of a High Performance Computing (HPC) capability, dedicated to environmental modelling, underscores the commitment of CMRE to advancing research and innovation. Operational since May 2023, the CMRE HPC capability was designed in collaboration with Dell and resembles the architecture of a node of the Italian CINECA Galileo 100 engineered by Dell in 2021. The CMRE Pan-Arctic Ocean Model is currently implemented on the HPC,

and numerical computation speeds have increased by a factor of four compared with CMRE's previous capability.
A project is underway to replace the CMRE legacy datacentre with a state of the art hyper-converged infrastructure (HCI) to enhance resilience, scalability, and performance while reducing operational complexity. The design of the new HCI was completed in 2023.
Under the Maritime Resources Enablers (MARE) programme, a Data Catalogue hosted on the NATO Software Factory (NSF) now contains more than 1000 datasets from CMRE's recent scientific annual Programmes of Work. An inventory has been created of 768 scientific and engineering datasets from 62 CMRE trials in the period 2016 – 2022. Finally, a Cloud based Data Exploitation environment has been set up to support the climate change modelling work being carried out under the CMRE's new Climate Change and Security Programme.
CMRE IT Department staff have been funded by ACT to develop four software MVPs to support: anti-submarine warfare operations planning; naval mine warfare planning and evaluation; the monitoring and protection of critical undersea infrastructure; and, a modern data exploitation environment for use by CMRE scientists and engineers as well as external partners.

Future Goals

The HPC capability will be further increased by installing additional nodes in 2024. In the long term, the HPC cluster will be accredited to run at higher security classifications to meet NATO tactical needs.
The procurement and activation of the HCI is scheduled for the first half of 2024. The expansion of the infrastructure will allow the centre to accommodate cloud-based services and applications; centralized management of the HCI is expected to simplify cloud adoption by providing a unified interface for managing both on-site and cloud resources.
CMRE IT Department staff will continue to maintain and assure accessibility by NATO Nations to CMRE data catalogues, and to work on the development of MVPs under the direction of ACT staff.

IT DEPARTMENT

SUBMARINE ENVIRONMENTAL ASSESSMENT FOR WIDE AREA SONAR PREDICTION (SEA WASP) MINIMUM VIABLE PRODUCT 1

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

The Submarine Environmental Assessment for Wide Area Sonar Prediction (SEA WASP) is a Minimum Viable Product (MVP) being developed by CMRE on behalf of Allied Command Transformation (ACT). The aim of SEA WASP is to explore a solution for solving/mitigating the lack of modern tools available to the NATO maritime geospatial, meteorological and oceanographic (GEOMETOC) community and anti-submarine warfare (ASW) operations Commanders when planning and evaluating ASW missions with multiple heterogeneous assets equipped with active and passive sonars.
The tool is based on the CMRE Acoustic Engine for Sonar Prediction, and provides operators with an accurate sonar prediction based on environmental data. As with the other MVPs developed by CMRE staff, a modern approach to software development is followed, using Agile and development, security, and operations (DevSecOps) methodologies.

Results

Stable versions of the SEA WASP tool and the CMRE Acoustic Engine were deployed on the NATO Software Factory (NSF) cloud and tested during the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 2023 and DYNAMIC MESSENGER (DYMS) 2023 exercises. SEA WASP is now available to NATO Nations with a package installer to facilitate the installation of the tool either on a server baser or in a standalone configuration.
During the REPMUS 23 and DYMS 23 demonstrations, the tool was well received by participants, with several excellent expressions of interest from multiple partners. The SEA WASP MVP tool was used to provide daily sonar performance prediction reports informing exercise participants where and how to operate to maximize the probability of target detection. Initial analysis indicated that predicted detection ranges correlated well with those reported by participating ASW capabilities.

Future Goals

During 2024, SEA WASP experimentation is envisaged at the NATO Coalition Warrior Interoperability Exercise (CWIX) and/or during a live NATO ASW exercise such as Exercise DYNAMIC MONGOOSE.

IT DEPARTMENT

MINE COUNTERMEASURES TASKING/REPORTING FOR UNMANNED/ MANNED SYSTEMS AND PLANNING AND EVALUATION TOOL (MCM TRUMPET) MINIMUM VIABLE PRODUCT 2

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

The Mine Countermeasures Tasking/Reporting for Unmanned/Manned Systems and Planning and Evaluation Tool (MCM TRUMPET) project implements in a minimum viable product (MVP) tool planning and evaluation (P&E) algorithms for both legacy MCM assets and modern capabilities embarked on autonomous underwater vehicles (AUV) in order to support the effective exploitation of CMRE's scientific research conducted over several years within the ACT Maritime Science and Technology Programme of Work naval mine countermeasures (MCM) P&E project.
An Agile development methodology is followed using a team of CMRE software designers, software engineers, and scientific researchers, working in close collaboration with subject matter experts from Allied Command Transformation (ACT) and the NATO MCM operational community. The MVP has been developed in the NATO Software Factory (NSF) cloud environment.

Results

The tool was successfully deployed tested during the NATO DYNAMIC MOVE MCM exercise in September 2023, and delivers to the NATO MCM community an operational tool integrating important advancements in the P&E of MCM assets. Additionally, the MCM TRUMPET MVP 2 was demonstrated during the Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 23 and Exercise DYNAMIC MESSENGER (DYMS) 2023 exercises, with requests from several Nations to have access to MCM TRUMPET.
The completion of this MVP concludes a considerable amount of work, resulting in a complete and flexible tool for MCM P&E available to NATO Nations. The tool offers interoperability by implementing Allied Procedural Publication APP-11 NATO Message Catalogue standards, additional military layers (AML), as well as using custom and open JavaScript Object Notation (JSON) document formats. MCM Trumpet has reached a state where it can be used in exercises, and through the integration with the Light and Interoperable Naval Mine Warfare Evaluation (LIME711) and data exchange tool MVP, offers a complete digital solution supporting the MCM operational workflow, thereby facilitating data sharing across Nations using existing CIS infrastructures.
During the course of the year, the project team received positive and enthusiastic feedback from the Naval Mine Warfare Centre of Excellence as well as operators participating in the DYNAMIC MOVE, DYNAMIC MESSENGER and REPMUS exercises.

Future Goals

It is intended to continue the refinement of the MCM TRUMPET and LIME 711 MVPs through interaction with the NATO MCM operational community in a project focused on experimentation in desktop exercises and on demonstration during live NATO exercises and operational experiments.

IT DEPARTMENT

CRITICAL UNDERWATER INFRASTRUCTURE RISK ASSESSMENT TOOL DISCOVERY PHASE

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

Galvanized by recent events, the protection of critical underwater infrastructures (CUI) has become a priority issue for NATO. Allied Maritime Command (MARCOM) through Supreme Headquarters Allied Powers Europe (SHAPE) requested Allied Command Transformation (ACT) to investigate the development of a minimum viable product (MVP) software tool to support MARCOM staff in carrying out CUI risk assessments. This project is the first spiral of the development process and aims at fully exploiting the MVP discovery phase to foster a well-informed evaluation about the possibility to develop the MVP in 2024.

Results

To understand best practices, the CMRE project team interviewed many stakeholders from MARCOM, other NATO entities, and NATO Nations. A Design Thinking workshop was held at HQ MARCOM, where a multi-disciplinary team together with MARCOM operators defined the process and organization to support CUI risk assessments. The workshop was very successful, and the CMRE team were able to deliver a conceptual design of workflows and tools, along with a high-level technical architecture for the CUI MVP tool.

Future Goals

It is expected that the CUI MVP project will continue in 2024 with an agile implementation phase, starting with a detailed functional and technical design to decide on which existing components from completed projects can be reused.

IT DEPARTMENT

MARITIME RESOURCES ENABLERS – DATA MANAGEMENT

FUNDING BODY: NATO ALLIED COMMAND TRANSFORMATION

Overview

NATO's digital transformation is dependent on the effective and efficient management of vast data sets, such that reliable data is accessible for exploitation approaches. With a view to strengthening Alliance data exploitation, with a focus on scalable and interoperable data sharing, quality-assured whole life-cycle management of data, increased collaboration, and aligned data exploitation are required. Additionally, interoperability must drive the design of NATO's data exploitation models, algorithms, and data collection, storage, and accessibility.

This Maritime Resources Enablers (MARE) project develops and enhances standards and service specifications to ensure interoperable data exploitation capabilities by providing managed, easy accessible data, together with exploitation expertise, processes, and training to collect and use data appropriately. In executing this project, the CMRE project team has adopted a modern approach to software development based on Agile and development, security, and operations (DevSecOps) methodologies.

The work is done in collaboration with other stakeholders in NATO, including Allied Command Transformation (ACT) and the NATO Communications and Information Agency (NCIA).

Results

Work to automate the deployment and improve the ingestion of data into the CMRE Data Catalogue pilot was completed. The CMRE Data Catalogue pilot now contains more than 1000 datasets from CMRE Scientific Programme of Work. The catalogue is hosted on the NATO Software Factory (NSF) and accessible to all NATO Nations participating on the NATO Science and Technology Organization (STO) Maritime Science and Technology Experts Committee (MSTC).

An inventory was created of scientific and engineering data available at CMRE at the NATO Unclassified level, with a total of 768 datasets from 62 at-sea trials in the period 2016–2022.

Data governance roles and responsibilities have been developed, supported by a working group comprised of all CMRE staff involved with data acquisition. Key performance indicators (KPI) related to data acquired have been developed and implemented to increase transparency and help drive adoption of the governance model.

In cooperation with CMRE's Autonomy for Naval Mine Countermeasures (ANMCM) Programme and the NATO Naval Mine Warfare Centre of Excellence, work was started on building models and pipeline tools to improve the standardization and interoperability of the data needed to support NATO MCM operations.

Finally, the MARE team has been supporting the CMRE's Climate Change and Security Programme by setting up and exploring a cloud-based Data Exploitation environment hosted on the NATO Software Factory (NSF).

Future Goals

The MARE project is a medium- to long-term effort in providing the basic services and governance support enabling research in artificial intelligence and machine learning based on CMRE data. The long-term goal is to provide a maritime data hub and data exploitation environment facilitating sharing and collaboration across the NATO enterprise and NATO Nations.

IT DEPARTMENT

ALLIANCE RESEARCH & TECHNOLOGY EDGE MULTIDISCIPLINARY IMPACT SYSTEM

FUNDING BODY: NATO SCIENCE AND TECHNOLOGY ORGANIZATION

Overview

In the NATO Science and Technology Organization (STO) charter, the North Atlantic Council (NAC) tasks the NATO Science and Technology Board (STB) to exercise unified governance over NATO S&T. In doing so, the STB acts as the focal point for coordinating the STO programme of work (PoW) and the S&T activities of other NATO PoWs, ensuring alignment with the NATO S&T Strategy and NATO S&T priorities, mutual awareness of activities, and avoidance of duplications. In order to support the STB in fulfilling this role effectively and efficiently to the benefit of NATO and the Nations, the STO Office of the Chief Scientist (OCS) has developed the Alliance Research & Technology Edge Multidisciplinary Impact System (ARTEMIS), a database of all NATO S&T activities. ARTEMIS supports NATO and NATO Nations in coordinating and harmonizing NATO S&T activities—i.e. informed portfolio management—and in identifying potential exploitation paths.
However, the ARTEMIS system prototype developed by OCS staff is currently available only to NATO HQ staffs. The aim of this project is to make ARTEMIS more accessible to all NATO entities and NATO Nations by making it available on classified networks, and improving the overall user experience of the system.

Results

CMRE staff, in collaboration with OCS and NATO Communications and Information Agency (NCIA) staff, have carried out an initial scoping phase. A communication and information system (CIS) description, specifying the software architecture and target CIS environment, has been delivered, and the interaction design completed, including an information architecture and wireframes documenting key workflows.
Additionally, CMRE staff have supported the maintenance of the existing legacy ARTEMIS solution and periodically updated it with relevant 2023 data.

Future Goals

The iterative design and development of ARTEMIS is planned as Phase Two of this project to be executed in 2024, and continued refinement, deployment and operation of ARTEMIS is scheduled as a final Phase Three.


A 5301

MARINE OPERATIONS

Overview

CMRE executes its at-sea research and technology demonstration programme with two research ships, NATO Research Vessel (NRV) Alliance and Coastal Research Vessel (CRV) Leonardo. The vessels, owned by NATO, have operated under the Italian Navy flag since 2016 and are manned by Italian Navy crews.

The NRV Alliance is a 93-metre, 3,100-ton, global-class ship, designed and built to minimize the noise it radiates into the water, making it the ideal platform for research in underwater acoustics and sonar sensing. NRV Alliance can cruise economically at 11 knots for 7,200 nautical miles, with an endurance of 26 days, providing scientists and engineers the opportunity to perform extended research at sea in remote waters.

The NRV Alliance has 400 square metres of laboratory space including state-of-the-art wet labs, computers and connectivity. The vessel is equipped with a hull-mounted sensor suite, along with powerful winches, cranes and deck handling equipment to deploy, tow, and recover acoustic and oceanographic equipment such as: vertical and horizontal towed acoustic arrays; towed or moored oceanographic instruments; and, a range of autonomous surface and underwater platforms. Being ice-strengthened, the NRV Alliance is a highly versatile ship that has been employed in a wide range of ocean research from deployment and control of multiple autonomous underwater vehicles; to deep ocean anti-submarine warfare (ASW) experiments; to oceanographic and bathymetric surveys in the High North.

The CRV Leonardo is a 29-metre, 433-ton coastal ship designed to accommodate an array of scientific instrumentation and, like NRV Alliance, radiates minimal noise to facilitate underwater acoustic research. The CRV Leonardo is equipped with a dynamic positioning system capable of station-keeping to within one metre and can sail in quiet state at speeds up to five knots. The vessel can host up to 20 persons for day cruises and has 12 berths. It can accommodate a six-metre laboratory container augmenting the 35 square metre on-board laboratory space.

Results

The NRV Alliance had a very active 2023 in support of both NATO Allied Command Transformation's (ACT) and NATO Nation's maritime scientific programmes of work. Three sea trials were funded under the NATO ACT Maritime Science and Technology Programme of Work:

- Under the Autonomy for ASW (AASW) programme, the COherent Localization Detection (COLD) 23 ASW programme trial in the Barents Sea, and the MEDiterranean ASW Autonomous Network ASW MED Cruise 23 in the Tyrrhenian Sea, which was partially supported by the US Office of Naval Research (ONR); and,
- Under the Data and Environmental Knowledge and Operational Effectiveness (D-EKOE) programme, the Nordic Recognized Environmental Picture (NREP) 23 campaign in the Greenland Sea / Svalbard region.

NRV Alliance also conducted the Arctic Climate Observatory (ACO23) trial in the Greenland Sea/ Norwegian Sea in July 2023, which was funded by the NATO Science and Technology Organization (STO). Other significant 2023 at-sea trials included two commercially funded trials in January and April for the Active Towed Array Sonar (ATAS) system developed for the Italian Navy by Leonardo Defence Systems SpA.

In addition to programme of work sea trials, the NRV Alliance underwent a major scheduled dry-docking in February and March 2023, as part of its RINA Classification Society renewal survey. Significant maintenance work was completed on both the hull and machinery in order to maintain the vessel's operational capability.

CRV Leonardo also had a busy 2023, beginning the year by participating in the ATAS trials with NRV Alliance. Key programme engineering trials for the CMRE's AASW and Autonomy for Naval Mine Countermeasures (ANMCM) programmes were carried out from CRV Leonardo. Additionally, CRV Leonardo was the platform for a dedicated at-sea trial SUNFISH 23

in September 2023 off Elba Island, which was fully funded by NATO ACT under the New Sensing Technologies for Naval Mine Warfare project.

Future Goals

CMRE's Marine Operations Division maintains a rigorous maintenance programme in order to extend the service life of both vessels. Future goals include a complete modernization of NRV Alliance's communication capability in the main scientific laboratories. The addition of high-speed broadband connectivity will enable CMRE scientists to access CMRE's scientific networks in real-time, greatly enhancing research capacity during sea trials.

Additionally, there are plans to replace the original towing winch on NRV Alliance with a modern containerized solution. Not only will this solution better serve the needs of CMRE's scientists in the short-term, it will also remain an asset to CMRE when the NRV Alliance reaches her end of service.

CMRE EDUCATION AND OUTREACH

Since the 2017–2018 academic year, the CMRE Education and Outreach programme aims to promote science, technology, engineering and mathematics (STEM) disciplines in schools, with activities tailored for different age groups, with the goal of developing the necessary skills for new scientific professions. Specific attention is given to gender balance, trying to attract and include as many girls and young women as possible to participate in STEM research fields.

During 2023, the programme initiated in the 2022–2023 academic year was continued, with activities structured into four modules in collaboration with Progetto Giona, an initiative by schools in the area of La Spezia: bioacoustics, oceanography, underwater engineering and robotics.

With respect to the bioacoustics, oceanography and engineering modules, an initial practical activity took place on-board the beautiful schooner Pandora, in

collaboration with the ITA Traditional Sailing Association. Under the guidance of CMRE scientists, students from three higher institutes in the La Spezia Province—Liceo Scientifico Pacinotti, Liceo Scientifico Parentucelli, and Liceo di Scienze Applicate Capellini-Sauro—learned to use the conductivity, temperature and depth (CTD) oceanographic instruments to study water column properties, and hydrophones to listen to and analyse the soundscape from the fauna in the Cinque Terre Marine Park. Through lectures, observations, brainstorming and practical activities, the students were taught how different biological and physical-chemical aspects of the marine environment are studied. The lively discussions showed the students' curiosity and interest in deepening their knowledge of the different issues addressed.

During a follow-on activity, CMRE scientist emeritus Dr Walter Zimmer provided theoretical lessons to analyse the vocalizations of marine mammals, and the students learned to develop and use computer programs to make acoustic spectrograms from the hydrophone recordings made on-board the Pandora. A lecture on the theme of climate change and its impacts was provided by the Head of Scientific Research at CMRE Dr Sandro Carniel.

Students were subsequently divided into groups to prepare presentations on different topics—noise pollution and impact on marine mammals, physics of the propagation of sound in water, climate change, and underwater vehicles, which were given during a day of workshops on 27 May 2023 in the conference room of the port authority of La Spezia. Four groups of students were selected to present their work as part of the Seafuture Awards 2023 competition, at a ceremony held at the local Chamber of Commerce in October 2023.

Four students were also chosen to participate as speakers in the NATO Women and Girls in Science day, held on 08 February 2023 at NATO headquarters in Brussels. During a dedicated panel, they presented their experiences of taking part in the Giona/Outreach programme.

With respect to the robotics module, CMRE scientist Dr Gabriele Ferri provided a talk on the history and future of robotics. From December 2022 until April 2023, four students were engaged in the construction of two SeaPerch underwater remotely operated vehicles provided by Robonation, a non-profit US-based organization. The students had the opportunity to test them in the water and participate in the second Robotics for Asset Maintenance and Inspection (RAMI) 2023 competition held at the CMRE in July 2023. This activity also marks the start of a pilot project to involve a team of Italian students in future SeaPerch Challenge competitions held every year in the USA.

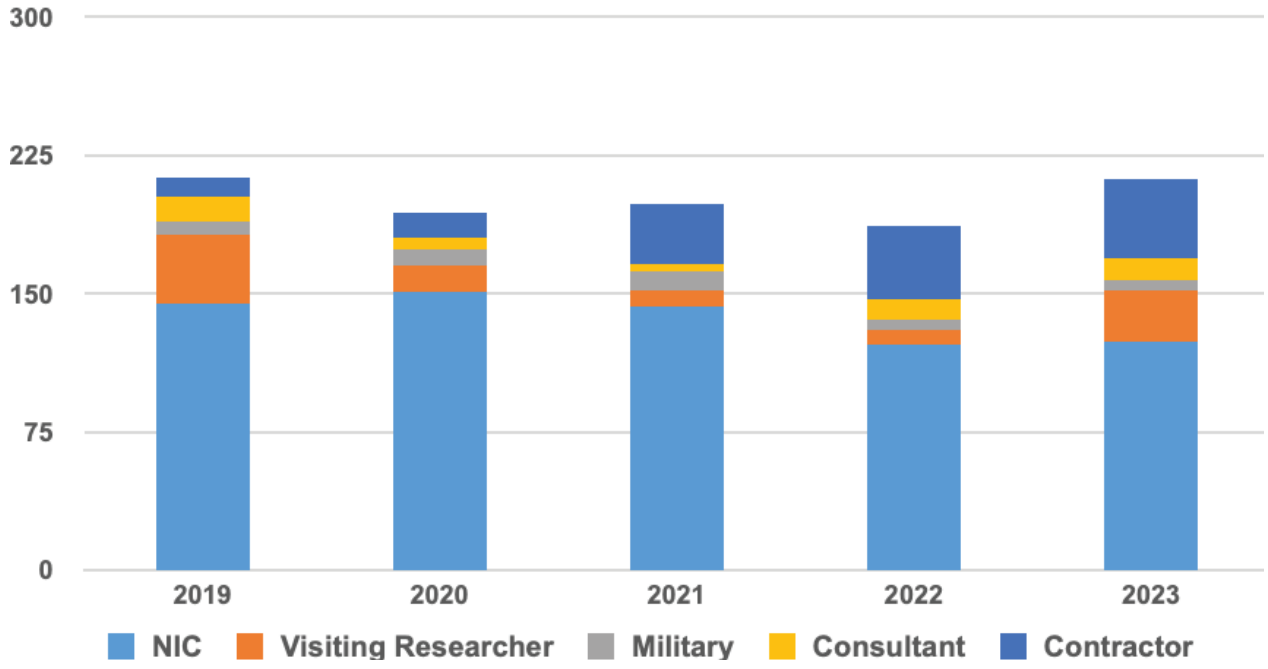
HUMAN RESOURCES AND INFRASTRUCTURE

Overview

The Human Resources & Infrastructure Branch is dedicated to recruiting, retaining, and training the most qualified individuals to fulfil CMRE's mission. Emphasizing diversity, inclusion, and accessibility, the branch manages payroll, pensions, contracts, legal and health matters, and assists staff and their families in settling upon arrival.
Additionally, it oversees CMRE's infrastructure, stockroom, and logistics.
Human Resources & Infrastructure Branch staff place utmost importance on fostering a harassment-free, inclusive work environment, committed to its preservation in all situations.
CMRE is committed to building a diverse workforce, representing all NATO Nations, and aspires to attract young scientists, engineers and technologists in particular. Job opportunities may be explored at www.cmre.nato.int.

Results

At the end of 2023, the CMRE workforce comprised 124 NATO International Civilians (NIC) and 5 military staff.
In 2023, 13 NICs were hired by the CMRE, while 11 NICs departed. Vacancy notices for 23 different posts were published.
The Centre hosted 40 visiting researchers, interns, and consultants of diverse backgrounds and nationalities during the year. Additionally, 43 contractors were employed, principally to ensure the timely delivery of CMRE products and services to customers.
The average age of staff at the Centre is 47, with an average length of service of 10 years. CMRE staff represent 18 NATO Nations and 22% of employees are female.



CMRE Five-Year Workforce Levels

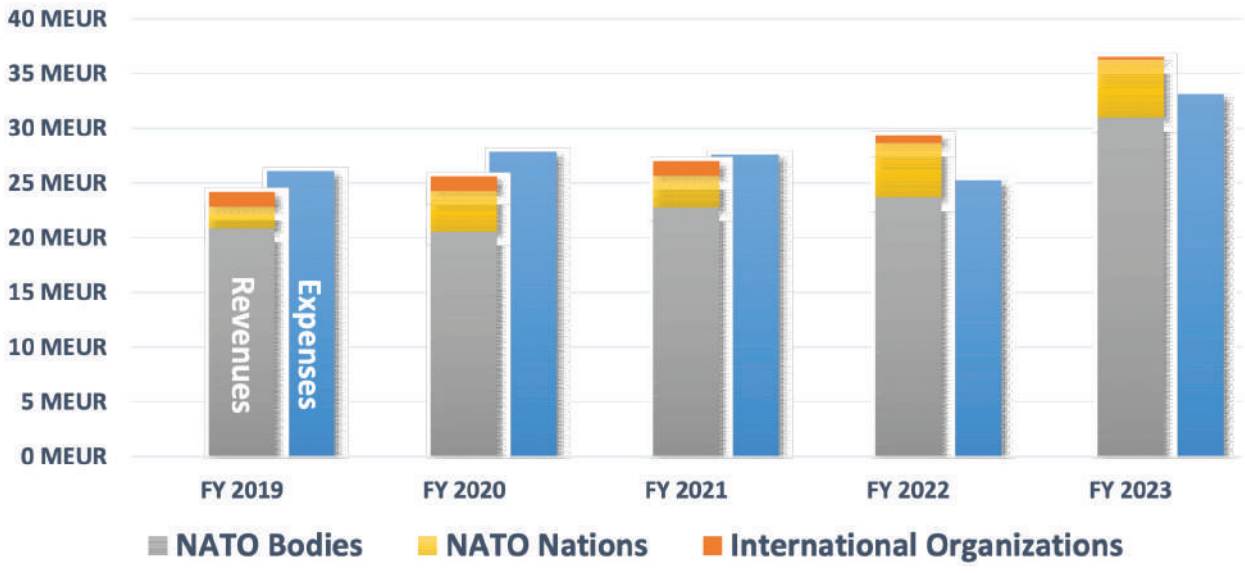
FINANCIAL OVERVIEW

As a customer-funded organization, the Centre must operate at no profit, no loss; however, it is necessary to build reserves to secure the Centre's long-term sustainability and continuation of world-class scientific research. Due to previously accumulated deficit and the financial impact of COVID-19, the Centre greatly curtailed spending during 2021 and 2022 to be able to recovezr depleted financial reserves and prepare for known, unavoidable cash requirements. The results for 2022–2023 showed a surplus because of these efforts, as well as benefiting from increased project and research vessel revenues.

CMRE revenue during 2023 reached a record high of 36.5 million euros (MEUR), representing an increase of over 40% on the average annual revenue of 26 MEUR over the preceding four years. NATO Allied Command Transformation continued to be the CMRE's key customer, contributing around 75% to CMRE annual revenue. The remaining revenue is generated by delivering products and services to customers from other NATO Bodies and Commands, NATO National government organizations and industry, and International Organizations.

CMRE's scientific, engineering and IT staff charge-out rates to customers must be approved on an annual basis by the relevant NATO committee, and are the way that indirect costs are recovered; indirect costs include administration labour, major vessel maintenance and IT infrastructure costs. The ratio of such indirect costs to the total cost of the CMRE workforce working directly on project-related work was 71.3% in 2023. The NATO-approved ratio for 2024 remains relatively flat at 71.2%, and has been calculated not only to recover the CMRE's indirect costs, but also to replenish the CMRE's financial reserves. The daily charge-out rate for NATO Research Vessel (NRV) Alliance has also remained relatively stable and competitive in the market place for global class research vessels.

Overall, the financial outlook for the CMRE is very positive as forecast revenues for the next three-year period remain at or above 30 MEUR, and costs continue to receive careful scrutiny to manage the cash flow and to deliver the CMRE's scientific programme of work in a diligent and timely manner. Ongoing recruitment efforts will increase the necessary CMRE workforce skill sets essential to ensuring deliverables exceed customer expectations. Through careful planning and strategic business management, the Centre is well positioned going forward to develop increased financial stability as a customer-funded organization.



Evolution of CMRE revenues and expenses for fiscal years 2019–2023

WORKING WITH CMRE

Overview

In July 2012, after over 50 years as part of the NATO Command Structure within Supreme Allied Command Atlantic and then Allied Command Transformation (ACT), the CMRE became an executive body of the NATO Science and Technology Organization (STO). CMRE's mission is to organize and conduct scientific research and technology development and deliver innovative and field-tested science and technology (S&T) solutions to address the defence and security needs of the Alliance, centred on the maritime domain. The STO Charter as approved by the North Atlantic Council required CMRE to be financed through customer funding, consistent with NATO policy.

Since 2013, CMRE has successfully provided scientific and engineering products and services for a spectrum of customers with a no-profit, no-loss business model. Past and existing CMRE customers include: NATO bodies—in particular ACT, which remains CMRE's largest customer by revenue, and, from 2023, the STO through the Office of the Chief Scientist; NATO National government organizations; NATO Nation industrial entities; and participation in consortia executing projects funded by EU grants. CMRE delivers products and services for these different customers in different ways:

- For NATO entities, the mechanism used is usually a requirements statement document that is provides intent, direction and guidance for the required products and services, thereby engendering a certain degree of flexibility in the research undertaken.
- For NATO Nation industrial entities, a commercial contract is used, usually supported by a non-disclosure of proprietary information agreement.
- For NATO entities and government organizations, an overarching memorandum of agreement or understanding is agreed under which specific projects are carried out under government grants.

Additionally, the Centre collaborates on multi-national projects with customers and funding or contribution in kind from several different nations.

What CMRE offers

CMRE operates two research vessels, the Global Class (and ice strengthened) NATO Research Vessel (NRV) Alliance and the Coastal/Littoral Class Research Vessel (CRV) Leonardo, each with extensive laboratory facilities and fitted with a wide range of advanced sensing and equipment handling systems capable of precise manoeuvring for scientific research tasks. The Centre has a diverse fleet of autonomous underwater and surface vehicles and a world-class inventory of many different types of state-of-the-art sensors, principally to conduct experimentation at sea for basic research, experimentation, concept validation, and demonstration to the NATO operational community. The research vessels and autonomous vehicles can be made available for use by customers through charter arrangements.

CMRE scientists create fundamental knowledge through multidisciplinary theoretical, numerical, and experimental research. CMRE offers scientific research services in the fields of: signal processing; oceanographic remote and in-situ sensing; ocean-atmosphere modelling; control theory; acoustic modelling; modelling and simulation; operations research and analysis; big data analytics; data fusion; autonomy; artificial intelligence; algorithm development; and, climate change and security studies. CMRE has successfully provided research services to customers outside the maritime domain, such as the Lessons Learned Ontology Support Project delivered to NATO's Joint Analysis and Lessons Learned Centre.

CMRE has a world-class ocean engineering capability that enables the rapid development of concepts and prototypes for scientific trials, and military experiments and technical demonstrations. CMRE has developed and tested successfully at sea many prototypes of active/passive sonar arrays and unmanned systems in the fields of: anti-submarine warfare; naval mine countermeasures; port security; and environmental monitoring. CMRE's expertise covers mechanical, electrical, software—including rapid prototyping and the development of minimum viable products, data curation, command and control, and ocean engineering. CMRE has organic test and calibration facili-

ties, which ensure the acquisition of curated calibrated data during experimentation at sea.
Additionally, CMRE staff have experience in preparing people for new maritime system capabilities through awareness training, serious gaming, and by offering specific educational courses.

How to contact us

In summary, CMRE is open for business and stands ready to provide to customers cost-effective research, engineering and software products and services centred on the maritime domain, and also more generic services such as M&S, data analytics and training. Additionally, research vessel charter at competitive market rates is available on a case-by-case basis. Please contact CMRE's Integrated Business Support team at registry.cmre@cmre.nato.int to discuss how CMRE may be able to work with your organization.

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LIST OF ACRONYMS AND ABBREVIATIONS

A&I-NMW	Autonomy and Interoperability for Naval Mine Warfare
AASW	Autonomy for Anti-Submarine Warfare
ACT	Allied Command Transformation
AI	Artificial intelligence
AI2F	Artificial intelligence and information fusion
AML	Additional military layers
ANMCM	Autonomy for Naval Mine Countermeasures
ANOCLAP	Ambient Noise Characterization using Lagrangian Platforms
APP	Allied Procedural Publication
ARTEMIS	Alliance Research & Technology Edge Multidisciplinary Impact System
ASW	Anti-submarine warfare
ATAS	Active Towed Array System
ATR	Automatic target recognition
AUV	Autonomous underwater vehicle
BONO	Bottom node
C2	Command and control
C3	Command, control and communications
C3MRE	Command Control and Communications for Maritime Robotic Exploitation
CATL	Collaborative Autonomy Tasking Layer
CC	Climate change
CCAS	Climate Change and Security
CEDAR	Controlled Electric Detection And Ranging
CHOBIN	Complex Holistic Outline Based Interoperable Network
C-IED	Counter improvised explosive device
CIS	Communication and information system
CISE	Common Information Sharing Environment
CMRE	Centre for Maritime Research and Experimentation
CMS	Combat management systems
CNAD	Conference of National Armaments Directors
COLD	COherent Localization Detection
COTS	Commercial off the shelf
CRV	Coastal Research Vessel
CSSN	Centro di Supporto e Sperimentazione Navale
CST	Custodian Support Team
CTD	Conductivity temperature and depth
CUI	Critical underwater infrastructure
CWIX	Coalition Warrior Interoperability Exercise
D-EKOE	Data and Environmental Knowledge and Operational Effectiveness
DevSecOps	Development, security, and operations
DGA	Direction Générale de l'Armement
DIANA	Defence Innovation Accelerator for the North Atlantic
DKOE	Data Knowledge and Operational Effectiveness
DOD	Department of Defense

DTEX	Disruptive Technology Experiment
DYMS	DYNAMIC MESSENGER
ED	Engineering Department
EDT	Emerging and disruptive technologies
ELINT	Electronic intelligence
EOD	Explosive ordnance disposal
ESTCP	Environmental Security Technology Certification Program
FDTD	Finite-difference time domain
FLS	Forward looking sonar
GCM	Global Climate Model
GCS	Ground control stations
GEOMAR	Helmholtz Centre for Ocean Research
GEOMETOC	Geospatial, meteorological and oceanographic
HCI	Hyper-converged infrastructure
HPC	High Performance Computing
HRLFSAS	High Resolution Low Frequency Synthetic Aperture Sonar
IDA	Institute of Defense Analyses
IDT	In-stride Debriefing in support of Training
IEEE	Institute of Electrical and Electronics Engineers
IST	Information Systems Technology
JALLC	Joint Analysis and Lessons Learned Centre
JSON	JavaScript Object Notation
KPI	Key performance indicators
LARS	Launch and recovery system
LIME	Light and Interoperable Naval Mine Warfare Evaluation
LL	Lessons learned
LLaMa	Large Language Model Meta Artificial Intelligence
LOON	Littoral Ocean Observatory Network
M&S	Modelling and simulation
MARCOM	Allied Maritime Command
MARE	Maritime Resources Enablers
MC	Military Committee
MCM	Mine countermeasures
MCM TRUMPET	Mine Countermeasures Tasking/Reporting for Unmanned/Manned Systems and Planning and Evaluation Tool
MDO	Multi-domain operations
MED ASWAN23	MEDiterranean ASW Autonomous Network
METOC	Meteorological and oceanographic
METRICS	Metrological Evaluation and Testing of Robots in International Competitions
MEUR	Million euros
MIMO	Multiple input multiple output
MNIST	Modified National Institute of Standards and Technology

MOC	Maritime Operations Centre
MSA	Maritime situational awareness
MSTC	Maritime Science and Technology Experts Committee
MUS	Maritime unmanned systems
MUSE	Maritime Unmanned Systems Enablers
MVP	Minimum Viable Product
NAC	North Atlantic Council
NACO	NATO underwater Arctic Climate Observatory
NCIA	NATO Communications and Information Agency
NMW	Naval mine warfare
NORSE	Northern Ocean Rapid Surface Evolution
NREP	Nordic Recognized Environmental Picture
NRL	Naval Research Laboratory
NRV	NATO Research Vessel
NSF	NATO Software Factory
NWCC	NATO Warfighting Capstone Concept
OBS	Ocean bottom seismometers
OCS	Office of the Chief Scientist
ODCR	Observation - discussion - conclusion - recommendation
OES	Ocean Engineering Society
OEX	Ocean Explorer
ONR	Office of Naval Research
OPEX	Operational experiments
P&E	Planning and evaluation
PNT	Positioning, navigation, and timing
PoW	Programme of work
PROMENADE	Improved Maritime Awareness by Means of AI and Big Data Methods
p-SLIM	Slim Vertical Array
PSU-ARL	Pennsylvania State University – Applied Research Lab
QKD	Quantum key distribution
QT	Quantum technologies
RAMI	Robotics for Asset Maintenance and Inspection
RAPS	Rapid Acoustic Prediction Service
RD	Research Division
REA	Rapid environmental assessment
REPMUS	Robotic Experimentation and Prototyping with Maritime Unmanned Systems
RMP	Recognized maritime picture
ROV	Remotely operated vehicle
RTG	Research Task Group
RV	Research Vessel
S&T	Science and technology
S3A	Seabed-to-space situational awareness
SACLANT	Supreme Allied Commander Atlantic

SAS	Synthetic aperture sonar
SCI	Systems Concepts and Integration
SEAWASP	Submarine Environmental Assessment for Wide Area Sonar Prediction
SHAPE	Supreme Headquarters Allied Powers Europe
SLICTA	Slim LIne Cardioid Towed Array
SLOC	Sea lines of communication
SNF	Standing Naval Force
SNMCMG2	Standing NATO Mine Countermeasures Group 2
SPS	Science for Peace and Security
SSS	Side-scan sonar
STANAG	NATO Standardization Agreement
STB	Science and Technology Board
STEM	Science, technology, engineering and mathematics
STO	Science and Technology Organization
TB	Terabyte
THORA	Three-Octave Research Array
TRL	Technology readiness level
UAV	Unmanned aerial vehicles
UGV	Unmanned ground vehicles
USV	Unmanned surface vehicles
UWNET	Underwater communications and networks
UWSAS	Ultra-wideband synthetic aperture sonar
UXO	Unexploded ordnance
VLIZ	Vlaams Instituut voor de Zee
VMI	Virginia Military Institute
WDA	Warfare Development Agenda
WIN	Wargaming Initiative for NATO
XBT	Expendable bathythermographs

April 2024

CMRE-AR-2023

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