



# NATO STO-CMRE

## 2020 ANNUAL REPORT

Science and Technology Organization

Centre for Maritime  
Research and Experimentation









# 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).

# 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.

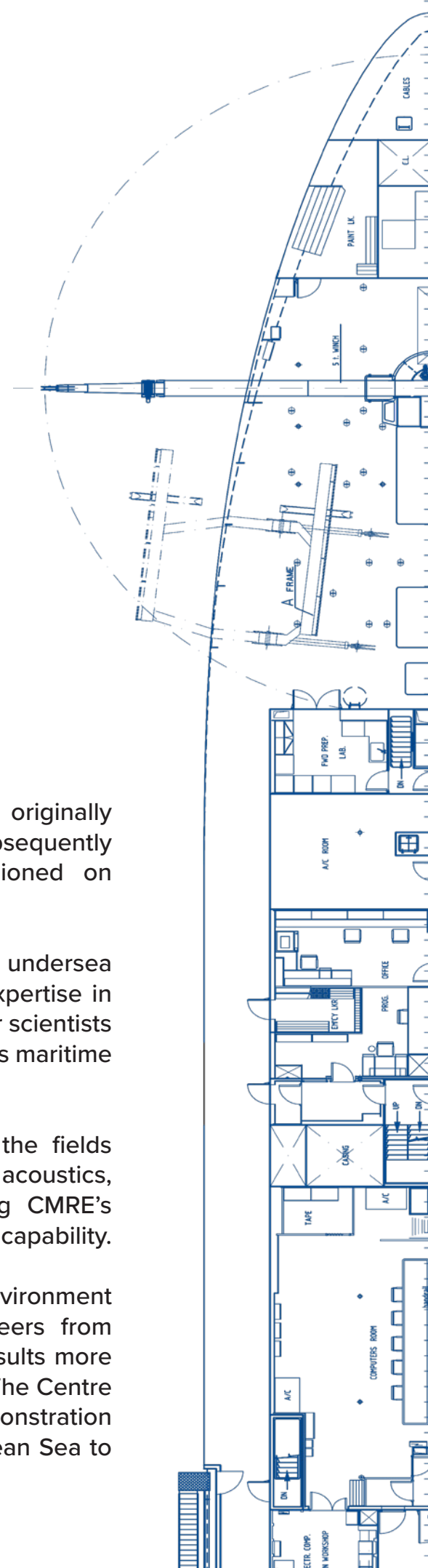
# ABOUT

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 and autonomous systems. Underpinning CMRE's success in maritime research over the years is its sea-going capability.

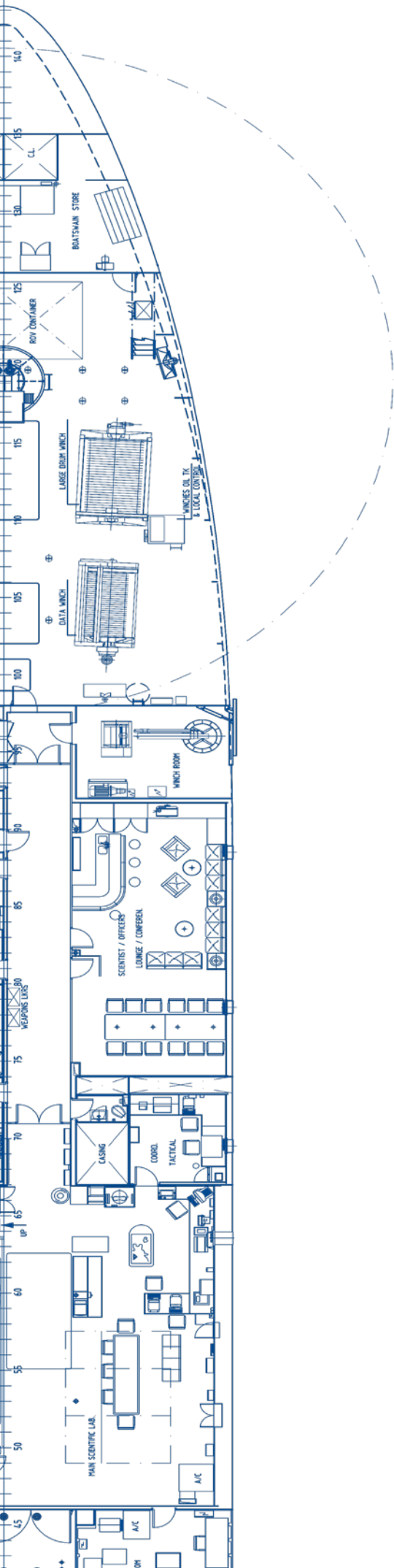
CMRE provides an outstanding at-sea research environment where internationally recognized scientists and engineers from NATO Nations share their knowledge while delivering results more effectively than would be possible by individual nations. The Centre conducts cutting-edge maritime experimentation and demonstration in extremely challenging conditions from the Mediterranean Sea to the Arctic Ocean.





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# FOREWORD

2020 started out to be a promising year of sea trials with NATO Research Vessel (NRV) *Alliance* already off the coast of Sicily in February. We were participating in the NATO Anti-submarine Warfare Exercise, DYNAMIC MANTA, while also conducting technical demonstrations for NATO Allied Command Transformation (ACT), and following that, conducting the last sea trial for the multi-national Littoral Continuous Active Sonar programme. However, things quickly changed to something unrecognizable. A crew member needed to be removed from NRV *Alliance* and put in quarantine because of a potential outbreak in his hometown of the new coronavirus that we had only recently heard about on the news.

Before long, Italy closed its borders, a worldwide pandemic was declared, and we were told to stay home, while stores, restaurants, ski areas, and all non-essential businesses were closed. It was strange and scary for most of us.

But the Centre didn't stop working. We followed the best guidance, lowered the number of staff on site, found enough masks and hand sanitizer for everyone, and through the many new government decrees, seemingly daily at times, we reacted, we adapted, and we continued our work.

Thanks to the perseverance and ingenuity of our staff, the Centre was able to maintain our most important and time-sensitive activities while meeting or exceeding the Italian government's (and NATO's) guidance for safe, hygienic, spatially separated working conditions.

It is legend by now, but our IT team, linked with our on-site NATO Communications and Information Agency (NCIA) team, worked non-stop to develop remote access to our scientific network. Thanks to their dedication, we ultimately ended up with two new methods, which allowed our scientists and others to work more effectively from home.

Our registry and stockroom ensured mail and packages were received and NATO documents were distributed to all. Registry even made it



**Dr Catherine Warner, Director**

possible for our deliverables to be accessed by our customers working from their homes in different countries. We mailed laptops to staff stuck in their home countries, and we even hired new staff remotely!

I am grateful for the dedication and commitment of our staff throughout the year—both on site and at home.

Our support contractors kept our offices and building sanitized every morning; our logistics team kept the hand sanitizers full and constantly arranged spatially separated tables for eating lunch, or moved offices for personal safety; security managed the safety of visitors and coordinated with our Italian hosts, Centro di Supporto e Sperimentazione Navale (CSSN). Finance kept the lights on and our pay cheques coming while coordinating the financial aspects of contracts with our partners and customers. Human Resources managed to track down every single employee, NATO, contractor, or consultant and their phone number for easy recall and emergency notices—and was always a shoulder to lean on when things were just too much. Our administrative assistants, while hardly seen this year due to on-site restrictions, kept things running smoothly in the background and kept us on time and on schedule. Contracting kept our vital supplies

and services coming, despite a nightmare of old software. The Directorate and Business Support Unit staff kept looking at the future, building new business relationships and managing risks associated with working on site, with new customers, and new infrastructure to support remote working.

Our engineers proved once again that the Centre remains at the forefront of technology—using innovation and ingenuity, several advances in acoustic sensors were achieved. Despite infrastructure challenges, a team built a towed array. Vector sensor arrays were mounted to gliders and even quantum magnetic technologies are appearing. Furthermore, our engineers tirelessly prepared for sea trials in March and April. Unfortunately, the Centre's participation in the US-led Exercise BALTOPS and planned sea trials in the High North as part of the NATO ACT Maritime S&T programme of work were not to be. Sea trials were postponed to the fall and to the Mediterranean—in no small part thanks to the flexibility of our customers.

Still—we persevered.

Research teams showed their resilience as well with the capability to adapt theoretical and mathematical tools and concepts to provide help in assessing the evolution of the COVID-19 pandemic. All programmes came together showing the capability to execute our programme of work, while respecting the limited number of people allowed on site.

The Centre's dining facility (mensa) opened for lunch takeout, and when the summer months came, Italy loosened the lockdown and opened her borders. Liguria was almost free of the virus in July. By 15 August, preparations for NATO Exercise DYNAMIC MARINER 2020 were in full force, but the virus came back for another round.

By the fall, we instituted an information campaign that provided us with reminders, posters, floor stickers, a new intranet page for helpful information, and big screen displays of COVID-19 prevalence throughout all the NATO Nations. Personal travel and returning to work had new sets of constraints and requirements, including getting a swab test.

Our first sea trial during the pandemic posed many challenges. We were all concerned about the risk and there were more questions than answers. Protocols for the ship changed as the rates of COVID-19 in La Spezia skyrocketed. I learned more about  $R_0$ , epidemics, HVAC systems, and COVID-19 testing, than I ever wanted to know. However, I am so thankful that I am surrounded by people smarter than me who provided me with data, analyses, and helpful considerations in trying to balance the risk of keeping the Centre running while not risking the health and safety of our staff. The MCM team rallied and boarded NRV *Alliance* for pre-trial testing and quarantine; we even had volunteers for alternates, who quarantined alongside the MCM team. Despite some initial weather delays, DYNAMIC MARINER was a great trial, which included an MCM detachment from the US, who came to Italy and quarantined 14 days BEFORE the pre-trial procedures began. The CMRE team reported feeling completely safe and supported by the ITA N and the new Commanding Officer of NRV *Alliance*, C.F. Nicola Pizzeghello.

To replace the cancelled sea trials in the High North, ACT and ONR agreed to move the planned activities to the Mediterranean (MREP20), which immediately followed DYNAMIC MARINER. This time the quarantine was a bit longer, and we also had volunteer alternates, fortunately they were not needed. The trials gathered a huge amount of data and deployed some new sensors in the Strait of Sicily in preparation for future trials in the High North, again a great success.

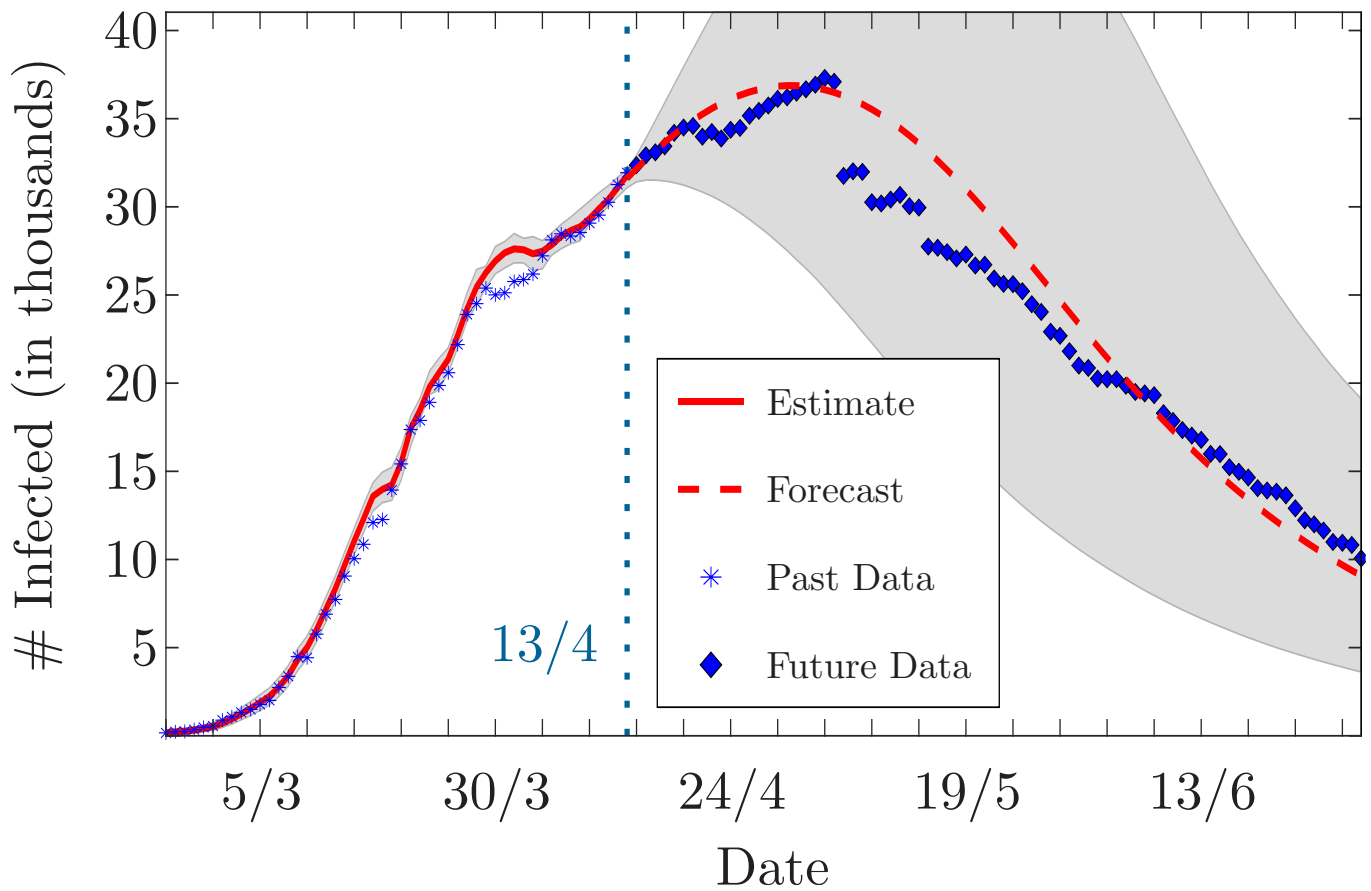
And finally came the multi-national Distributed Autonomous Networked Systems (DANS) trial, our THIRD sea trial under COVID-19 protocols. The team had an even longer quarantine, but it was our crowning achievement of the year, demonstrating our shining engineering work over the past years—deploying so many assets (including my new favourite—the BonBon!!)—dodging bad weather—and working alongside Coastal Research Vessel (CRV) *Leonardo* as well.

With pleasure, I submit this report summarizing the scientific, engineering, and business support activities accomplished in 2020.



# CMRE'S COVID-19 RESEARCH

## COLLABORATION LEADS TO NEW MODELLING APPROACH



**Forecast of the COVID-19 infection in Lombardia region, Italy, produced with the developed learning and forecasting algorithm on 13 April 2020.**

Since the beginning of 2020, the outbreak of a new strain of coronavirus has caused hundreds of thousands of deaths and put the world's most advanced healthcare systems under heavy pressure. In order to slow down the spread of the disease, known as COVID-19, and reduce the stress on healthcare structures and intensive care units, many governments have taken drastic and unprecedented measures, such as the forced closure of businesses and industries and enforced social distancing regulations, including local and national lockdowns. To effectively address such pandemics in a systematic and informed manner in the future, it is of fundamental importance to develop mathematical models and algorithms to predict the evolution of the spread of the disease to support policy and decision making at the governmental level.

CMRE's Data Knowledge and Operational Effectiveness (DKOE) team, in collaboration with

researchers at the University of Connecticut (UConn), have developed a modelling approach to forecast the evolution of the COVID-19 epidemic. This new method helps decision makers to anticipate possible future outbreaks of the virus. The collaboration between DKOE and UConn contributed to the work of the Connecticut Academy of Science and Engineering (CASE) council, which advised the Governor of Connecticut on adopting appropriate precautionary measures in spring 2020 as well as on a strategy to re-open the State after lockdown.

DKOE's contribution was to adapt their knowledge of tracking and predicting the movement of targets (such as ships, submarines and aircrafts) to tracking and forecasting the number of people in a population infected with COVID-19. The researchers applied a technique called Adaptive Bayesian Learning to a number of epidemiological models, which allowed key parameters, such as the infection rate, to be modelled as time-varying



**CMRE staff discuss a graph of the reported and modelled COVID-19 infections in the US. Estimated infections during the learning phase of the model are shown as a solid red line. The forecast infections are shown as a dashed line. The vertical dashed line is 26 April 2020, the beginning the forecast. The reported number of infections are shown as a solid blue line. The red area represents the 90% confidence interval of the forecast.**

instead of stationary. Additionally, leveraging their expertise in the analysis of maritime traffic patterns-of-life, DKOE scientists are assessing the impact of national and local lockdowns on global maritime mobility.

**Achievements**

- **Official COVID-19 data:** The algorithm has been successfully validated with COVID-19 infection data from National authorities, including data from Italy and United States.
- **Improved forecasting performance:** The new model has better forecasting accuracy than many existing epidemiological models.
- **Time-varying epidemic spread parameters:** The proposed approach learns the virus-spreading model parameters (the infection and recovery rates) at each time iteration. The evolution of the parameters is useful in addressing the effectiveness of containment measures.
- **Quicker detection:** Further work is being performed on the early detection of changes in the infection rate in order to allow authorities sufficient time to implement containment measures.

- **COVID-19 impact on shipping:** A synthetic composed index that quantitatively assesses ship mobility in a given unit of time has been used to quantify the impact of lockdown measures on global maritime traffic. The index, computed on an Automatic Identification Systems data set that comprises a trillion messages broadcast worldwide by 50,000 ships, has revealed an unprecedented drop in maritime mobility.

**Publications**

[1] D. Gaglione, P. Braca, L.M. Millefiori, G. Soldi, N. Forti, S. Marano, P.K. Willett and K.R. Pattipati, “Adaptive Bayesian Learning and Forecasting of Epidemic Evolution—Data Analysis of the COVID-19 Outbreak,” in *IEEE Access*, vol. 8, pp. 175244- 175264, 2020.

[2] L.M. Millefiori, P. Braca, D. Zizzis, G. Spiliopoulos, S. Marano, P.K. Willett and S. Carniel, “COVID-19 Impact on Global Maritime Mobility,” under review, 2020.

[3] Braca, P. Gaglione, S. Marano, L. M. Millefiori, P. Willett and K. Pattipati, “Quickest detection of COVID-19 pandemic onset,” under review, 2020.

[4] Braca, P. Gaglione, S. Marano, L. M. Millefiori, P. Willett and K. Pattipati, “Quickest Detection of Critical COVID-19 Phases: When Should Restrictive Measures Be Taken?” under review, 2020.

# RESEARCH DIVISION

## Innovation Landscape

CMRE's research programme is closely aligned with themes identified by NATO as Emerging or Disruptive Technologies (EDTs). Underlying the EDTs are four primary drivers, Intelligent, Digital, Interconnected and Distributed, which will play an increasing role in defence science and technology (S&T) over the next two decades. The ultimate goal of research in these areas is future military capabilities that will seamlessly integrate the human, physical and data dimensions through a decentralized and ubiquitous large-scale network of Artificial Intelligence (AI) enabled assets.

Using the taxonomy of the *NATO STO S&T Trends 2020-2040* report, CMRE's strengths align with EDTs "AI" (B.6 Optimize Vehicle Use), "Data" (A.9 Algorithmic Advantage, A.7 Courses of Action) and "Autonomy" (C.7 Deploy a Swarm). CMRE's expertise in these areas is supplemented by ongoing maritime-related activities in B.2 Virtual Command Advisor, B.9 Automated Targeting, A.4 Situational Awareness, A.8 Global Intelligence, C.2 Repurpose Commercial Systems and E.4 Commercial Space ISR. Furthermore, activities in the Quantum domain are emerging at CMRE in support of EDTs D.1 Transparent Ocean, D.5 GPS Denied Environment, D.6 Precision Navigation and D.8 Quantum Communications, with great potential for growth in G.1 Super Sensing and G.7 Train in Reality.

CMRE is well positioned to address EDTs thanks to its deep knowledge base, developed over decades of investment by NATO Allied Command Transformation (ACT) through their Maritime S&T programme. In recent years, CMRE's expertise has further strengthened through its broadening customer base in maritime defence research.

The range of potential NATO operations is expanding and evolving due to changes in the global political, military, economic, technological, social and climatic landscapes. The 2020 COVID-19 pandemic underscored the fact that our security and environment are inextricably linked. Another example of this connection is arising in the Arctic where climate change is rapidly reducing the extent of ocean ice leading to increased resource extraction and commercial and military activity, with the inevitable risk of conflict. The Arctic is now an area of concern for NATO. Also driven by climate change, uncontrolled mass migration of people has

become a significant security issue for many NATO Nations, and in 2020 the problem was exacerbated by the COVID-19 pandemic.

CMRE is re-evaluating its competencies and organizing its resources to focus on EDTs. More than ever, the Centre is drawing on collaboration with the Nations' experts for new EDT-related research. CMRE's status as a hub for the Nations' researchers to exchange ideas and work together has never been more valuable than it is today for addressing the science challenges and opportunities posed by EDTs.

## Future Work

The role of CMRE in the new innovation landscape will not only be its focus on EDTs, but also on the complex and difficult-to-predict interactions between them. Staying ahead of the technological curve will require a heightened emphasis on collaboration with the Nations and unerring alignment with the direction of ACT, and with the requirements of NATO as a whole. The Centre's multidisciplinary approach to research and its heritage of collaboration with the academic and private sectors of the Nations is well-suited to foster the synergies that will crack the tough S&T challenges ahead.

The COVID-19 pandemic dramatically revealed the impact of globalization on our common future. The global transportation network spread the SARS-CoV-2 coronavirus around the world before medical authorities and governments could understand it and respond to the threat. Similarly, globalization has made EDTs available to non-state actors. For example, today terrorists can easily deploy inexpensive but sophisticated drones for surveillance and to deliver weapons, and crowdsourced information from social media can be easily distilled into actionable intelligence by insurgents. The rapid development and proliferation of high-tech capability has resulted in a renewed commitment by NATO to maintain its technological edge, which CMRE is contributing to in the Maritime domain.

A current EDT initiative at CMRE is the application of AI to automatic target classification for Anti-submarine Warfare (ASW) and Mine Countermeasures (MCM). This work has been so successful that many Nations have expressed

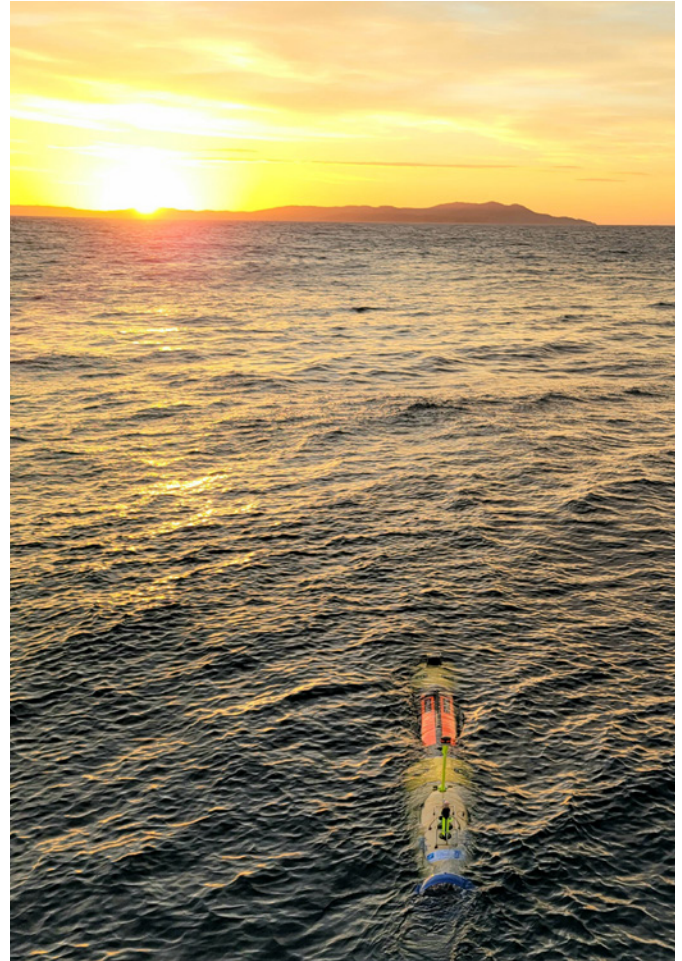


interest in incorporating resultant innovations into their defence acquisition programmes. And Nations have relied on CMRE advice for evaluation and procurement of advanced ASW and MCM military equipment.

Related to the AI EDT theme is the overarching theme of Data, that not only drives AI, but is also key to the development of analytical methods to ensure decision advantage. As in the case of AI, a balance is required between privacy, exploitation, sharing and utility, together with a common governance approach to data interoperability, integrity, and standards. CMRE envisages future contributions to NATO's efforts on EDT-based Intelligence, Surveillance, Targeting and Reconnaissance, to synthetic acoustic sensing of the ocean ("Ocean of Things") and to the exploitation of the ever-increasing streams of data from satellites. The Centre's expertise in data fusion can be harnessed to help develop next-generation "full-force situational awareness". This requires the support of the Centre's Modelling and Simulation (M&S) capability, which will continue to grow as a way to de-risk concept development.

Since AI requires vast amounts of data, CMRE also intends to take on the challenge of "data integrity" by developing, distributing and supporting curated data sets which are needed for the training of Machine Learning algorithms. This would support future work in AI Model Integrity, aimed at providing validation of AI systems thus helping to build trust and acceptance of this technology among users. However, a prerequisite to such work is a Data and Analytics Governance framework spanning NATO and the Nations, which would provide interoperability among AI developments. Such a framework would stimulate research in Agent-Based AI-powered M&S and Multi-domain Virtual Command and Control, which are steps toward Human-Machine teaming. As trust in AI-powered autonomous systems grows, the stage will be set for highly capable military systems, such as un-crewed submarines with independent capabilities.

Environmental science is emerging as a domain of interest for NATO due to the growing importance of maritime security matters, partly driven by climate change. With a Global class research ship, *NRV Alliance*, and a strong oceanography team, CMRE is ideally suited for research on climate change in maritime environments of interest to NATO such as the Arctic and the Mediterranean regions. Equipped with a new Arctic Research Strategy



**CMRE researchers run tests with the MUSCLE AUV October 2020 during the NATO MCM Exercise DYNAMIC MARINER.**

agreed between CMRE and ACT, the Centre will be able to help NATO and the Nations understand and adapt to the defence and security implications of climate change.

Quantum technologies hold great potential for advances in many areas, such as sensing, timing, navigation and precision positioning, computation, communications, and cryptography. CMRE is actively doing research in quantum-based magnetic sensing and secure underwater communications. There is enormous latitude to take on other areas relevant to maritime defence, such as underwater navigation and ultra-fast target detection and classification from passive sonar.

Taken together, the EDTs identified by NATO present a rich and diverse set of research challenges that are critical to maintaining the Alliance's technological edge and for which CMRE is well-positioned to contribute to through its in-house research and experimentation capability, and through collaboration with the Nations' research institutions.

# AUTONOMOUS NAVAL MINE COUNTERMEASURES

## Overview

CMRE's Autonomous Naval Mine Countermeasures (ANMCM) programme focuses on delivering technologies, methods, algorithms and data that will enable CMRE and Allied Navies to design, develop and test a network of securely communicating autonomous vehicles under realistic operational conditions for the localization, detection, identification and neutralization of naval mines.

As part of the Allied Command Transformation (ACT) Maritime S&T Programme of Work (POW), the CMRE ANMCM programme for 2020 included four projects.

- The Collaborative Autonomous MCM (CAMCM) project utilizes robotics in MCM to deliver doctrinally relevant autonomy, collaborative autonomy and on-board machine intelligence. This project is enabling a high-level generic autonomy architecture to facilitate heterogeneous system interoperability and collaboration for future exploitation by NATO Nations.
- The High-Resolution, Low-Frequency Synthetic Aperture Sonar (HRLFSAS) project is focused on the development of a prototype advanced sensor for the enhanced detection, classification and identification of objects not detectable by higher-frequency sonar systems such as buried objects or objects in complex environments, thereby improving the effectiveness of the capability envelope for naval MCM sensors.
- The Planning and Evaluation (P&E) for MCM project focuses on addressing the current deficiencies in the P&E of minehunting missions performed by autonomous underwater vehicles employing side scan or synthetic aperture sonars, high resolution acoustic systems or optical sensors, and the evaluation of a system of systems tasked with a full MCM mission.
- The S&T Trials for MCM project aims to test and demonstrate in realistic scenarios recent S&T advances in either controlled trial conditions or with partners in high visibility events such as NATO exercises. This project is dedicated to the experimentation and analysis of the R&D outcomes of the CAMCM and P&E for MCM projects.



**The CMRE team deploy the MUSCLE AUV from NRV *Alliance* during DYNAMIC MARINER 2020.**

## Activity

In 2020, the CAMCM Project team carried out the following activities:

- Work started on task allocation for multi-vehicle autonomy, which focused on defining a strategy for simultaneous survey and reacquisition. A new cost function for defining task priority was developed, taking into account the probability of a contact being a mine, information provided by the onboard Automatic Target Recognition (ATR) algorithm, contact locations vis-à-vis transit costs, and preferential zones of the survey area (e.g. Q-routes). Initial tests began in collaboration with the P&E simulation tool development.
- A key enabler of machine decision-making is machine perception and situational awareness. In order to provide this capability, CMRE's work on deep learning focused on the development of ATR for other vehicles' sensors and the development of synthetic images utilizing generative adversarial networks.
- Implementing a multi-sensor data management strategy and meta-data tagging for effective environmental data exploitation to enable the fusion of multi-sensor ATR and the performance evaluation of future systems of systems.
- Work continued on developing and defining a generic collaborative autonomy framework,



sharing the machine intelligence across an acoustic communications-enabled network of self-organizing vehicles to maximize vehicle capability.

The CMRE HRLFSAS project team initiated a study on Multiple input Multiple output SAS (MIMO SAS) with the aim to decrease the dimensions of the HRLFSAS system for better portability. The team is developing a realistic 3D LFSAS simulator to generate synthetic data to support data analysis, learning algorithms, and system performance evaluation.

The P&E for MCM project team research and develop algorithms to improve the planning of autonomous MCM missions consisting of multiple vehicles conducting multiple phases (detection, classification, re-localization, and identification). During 2020, the project team continued to improve the vehicle self-awareness through on-board evaluation of minehunting performance and feedback into the autonomy engine of the vehicle. This CMRE effort focused on developing novel techniques, based on machine learning and Gaussian models to estimate sonar performance from actual sensor information—such as quality of data and complexity of an area. This through-the-sensor approach allows for continually updating assessments taking into account sonar system measures. Further input to the performance assessment may be made by estimating the real world conditions directly—such as the complexity or type of bottom (e.g. flat, rippled, cluttered, etc). Machine learning techniques are used to derive this information from the sonar images themselves—adding further input to the assessment of sonar performance.

In addition to supporting the ANMCM programme at-sea trials and participation in exercises, the S&T Trials for MCM project team performed an initial scoping study to capture relevant use cases and requirements for a test site and infrastructure that would enable the study of long term performance of sensors and autonomy approaches. In the context of naval MCM specifically, such a test range would allow a fine-grained characterization of mine hunting sensors with respect to temporal environmental changes, and further study of long term/long range approaches to autonomous minehunting.

## Highlights

From 29 September — 10 October 2020, the CMRE ANMCM team, along with collaborators from the US 6th Fleet, MCM detachment from Rota, Spain, embarked on-board NRV *Alliance* and sailed to waters south of France to participate in DYNAMIC

MARINER 2020 (DYMR20). DYMR20 was a NATO exercise designed to train the maritime component of the NATO Response Force, a high readiness and highly capable multinational force that can deploy quickly, wherever needed. CMRE ANMCM researchers tested technologies, developed at the Centre, to study the on-board detection and classification systems of autonomous underwater vehicles. Notable achievements included:

- Demonstrated on-board seabed characterization, P&E products, and ATR;
- Demonstrated adaptive survey behaviour optimizing time constraints without compromising on data quality;
- Predicted performance characteristics of deployed sensors;
- Deployed a new vehicle in the water and acquired data with an acoustic camera for object identification;
- Exchanged messages between heterogeneous vehicles (CMRE and US MCM 6th fleet detachment from Rota, Spain);
- Completed operator post-mission analysis; and,
- Reported on a daily basis to COM MARCOM as the officer scheduling/conducting the exercise providing a comparison between the legacy MCM systems participating in the exercise and the new autonomous concepts.

Other highlights of the CMRE ANMCM programme during 2020 include:

- Within the CAMCM project, 2020 saw the initial developments of an online task decomposition in simulation and the optimization of the high-level generic autonomy architecture—the Distributed Decoupled Collaborative Autonomy Framework (D2CAF).
- For the first time, CMRE's prototype HRLFSAS system was successfully embarked and used on-board a platform at sea: the system was embarked on CRV *Leonardo* and deployed to obtain preliminary HRLFSAS imagery of sandy sea floors in the open waters close to CMRE facilities.
- Main developments in the P&E for MCM project during 2020 were in implementing the performance predictions leveraging input from the bottom characterization.



## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY OFFICE OF NAVAL RESEARCH GLOBAL (ONR-G)

# DYNAMIC MARINER 2020

### Overview

CMRE hosted the US Navy (USN) Sixth Fleet Mine Countermeasures (MCM) Detachment Rota team, together with supporting staff, on-board NATO Research Vessel (NRV) *Alliance* for NATO Exercise DYNAMIC MARINER 20 from 29 September – 10 October 2020. The US team operated their three MK18 Mod II autonomous underwater vehicles (AUVs) for minehunting operations. On-board NRV *Alliance*, the US team partnered with the CMRE ANMCM team and its embarked MUSCLE, BlackCAT, and BIONDO AUVs, with the intent of accelerating autonomous underwater vehicle technology and pushing forward heterogeneous vehicle collaborative autonomy concepts for naval MCM.

The MCM environment within NATO Response Force-Maritime (NRF-M) certification Exercise DYNAMIC MARINER 20 and the concurrent national French Navy Exercise OLIVES NOIRES 20 proved an ideal scenario for testing the deployed capabilities for naval mine detection, classification and identification. The MCM training objectives for the exercises focused on port breakout, amphibious operations, and force protection of maritime assets. US participants appreciated the opportunity to conduct MCM and explosive ordnance disposal (EOD) training with NATO Allies.

### Results

- USN and CMRE teams shared information and valuable new perspectives on minehunting sensors, tactics, adaptive vehicle behaviours, and collaborative autonomy concepts.
- CMRE vehicles received underwater communication messages from the US AUVs. Such inter-vehicle communication is an essential enabler for collaborative autonomy among a system of heterogeneous vehicles.
- USN participants reported a number of notable achievements, including: the first autonomous reacquire-in-stride (detection to identification) by a US Navy MK18 Mod II vehicle equipped with forward looking sonar (FLS); the first application of US MK18 collaborative autonomy framework during a NATO exercise; the first application and successful demonstration of FLS object avoidance in an operational environment; the first demonstration of rapid intelligence preparation of the environment using autonomous reacquire-in-stride technology; and, first demonstration of squad-level objective redundancy by operational US MK18 Mod II AUVs.
- The opportunity to learn from USN operational experience of using minehunting AUVs was much appreciated by the CMRE team. Such learning contributes significantly to achieving the aim of 'day zero' interoperability among the different autonomous systems for minehunting operations being developed by NATO Nations.

### Contact

For further information, please contact John Redmayne ([john.redmayne@cmre.nato.int](mailto:john.redmayne@cmre.nato.int)).



In October 2020, NRV *Alliance* participated in the NATO Exercise DYNAMIC MARINER to demonstrate the on-board detection and classification systems of autonomous underwater vehicles.





## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY US OFFICE OF NAVAL RESEARCH

# IMAGING SAS PERFORMANCE ESTIMATION & E3ISD

### Overview

The common long-term goal of the closely related Imaging SAS Performance Estimation and Extracting, Explaining, and Estimating Information in Sonar Data (E3ISD) projects are to develop principled performance-estimation models that can leverage quantities measured through-the-sensor to predict accurately automatic target recognition (ATR) performance. More pointedly, the goal is to address this challenge in the context of naval minehunting operations using various high-frequency (HF) and low-frequency (LF) sonar data products. The two projects are distinguished by the frequency band considered and exploited.

The three main scientific objectives are: the development of a robust detection and classification approach (i.e. ATR); the development of ways to quantify information content; and, the development of a performance-estimation tool that links information content to ATR performance. Fulfillment of these objectives will then enable the estimation or prediction of ATR performance—the probability of detection and classification with respect to false alarm rate—as a function of the information quantities.

### Results

The research performed under the high-frequency project focused on leveraging sonar data represented in the physical image domain. The technical approach was to compute image quality and complexity metrics to obtain estimates corresponding to each local patch of seafloor in the imagery. A newly developed target detection algorithm was then applied to each image to generate a list of contacts, which was then passed to a deep-learning-based classification algorithm that outputs the probability that each contact is a target based on the sonar “mugshot” directly. The quality and complexity values associated with each contact can then be paired with the classification scores to develop a performance prediction model for future test data.

The research performed under the low-frequency project focused on leveraging sonar data represented in the acoustic colour domain, where target responses are presented as a function of frequency and aspect. To exploit fully the information contained in this novel data representation, specially controlled experiments within a convolutional neural network (CNN) framework were developed for three classification-related purposes. The first task was to learn principled, explainable features for classification that could be tied directly to specific object characteristics. The second task was to establish when an increase in model complexity makes a material difference for classification purposes. The third task was to determine quantitatively whether simulated (model) data contained the same discriminatory information as measured (real) data, or whether additional model development was needed before the two types of data can be used interchangeably for classifier training.

### Contact

For more information, please contact David Williams ([david.williams@cmre.nato.int](mailto:david.williams@cmre.nato.int)).



## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY BELGIUM

# SANDY COAST 2020 MAUV ANALYSIS SUPPORT

### Overview

The Belgian Navy tasked CMRE to support medium sized AUV minehunting trials during the bi-National MCM Exercise SANDY COAST 2020. CMRE staff provided similar support in 2017 during which the performance of various unmanned platforms was assessed. This assessment provided valuable input into the procurement process for the combined BEL/NLD future MCM capability—which will include a manned mothership deploying various autonomous platforms. For 2020, the analysis focussed on the performance of medium sized AUVs as will be employed within the future system. Three such platforms performed minehunting trials during the course of the exercise.

### Results

- A number of reporting formats were jointly developed to ensure that sufficient details were captured during the platform deployments.
- A CMRE analyst deployed to Belgium in order to work closely with the trial's team.
- CMRE reconstructed the mine hunting missions and determined a number of performance metrics, including: overall clearance, coverage rate, false alarm rate, and probability of detection/classification.
- Further analysis methods were developed to automate the determination of sonar detection performance as a function of cross track range, to provide a more detailed characterization of sensor performance as input for planning and evaluation tools.
- CMRE briefed individual performance to the various participants of the trials and further generated a combined analysis report for the Belgian Navy, which included a side-by-side comparison of vehicle performance across the various metrics mentioned above.
- The CMRE analysis provided further insight for the Belgian Navy as to the real world performance of the autonomous system that will be included in their future MCM capability toolbox.
- The close (and continued) cooperation between the Belgian Navy and CMRE exposes the Planning and Evaluation project within the ANMCM programme to the real world performance of autonomous platforms employing synthetic aperture sonar (SAS) systems. The accurate planning and evaluation of such systems will be critical towards maximizing the potential of autonomous mine hunting in future systems—such as the BEL/NLD MCM mission toolbox.

### Contact

For more information about this activity, or the potential for future CMRE support for the analysis of naval mine warfare trials and exercises, please contact Chris Strode ([christopher.strode@cmre.nato.int](mailto:christopher.strode@cmre.nato.int)).

## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY DIRECTION GÉNÉRALE DE L'ARMEMENT (DGA), FRANCE

# FRATRe PROJECT

### Overview

Under the new French mine countermeasures programme, DGA proposed in 2018 a study to improve, using deep learning (DL), the algorithms developed to detect and classify mines in high resolution synthetic aperture sonar (SAS) images provided by autonomous underwater vehicles (AUVs) or by unmanned surface vessel (USV).

With the FRATRe (Tâche détection et classification simultanée de cibles) project, DGA wanted to leverage the advances CMRE has made in automatic target recognition (ATR) using deep learning for the classification of targets in high resolution SAS images by funding collaboration between CMRE, the Ecole Nationale Supérieure de Techniques Avancées (ENSTA) Bretagne, and SCALIAN, a small French company specialized in software development. The main objectives are: to develop a high fidelity acoustical image simulator (SCALIAN) to overcome data limitations for convolutional neural net (CNN) classifiers; an automatic seabed characterizer (ENSTA Bretagne) to improve and evaluate performance in complex seabeds; and, a deep learning algorithm (CMRE) to detect and classify targets in simulated and real sonar images.

ATR is usually performed in three stages: object detection, binary classification and target recognition. The detector aims to localize all the potential targets on the sea floor whereas the binary classifier distinguishes between real targets and false alarms. In 2019, the CMRE team proposed to adapt the latest version of the CMRE classifier on small SAS snippets to large SAS tiles; and implemented a new single stage detection/classification algorithm based on the CNN classifier trained for classification. A subset of MANEX'14 database was manually segmented and a framework developed to evaluate the algorithm performance according to the seabed environment. Although detection and classification in a single stage showed promising results; its performance was improved, especially in complex environment, using a deep learning architecture and prior environment filter to compensate for the lack of training data.

### Results

- In 2020, the detection/classification framework was finalized and the final algorithm performance evaluated on MANEX'14 subset of segmented data. In parallel, the SCALIAN was released, a first version at the end of 2019 and a second one at the end of 2020.
- The evaluation framework was updated to use two simulated side scan sonar databases released by SCALIAN. Early experimental results using simulated data coupled with ENSTA Bretagne outcomes on seabed characterization are promising.

### Contact

For more information about this project, please contact  
Thibaud Berthomier (thibaud.berthomier@cmre.nato.int).

## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY THE STRATEGIC ENVIRONMENTAL RESEARCH AND DEVELOPMENT PROGRAM, USA

# DEEP LEARNING FOR UNDERWATER UXO REMEDIATION

### Overview

An unfortunate legacy of former military activities is the contamination of aquatic environments with military munitions. In the United States alone, more than 400 underwater sites, spanning an area in excess of 10 million acres, potentially contain such munitions. The presence of these munitions is a serious threat to both humans and the environment, so remediation is necessary. But the return of these contaminated waters to public use is contingent upon the analysis and assessment of wide-area and detailed underwater surveys. Therefore, the US Department of Defense (DoD) has expressed a need for the development of technologies that will enable the detection and classification, at high probability, of military munitions at underwater sites.

The objective of this project is to develop a novel detection and classification framework for unexploded ordnance (UXO) that exploits sonar data. The new algorithms will be based on deep-learning techniques, specifically deep convolutional neural networks (CNNs). The successful development of this approach should enable the attainment of higher probabilities of detection and classification, at much lower false alarm rates, than is possible with existing approaches. As a result, the application of these machine-learning algorithms to sonar data collected at potentially contaminated underwater sites can guide more efficient remediation efforts. Specifically, because fewer resources will be spent investigating harmless clutter, the cost of remediation should decrease substantially.

### Results

- The project has focused on the development of data normalization and detection algorithms for measured data from two low-frequency sonar systems: the Sediment Volume Search Sonar (SVSS), and the Multi-Sensor Towbody (MuST). These downward-looking synthetic aperture sonar (SAS) systems, designed to achieve sediment penetration, provide high-resolution three-dimensional (3D) volumetric imagery below the sea floor, making large-scale buried object detection feasible.
- The fast algorithm for the automated detection of buried and proud objects in 3D SAS imagery establishes the positions of underwater targets by finding localized volumes of strong acoustic returns on or within the sediment. The algorithm relies on a physics-based data normalization step, and greatly reduces the amount of data that must be passed to a follow-on classification stage. The promise of the approach has been demonstrated for man-made objects present in real, measured SAS data cubes collected at multiple aquatic sites by both of the aforementioned experimental systems. The alarms generated by the detection algorithm will next be used as inputs to train 3D CNNs for classification.

### Contact

For more information about the Sonar-Based Deep Learning for Underwater UXO Remediation Project project, please contact David Williams ([david.williams@cmre.nato.int](mailto:david.williams@cmre.nato.int)).



## AUTONOMOUS NAVAL MINE COUNTERMEASURES

FUNDED BY THE EU COMMISSION

# OCEAN2020 PROJECT

### Overview

The Open Cooperation for European Maritime Awareness (OCEAN2020) project is funded by the European Union's Preparatory Action on Defence Research and implemented by the European Defence Agency. The project has the main objective to demonstrate enhanced situational awareness in a maritime environment through the integration of legacy and new technologies for unmanned systems with intelligence, surveillance, target acquisition, and reconnaissance (ISTAR) payloads, by pulling together technical specialists in the maritime domain, to support the efficient and effective execution of the operational decision cycle. Led by Leonardo SpA, the team involving 43 entities is drawn from 15 countries across Europe. In particular, the OCEAN2020 consortium will address the problems of integrating EU systems and individual organizations into a coherent framework.

A technical demonstration in the Mediterranean in 2019, and a planned one in the Baltic during 2021, both contribute to the EU's ability to lead innovation in support of Europe's strategic vision in the maritime domain.

### Results

- CMRE's BIONDO AUV was refitted with a larger hull section and more options for ballast and floatation placement, which will allow the vehicle to be operated in waters of low salinity, such as in the Baltic Sea, where the OCEAN2020 Baltic Sea Demonstration is to be conducted in 2021.
- The software and communications suite of CMRE's BIONDO AUV was upgraded, including developing an adaptation layer that will connect CMRE BIONDO C2 system to other project partners (Saab and TNO).
- Preliminary development of an offline detector for acoustic camera imagery.
- Data collection with acoustic camera (on-board BIONDO) for additional analysis in preparation for August 2021 demonstration in the Baltic.
- Ongoing development of security accreditation for BIONDO's network to be ready for connection to partner networks.
- The first simulated trial was successfully completed by CMRE's Modelling and Simulation team. This advanced four project objectives: De-Risking, Complementing, Integrating and Demonstrating key requirements.

### Contact

For more information about the OCEAN2020 project, please visit <https://ocean2020.eu/> or contact Samantha Dugelay ([samantha.dugelay@cmre.nato.int](mailto:samantha.dugelay@cmre.nato.int)).





**The BIONDO AUV is deployed from NRV Alliance during DYNAMIC MARINER 2020.**



# AUTONOMY FOR ANTI-SUBMARINE WARFARE

## Overview

The Autonomy for Anti-submarine Warfare (ASW) programme seeks to develop, test and validate advanced concepts for unmanned ASW. As part of the overall ACT Maritime S&T POW, the CMRE AASW programme contains two principal projects: Maritime Unmanned Systems (MUS) for ASW and ASW Decision Support.

The focus of the MUS for ASW project is on the development of advanced algorithms for the enhancement of the perception element of unmanned systems for ASW, a parallel effort in advanced autonomy algorithm development, and a significant seagoing project where systems are tested in representative ASW environments, often against actual submarine targets. In the perception enhancement area, advanced signal processing algorithms are created for the Detection, Localization, Classification and Tracking chain. This work is performed for the development of both passive and active ASW. In the autonomy development area, high-level task allocation algorithms are developed alongside collaborative and single vehicle autonomy rules, with the objective to maximize the utility of unmanned systems as they manoeuvre to detect, localize, classify and track submarines. The seagoing element includes participation in multi-national projects for the development and testing of advanced ASW concepts in a collaborative environment, and participation in NATO ASW exercises and Passing Exercise (PASSEX) opportunities.

The ASW Decision Support project has significant elements in doctrine development, Operations Research for unmanned ASW, advanced ASW Decision Support, and Operational Analysis of data collected in sea trials and ASW exercises. By combining simulation with measured performance from CMRE at-sea experimentation, this work explores the real-world performance of unmanned ASW systems. The performance of other platform types not within the CMRE fleet—such as larger AUVs or unmanned surface platforms—is determined, resulting in the ability to perform a more complete cost benefit analysis for future ASW missions deploying an unmanned ‘system of systems’ consisting of a heterogeneous mix of platforms.

Additionally, an ACT-funded Exploring Future Science and Technology (EFST) project on quantum magnetometry was included in the CMRE AASW programme for 2020.

## Activity

In the MUS for ASW project, the scientists developing the signal processing chain have been working to test a number of novel sensor and algorithmic advances for the detection of submarines. All algorithms developed in this effort are implemented in embedded real-time software capable of running on-board low-power long-endurance unmanned systems.

- For active sonar ASW, work in 2020 centred on the continued development of multi-static active concepts built around 21” AUVs with towed arrays, including: the testing of high-gain arrays with port-starboard discrimination capabilities; implementation of cognitive sonar concepts enabling waveform adaptation to the environment; development of automatic target classification algorithms using Deep Convolutional Neural Networks; and the development of advanced contact and track-level multi-target tracking and data fusion algorithms. Work in 2020 also continued to refine algorithms for the extraction of environmental information through the sensors, for use by on-board ASW decision support algorithms.
- For passive acoustic ASW domain, the emphasis was on the development and testing of Acoustic Vector Sensors (AVS) for deployment from low-power long-endurance platforms such as buoyancy and wave gliders, and bottom nodes. Research was concentrated on broadband and narrow-band passive detection algorithms, including holomorphic processing for depth classification; and passive multi-vehicle tracking/data fusion algorithms suitable for merging bearing tracks into fully four dimensional kinematic tracks.
- In the area of network autonomy, in 2020 a high-level task allocation framework developed over the last several years was finished. The framework is capable of determining which optimal tasks to assign to the individual elements of a heterogeneous unmanned ASW network. At the collaborative autonomy level, a depth-adaptive behaviour optimizing communications throughput was developed. Finally, vehicle and collaborative-level autonomous ASW behaviours—seeking to maximize the probability of detection, maximize track hold, or to clear an area—have been upgraded to utilize the through-the-sensor ASW performance estimates provided by the on-board ASW decision support tool.



The ASW Decision Support project is enhancing NATO exercises through dynamic in-stride analysis and acoustic reach-back services. The former allows for a detailed reconstruction of serials to include acoustic simulation, enhancing lessons learned by providing insight into the reasons behind observed sonar performance. The acoustic reach back allows for detailed maps of range dependent sonar performance to be determined throughout an exercise. Daily reports may be produced providing performance maps and indications of optimum sonar depth—together with submarine evasion depth.

In the Quantum Magnetometry EFST project, novel quantum effect magnetometers characterized by low noise, high sensitivity and low power consumption have been evaluated for their suitability to add a magnetic anomaly detection capability to MUS for ASW.

## Highlights

During the period 22 — 25 February 2020, the CMRE AASW team on-board NRV *Alliance* participated in DYNAMIC MANTA 2020, a NATO ASW live exercise in the waters around Sicily. This Technical Demonstration activity, funded by ACT, resulted in a number of notable achievements, including:

- First-time demonstration of CMRE's low-power, long-endurance ASW barrier during a NATO ASW exercise. Barrier elements included buoyancy gliders with AVS and wave gliders providing gateway connectivity and navigation services.
- Successful deployment of CMRE's AUV-based active multistatic sensors in four ASW serials including a deep water ASW serial.
- First testing of a real-time Deep Convolutional Neural Network target classifier embedded in an AUV.
- The deployment of an ASW subject matter expert to the MARCOM led In-stride Debrief Team to demonstrate advanced concepts for acoustic serial reconstruction using Multistatic Tactical Planning Aid (MSTPA) and Rapid Acoustic Prediction Service (RAPS).
- Provision of predicted ASW performance for the exercise area to DYNAMIC MANTA Exercise Control (EXCON), informed by near real-time measurements from oceanographic gliders.

A second sea-going activity was a Distributed Autonomous Networked Systems (DANS) sea trial conducted in local La Spezia waters in December 2020. DANS is a multi-national cooperation



**The Ocean Explorer AUV is deployed from NRV *Alliance* during the Distributed Autonomous Networked Systems sea trial in December 2020.**

programme comprising CMRE, Canada, Germany, UK, Italy and Portugal. During the 2020 DANS sea trial, CMRE successfully tested: a new advanced eight-element AVS array for a wave glider vehicle; improvements to the AVSs installed on underwater buoyancy gliders; and, a new bottom node with an integrated AVS.

In the ASW Decision Support project, an Experimental Tactic (EXTAC) for the use of MUS for ASW was developed in the underwater warfare syndicate of the Maritime Operations (MAROPS) working group for eventual inclusion into NATO Experimental Tactics and Amplifying Tactical Instructions (AXP-5). ASW performance surfaces computed with Rapid Acoustic Prediction Service (RAPS) using a blade server reach-back service at CMRE were provided to MARCOM for the NATO DYNAMIC MARINER and UK JOINT WARRIOR Exercises. Additionally, in collaboration with the CMRE DKOE project team, a Table Top Exercise (TTX) was developed and executed for evaluating the utility of Maritime Unmanned Systems for ASW in a Sea Lines of Communication scenario.

For the Quantum Magnetometry EFST project, a pair of representative state-of-the-art in high sensitivity, low power and low noise quantum-effect magnetometers were acquired and tested against other state-of-the-art conventional and quantum-effect magnetometers in both laboratory and open-field environments.

## AUTONOMY FOR ANTI-SUBMARINE WARFARE

FUNDED BY ACT INNOVATION BRANCH

# TECHNICAL DEMONSTRATIONS AT DYMA2020



**In February 2020, NRV *Alliance* participated in the NATO ASW Exercise DYNAMIC MANTA to test and demonstrate advanced concepts for unmanned ASW.**

### Overview

From 21 February — 6 March CMRE participated in the NATO Exercise DYNAMIC MANTA 2020 (DYMA20) in the Ionian Sea south of Sicily, with NRV *Alliance* joining ships, submarines and aircraft from nine NATO nations. This was the fifth time since 2012 that CMRE has participated in a NATO anti-submarine warfare (ASW) exercise with unmanned systems. In addition to supporting DYMA20, ACT Innovation Branch funded CMRE to conduct two technical demonstrations during the exercise.

### Passive ASW Barrier

The first technical demonstration was the deployment of a passive ASW barrier composed of buoyancy gliders and a wave glider. The buoyancy gliders were equipped with acoustic vector sensors and signal processing that allowed them to make real-time detections and estimates of the direction of arrival of sounds. The detection information was then relayed underwater via acoustic



modems to the command and control centre on-board NRV *Alliance* using the surface wave glider as a communication gateway. The wave glider also provided acoustic navigation services to the underwater gliders, improving their navigational accuracy over the usual dead reckoning. The system proved it was capable of detecting narrowband transmissions from NRV *Alliance* as well as white shipping noise. Reports of the glider network's detections were sent to the Instride Debrief Team (IDT) at Sigonella Naval Air Station for the preparation of daily exercise de-briefs.

### **Blue Force Situational Awareness**

The second technical demonstration, Blue Force Situational Awareness, demonstrated a CMRE oceanographic model that assimilated in situ measurements from oceanographic gliders, to provide a high quality ocean forecast for the DYMA20 daily METOC brief. This product was augmented with daily maps showing sonar performance for the exercise area generated using CMRE's Rapid Acoustic Prediction Service. To provide further situational awareness, CMRE deployed an acoustic glider for the measurement and characterization of ambient noise profiles. These measurements were generated in real-time on-board the glider, compressed and incorporated into the glider's periodic SATCOM reports.

The Blue Force Situational Awareness technical demonstration included the use of the STANAG 4748 JANUS protocol, developed at CMRE, to allow NRV *Alliance* to communicate acoustically with a submarine. This was the first demonstration of JANUS during a NATO ASW exercise, and also the first time that a JANUS installation on-board a submarine was operated by the submarine's crew without any assistance from embarked CMRE personnel. The JANUS installation was utilized to communicate the local white ship picture to the submarine, and also supported an underwater digital text messaging functionality called "WetsApp". The submarine crew quickly adopted WetsApp as their preferred mode of communications with NRV *Alliance* while the submarine was submerged.

### **Results**

- First deployment and successful demonstration of a low-power, long-endurance autonomous passive barrier in the operational setting of a NATO ASW exercise.
- Successful demonstration of support to water space management through enhanced underwater navigation for gliders and reporting asset location, course and speed through an underwater acoustic communication network.
- First use of the STANAG 4748 JANUS protocol to allow NRV *Alliance* to communicate acoustically with a submarine in a NATO ASW exercise.
- First time that the JANUS installation on-board a submarine was operated by the submarine's crew without any assistance from CMRE personnel.
- First use of CMRE's underwater digital text messaging system "WetsApp" in the context of a NATO ASW exercise.

### **Contact**

For further information on DYMA20 technical demonstrations, please contact Alessandra Tesei ([alessandra.tesei@cmre.nato.int](mailto:alessandra.tesei@cmre.nato.int)).



## AUTONOMY FOR ANTI-SUBMARINE WARFARE MULTINATIONATIONAL-JOINT RESEARCH PROJECT

# LCAS PROJECT

### Overview

The ability to detect and track underwater targets is a key capability for Anti-Submarine Warfare (ASW). Continuous Active Sonar (CAS) is a relatively new sonar concept that has the advantage of near-continuous acoustic illumination of the target, capturing favourable target aspects, no matter how fleeting. The Littoral Continuous Active Sonar (LCAS) Multinational Joint Research Project was established to evaluate and enhance the performance of CAS waveforms in littoral areas which are acoustically complex environments characterized by significant boundary interactions, high oceanographic variability, and high ambient noise. The project successfully delivered an experimentally validated theoretical understanding of how to design and implement CAS for littoral areas, thereby enabling NATO forces to improve ASW performance in these vulnerable near-shore and confined waters.

Joining CMRE on the LCAS team were NATO nations Canada, Italy, Norway, the United States and the United Kingdom, and partner nations Australia and New Zealand. Started in 2014, LCAS was extended for an additional two years in 2018 due to the recognition of its success and military relevance. The six-year LCAS partnership resulted in four sea trials on NRV *Alliance* and a substantial publication record including 20 NATO reports and trial plans, 6 journal articles, 20 conference papers, and 33 papers presented at workshops and at scientific conferences in three sessions organized specifically to address the topic. Knowledge gained from LCAS has already influenced military procurement decisions. The LCAS Multinational Joint Research Project was nominated for the 2021 STO Excellence Award.

### Results

- CAS waveforms were always evaluated contemporaneously with Pulsed Active Sonar (PAS) waveforms, using the same target geometries, bandwidths, and total waveform energy thus allowing a fair assessment of the potential performance advantages of CAS over PAS, as a function of the transmitted waveforms, signal processing, and the environmental conditions.
- Extensive characterization of the littoral environments was carried out in order to understand the acoustic propagation and reverberation conditions during trials. Oceanographic profiles and surface wave spectra were continuously collected, along with ambient noise levels and, in some cases, sea bed properties. The measured environmental parameters were utilized in the models and theories developed within the project to understand and predict the impact of the environment on CAS performance.
- Theoretical and experimental analyses were conducted to understand how the range and frequency of faint target returns could be obtained in the presence of a very loud simultaneously transmitting CAS source.
- New theoretical understanding of the gain CAS waveforms can achieve against reverberation and noise led to the development of signal processing methods for different combinations of coherent and incoherent techniques which can be selected for best performance given environmental conditions.
- New data fusion and tracking algorithms suitable for high time-bandwidth CAS waveforms were developed. A new track initiation criterion suitable for CAS waveforms was developed and validated.

### Contact

For more information about the LCAS Project, Multinational Joint Research Project, please contact Kevin LePage ([kevin.lepage@cmre.nato.int](mailto:kevin.lepage@cmre.nato.int)).

## AUTONOMY FOR ANTI-SUBMARINE WARFARE

FUNDED BY LEONARDO SPA

# SONAR PERFORMANCE PREDICTION SOFTWARE

### Overview

Since late 2018, CMRE has been developing a decision support tool called Sonar Performance Prediction Software (SPP-SW) for the Italian company Leonardo SpA - Underwater Armaments & Systems. The tool will provide the ability to predict naval sonar performance under operational conditions and provide recommendations for system settings to optimize the performance of the sonar in both passive and monostatic active modes. The CMRE software will be integrated into a comprehensive system developed by Leonardo, which will be interfaced with the navigation and sonar systems of the Italian Navy's new multipurpose offshore patrol ships, Pattugliatori Polivalenti d'Altura (PPA).

The development of the SSP-SW decision support tool draws upon the experience CMRE gained from the development of the Multistatic Tactical Planning Aid (MSTPA) and Rapid Acoustic Prediction System (RAPS). The SPP-SW is customized for the variable depth sonar of the Italian Navy's PPAs and will recommend the optimal depth of the sonar based on numerous parameters such as the ship's location, its motion, and the ocean acoustic environment (including sound speed profile, bottom type, sea surface roughness, ambient noise level and modelled reverberation).

The project has been extended into 2021 with the objectives of extending the applicability of the decision support tool beyond the PPA sonar to generic sonars, and developing a stand-alone version of the tool for use on any Italian navy ship, ashore and for training.

### Results

- One of the underlying acoustic propagation models, Bellhop, was extended to include the computation of the underwater reverberation level using a rapid, efficient algorithm.
- Algorithms to optimize the depth of the PPA sonar were developed, implemented in a Matlab prototype version, and extensively tested under a variety of modelled environmental and operational conditions.
- The decision support tool was extensively tested for reliability and robustness, critical for operational use at sea.

### Contact

For more information on the Sonar Performance Prediction Software Project, please contact Alessandra Tesei ([alessandra.tesei@cmre.nato.int](mailto:alessandra.tesei@cmre.nato.int)).

## AUTONOMY FOR ANTI-SUBMARINE WARFARE

FUNDED BY THE EU COMMISSION

# METRICS PROJECT

### Overview

The Metrological Evaluation and Testing of Robots in International Competitions (METRICS) project will organize physical and virtual challenge-led robotics competitions in four priority research areas: healthcare, inspection and maintenance (I&M), agri-food, and agile production. METRICS is designed to organize competitions as reproducible and objective evaluation campaigns and aims to support the European robotics and artificial intelligence community by building a sustainable network of European robotics stakeholders.

In order to assess the reliability of the different competing robots in a rigorous and unbiased way, METRICS will develop an evaluation framework based on metrological principles. The competitions are designed to engage European industry, academia and innovation hubs, while stimulating public engagement.

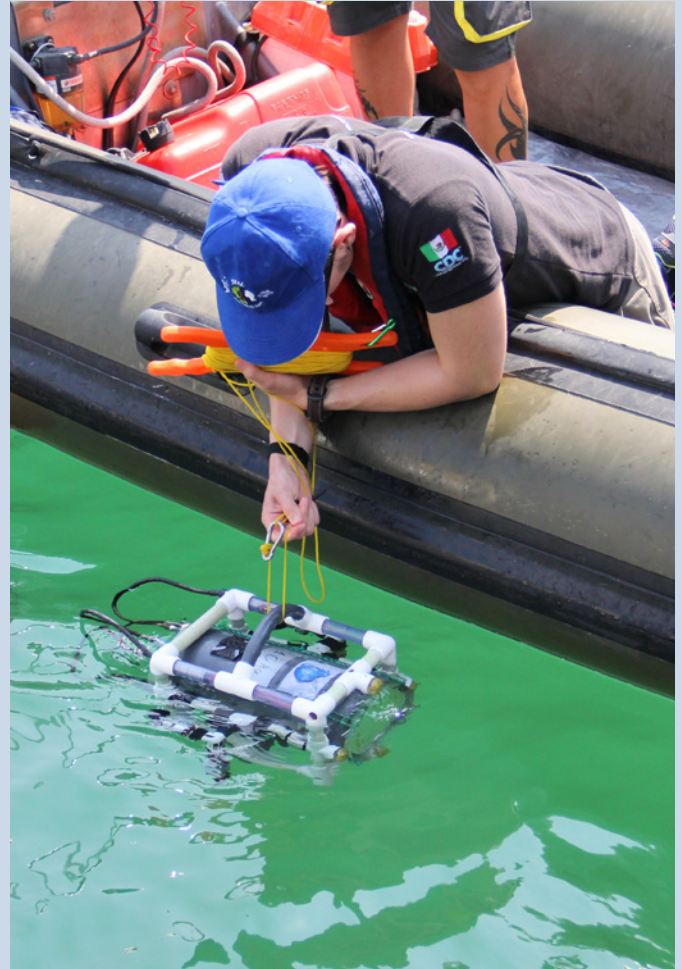
With a breadth and depth of experience in the organization of robotics competitions, CMRE is a key partner in the project. CMRE is responsible for the marine segment of the I&M competition and will organize two events at CMRE in 2021 and 2022, as well as two virtual challenges. The physical competitions will involve underwater robots challenged with response tasks in a realistic oil and gas emergency scenario, which will require the participating robots to demonstrate perception, autonomy and manipulation skills.

### Results

- Definition of the Evaluation Plan for the I&M competition.
- Definition of the virtual competition: selected underwater images of objects of potential interest (pipes, coloured shapes, coloured buoys, etc) have been collected and labelled. This data set will be given to teams participating in the competition to train their detection and classification algorithms, that will be tested and evaluated in 2021 on a validation data set.

### Contact

For more information about the METRICS project, please visit <https://metricsproject.eu/> or contact Gabriele Ferri ([gabriele.ferri@cmre.nato.int](mailto:gabriele.ferri@cmre.nato.int)).



**A student tests an AUV during the 2019 European Robotics League Competition held at CMRE.**



## AUTONOMY FOR ANTI-SUBMARINE WARFARE

FUNDED BY THE EU COMMISSION

# INFORE PROJECT

### Overview

The aim of the INFORE project is to address the challenges posed by huge data sets and pave the way for real-time, interactive extreme-scale analytics and forecasting. Today, at an increasing rate, industrial and scientific institutions need to deal with massive data streams from a multitude of sources. The ability to construct accurate forecasts from such streams allows decision-makers to identify undesired outcomes, potentially saving valuable time, effort and resources.

The INFORE project addresses three use cases: financial, biological and maritime. CMRE is involved in the maritime use case, the goal of which is to extract insights from incoming data streams and accumulated big data to forecast events of interest, facilitating improved maritime Intelligence, Surveillance and Reconnaissance.

In particular, CMRE and partners are committed to design, develop and test at-sea a hybrid surveillance network composed of shore-based fixed imaging sensors and autonomous robot wave gliders equipped with acoustic passive sensors, cooperating together to detect and localize ship targets. The downstream fusion of the data stream generated by the network with the Automatic Identification System (AIS) data stream and satellite remote sensor data will enable improved situational awareness and further enhance the capability to detect ship traffic anomalies.



**A wave glider runs tests at sea.**

### Results

- Defined Key Performance Indicators for the Maritime Use Case.
- Defined the sensor network fusion architecture.
- Tested in simulation cooperative target localization algorithms using acoustic data, ready to be ported on-board the wave glider hardware.
- Developed autonomy for the wave gliders, enabling the vehicles to make autonomous decisions on the basis of the data collected.
- Extended the Maritime Situational Awareness–Heterogeneous Sensor Network Ontology design with entity profiles and the context for threat assessment; including the initial development of an ontology knowledge graph application programming interface.
- Developed and tested ship target classification algorithms for multi-spectral satellite data based on convolutional neural networks.

### Contact

For more information about the INFORE project, please visit <http://www.infore-project.eu/> or contact Kevin LePage ([kevin.lepage@cmre.nato.int](mailto:kevin.lepage@cmre.nato.int)).

# DATA KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

## Overview

As part of the ACT Maritime S&T POW, the Data Knowledge and Operational Effectiveness (DKOE) programme aims to inform the future design of NATO information systems for Maritime Situational Awareness (MSA) through research products for all-source information integration and fusion, target tracking, traffic patterns learning, uncertainty handling and reasoning, and anomaly detection. The intent is for such research products to be integrated into test bed environments able to interoperate with networked systems, including military Command and Control (C2) systems, to ensure NATO maritime information superiority.

## Activity

The DKOE project aims to provide solutions to a wide range of underlying MSA problems, both above and below water. The project exploits advanced approaches in the fields of statistical signal processing, machine learning, information and data fusion, artificial intelligence, reasoning under uncertainty, gamification and semantic knowledge representation and reasoning.

The CMRE DKOE team addressed the problems associated with processing increasing volumes of data available from sensors and historical information through the following activities:

- Maritime knowledge discovery methods from historical data;
- Maritime anomaly detection techniques and countermeasures; and,
- Advanced belief propagation multi-sensor and multi-target tracking algorithms, which not only achieve improved accuracy compared to competing algorithms, but also exhibit superior scalability properties.

The DKOE team continued to develop explainable Artificial Intelligence techniques in support of MSA by building on recent developments in multi-source fusion frameworks:

- Using multiple sources of information for monitoring and predicting vessel activity and

behaviour, informing the design by means of knowledge acquisition techniques.

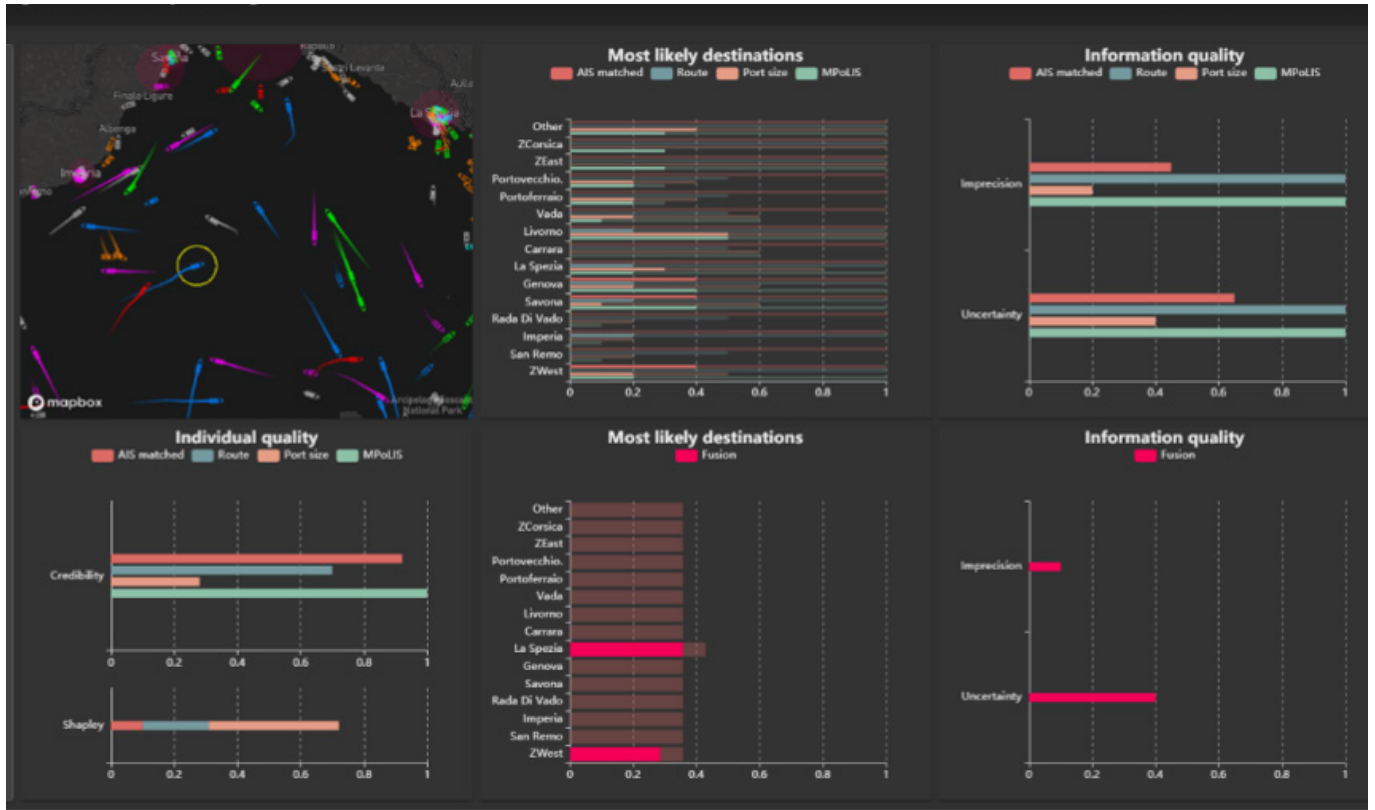
- Developing formal models and methodologies to assess algorithms, together with associated metrics for selected criteria (e.g. accuracy, uncertainty, credibility, reliability, confidence, inconsistency).
- Implementing Bayesian deep learning techniques.

Additionally, exploratory research was carried out on the dynamic localization of underwater acoustic sources.

## Highlights

In support of improved MSA, the following enhancements were achieved in 2020 for vessel tracking, movement prediction, anomalous behaviour detection, and vessel class recognition:

- A novel full vessel movement prediction strategy based only on deep learning was implemented using a recurrent neural network, where the whole 'learning' phase depends only on the dataset without any further information.
- The DKOE-pioneered belief propagation multi-sensor and multi-target tracking framework was extended to process not only target measurements such as position, course and speed, but also target classification information such as vessel size and type from automated target recognition, with improved tracking performance.
- The automatic detection of anomalous vessel behaviour within maritime traffic has been improved; dark route deviations (i.e. with the Automatic Identification System (AIS) turned off) can be detected even if AIS spoofing is present.
- As part of the exploitation of satellite sensors, a Siamese network architecture based on convolutional neural networks was implemented and, using Sentinel 2 Multispectral Instrument (MSI) data, shown



**FORUM User Input and Information Quality Display services supporting the problem of vessel destination prediction with multiple information sources.**

to be able to correctly recognize different classes of ship at a success rate of greater than 90%. Additionally, maritime traffic has been successfully analysed through light emission captured by the NASA/NOAA Visible/Infra-red Imager and Radiometer Suite (VIIRS) sensor.

The CMRE DKOE team developed the FORUM (Fusion and Reasoning under Uncertainty Modelling) research platform. The aim of FORUM is to inform the design and evaluation of semi-automated solutions supporting the complex cognitive task of reasoning and information fusion under uncertainty with multiple partially reliable sources. FORUM is compliant with the mathematical framework of valuation algebra for fusing and representing uncertain information in a multi-intelligence source context. The FORUM architecture allows the correlation of information from MSA services developed at CMRE with user inputs and other available sources; and supports message exchange formats compliant with standards for evaluating uncertainty, such as the Allied Joint Publication 2.1 for Intelligence Procedures. The use case of vessel destination prediction combines outputs from five different services—including a user input service; results

are presented through an information quality display service.

Other highlights of the DKOE POW outputs for 2020 include the development of:

- An ontology for describing experimental evaluations, which is both human and machine interpretable; based on a formal logic, it semantically enriches and validates information from different sources, and bridges the gap between different types of uncertainty representations.
- A transparent and explainable solution to support the investigation of vessel behaviour and assessment of threats to underwater critical infrastructure, combining sensor information and human intelligence, and implementing original expert elicitation methods.
- A novel sequential filtering approach implemented via multiple-model ensemble Kalman filters for the dynamic localization of underwater acoustic sources based on acoustic propagation models, which promises computational efficiency and robustness to noisy environments.



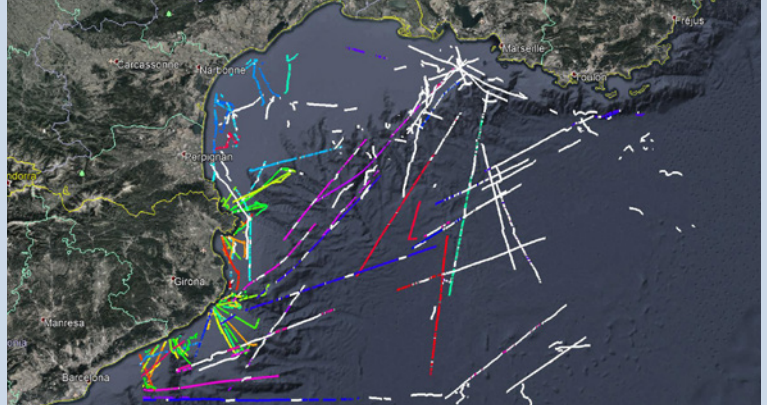
## DATA KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

FUNDED BY THE EU COMMISSION

# RANGER PROJECT

### Overview

The Radars for Long Distance Maritime Surveillance and SAR operations (RANGER) project, funded by the EU's H2020 research and innovation programme, successfully completed after 44 months of research work, within a consortium of ten partners from seven member states of the EU. The RANGER project created an innovative maritime surveillance platform by combining ground-breaking radar technologies, such as the over-the-horizon (OTH) radar and the photonically-enhanced multiple-input multiple-output (PE-MIMO) radar, with state-of-the-art early warning solutions in order to detect, track, classify, and identify vessels far beyond the capability of legacy systems. The RANGER platform allows for continuous long and short-range detection and tracking of large and small vessels, prediction of vessel routes, and provision of early warnings through novel data fusion and machine learning techniques. Moreover, RANGER was designed for interoperability and integration with existing legacy systems and with EU's Common Information-Sharing Environment (CISE). During the course of the project, the partners implemented, integrated, tested and validated the developed solutions in real operational environments in four sea trials in France and Greece.



**Tracks produced by the RANGER data fusion engine developed by CMRE during one of the French sea trials. Coloured tracks are radar tracks that have been successfully associated with AIS; tracks in white are radar tracks from vessels that did not broadcast AIS.**

### Results

- CMRE developed, implemented and deployed the core of the RANGER platform, the scalable and flexible data fusion engine based on the sum-product algorithm (SPA), able to fuse measurements from OTH radar, PE-MIMO radar, and legacy radars, as well as automatic identification system (AIS) data. The output of the fusion engine was vessel tracks and a view of the current maritime situational picture.
- The data fusion engine was enhanced and improved to adaptively tune in real time some model parameters, such as the probability of detection, without requiring user intervention.
- The fusion of AIS information with other sensor data, allowed the continuous identification and classification of vessels, even when the vessels were not transmitting AIS messages.

### Contact

For more information about the RANGER Project, please visit <https://ranger-project.eu/> or contact Paolo Braca ([paolo.braca@cmre.nato.int](mailto:paolo.braca@cmre.nato.int)).

## DATA KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

FUNDED BY THE EU COMMISSION

# MARISA PROJECT

### Overview

The Maritime Integrated Surveillance Awareness (MARISA) project, funded by the EU's H2020 research and innovation programme was successfully completed in February 2020 after 34 months of work, within a consortium of 22 partners from nine EU countries. The MARISA project developed a toolkit of integrated data fusion services for maritime traffic monitoring and operational planning, supporting enhanced Maritime Situational Awareness capabilities. The toolkit allows end-users to perform analysis on a variety of data based on geographical and spatial representation, searching for patterns, analysing connections between events, and exploring relationships by means of predictive analytics. The project validated the developed capabilities during two series of trials across different user sites, addressing operational maritime security and safety scenarios. MARISA ensured the interoperability of services by compliance with the EU's Common Information-Sharing Environment (CISE) data model.

### Results

CMRE contributed to MARISA by providing four services: the Density Map service; the Multi-Source Dynamic Bayesian Network (MDBN) for Behavioural Analysis service, jointly developed with Fraunhofer IOSB; the Ship Routes service; and, the Ship Prediction service.

- The Density Map service enables users to access historical vessel traffic information in given areas of interest, with the possibility of filtering by season and traffic category of interest, with visualization of automatically computed vessel motion patterns.
- The MDBN for Behavioural Analysis service estimates the likelihood of situations or events of interest—e.g. illegal diving, smuggling of goods, illegal migration—through the combination of information from different sources of varying quality, mixing sensor and human inputs. Expert knowledge was formally captured and implemented in the design of the solution.
- The Ship Routes service provides a visualization of historical automatic identification system (AIS) information on recurrent maritime routes in a given area of interest.
- The Ship Prediction service employs an accurate statistical vessel motion model and allows MARISA users to compute the predicted position of a vessel of interest after a desired amount of time—up to 24 hours—from its last AIS observation, along with the prediction uncertainty.

### Contact

For more information about the MARISA Project, please visit <https://www.marisaproject.eu/> or contact Anne-Laure Joussetme ([anne-laure.joussetme@cmre.nato.int](mailto:anne-laure.joussetme@cmre.nato.int)).

## ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS

### Overview

As part of the ACT Maritime S&T POW, the CMRE Environmental Knowledge and Operational Effectiveness (EKOE) programme is investigating the use of emerging and disruptive technologies to implement distributed sensing solutions for near-real time characterization of environments with restricted or denied access. The ultimate aim is to develop a sensing network inherently distributed in space, time and functionality, complemented by enhanced numerical models and remote sensing, to assess in a timely and covert manner the environmental conditions in restricted or denied littoral and open seas, with special emphasis on the High North. A CMRE Arctic Science and Technology Strategy guides current and future EKOE research in High North regions.

The CMRE EKOE programme for 2020 consisted of two projects; Maritime Autonomous Networks and Smart Sensing for Stealth and Secure Battlespace Characterization, and Sensing and Predicting Underwater Noise using Robotic Platforms and Forecast Models for Maritime ISR.

The Maritime Autonomous Networks and Smart Sensing for Stealth and Secure Battlespace Characterization project is developing a network-based capability for environmental characterization. A basic assumption is that the most effective and efficient way to monitor vast marine regions is through widely dispersed, persistent, networks of platforms employing a broad range of low-power smart sensors which use built-in computing resources to perform predefined data processing. Present sensor technologies are analysed for use as potential network nodes, existing commercial platforms are repurposed to the requirements for maritime military surveillance, and oceanographic knowledge is extracted from the implementation of the network-based solutions. In particular, the project is developing autonomous acoustic profilers to monitor underwater acoustic noise levels, among other environmental variables of interest.

The Sensing and Predicting Underwater Noise using Robotic Platforms and Forecast Models for Maritime ISR project generates understanding and provides insights and forecasts of current (descriptive) or future states (predictive) of the environment. The aim is to increase naval situational awareness at strategic, operational and tactical levels through



**CMRE researchers and ITA N crew members deploy a Wirewalker in the rain from NRV Alliance during the MREP20 sea trial in the Strait of Sicily.**

advanced analytics by using and developing novel mathematical and statistical methods for the timely provision of predictive assessments. Whereas ocean modelling and data assimilation/fusion provide a coherent view of the marine environment with high signal-to-noise ratio, environmental advanced analytics requires complementary information management systems to facilitate data sharing within NATO.

### Activity

Research initiatives conducted during 2020 included the use and development of new sensing technology (e.g. Wirewalkers, acoustic floats, etc.), improved methods for underwater glider navigation (e.g. using onboard acoustic Doppler current profiler (ADCP) data) and the integration of acoustic sensing technology in autonomous platforms (e.g. the detection of intensity and directionality of acoustic anomalies with gliders). Research has also been performed to develop algorithms to support on-board communication range estimates of network nodes.

Advanced analytics to support naval decision-making have been developed, based on novel data assimilation techniques for ocean prediction. These techniques allow the extraction of information from acoustic transmission data to improve model forecasts in addition to incorporating as many small scale processes as allowed by computational limitations. A prototype of a Shared Environmental In-



formation System was developed to manage and classify the information received from the sensors and processed by the analytics system.

A method for assimilating acoustic data into an ocean prediction system was investigated. Among the other acoustic variables, travel times depending on the sound speed field along the eigen-ray path were selected. Numerical experiments in the Ligurian Sea indicate that the method is able to adjust temperature fields over the full water column, reducing biases present in the control simulation, improving Ligurian model forecasts even at distance from the propagation transect.

An oceanographic tangent-linear and adjoint model (TL/AD) for primary use in four-dimensional data assimilation was implemented. The new TL/AD model has a stand-alone and modular code. A strategy to reduce the computational costs of the TL/AD execution by means of spatial resolution degradation (Multi grid/Multi scale approach) was also investigated.

## Highlights

Co-funded by the NATO ACT Maritime S&T POW and the US Office of Naval Research (ONR), the Mediterranean Recognized Environmental Picture (MREP20) cruise was conducted on-board *NRV Alliance* in the Strait of Sicily (Mediterranean Sea) from 24 October to 11 November 2020. The aim of this activity was to quantitatively assess the capability of present numerical/observational technology to predict the variability of the underwater sound channels associated with strong frontal dynamics. Moreover, 3D effects on underwater acoustic propagation were investigated. An oceanographic observation network (gliders, moorings, drifters, underway conductivity temperature and depth (CTD) measurements, and satellite) was deployed in the region. Of note, an autonomous Wirewalker profiling system fitted with oceanographic sensors—including temperature and salinity, CTD and a Nortek ADCP—and real-time satellite telemetry capability was deployed for the first time. A second network was implemented for acoustic validation purposes; this network monitored at locations around the oceanic front the signals received from a set of moored and towed acoustic sources. External collaborators were Woods Hole Oceanographic Institution (WHOI) USA, Heat Light & Sound Research Inc. (HLS) USA, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) ITA, University of Bologna (UNI-BO) ITA, Direction générale de l'armement (DGA) FRA, Service hydrographique et océanographique

de la Marine (SHOM) FRA, and Defence Research and Development Canada (DRDC) CAN.

The Drifter Demonstration and Research (DDR20) sea trial was performed during the period 06 — 10 October 2020 in the eastern Ligurian Sea (off Livorno) to demonstrate the effectiveness of drifters and floats to characterize the littoral marine environment with high spatial (0.5 km) and temporal (30 minute) resolution. In addition to CMRE, the following international partners were involved: Istituto di Scienze Marine—Consiglio Nazionale delle Ricerche (ISMAR-CNR) ITA, Laboratorio di Meteorologia Modellistica Ambientale—CNR (LAMMA-CNR) ITA, OGS ITA, Scripps Institution of Oceanography—University of California San Diego (SIO-UCSD) USA and Defense Advanced Research Projects Agency (DARPA) USA.

A high-quality historical oceanographic dataset for the Arctic region, covering the period from 1980 to 2020, was compiled by merging three datasets. The core is the Unified Database for Arctic and Subarctic Hydrography (UDASH), with the addition of data from the Ice-Tethered Profiler (ITP) programme and the World Ocean Database 2018 (WOD18). This merged Arctic Dataset is periodically updated with new data made available by both the World Ocean Database and the ITP programme, in order to have an up-to-date reference dataset for further studies and planning.

Other highlights during 2020 include:

- An efficient algorithm based on advanced intelligent and automatic pattern recognition techniques was developed to classify Sound Speed Profiles (SSP) to infer acoustic performance in terms of favourable, marginal or unfavourable acoustic propagation conditions.
- A smart sensor for use on-board gliders was prototyped to analyse the intensity and directionality of underwater ambient noise in near real time; this sensor will allow the vehicle to adapt its behaviour to optimize the strategy to sample the underwater soundscape.
- A comprehensive analysis of underwater sensors and platforms was performed to assess the capability of current unmanned technology to monitor underwater communication cables. The research was conducted for three key scenarios (shallow/coastal, deep-littoral and deep-water areas).

## ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS COLLABORATIVE PROJECT WITH DEFENCE RESEARCH AND DEVELOPMENT CANADA

### CRACCEN INITIATIVE



**Royal Canadian Navy assets at sea. CMRE is working with DRDC to improve sonar performance prediction for the RCN.**

#### Overview

CMRE is supporting Defence Research and Development Canada (DRDC)—Atlantic Research Centre through a collaboration entitled “Incorporating uncertainty and battlespace data sources into real-time sonar performance predictions”. The work is part of DRDC’s Command Reconnaissance Area Coordination and Control Environment Network (CRACCEN) initiative. The goal of CRACCEN is to provide the Royal Canadian Navy (RCN) with a revolutionary Underwater Warfare (UWW) command and control (C2) system with predictive situational awareness, battlespace management, operations planning, and mission execution capability. CMRE is contributing its expertise in three areas: accessing distributed data sources for sonar performance prediction, rapid environmental assessment (REA) and Artificial Intelligence (AI) for autonomous systems. The three-year technical agreement with DRDC began in 2018, but because of the success of the activity, DRDC extended the agreement until the end of 2021 and included a new collaboration on ocean-acoustic modelling and data assimilation.

#### Results

- Impact of environmental uncertainty: CMRE carried out a study on REA techniques and the impact of environmental uncertainty on the accuracy of underwater acoustic prediction. The propagation of errors in environmental data through the various stages of processing and modelling, known as the ‘uncertainty cascade’ was examined with the goal of anticipating and reducing the errors in the underwater acoustic predictions. This is critical for the design and implementation of underwater predictive situational awareness for CRACCEN.
- Sonar performance prediction modelling: CMRE designed a data management system to act as an interface between different data sources and a generic sonar performance prediction model. The proposed system supports the deployment of a distributed sonar performance model with both on-shore and at-sea components. The system design conforms to NATO interoperability standards.

#### Contact

For more information on this activity, please contact Paolo Oddo ([paolo.oddo@cmre.nato.int](mailto:paolo.oddo@cmre.nato.int)).

## ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS COLLABORATIVE PROJECT WITH DARPA

# OCEAN OF THINGS DRIFTER DEPLOYMENT

### Overview

CMRE and the U.S. Defense Advanced Research Projects Agency (DARPA) have begun a collaboration to use freely drifting autonomous instruments (called drifters) to characterize the maritime domain near the sea surface. This effort is part of DARPA's Ocean of Things (OoT) initiative and CMRE's Environmental Knowledge and Operational Effectiveness (EKOE) programme. The drifters are equipped with a suite of commercially available sensors that collect environmental data such as sea surface temperature and currents, sea state, and atmospheric pressure as well as situational awareness information such as the presence of ships and aircraft. DARPA's OoT programme aims to enable persistent maritime situational awareness over large areas of the ocean by deploying thousands of low-cost, environmentally friendly and intelligent drifters.



**A CMRE technician prepares to deploy an autonomous drifter to characterize the maritime environment off Italy.**

CMRE has utilized DARPA drifters amongst other freely drifting instruments in recent activities such as the MREP20 trial, which took place in the Strait of Sicily and the DDR20 trial in the Ligurian Sea. DARPA drifters complement CMRE's suite of assets to characterize the marine environment and operate as a distributed sensing network, transmitting data via satellite to DARPA and CMRE for storage and real-time analysis. The network of CMRE and DARPA drifting instruments provides oceanographic data at fine space and timescales in support of underwater acoustic research and, hopefully in the future, NATO exercises.

### Contact

For more information about this project, please visit [oceanofthings.darpa.mil](http://oceanofthings.darpa.mil) or contact Pierre-Marie Poulain ([pierre-marie.poulain@cmre.nato.int](mailto:pierre-marie.poulain@cmre.nato.int)).



ENVIRONMENTAL KNOWLEDGE AND OPERATIONAL EFFECTIVENESS  
COLLABORATIVE PROJECT WITH THE ONE OCEAN FOUNDATION

## CAPRERA CANYON DEEP DIVERS



**CMRE Director Dr Catherine Warner signs the One Ocean Foundation partnership agreement at the Yacht Club Costa Smeralda in Sardinia.**

### Overview

On 11 September, a partnership agreement was signed between CMRE and the One Ocean Foundation to launch a collaborative research project that raises awareness of the impacts of environmental and acoustic pollution on the marine wildlife in the Caprera Canyon off Sardinia's Costa Smeralda (or Emerald Coast). The project will run from October 2020 to the end of 2021 with the results to be published in peer-reviewed, scientific literature. The mission of the One Ocean Foundation is to protect marine environments and CMRE, with over 20 years of experience in studying the impact of underwater sound on marine mammals, is well positioned to help. The collaborative project will measure the impacts of human activity on the survival of whales and dolphins in the Caprera Canyon.

CMRE will provide acoustic monitoring technologies consisting of smart sensor-based 3D recorders that will capture the underwater soundscape. Through analysis of the vocalizations of the marine mammals in the canyon, the research will provide a greater understanding of their behaviour and will help identify sources of acoustic pollution in the area. The project will support the official recognition of the Caprera Canyon as an Important Marine Mammal Area (IMMA), as designated by the International Committee on Marine Mammal Protected Areas and the International Union for the Conservation of Nature.



**A Cuvier's beaked whale swimming in the Ligurian Sea. These whales are one of the primary target species to be analysed through this project.**

## **Results**

- Development of deep-sea capable 3D directional acoustic recorders to record cetacean vocalizations.
- Development of the algorithms to perform the analysis on the acoustic data that will be retrieved from the recorders.
- The deployment of the acoustic recorders in the Caprera Canyon is scheduled for April 2021 for a duration of approximately six months. The recorders will be deployed from CMRE's vessel CRV *Leonardo*.

## **Contact**

For more information on this activity, please contact  
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# MARITIME UNMANNED SYSTEMS ENABLERS

## Overview

As part of the ACT Maritime S&T POW, the Maritime Unmanned Systems Enablers (MUSE) programme at CMRE seeks to design the architectural framework in which future autonomous underwater systems and missions will be cast, establishing interoperability standards for control, data flow, information security, performance and interfaces, to provide NATO future forces with secure, interoperable and scalable systems that increase effectiveness while reducing risk and cost.

The CMRE MUSE team have defined three themes, all supporting the underpinning requirement for system interoperability—a key enabler and an important capability multiplier for NATO forces. These three themes are:

- Maritime Command and Control (C2) support and development from a system-level architecture to vehicle-level (underwater communications) all the way up to maritime picture aggregation;
- Mission assurance and security aspects of Maritime Unmanned Systems (MUS); and
- Digital twins for concept development, testing and validation of autonomous maritime systems and missions.

The CMRE MUSE programme is organized into three projects.

The Interoperability Standards and Security for Maritime Unmanned Systems (MUS-ISS) project addresses the technology and engineering requirements for future unmanned maritime systems of systems. The project includes topics such as interoperability, potential standards for information assurance, cyber security and unmanned maritime system software architectures, emphasizing the use of open systems with a Service-Oriented-Architecture (SOA) approach.

The Modelling and Simulation (M&S) for MUS project focuses on improving and enabling the development and adoption of new autonomous systems, manned systems, and command and control (C2) capabilities over the different phases of the platform life cycle. The M&S team creates M&S tools that allow efficient and effective testing

of new concepts, ideas and systems. Collaboration with other CMRE programmes enables the development of new capabilities and exploring innovative ways to deliver CMRE knowledge and experience to the operational community.

The Underwater Communications and Networks (UWNET) project aims at providing leading edge underwater communications science and technology for the benefit of NATO and other CMRE programmes. Efforts are focused on security in underwater networks, automatic adaptation to channel variations, and mission requirements and interoperability. The overarching intent is to promote interoperability and standardization for military underwater communications as a fundamental enabler for collaborative missions involving heterogeneous assets.

## Activity

The MUS-ISS project team continued its work as part of the STANAG 4817 Custodian Support team towards establishing a NATO-wide C2 system to support multi-domain assets. CMRE performed research on the International Regulations for Preventing Collisions at Sea (COLREGs) and its adaptation to include both Autonomous Surface Vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs). CMRE participated in the Multi-Domain Control Stations (MDCS) STANAG working group (WG) and a number of STO Research Task Groups (RTG). In order to support interoperability, MUS-ISS also investigated protocols that regulate the simultaneous use of unmanned and manned surface and underwater assets. In addition, MUSE-ISS is exploring the definition of a framework for MUS validation and verification (V&V), as an integral part of MUS system design. Finally, within the context of a STO RTG, work has continued towards achieving cyber security and mission assurance of autonomous systems; collaboration with academia in the USA and Italy has been established to tackle this complex subject.

The M&S for MUS project team continued the development of new capabilities and innovative ways to deliver CMRE knowledge and experience to the operational community. Interoperability and standards applied to Live-Virtual-Constructive (LVC) simulation provide enabling concepts for serious gaming and augmented/mixed reality. Such capabilities were employed in support





**A wave glider, part of the underwater communications network, is deployed from NRV *Alliance* during the Distributed Autonomous Networked Systems sea trial in December 2020.**

of concept development for cooperative and autonomous ASW providing ways to experiment and validate new tactics and algorithms.

The UWNET project team continued its research in security mechanisms for underwater networks. Two specific lines of work were pursued for the generation and distribution of cryptographic keys: one based on the intrinsic properties of the acoustic channel; and another based on quantum properties. Additionally, various Denial of Service attacks and possible countermeasures were investigated. This work will allow CMRE and NATO to establish ways forward on achieving

underwater quantum security and underwater post-quantum cryptography. The project team carried out research into cognitive underwater communications based on machine learning, which will permit a system to automatically change its communications parameters (mode, waveform, bits-per-second, etc.) to overcome the challenges of specific environments. Furthermore, novel networking cooperative solutions were designed to support underwater vehicle navigation in deep water. These solutions were successfully integrated with the vehicle control software developed by the CASW programme and validated during the DANS20 sea trial.

## Highlights

The UWNET project team participated in the NATO Exercise DYNAMIC MANTA 2020, conducted in Southern Italian waters in February 2020, and successfully demonstrated the use of standardized digital underwater communications in support of submarine operations. Text chat and surface ship positions were exchanged in real time with the Hellenic Navy HS Katsonis submarine while at depth and speed; the CMRE team trained the crew of the submarine who operated the CMRE-developed JANUS digital underwater communications system.

During 2020, the CMRE MUS-ISS project team:

- Developed an autonomous vehicle reference software architecture based on the outcomes of the STO SCI-288 ‘Autonomy in Communication Limited Environment’ RTG; and verified with multiple integration options—including vehicles running D2CAF, MOOS-IvP, and ROS—and in different scenarios for multi-domain unmanned vehicles.
- Produced a legal-technical analysis and proposal for clarifications/possible amendments of the COLREGs treaty for a use case with autonomous surface vehicles (ASVs).
- Produced an initial set of “Rules of the Road” for the interaction of manned/unmanned underwater vessels and their interaction with surface vessels when surfacing/diving.
- Participated in the STO IST-164 ‘Securing Unmanned and Autonomous Vehicles for Mission Assurance’ RTG, which completed a high-level reference architecture that represents a structured model of security challenges for autonomous vehicles based on existing standards security, autonomy and risk assessment.
- Conducted preliminary studies on Validation and Verification of autonomous systems. CMRE is now part of the NATO Industrial Advisory Group (NIAG) Study Group (SG) 259 ‘Testing, Evaluating, Verifying and Validating (TEVV) of systems-embedded autonomous functions (SAF), for future military operations.

In 2020 the main achievement of the M&S for MUS project was the concept development and testing of a federation of cooperative and autonomous

ASW assets. Sixteen key performance indicators (KPIs) addressing area coverage, time on target, tracking localization error, and signal to noise ratio (SNR) are assessed and clustered according to the number of vehicles (‘single’ performance and ‘multi’ for a team of vehicles). Computation of SNR is done with CMRE’s Multi-Static Tactical Planning Aid (MSTPA), used to assess the performance of a given emitter-target-receiver configuration. Additionally, the UWNET Cognitive Communications Architecture (CCA) stack was integrated into the High Level Architecture (HLA) federation, and physical layer fidelity has been improved through the inclusion of the BELLHOP acoustic propagation model.

In 2020, the M&S team also conducted a preliminary investigation on how to support and enhance underwater—and in particular ASW—scenarios in NATO Collective Training and Exercises. The outcome was a set of proposed gaps and recommendations.

During 2020, the UWNET project team successfully:

- Developed a novel cryptographic key generation method to secure undersea acoustic transmissions, which does not require a central entity or a security infrastructure—both of which are difficult to implement underwater.
- Developed a proof-of-concept system for underwater Quantum Key Distribution (QKD) to support further research into Quantum security and post-quantum cryptography.
- Implemented and tested a cognitive underwater communications modem, capable of automatically selecting in real-time which waveform to use in response to the acoustic channel conditions; the approach is based on acoustic measurement and machine-learning techniques.
- Developed novel networking cooperative solutions to support underwater vehicle navigation in deep water scenarios through the use of one-way and two-way range estimation techniques.
- Investigated various Denial of Service attacks for underwater acoustic networks, including Jamming, Replay Attack, Resource exhaustion and Sinkhole Attack. Possible countermeasures were proposed and evaluated via simulations.



## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY NATO ACT

# MODELLING AND SIMULATION SUPPORT

### Overview

The ACT Modelling and Simulation (M&S) Support project is the continuation of a series of projects carried out in the last five years by the CMRE M&S team. The main goal of this project is to assist ACT with the investigation, analysis, and development of solutions based on the use of M&S to support a wide range of NATO activities, including training, decision-making, advance planning, operations planning, and concept development & experimentation (CD&E).

The objectives of the project for 2020 were:

- To support the definition and development of the implementation of the next generation NATO M&S capability.
- To contribute to the investigation and identification of solutions to overcome obstacles preventing the efficient use of M&S to support NATO decision-making.
- To design and develop a software simulator to be used during the CD&E NATO Course for demonstrating the use of M&S to support CD&E in NATO.

### Results

- Developed and delivered to HQ SACT staff a white paper describing the fundamentals of the next generation M&S enabling capability in terms of: what problems shall be solved for whom; how to generate benefits; and how to transfer those benefits to stakeholders. Additionally, the paper identified gaps in the Alliance's strategic direction to implement the next generation NATO M&S capability.
- A Capability Architecture final report based on the NATO Architectural Framework (NAF): the report focusses on the adoption of NAF to provide strategic guidance, shared project management approaches and a common language and set of communication tools for supporting the creation of the future NATO Next Generation M&S capability.
- Supported the NATO STO joint Modelling and Simulation Group (MSG) and Systems Analysis and Studies (SAS) 178 research task group (RTG) on 'Using Simulation to better inform Decision Making for Warfare, Planning, Operations and Assessment'. This multinational RTG—with representatives from NATO entities (ACT, NCIA, CMRE, and NATO M&S Centre of Excellence) and Nations (including CAN, DEU, ITA, NLD, TUR)—continues its work on overcoming the barriers preventing an efficient use of M&S within NATO.
- Delivered a prototype simulator to be used during the CD&E training course delivered by HQ SACT CD&E and Operational Experimentation (OPEX) branch staff at the NATO School Oberammergau. The simulator implements a logistic support operation; students develop and validate a concept on the use of unmanned ground vehicles. By doing so, students learn and explore the benefits of experimentation, and the use of M&S to support the development and validation of concepts in the context of NATO CD&E.

### Contact

For more information about the M&S Support project, please contact Alberto Tremori ([alberto.tremori@cmre.nato.int](mailto:alberto.tremori@cmre.nato.int)).



## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY OFFICE OF NAVAL RESEARCH GLOBAL (ONR-G)

# SECURITY IN AD-HOC UNDERWATER ACOUSTIC NETWORKS

### Overview

As Nations start to employ Underwater Acoustic Networks (UANs) in military applications new protocols must be designed to ensure the security of the data transmitted underwater. The Security in Ad-hoc Underwater Acoustic Networks project addresses network security from a cognitive and cross-layer perspective. At the physical layer, Low-probability-of-intercept (LPI) and anti-jamming (AJ) capabilities are being investigated by combining various coded modulation techniques. Moreover, a novel encryption key management protocol is being developed. At the networking layer, cooperation between nodes will be employed to enable the network to respond to Denial of Service (DoS) attacks.

### Results

- A software modem with the ability to operate at very low transmit power, hence achieving LPI capability, was developed and successfully tested. The transmitter uses Direct Sequence Spread Spectrum (DSSS) modulation and the receiver design is based on single or multi-band equalization.
- An adaptive modulation technique was developed that allows the modem to maximize its bit rate subject to reliability and LPI constraints. This was achieved by using machine learning to understand the relationship between the bit-error rate and channel quality metrics.
- It was demonstrated through simulation that network performance could be enhanced in terms of increased data throughput, reduced energy consumption and better signal covertness, by employing adaptive signal selection between neighbouring nodes.
- Progress was made towards an algorithm that generates a symmetric cryptographic key between two trusted nodes. The key is independently generated at both nodes and is based on measured channel metrics. This ensures that an eavesdropper cannot obtain the key.
- Strategies to counteract DoS attacks in an underwater acoustic network were investigated. Replay and Sinkhole DoS attacks were examined as test cases.

### Contact

For more information about the Security in ad-hoc Underwater Acoustic Networks project, please contact João Alves ([joao.alves@cmre.nato.int](mailto:joao.alves@cmre.nato.int)).

## MARITIME UNMANNED SYSTEMS ENABLERS

COLLABORATIVE PROJECT WITH DEFENCE RESEARCH AND DEVELOPMENT CANADA

# UNDER-ICE ACOUSTIC COMMUNICATIONS NETWORK

### Overview

Defence Research and Development Canada (DRDC) aspires to develop an underwater, under-ice acoustic communication capability for use in Canadian Arctic waters. DRDC seeks a solution that maximizes endurance and range in the harsh Arctic ocean environment. CMRE contributed in two areas. For the physical layer, CMRE analysed modulation and coding schemes for the digital bit stream, the effect of acoustic propagation, and the processing required to retrieve the bits at the receiving end. For the networking layer, the work dealt with the medium access and routing protocols needed to design a network that efficiently addresses the requirements of end-to-end achievable data rates, latency and node power consumption.



**DRDC technologists tow a Distributed Underwater Sensor Network (DUSN) node to the middle of Gascoyne Inlet, Devon Island, Canada, during at-sea testing of its underwater communications capability in 2019.**

### Results

- Four coded modulation schemes were investigated. To cope with extended multi-path propagation, the waveforms use either Frequency-shift Keying modulation with non-coherent detection or single-carrier Phase-Shift Keying (PSK) modulation combined with Spread-Spectrum and a Decision Feedback Equalizer (DFE) receiver. The reliability of the four waveforms was analysed by using real data recorded during DRDC's 2019 summer sea trial in the Canadian High Arctic at Gascoyne Inlet. The results confirm robust long range communications with the potential to support higher data rates.
- A comparative performance evaluation of various medium access and routing protocols was performed for the networking layer. The results showed that the use of an adaptive strategy, selecting the modulation scheme and the relay node according to conditions, is feasible and effective for the network scenarios considered. It was also demonstrated that the availability of more nodes and links contributes to the endurance of the network and improved robustness against failures.

### Contact

For more information about the Under-Ice Communication Network project, please contact Konstantinos Pelekanakis ([konstantinos.pelekanakis@cmre.nato.int](mailto:konstantinos.pelekanakis@cmre.nato.int)).

## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY THE EU COMMISSION

# CAMELOT PROJECT

### Overview

C2 Advanced Multi-Domain Environment and Live Observation Technologies (CAMELOT) is an EU Horizon 2020 project to develop and demonstrate customizable command and control service modules for multiple platform domains. Currently, there is no widespread standard for multi-service, multi-domain command and control (C2) systems. The CAMELOT architecture and modules will help build support within industry and the user community for the adoption of these technologies. The underwater domain is a special case in C2 as communication and localization have to be implemented in a completely different way. CMRE developed an acoustic localization beacon system (LBS), to provide underwater assets with a positioning service. Like the Global Positioning System (GPS) in the surface domain, the CAMELOT LBS provides autonomous underwater vehicles (AUVs) with their position by emitting acoustic localization pulses that are received by all the AUVs within range. The ability to communicate with multiple AUVs from a single unmanned surface vehicle would allow NATO maritime forces greater mission scalability while maintaining a constant connection with any number of underwater assets.



**Through the CAMELOT Project, CMRE researchers have been experimenting with the unmanned surface vehicle, Gulliver, to provide navigation aids to multiple underwater vehicles at once.**

### Results

- CMRE designed and realized the LBS hardware components and completed the integration of the system on CMRE's unmanned surface vehicle (USV) "Gulliver".
- CMRE optimized the real-time position estimation algorithms at the receiver side using data acquired using the Gulliver USV.
- The CAMELOT consortium conducted several virtual experiments to demonstrate interoperability between unmanned assets achieved by the CAMELOT C2 system. The tests will assess the ability of commanding and controlling multiple unmanned platforms and delivering services such as automatic asset tasking, mission planning and re-planning.

### Contact

For more information about the CAMELOT project, please contact Stefano Fioravanti ([stefano.fioravanti@cmre.nato.int](mailto:stefano.fioravanti@cmre.nato.int)).



## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY THE EU COMMISSION

# ROBORDER PROJECT

### Overview

Funded by the EU Horizon 2020 programme, ROBORDER seeks to develop and demonstrate an autonomous border surveillance system composed of a network of unmanned platforms including aerial, water surface, underwater and ground vehicles, capable of functioning both individually and in swarms. The system will be equipped with adaptable sensing and robotic technologies that can operate in a wide range of operational settings. Artificial intelligence for detection, classification and tracking of threats will be developed and embedded in the ROBORDER command and control (C2) system. The exploitation of large volumes of data and the provision of a rapid situational awareness will support operator's decision-making. CMRE leads the evaluation work package and supports the organization of the demonstrations.



**Unmanned aerial vehicle being prepared for take off at the ROBORDER trial in Portugal.**

### Results

- CMRE developed a Modelling and Simulation (M&S)-based test bed which complies with High Level Architecture (HLA) interoperability standards and is designed according to IEEE and NATO best practices. It consists of a federation of simulators including virtual and constructive components and is able to run in both real and fast time.
- ROBORDER components developed by consortium members were tested using CMRE's M&S test bed. The test bed proved a valuable tool for the assessment, contributing insight used in the re-design of the components.
- CMRE led the organization of the first ROBORDER live demonstration in Portugal in mid-November. During the event the ROBORDER C2 system was deployed for the first time to successfully control unmanned underwater vehicles and fixed-wing unmanned aerial vehicles (UAVs) fitted with pollution detection sensors. CMRE will coordinate two more demonstrations in Hungary and Greece in 2021. These demonstrations will also include unmanned ground vehicles and rotary-wing UAVs.
- CMRE refined the Key Performance Indicators (KPIs) for quantitative evaluation of ROBORDER system performance and created a qualitative evaluation tool used to collect feedback from stakeholders during the live demonstration.

### Contact

For more information the ROBORDER project, please contact Alberto Tremori ([alberto.tremori@cmre.nato.int](mailto:alberto.tremori@cmre.nato.int)).

## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY THE EU COMMISSION

# EU MARINE ROBOTS

### Overview

Today, there is a pressing need for a sustained, persistent, and affordable presence in the oceans that will help us to understand and monitor key issues such as climate change, pollution, shipping and security. Equally important is the development of technologies that will allow us to explore and exploit the ocean in a sustainable manner. EU Marine Robots (EUMR) is a Horizon 2020 Research and Innovation project aimed at establishing an integrated marine robotics infrastructure in Europe. This will be achieved by opening key national and regional marine robotics research facilities to researchers, from both academia and industry, ensuring their optimal use and joint development. The EUMR consortium comprises 15 partners from 10 countries who, collectively, can deploy a comprehensive portfolio of marine robotic assets and expertise. CMRE's contribution to EUMR is the use of the Littoral Ocean Observatory Network (LOON) test bed for joint research.



**A node of CMRE's LOON underwater communication network being deployed.**

### Results

- CMRE received six project proposals from academia, research centres and industry located in the EU and US wanting to use the LOON (50 days of usage in total) to conduct research on underwater acoustic communications, networking and interoperability. The execution of the experimental activities is currently ongoing and will continue into 2021.
- Development of an adaptive acoustic-optical communications system using the CMRE Cognitive Communication Architecture (CCA) and the optical communication solution developed by the EUMR consortium. The system uses acoustic links to obtain situational awareness and to enable or disable fast optical links when available, thus optimizing the use of resources at the network nodes. Initial validation of the proposed solution was performed via simulations during 2020, with at-sea tests planned for 2021 using the LOON and unmanned surface and underwater vehicles.
- Development of a generic communication interface to enable the interaction between the CMRE CCA and the control software on-board partner underwater and surface vehicles. This enables the unmanned platforms to use the acoustic-optical communications system.

### Contact

For more information about the EUMR project, please contact Roberto Petroccia ([roberto.petroccia@cmre.nato.int](mailto:roberto.petroccia@cmre.nato.int)).

## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY THE EU COMMISSION

# ARESIBO PROJECT

### Overview

Augmented Reality Enriched Situation Awareness for Border Security (ARESIBO) is an EU Horizon 2020 project to develop a cloud-based integrated situational awareness system for border security. It will feature simple but complete and highly-standardized interfaces showing real-time information in a user-friendly way with the support of augmented reality technologies. ARESIBO will help border guards in decision-making and in remaining in contact with their command and control (C2) centre during operations.

CMRE's main role is in the development of a serious gaming framework based on Modelling and Simulation (M&S) to support the training of field officers, field commanders and C2 operators on border protection operations. The development of an integrated training environment is designed to help operators improve their skills and competences and focused on border security in land and maritime operations. CMRE has been assessing the operational interest, relevance, impact and value of integrating innovative technologies like augmented reality with serious games.

### Results

To provide the trainee with more realistic and immersive visual feedback, CMRE staff improved the realism and fidelity of the existing CMRE 3D synthetic environment for maritime scenarios, and extended it to support the simulation of land-border scenarios, complete with geo-referenced terrain data, streets, and realistic vegetation.

- Successful training relies not only on realistic environments, but also the virtual and physical integration of the ARESIBO system. The various ARESIBO vehicles were integrated into the M&S capability to provide trainees with realistic-looking vehicles and behaviours through kinematic and 3D models.
- A software module was developed to allow communication between the Training Environment (based on High Level Architecture interoperability standard) and the ARESIBO system (based on KAFKA).
- Three brand new, map-based graphical software tools were developed to help the trainers design and set-up the simulated training scenarios. The definition of scenarios includes selecting the geographical location, vehicles with their payloads and missions, and the meteorological conditions. This set of tools will help the trainers to tailor the simulation scenarios to match specific training needs.

### Contact

For more information the ARESIBO project, please visit <https://aresibo.eu> or contact Alberto Tremori ([alberto.tremori@cmre.nato.int](mailto:alberto.tremori@cmre.nato.int)).



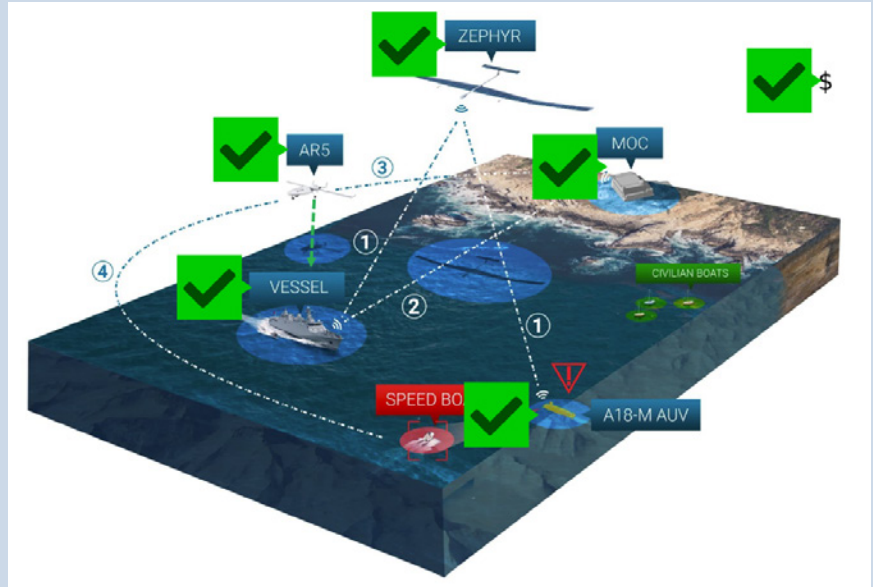
## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY THE EU COMMISSION

# COMPASS2020

### Overview

COMPASS2020, funded by the EU Horizon 2020 Innovation programme, is demonstrating the operational utility of Remotely Piloted Aircraft Systems (RPAS) such as Unmanned Aerial Vehicles (UAVs) and High Altitude Pseudo-Satellite (HAPS), integrated with Underwater Unmanned Vehicles (UUVs) and traditional surveillance assets, for maritime border missions. Two maritime surveillance scenarios will be demonstrated: detection of drug smuggling and detection of migration. The demonstrations will employ improved algorithms for RPAS control and provide information on how to optimize missions with unmanned assets to reduce cost and response time.



**A visualization of the COMPASS2020 surveillance assets modelled by the CMRE Modelling and Simulation team.**

### Results

- Bringing together stakeholders: CMRE leads the task to generate a reference requirements architecture that will form the blueprint of future projects involving unmanned systems in the maritime domain. Two candidate requirements architectures were developed for the COMPASS2020 surveillance system.
- Key Performance Indicators (KPIs): In order to test the candidate architectures, a set of KPIs were identified by the consortium during a three-day virtual workshop organized by CMRE. The workshop participants then applied their knowledge to score current manned maritime surveillance systems against the KPIs, resulting in baseline performance indicators that the unmanned systems can be assessed against.
- COMPASS2020 webinar: CMRE held the first COMPASS2020 webinar 16 – 19 November 2020. The objectives were to identify the highest impact areas for deployment of unmanned systems in maritime operations and to have community discussion about the identified architectures and KPIs. The outcomes of the webinar will guide the final stages of the project, resulting in a demonstration that reveals the true potential of unmanned systems in the maritime domain.

### Contact

For more information about the COMPASS2020, please contact Alberto Tremori ([alberto.tremori@cmre.nato.int](mailto:alberto.tremori@cmre.nato.int)).

## MARITIME UNMANNED SYSTEMS ENABLERS

FUNDED BY NATO ACT

# M&S SUPPORT TO INNOVATION HUB

### Overview

This project provided support to the ACT Innovation Hub (ACT IH) on Modelling and Simulation (M&S). The work developed in 2020 was based on the preliminary 2019 work, when CMRE drafted technical requirements, recommendations and options for the implementation of a future synthetic environment (SEN) for testing hypotheses and solutions. This synthetic environment will support the ACT IH strategic goal of turning prototype solutions into ‘user-centric’ Minimum Viable Products and is to be used during IH disruptive technology assessment games (DTAG) and disruptive technology experiments (DTEX), representing a new approach to NATO wargaming designed to quickly test ideas and technologies that can solve problems for NATO.

CMRE led the project, coordinating and managing the activities of a team including the Old Dominion University (ODU) and its M&S research centre Virginia Modelling and Simulation Centre (VMASC). The objective for CMRE in 2020 was to develop, together with ODU/VMASC, a prototype solution of the IH synthetic environment and to support the organization of a 2020 event. CMRE’s efforts focused on the development of a web-based and reusable tool with the intent to improve communication, increase quality and optimize the value of the findings to lead to better-informed discussions among participants.

### Results

- Building on the CMRE M&S team’s experience in the use of the NATO Architectural Framework (NAF), the team developed a web-based configurable dashboard tool to present appropriate information to each community among a wide range of project stakeholders and to facilitate the visualization and evaluation of data provided to event attendees or collected during the event. The NAF Dashboard prototype for the DTAG/DTEX events consists of three main functions.
- The first and most mature function presents NAF diagrams: in past events, it has been observed that the level of understanding of the event scenario differed among participants. The CMRE Dashboard provides participants with an overview of the event process and each scenario, using targeted NAF diagrams for ease of understanding, to ensure similar baseline knowledge for all participants.
- The second function supports learning about individual Ideas of Systems (IoS) cards, by exploring each card and any background information made available by the technology provider, while the third function aids management of the IoS cards to facilitate selection and refinement. These two functions were not mature enough to be used during the 2020 event and were demonstrated to participants at the event’s conclusion.
- An informal question and answer session indicated that the three functions added value and warranted further development.

### Contact

For more information about the project, please visit <https://www.innovationhub-act.org/blog/simulation-and-distributed-wargaming-experiment> or contact Alberto Tremori ([alberto.tremori@cmre.nato.int](mailto:alberto.tremori@cmre.nato.int)).

# ENGINEERING & IT DIVISION

## Overview

The Engineering and Information Technology Division (EITD) is a group of sixty engineers, technicians and craftsmen with varied backgrounds including acoustics, electronics, fabrication, ocean engineering and robotics complemented by a team of Information Technology (IT) professionals with expertise in software development, data management, networks and security. Organized as two departments, Engineering and IT, they provide all the services necessary to support the Centre's experimentation activities. EITD enables the Centre's success by ensuring the acquisition and management of scientific datasets in a secure and accredited environment in accordance with NATO policies.

## Technological landscape

NATO finds itself in a new and dynamic reality, marked by growing uncertainty, instability and risks amid rapid scientific and technological change with the potential to disrupt the global strategic balance. The current explosion of emerging technologies offers great opportunity—and potential peril—for NATO, with respect to maintaining its technological and operational advantage. In 2019, the North Atlantic Council approved the Emerging and Disruptive Technologies (EDT) Roadmap to help guide Alliance work. The EDT Roadmap promotes rapid development of demonstrations in operational conditions in order to understand the potential of EDTs from both the opportunity and threat standpoints and to set the conditions to exploit them within NATO and the Nations.

With its proven track record of rapid engineering development and at-sea demonstration, CMRE-EITD is well-positioned to respond to the EDT Roadmap. There are clear synergies and economies of scale to be gained by Nations exploiting CMRE's sea-going capability and its role as a collaboration hub for collective research that benefits all Nations.

CMRE will continue to support the Nations in de-risking the assessment and introduction of EDTs to the maritime operational community, including understanding, mitigating and solving some of the challenges posed by the introduction of

Maritime Unmanned Systems (MUS). However, CMRE needs a refresh of much of its engineering and IT infrastructure to fully realize its potential to support NATO.

## Engineering modernization

CMRE owns a working inventory of over 20 autonomous platforms of at least eight varieties ranging from large 21-inch autonomous underwater vehicles (AUVs) to smaller man-portable gliders, and unmanned surface vehicles (USVs). Many of these are equipped with state-of-the-art acoustic sensors, such as synthetic aperture sonars and thin-line towed arrays, often designed and built at CMRE.

Key enabling engineering technologies that CMRE could use to help NATO address capability shortfalls include:

- long endurance, cyber-secure unmanned systems for sea surface, underwater and air domains;
- advanced electric, magnetic, optical and acoustic sensing technologies for use above and underwater to provide real-time data for battlespace awareness and decision-making;
- improved above-water and underwater secure datalinks and networks; and
- modular expeditionary capability to allow deployment of experimental platforms from naval ships in operational settings.

## IT modernization

The execution of the CMRE programme of work requires state-of-the-art IT infrastructure. CMRE's IT modernization plan based on the following tenets:

- reduction of the number of IT assets while increasing overall capability, coupled with adoption of a common enterprise architecture and service-based maintenance;
- move from physical workstations to virtualized computing resulting in improved efficiencies, better security and reduced operating costs;





**CMRE engineers run tests from the deployable AUV control station.**

- migration from personal, fragmented storage to centralised storage to improve efficiency, reliability and security;
- convergence to a single classified IT system to be shared among all CMRE projects for security compliance and improved efficiency; and
- deployable classified IT modules with reach back to CMRE and the ability to interface with NATO C2 networks.

‘Although significant investment is required to modernize CMRE’s engineering and information technology capability, initial steps are already underway.

CMRE is working with NATO Allied Command Transformation to identify additional NATO support, which will allow the modernization to be completed. This will enable the Centre to realize its full potential to support NATO’s science and technology requirements in the maritime domain.

# ENGINEERING DEPARTMENT

## Overview

The mission of the Engineering Department (ED) is to support the Centre's scientific research by enabling the collection of experimental data in the above-water and underwater domains. ED has about forty engineers, technicians and craftsmen who address the challenges of taking CMRE's science to sea. They design and develop unique experimental systems, augment off-the-shelf technology with in-house developed capabilities such as advanced sensor suites, and they test, operate and maintain the broad range of equipment, instruments and machinery in CMRE's engineering and scientific inventory.

The work of ED is structured along two axes: "Horizontal" activities include the maintenance, repair, calibration and improvement of existing equipment in preparation for operations at sea, and "Support to Projects" which develops new equipment and instruments, designed and integrated according to CMRE's or external customer's needs.

To meet the demand, ED's multidisciplinary staff are organized into the following Sections:

- Acoustic: develops and operates state-of-the-art sonar systems, including transmitting and receiving transducers, sensors and arrays to be towed from ships, moored to the sea floor, or installed in autonomous platforms;
- Electronic: supports data acquisition, storage and processing, as well as the needs of propulsion, communication and control of unmanned systems through the integration of custom electronics. Emphasis is placed on miniaturization, energy efficiency and endurance;
- Oceanographic: provides knowledge of the ocean environment with traditional and custom sensors deployed in moorings, towed from ships or installed onboard CMRE's fleet of buoyancy gliders for persistent data collection in large ocean areas;
- Unmanned Systems: supports most CMRE activities through the custom integration and operation at sea of surface and underwater autonomous platforms, often working collaboratively, complementing one another with their specific capabilities and sensors; and
- Mechanical: provides support through the design, fabrication, integration, testing, operation at sea and maintenance of all CMRE engineering equipment, using state-of-the-art electro-mechanical fabrication machinery, integrated in 2020 with a 3D printing machine.

## Activity

Activities in 2020 were dominated by the COVID-19 pandemic which had significant consequences for ED operations and staff. ED's core activities require teams of craftsmen, technicians and engineers to work hands-on, in close contact, on equipment, ashore and at sea. The challenge for ED in 2020 was to continue to work under the constraints of COVID health and safety protocols of the Government of Italy, of NATO and of CMRE. With the rapid acquisition of Personal Protective Equipment (PPE) in March including N95 face masks, face shields, latex gloves and various sanitization products, ED was able to adapt to reduced staff on site while allowing staff to work safely in close proximity when required. Although most CMRE staff were able to work remotely during the spring and end-of-year lock-downs, many ED staff were on-site most of the time because their work cannot be done remotely. In the end, ED was able to fully meet its 2020 mandate, including supporting five sea trials, thanks to the dedication and strict adherence to the health and safety rules by staff. We are proud of this success!

## Highlights

- Support to the execution of two consecutive sea trials on-board NRV *Alliance*, DYNAMIC MANTA 2020 (DYMA20) and Littoral Continuous Active Sonar 2020 (LCAS20). For DYMA20, NRV *Alliance* participated as a member of an ASW task group. The trials took place during 30 days at sea in the southern Mediterranean in February and March. The first incident of the COVID-19 pandemic affected DYMA20 when someone on-board NRV *Alliance* was sent ashore for observation due to potential close contact with coronavirus prior to the trial. The ship was placed under quarantine, but was able to complete the trials. The two trials involved the full suite of CMRE Autonomous Anti-Submarine Warfare (AASW) assets conducting ship and AUV-based active and passive sonar operations.



- First deployment at sea during DYMA20, of a demonstration of a Passive Acoustic Barrier using two buoyancy gliders equipped with acoustic vector sensors (AVSs) and data acquisition and processing payloads, both communicating with the NRV *Alliance* Command and Control (C2) system through a Wave Glider gateway.
- Demonstration, during DYMA20, of the JANUS underwater communication system in an operational ASW setting.
- First deployment from a ship of the High Resolution Low Frequency Synthetic Aperture Sonar (HRLFSAS), from CRV *Leonardo* in July. The sonar was in a new extended configuration consisting of 192 transmitting transducers driven by custom-designed amplifiers, 320 receiving hydrophones and two supplementary low frequency transducers. The tests took place in a local shallow water area with a number of deployed proud and buried mine-like targets.
- Support to the execution of the DYMR20 sea trial with NRV *Alliance* in the Mediterranean south of France during September-October. CMRE participated with the NATO Response Force Maritime during DYMR20, contributing to the mine countermeasure activities. The full suite of CMRE Autonomous Naval Mine Countermeasures (AN-MCM) unmanned systems and payloads were deployed as well as demonstrating the ability to interoperate with the US Navy MCM team from the 6th fleet detachment from Rota, Spain, with their three Remus MK18 Mod II vehicles.
- First deployment at sea, during DYMR20, of the Bi-modal Identification Or Neutralization Demonstrator (BIONDO), based on a commercially available Sparus AUV, customized and improved with the installation of an inertial navigation system (INS) and a forward-looking ARIS acoustic camera for target reacquisition, identification and classification.
- Sustained support during 2020 to the operation of the Littoral Ocean Observatory Network (LOON), the test bed implemented at the CMRE basin to foster cooperative development of underwater communications and networking.
- Support to the execution of the Mediterranean Recognized Environmental Picture (MREP20) sea trial in the Strait of Sicily on-board NRV *Alliance* in October-November. The trial involved the full suite of CMRE Environmental Knowledge and Operational Effectiveness (EKOE) assets, with the deployment of oceanographic and acoustic sensors on moorings, buoyancy gliders, or towed from the ship.
- First deployment at sea, during MREP20, of several new pieces of equipment: the Underway towed CTD system (UCTD), which measures water conductivity and temperature with depth; the Alseamar Moored Acoustic Source; and the Wirewalker real-time CTD profiling system.
- Support to the execution of the Distributed Autonomous Networked Systems 2020 (DANS20) sea trial, held in the Ligurian Sea near CMRE on-board NRV *Alliance* in December. DANS20 focused on passive detection using autonomous platforms and exploited the full suite of CMRE AASW assets.
- First operation at sea, during DANS20, of the newly designed Bottom Node for Broadband Observation of Naval systems (BonBon), equipped with two 3D acoustic vector sensors (AVSs) and a volumetric acoustic sensor, capable of acquiring and processing data to autonomously resolve and transmit contacts to a ship-based C2 centre.
- First deployment at sea, during DANS20, of an OEX-C-class AUV equipped with a new CMRE-designed acoustic transducer with a custom power amplifier section, to operate as a noise source and artificial target during passive acoustic experimentation.
- Demonstration at sea, during DANS20, of an improved version of the Vector Sensor Prototype Array (VESPA), under tow of a Wave Glider USV. The new features include a MOOS-based back-seat capability, a newly designed data acquisition and processing tow-body, and the installation and testing of a Wilcoxon 3D AVS.
- Support to projects outside the ACT Maritime S&T Programme of Work include: (1) design and construction of a new towed acoustic array for Penn State University (US); (2) initiation of a project with the Italian Navy Centro di Supporto e Sperimentazione Navale (CSSN) for the design and integration of a new portable acoustic ranging system for Italian navy ships and submarines (ITA); (3) completion of the preparation phase (including NRV *Alliance* modifications) for tests at sea of the Leonardo ATAS System (ITA); (4) continued support to the European Commission funded project CAMELOT with the integration and test at CMRE of a new acoustic localization beacon on-board CMRE's Gulliver USV.



## ENGINEERING DEPARTMENT

FUNDED BY US DEFENSE UNIVERSITY RESEARCH INSTRUMENTATION PROGRAM (DURIP)

# TOWED HYDROPHONE ARRAY SYSTEM FOR PENN STATE

### Overview

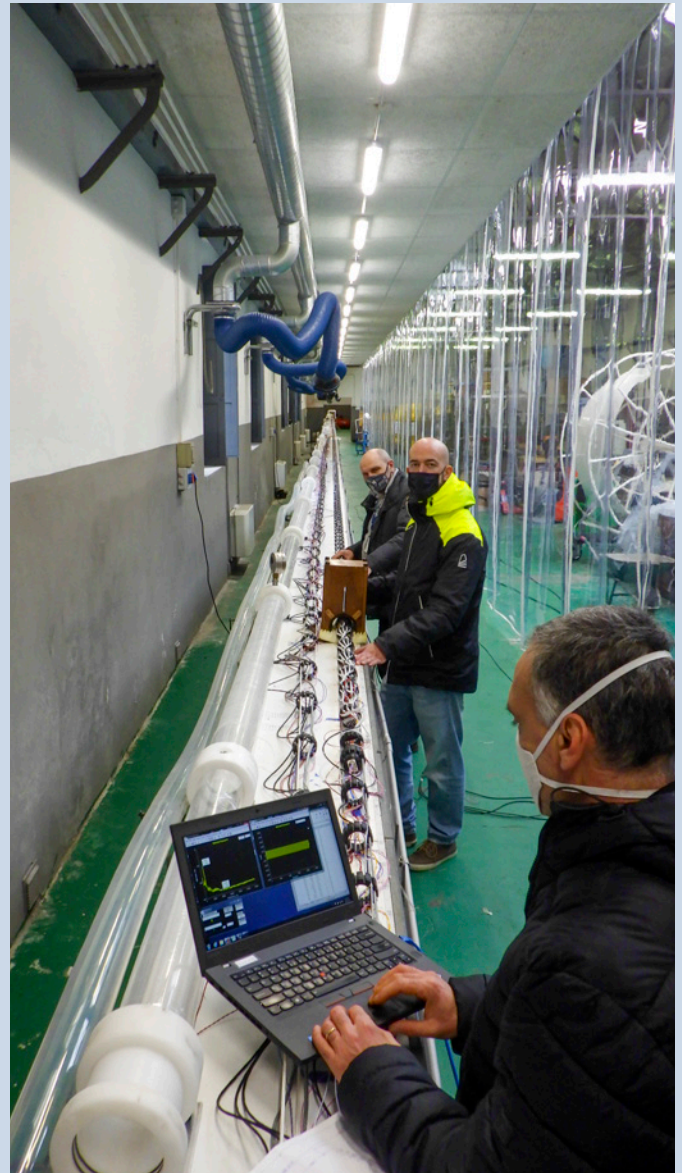
CMRE was first contacted by Penn State University, Applied Research Laboratory (ARL) in 2016, requesting a cost estimate for the replacement of their successful but obsolete Five Octave Research Array (FORA), which had been built in 2002. The main challenge during the ensuing costing exercise, was to find a solution that would provide a comparable replacement, at a fraction of FORA's original cost. CMRE and ARL worked together to come up with a practical compromise; reducing the number of octaves to three but using a modular design which would allow straightforward addition of more sections (octaves) in the future. CMRE's other major cost-cutting solution was to re-use the FORA system's tow-cable and winch. In June 2019, CMRE was contracted by Penn State University to build the complete towed array system which consists of:

- Drogue (re-used from FORA)
- A 50-metre long acoustic module, containing 128 hydrophone/preamplifiers, plus digitisers and attitude/depth sensors
- A 25-metre long Vibration Isolation Module (VIM)
- Electro-opto-mechanical termination for the tow-cable
- Tow-cable and winch (re-used from FORA)
- Deck cable
- Data-acquisition, control, power supply system, and associated software

CMRE has leveraged its multi-decade experience in array design together with its manufacturing and testing facilities, to provide Penn State ARL with a complete acoustic towed array system, from the hydrophones to the stored acoustic data, which is both technologically advanced and cost-effective. The completed system is due for delivery in early 2021.

### Contact

For more information about the Towed Hydrophone Array System for Penn State ARL, please contact Luigi Troiano ([luigi.troiano@cmre.nato.int](mailto:luigi.troiano@cmre.nato.int)).



**Acoustic bench-testing of the 128 hydrophone channels, at CMRE's array manufacturing facility.**

## ENGINEERING DEPARTMENT

FUNDED BY ITA N THROUGH THE NATO SUPPORT AND PROCUREMENT AGENCY (NSPA)

# PRODES PROJECT

### Overview

The Italian Navy has a requirement for a deployable system for the measurement of the acoustic signatures of Navy ships and submarines. The system will be delivered to and managed by the Italian Naval Support and Experimentation Centre (Centro di Supporto e Sperimentazione Navale - CSSN) and will replace the legacy Italian Navy system. To meet this requirement, the Italian National Armaments Directorate - Navy Procurement Agency (NAVARM) requested the NSPA to procure the above capability through a contract with CMRE, supported by a Memorandum of Understanding (MoU) between CMRE and CSSN.

This Prototype Deployable Signature Range (PRODES) Project covers the design, development and at-sea testing of a prototype deployable acoustic signature range to measure the radiated noise of ships and submarines. The project is divided into two major activities: the production of the acoustic suite with data acquisition system (AS-DAS); and, the integration of a radio buoy, mooring system, and real-time monitoring and post processing system. The following results have been achieved thanks to a continuous sharing of information and collaboration among technical personnel of CMRE and CSSN.

### Results

- The acoustic array design at both the mechanical and sensor level has been proposed to the end user for acceptance, including possible alternatives for hydrophone design and non-acoustic sensors, with predicted performance based on simulation.
- The end user agreed to the Data Acquisition (DAQ) device design. The DAQ design provides capacity for future improvements and enhancements.
- The end user agreed to the array design. The design meets the spatial resolution and signal-to-noise ratio (SNR) technical specifications, and accommodates system expansion by providing spare connectors and reserved data acquisition channels for future signature measurement capabilities—such as Acoustic Vector Sensors, in which both CMRE and CSSN are investing and exchanging experience.
- CMRE and CSSN personnel carried out surveys of the destination sites for the system's deployment to assess the physical compatibility of selected components with the intended operational environment.
- The interfaces between the acoustic segment and processing units have been identified and specified in a System/Subsystem Design Document.

### Contact

For more information about the PRODES project, please contact Alberto Grati ([alberto.grati@cmre.nato.int](mailto:alberto.grati@cmre.nato.int)).



ENGINEERING DEPARTMENT

FUNDED BY DEIMOS SPACE

EO-ALERT MARITIME EXPERIMENTAL CAMPAIGN



The EO-ALERT experimentation team from DEIMOS Space, CMRE and the Italian Navy.

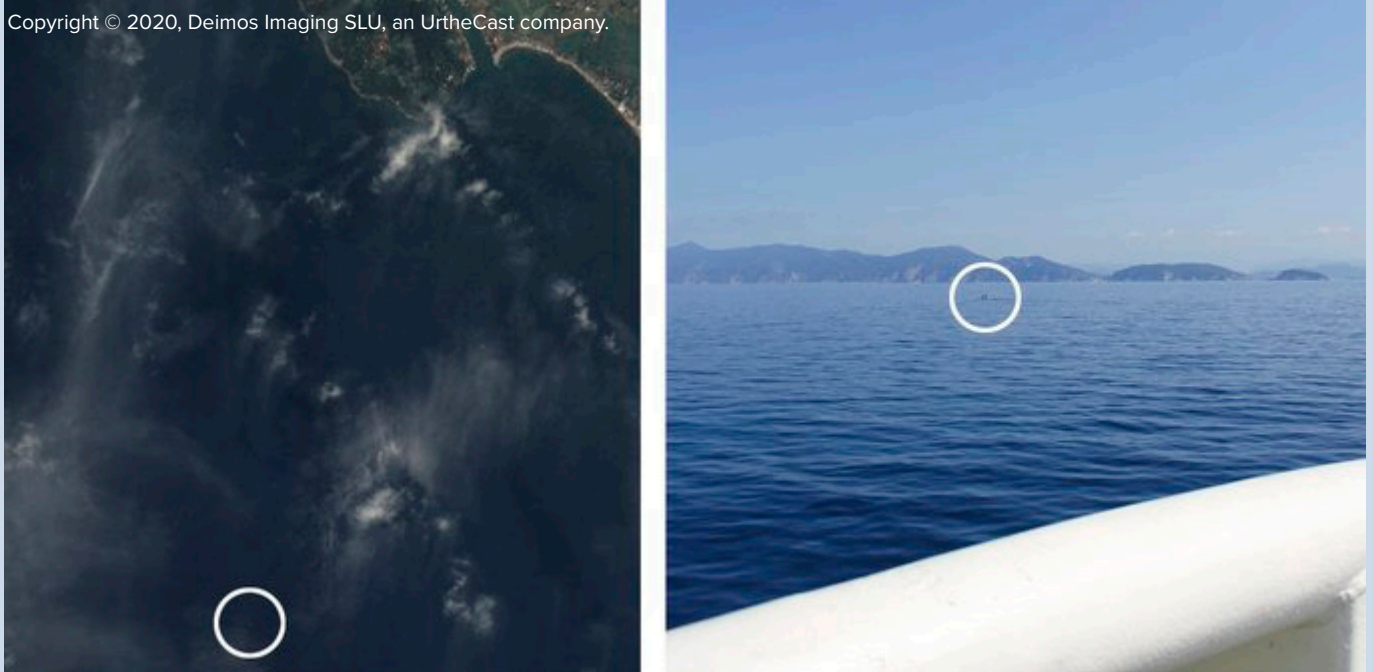
Overview

Earth observation (EO) data from satellites is used to monitor and assess changes in natural environments and industrial activities across the globe. The data generated by EO satellites is ubiquitous in diverse applications such as meteorology, oceanography, environmental and resource monitoring, and emergency management. EO-ALERT is a three-year project funded by the European Commission’s Horizon 2020 research programme, aimed at improving the delivery times of EO imagery products and data services. The project is coordinated by DEIMOS Space, a European engineering company based in Spain.

The goal of EO-ALERT is to demonstrate the next-generation EO data processing chain, based on a novel architecture that moves key processing elements from the ground to on-board the satellite. This will result in enhanced and faster EO products and services, providing the EO products to the end user with very low latency. For instance, the ship detection algorithm developed within EO-



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**On the left is a DEIMOS2 satellite image of a boat compared with the sea view of the same boat taken by CMRE on-board CRV *Leonardo* during the EO-ALERT campaign.**

ALERT uses AI and machine learning techniques on-board satellites to deliver results in less than one minute. This represents a significant improvement in delivery time over conventional methods.

Through a contract with DEIMOS Space, CMRE's contribution to EO-ALERT was a trial using CRV *Leonardo* from 01 — 11 July in the Ligurian Sea. Working from the vessel, CMRE researchers acquired ground truth data of environmental conditions during overpasses of satellites with synthetic aperture radar (SAR) and electro-optical (EO) sensors to test the performance of EO-ALERT algorithms. During the trial, CRV *Leonardo* itself and its deployed work boat acted as targets to test EO-ALERT's ship detection capability.

## Results

- Successful real-time acquisition of ground truth data, synchronized with SAR imagery from the TerraSAR-X satellite operated by the German Aerospace Agency DLR, and EO imagery from the VHR Deimos-2 satellite operated by DEIMOS Imaging.
- First demonstration and validation of EO-ALERT's integrated EO data processing chain in a maritime environment with ground-truth data.
- Evaluation of the impact of maritime environmental factors on the performance of the EO algorithms developed within the EO-ALERT project.

## Contact

For more information about the EO-ALERT Maritime experimental campaign, please contact Raul Vicen ([raul.vicen@cmre.nato.int](mailto:raul.vicen@cmre.nato.int)).

# INFORMATION TECHNOLOGY DEPARTMENT

## Overview

The Information Technology (IT) department is responsible for software development, data management and scientific Computer and Information Systems (CIS) at CMRE.

In 2020, IT carried out a rigorous review of data management practices at the Centre with the objective of modernizing processes from planning and acquisition to storage, processing and export. The review was carried out through a series of internal and external workshops and resulted in a Data Management Roadmap. The Roadmap articulates the transformation in the way data is managed at CMRE from a sequential and 'silo'-based approach to one that uses best practices from the scientific and industrial domains including the application of Agile and DevOps principles along with increased automation and an update of the skill sets of our IT staff. These capabilities are needed in the coming years to achieve CMRE's vision to become a leader in maritime AI and Big Data in support of NATO's S&T strategy.

The Centre is in the process of virtualizing its computational resources. The initiative was accelerated in 2020 as consequence of the COVID-19 pandemic, which saw the majority of the Centre's workforce needing to work remotely.

NATO is a 'cloud first' organization and CMRE, through its IT activities, aims for alignment and interoperability with the NATO enterprise.

## Activity

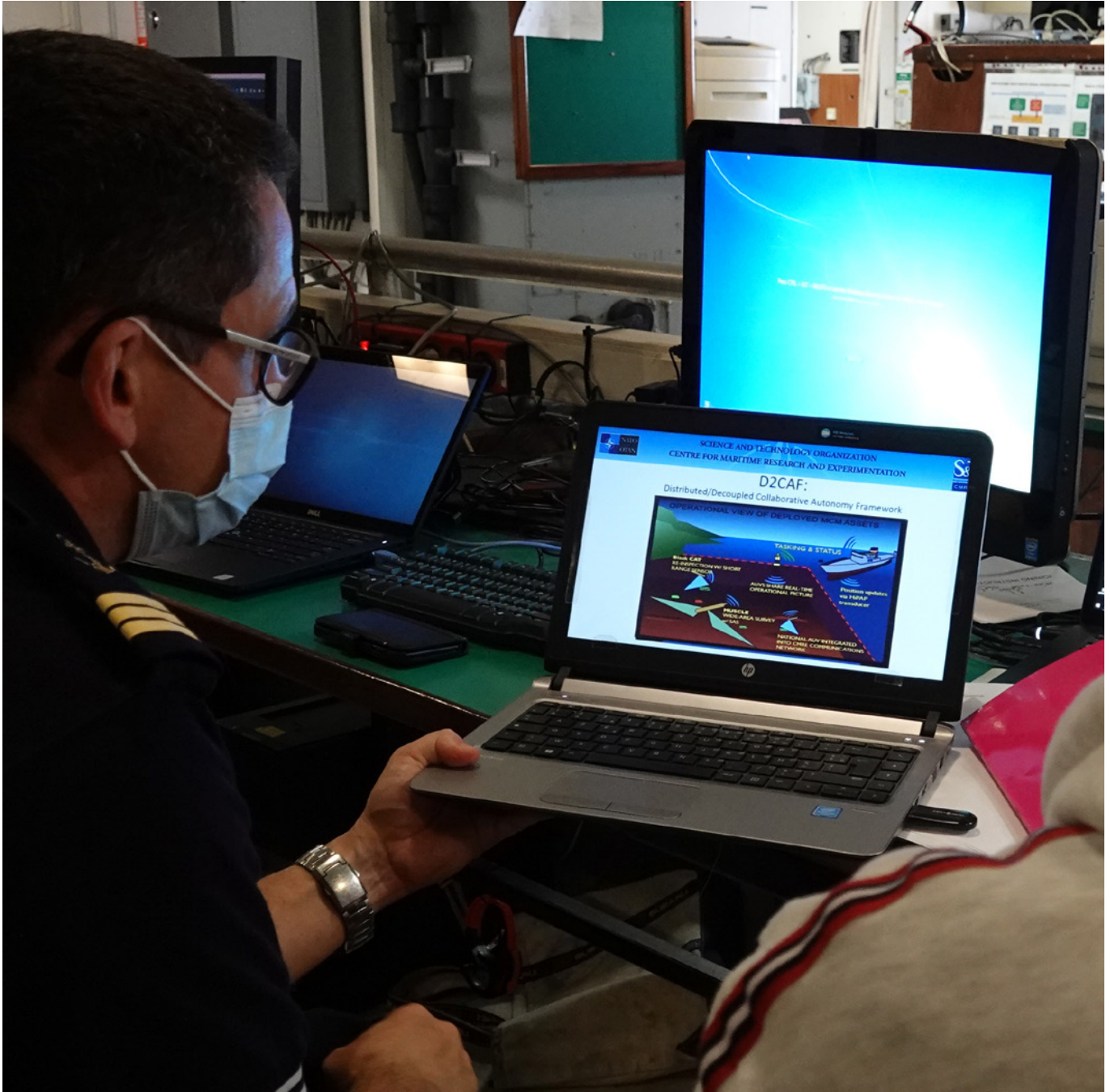
Much of the work of CMRE IT is the sustainment and improvement of classified and unclassified IT infrastructure needed to manage and exchange data and information with the NATO Enterprise and with external partners such as the Nations and industry. One of the challenges is that changes must be implemented during the execution of the CMRE Programme of Work. This requires a continuous risk management approach to balance and de-conflict support and modernization activities. Specific activities in 2020 include:

- A major investment in hardware to mitigate the obsolescence of critical systems and to support the migration from legacy operating systems to more recent ones;

- Steps toward a modern, 'Agile' approach to software development with integrated configuration management through GitLab and continuous testing, deployment and operations;
- Adopting the Information Technology Infrastructure Library (ITIL) as a service management framework to define and provide current IT capabilities as services. This will result in more structured processes which are more efficient and secure;
- Trials preparation, by designing and providing the necessary IT infrastructure, including security aspects, both for CMRE experimentation and participation in NATO exercises;
- Participation in trials, with sea-going IT specialists embarking on-board NRV *Alliance* and CRV *Leonardo* for three major sea trials in 2020;
- Support to European Commission projects: virtual sea trials over the internet, unmanned system network design and preparation for 2021 sea trial; and
- CMRE's IT team provided expertise to STO activity IST-164 on securing unmanned and autonomous vehicles for mission assurance, and co-authored several publications.

## Highlights

- In a quick response to the March COVID-19 outbreak, the CMRE IT team enabled the Centre's workforce to telework on the Scientific Network (SciNet) thereby ensuring CMRE business continuity. Thanks to collaboration with the NATO Communications and Information Agency (NCIA), the CMRE remote access capability is also accessible from the NATO enterprise network (Reach).
- Upgrade of CMRE's unclassified data centre was completed with the implementation of state-of-the-art backup and archive systems at both CMRE and on-board NRV *Alliance*. The system provides backup to the virtualization environments used to provide Infrastructure



**CMRE researchers and a French Naval Officer work on-board the NRV *Alliance*, supported by CMRE IT, during DYNAMIC MARINER.**

as a Service (IaaS) to CMRE scientists and engineers. The scientific data storage capacity increased from 250 to 360 TB with a significant increase in performance.

- Implementation of the enterprise version of GitLab as a service to CMRE developers. GitLab, a collaboration tool for software production, is a single application to manage the life cycles of both software development and operations.
- Start of project LIME 711 with ACT's Innovation Hub. The project is to develop a Minimal Viable Product (MVP) of the Light and Interoperable

Naval Mine Warfare Evolution (LIME) tool. After a successful start in 2020, the project will continue in 2021.

- With the support of the STO Maritime S&T Experts Committee (MSTC), CMRE IT held a virtual International workshop on data management, 24-27 August. The goal was to elicit NATO Nations' requirements for exploring and accessing CMRE data. Twenty experts attended from the USA, CAN, FRA, GER, NOR, NED, BEL, and EST. The conclusions from the workshop have been integrated into CMRE's Data Management Roadmap.



## INFORMATION TECHNOLOGY DEPARTMENT

FUNDED BY ACT INNOVATION HUB

# LIME 711 PROJECT

### Overview

In close collaboration with ACT Innovation Hub, CMRE developed the first Minimum Viable Product (MVP) of the Light and Interoperable Naval Mine Warfare Evaluation (LIME 711) and data exchange tool for the NATO Mine Countermeasures Task Group. CMRE is employing the Agile Software Development Methodology to develop the MVP, thereby allowing the ACT Product Owner to have visibility into the design and development process and to allow testing and changes on a bi-weekly schedule. The CMRE team included a software architect, an Agile SCRUM master (a role that facilitates the organization of the development in short bi-weekly cycles), software developers, a quality assurance engineer and a user experience designer. For the software development ACT iLab provided a development environment based on DevSecOps and Cloud technology—the use of the ACT iLab environment allowed the team to fully utilize modern Cloud technology and design and build the product based on security best practices. Based on the success of the project, a follow-on project is planned for 2021 where the aim is to test the software in trials, and further improve features, expand interoperability through OPREP NMW/OPTASK NMW message text formats and also explore how the research and data from CMRE can be integrated into future versions of the tool.

### Results

- A large number of features were developed, including role-based access, map-based navigation, insertion and editing of data through the map-based interface and import/export following the Advanced Military Layers (AML) standard.
- Successful application of DevSecOps principles for software design and development for the first time at CMRE.
- Successful application of Agile Software Development Methodology, resulting in increased collaboration between CMRE, ACT and the operational MCM community.

### Contact

For more information on the LIME 711 project, please contact  
Tue Andersen (tue.andersen@cmre.nato.int).

A HRLFSAS test is run from CRV *Leonardo* during the Sunfish sea trail in July 2020.





# RESEARCH VESSELS



**The NRV *Alliance* sails in local waters near La Spezia during the DANS20 sea trail.**

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. Able to sustain speeds over 16 knots, NRV *Alliance* can cruise economically at 11.5 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 precision navigation system and 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. 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 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 1-metre and can sail in quiet





**The CRV *Leonardo* sails near La Spezia.**

state at speeds up to five knots. The vessel can host up to 15 persons for day cruises and has 10 berths. It can accommodate a six-metre laboratory container augmenting the 35 square metre on-board laboratory space.

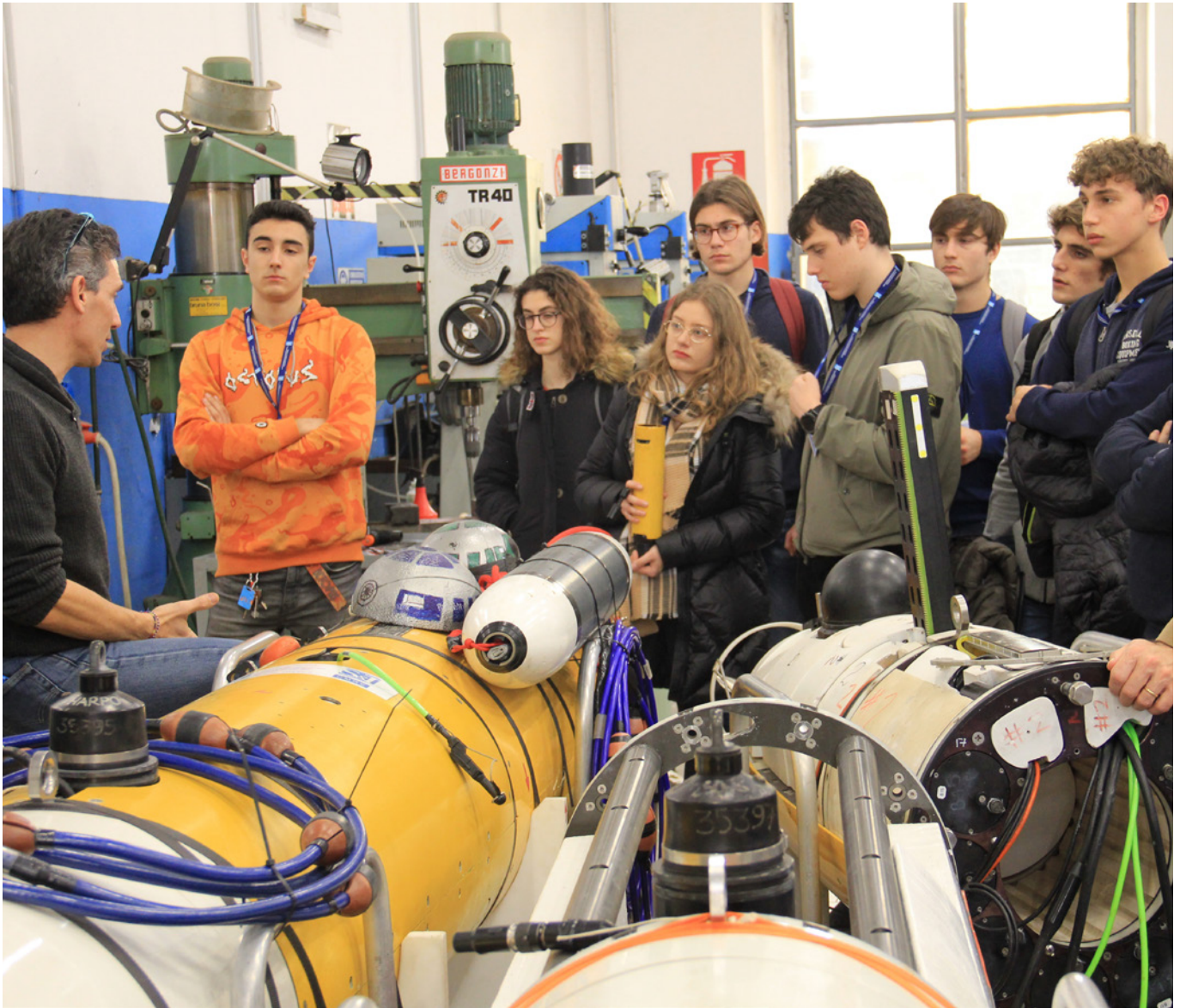
Like all of the Centre's activities, operation of NRV *Alliance* and CRV *Leonardo* in 2020 was affected by the COVID-19 pandemic. Stringent isolation and testing protocols were put in place to ensure the health and safety of personnel on-board. But the additional time alongside required by the protocol meant that the original ambitious 2020 schedule for NRV *Alliance* could not be fully met. In the end participation in the US Navy's BALTOPS Exercise in the Baltic Sea and CMRE's Arctic cruise had to be cancelled. Fortunately, NRV *Alliance* was able to support much of the work that would have been done on those trials through alternate trials closer to home: Mediterranean Rapid Environmental Picture (MREP20) in the Strait of Sicily and participation in

NATO Exercise DYNAMIC MARINER (DYMR20) off southern France.

The periods of isolation on-board prior to the trials prompted CMRE's Engineering and IT department to set up a wifi network to provide internet access for most CMRE cabins on NRV *Alliance*. Lessons learned from this temporary wifi installation will be implemented permanently on-board NRV *Alliance* during a maintenance period early in 2021. This, plus improved satellite communication bandwidth, will support CMRE's growing demand to interact with experts and analysts back at the Centre and clients around the world.

In September 2020, the new Head of CMRE's Marine Operations department, Darryn Debruyne, joined the Centre. As a Master Mariner with a background in ship management in the international oil and gas sector, Mr Debruyne is well-placed to manage NATO's capable research vessels.

# COMMUNITY OUTREACH



**Local students participating in the Giona Project visit the CMRE workshop in February 2020.**

## **Giona Project**

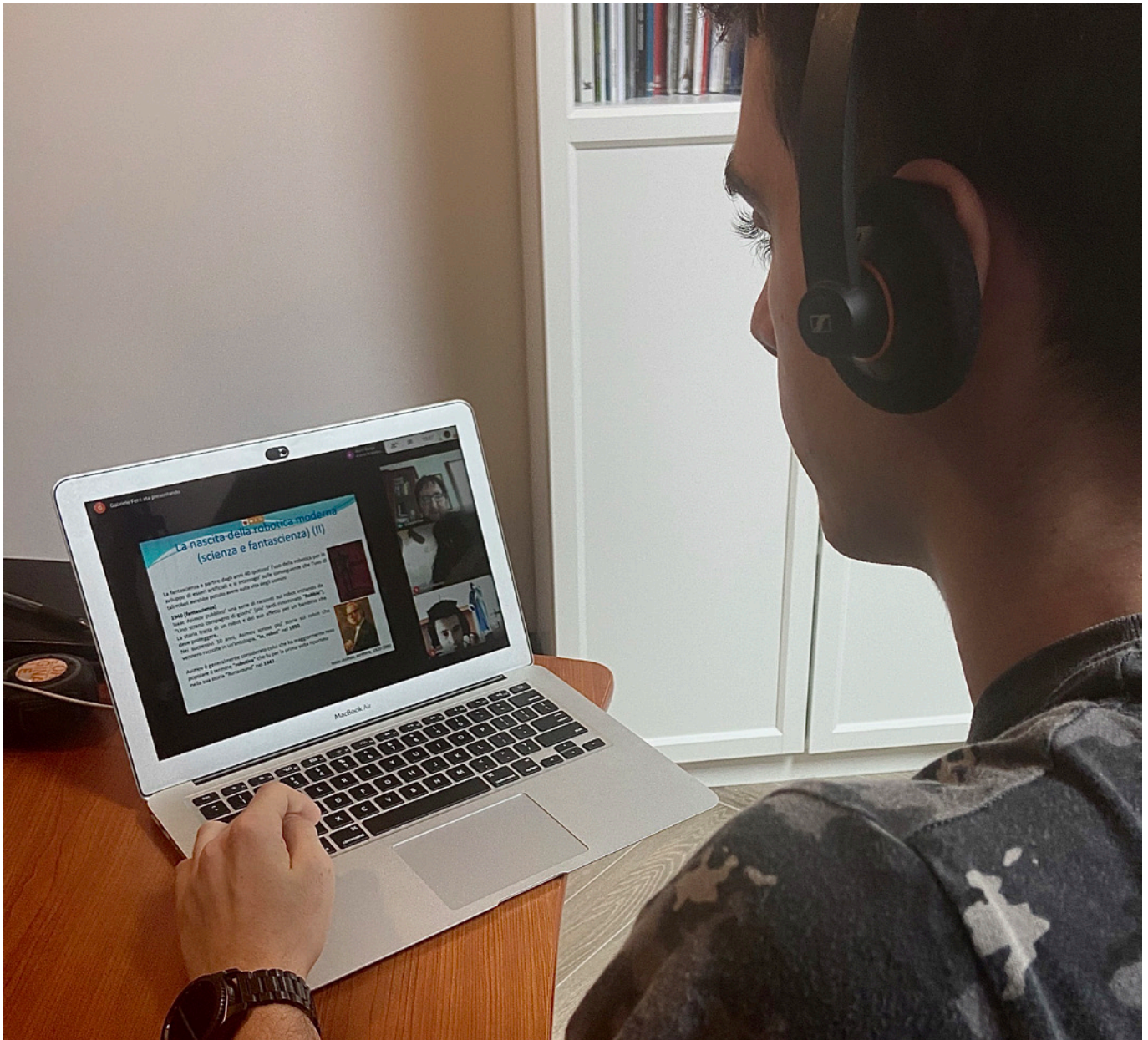
CMRE encourages young people to get involved with science, technology, engineering and mathematics (STEM) today so they will become the scientists, engineers and technicians of tomorrow.

CMRE continued its partnership with the Giona Project and schools in the La Spezia area by offering students the opportunity to acquire basic competencies in science and technology and the opportunity to apply them to real problems. The Giona project is aligned with national and European guidelines on environmental education with emphasis on gender parity, encouraging young women into research fields such as underwater robotics. In 2020, CMRE added

different disciplines and extended the invitation to additional schools.

Six students from technical high schools in the La Spezia area participated in the BARLAMARE (Bio-Acoustic Research to Learn About Marine Environment) experiment starting in 2019. Three moorings were deployed in the nearby Parco delle Cinque Terre, a national marine-protected area. Under the tuition of CMRE scientists Dr Alessandra Tesei and Dr Walter Zimmer, the students received talks from subject matter experts from Acquario di Genova, University of Pavia and University of Turin, and were given the opportunity to understand and discuss the basics of topics like underwater communications, ecology and





**In June 2020, the CMRE STEM education outreach programme continued with “Introduction to Robotics,” an online lecture given by CMRE scientist Dr Gabriele Ferri for a group of students participating in the robotics track of the Giona Project.**

anthropogenic pollution. Students also visited CMRE’s workshops and were familiarized with the scientific instrumentation used during sea trials.

During the initial phases of the project, the students participated in the planning of the experiment: the deployment and recovery of moorings; the geometry of sensors; and engagement with the appropriate stakeholders to obtain the necessary authorizations to conduct the experiments.

Unfortunately, the COVID pandemic forced an interruption of all schools’ external activities in March 2020, and therefore the students could not participate in the final phase of the experiment. The sea trial was initially postponed,

then cancelled. However, the activities with schools continued in May with an online talk by Dr Gabriele Ferri. Eighteen selected students of informatics and robotics, all attending high schools in the area of La Spezia, were given a talk about the history of robotics, and had the opportunity to interact online with Dr Ferri, asking questions and commenting with their own experiences. The purpose of the talk was to prepare the students for participation with their own underwater robot in the robotics competitions planned at CMRE for September 2020. Unfortunately, again the COVID situation did not allow the competition to happen, but the students continue work on their prototype and are eager to be ready for 2021.



# AWARDS

## NATO STO Scientific Achievement Team Award

In April 2020, CMRE staff received a NATO STO Scientific Achievement Team Award for the project 'Maritime Artificial Intelligence and Information Fusion' (MAI2F), part of CMRE's Data Knowledge and Operational Effectiveness (DKOE) programme funded by the NATO ACT Maritime S&T programme of work. The STO Scientific Achievement Award recognizes exceptional accomplishments within STO's collaborative and in-house research activities that have high impact on NATO and the Nations' scientific and operational communities.

Inspired by human cognitive abilities to automate routine tasks, the objective of the work was to address key issues in maritime situational awareness (MSA) by developing and advancing MAI2F techniques in support of cognitive processes (perception, comprehension, and prediction) of operators. The proposed techniques allow researchers to: analyse vast amounts of information for operators; merge heterogeneous data sources; and, resolve conflicting, intermittent, corrupted or irrelevant information. The result was a suite of improved products for multi-target tracking (MTT), anomaly detection, and ship track and destination prediction. In particular:

- Perception: An innovative and computationally efficient approach to MTT based on factor graphs and the sum-product algorithm (SPA) to fuse information from heterogeneous sensors was developed. The framework achieved significant improvement over competing techniques in terms of speed, accuracy and error performance, even in challenging operational scenarios. Moreover, by combining machine learning and big data techniques with modelling of ship kinematics, a data-driven unsupervised framework was formulated, based on the Ornstein-Uhlenbeck (OU) mean-reverting stochastic process, to learn ship traffic Patterns of Life (PoLs). Vast amounts of historical automatic identification system (AIS) data were encoded in a suitable graphical representation named Maritime Traffic Graphs (MTGs). The MTGs proved useful in detecting deviations from common ship traffic patterns, which may represent

anomalous behaviours. Indeed, a trans-shipment event of illegally caught fish that occurred in 2017 was successfully detected by the team's anomaly detection technique.

- Comprehension: An innovative generic multi-source automated reasoning (MAR) solution supporting the operator in handling conflicting information from cooperative and non-cooperative partially reliable sources (e.g. sensors, humans, and systems) was developed. The algorithm implements a hybrid 'automatic-manual' strategy to help the analyst understand the origin of the conflict in the information, and to decide the relevance of an anomaly based on the reliability of the source and the credibility of the information. Deployed during operational trials, MAR successfully detected anomalous behaviour earlier than other equivalent services, and without false alarms. In synergy with MAR, innovative knowledge acquisition (KA) techniques based on analytical gaming, that allow human reasoning to be captured quantitatively, were developed and successfully validated.
- Prediction: A long-term ship prediction (LTSP) method, which provides orders of magnitude improvement in the accuracy of predictions, was developed and successfully validated. The method, evaluated on real data, allowed predicting a ship's position 20 hours ahead of time with a 95% confidence region of approximately 10 square kilometres, compared with several thousand square kilometres for alternative methods. Additionally, a complementary method, based on MAR, was developed to predict a vessel's destination by processing information from heterogeneous and potentially conflicting sources (e.g. maritime routes, AIS, World Port Index, port visit statistics). Compared with using only a single source of information, a 30% improvement was obtained for correct destination prediction.

The operational benefits of the MAI2F techniques were confirmed by NATO Allied Maritime Command (MARCOM) staff during operations using CMRE's Maritime Pattern Of Life Information Service (MPOLIS) during exercises—e.g. the INTERNATIONAL MARITIME EXERCISE (IMX) 2019

organized by US Navy Fifth Fleet—and operational trials. NATO MARCOM staff assessed some of the CMRE team’s MAI2F techniques as essential to support MSA, and requested them to be included in the next increment of the new NATO Maritime Command and Control Information System TRITON.

The scientific quality of the MAI2F team’s work is validated by more than 100 peer-reviewed publications, including one in the prestigious Proceedings of the IEEE.

The MAI2F initiative was made possible through collaborations within STO as well as academia, industry, and national defence organizations. Congratulations to all who participated in this project:

- Team leaders: CMRE Scientists Prof. Dr Paolo Braca, Dr Anne-Laure Joussetme and Leonardo M. Millefiori.
- CMRE team members: Gianfranco Arcieri, Dr Nadia Ben Abdallah, Dr Elena Camossi, Ms Enrica d’Afflisio, Dr Francesca de Rosa, Dr Nicola Forti, Cdr Amleto Gabellone, Dr Domenico Gaglione, Dr Raffaele Grasso, Dr Clement Iphar, Cdr Thomas Miller, Dr Giovanni Soldi, Dr Murat Uney and Maximilian Zocholl.
- External team members: Ms Karna Bryan (US Department of Transportation), Dr Luca Cazzati (Zillow Group, Inc), Prof. Alessandro De Gloria (University of Genova), Steven Horn (Defence Research and Development Canada), Jonathan Locke (BAE), Dr Florian Meyer (MIT), Prof. Frederic Pichon (University of Artois), Cdr Davide Severino (Italian Navy) and Prof. Peter Willett (University of Connecticut).

### **NATO STO Systems Analysis and Studies Panel Award**

Funded by the NATO ACT Maritime S&T programme of work, Dr Anne-Laure Joussetme, Dr Francesca de Rosa, from CMRE’s Data Knowledge and Operational Effectiveness (DKOE) team, and Dr Raul Vicen of the Environmental Knowledge and Effectiveness (EKOE) programme participated in the NATO STO SAS-114 Research Task Group (RTG) ‘Assessment and Communication of Uncertainty in Intelligence to Support Decision-Making’. The RTG team, led by Dr David Mandel from Defence

Research and Development Canada (DRDC), brought together experts from Canada, United Kingdom, Germany, Italy, Norway, Netherlands, Spain, Sweden, United States and CMRE, and were recognized in the NATO STO SAS Panel Excellence Award for outstanding quality of research.

The RTG made progress in quantifying and communicating to decision-makers aspects of uncertainty within the information they use. For instance, the group studied the metrics of uncertainty and information gain as well as methods to communicate the uncertainty both numerically and in natural language in order to decrease the risk of miscommunication. Although utilizing best practices to communicate uncertainty between people is crucial, especially between operators, analysts or decision-makers from different nations, communicating uncertainty and understanding information quality between humans and machines is of paramount importance.

Practices on the communication of uncertainty differ from one nation to another, and between military functional areas. A better understanding of both the human and mathematical dimensions in perceiving, representing, and communicating uncertainty would lead to improved and standardized practices within NATO. Among the conclusions of the study, the final report highlights that scientific principles should be employed to bring the necessary coherency and clarity within NATO in rating, expressing and communicating uncertainty and related concepts, such as probabilities or confidence.

CMRE hosted two meetings in June 2016 and May 2017. During all SAS-114 RTG meetings, fruitful exchanges of ideas took place between academic researchers from psychology and data science fields, as well as intelligence practitioners. These interactions together with some outcomes of the study enriched CMRE’s research activities pertaining to the challenging tasks of complex automated reasoning with partially reliable sources, and to the elicitation of expert knowledge or subjective belief.

Dr Joussetme, Dr de Rosa and Dr Vicen have contributed from 2014 to 2019 to both the SAS-114 RTG and its initial exploratory team, and produced 18 publications on these topics.

# FINANCIAL OVERVIEW

Similar to many other organizations across the globe, 2020 was a difficult year financially for CMRE because of the COVID-19 pandemic, impacting both CMRE's ability to carry out science and technology projects effectively and efficiently, as well as meet the plans and ambitions of the customers. In particular, the necessity to implement COVID protocols for operations on-board the research vessels resulted in several planned sea trials and technical demonstrations being postponed or cancelled, reducing CMRE's revenue from these assets that are expensive to maintain. Unfortunately, these difficulties of operating the vessels during 2020 followed two years of extended maintenance periods for NRV *Alliance* resulting from mechanical failure of one of the vessel's engines.

In recent years annual revenues ranged from 26 to 29 MEURO, with NATO Allied Command Transformation, CMRE's largest customer in 2020, representing about 70% of CMRE's total revenue. The remaining revenue was generated by delivering products and services to customers from NATO Nation government organizations, industry and the European Union. It is estimated that 10% of revenue was lost because of project delays resulting from COVID-19 pandemic restrictions. CMRE is a not-for-profit organization and operates at a break-even target.

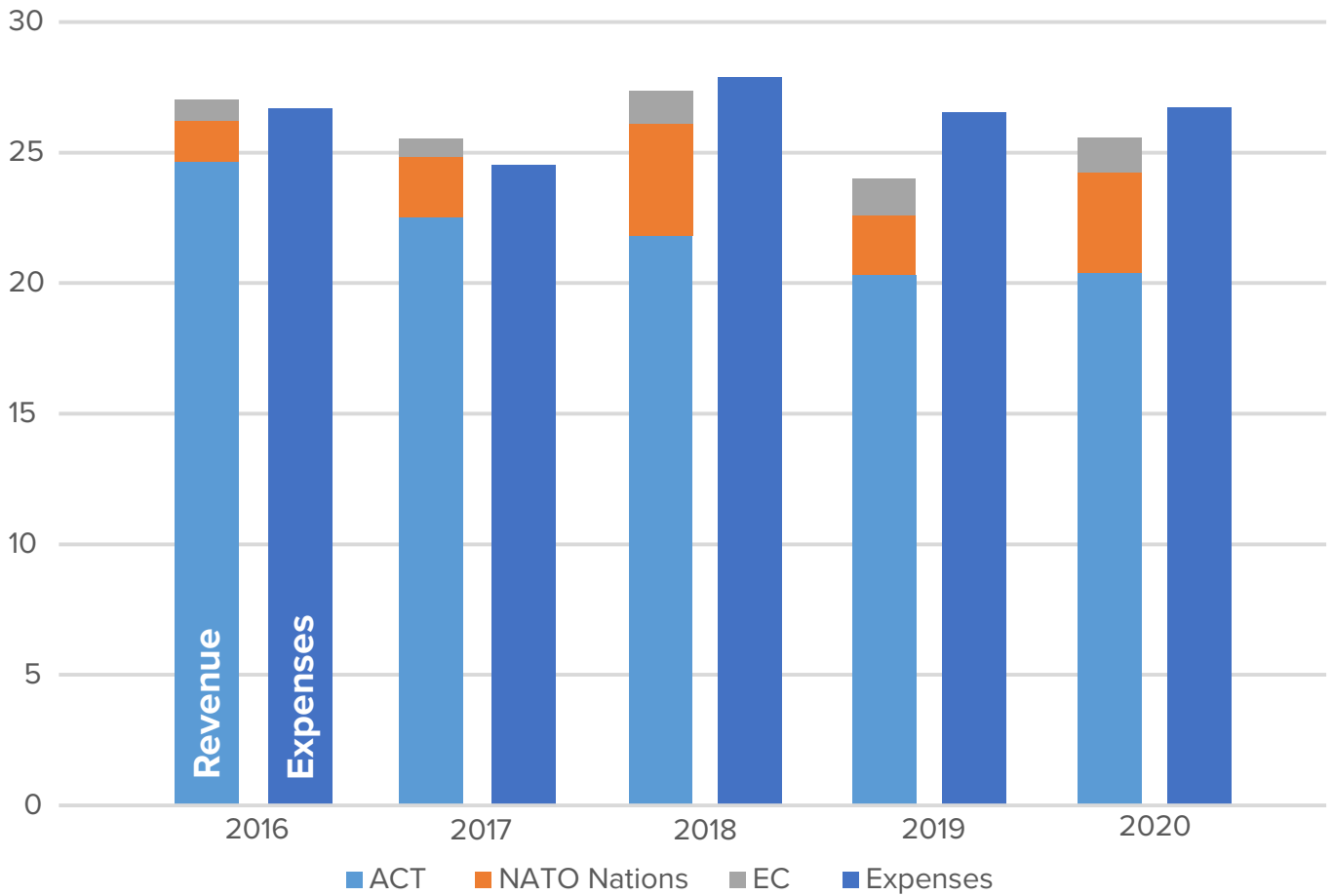
The CMRE workforce overhead rates, defined as the ratio of the total cost of operations and maintenance—including administration labour costs—to the total cost of the CMRE workforce booking directly to project-related work, have remained relatively stable over the last four years at around 60%. A slight increase is being made in 2021 to cover some relatively small investment costs for upgrading and modernizing IT capabilities, vital for CMRE to carry out its research and development work and share data and information with the NATO Alliance. The daily charge-out rates for research vessel services have also remained relatively stable and competitive in the market place.

CMRE has recently experienced an encouraging upward trend in securing funding from NATO Nation government organizations, with much of this funding originating from the US for oceanographic research and ensuring 'day zero' interoperable capabilities in maritime warfare domains. The outlook for CMRE is projected as stable for the next five years, although the continuing COVID-19 situation will impact CMRE's operations for at least the first half of 2021, and in particular the ability to maximize the operational use of NRV *Alliance*. Another encouraging development during 2020 has been ACT Innovation funding for Minimum Viable Products, which is a business area that CMRE is looking to grow in the future.

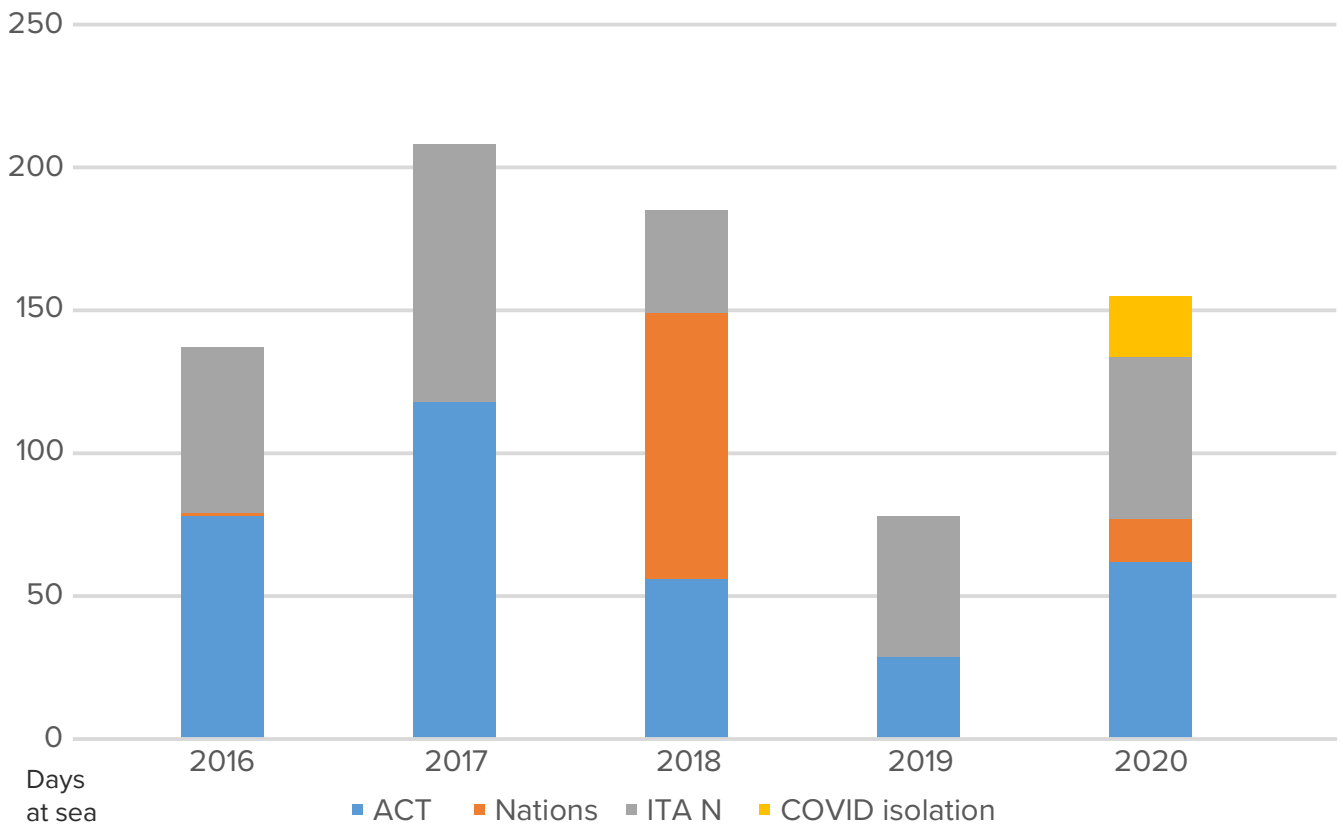




### Five-year trend of revenue and expenses in MEURO



### Five-year trend for NRV Alliance days at sea with major users indicated



Note: ITA N and COVID isolation days do not generate revenue.

# HUMAN RESOURCES

The Human Resources Branch provides the recruitment, retention and training of the best qualified people available to fulfil CMRE’s mission. The Branch manages payroll and allowances, pensions, employment contracts, legal and health inquiries and helps staff and their families get established upon arrival.

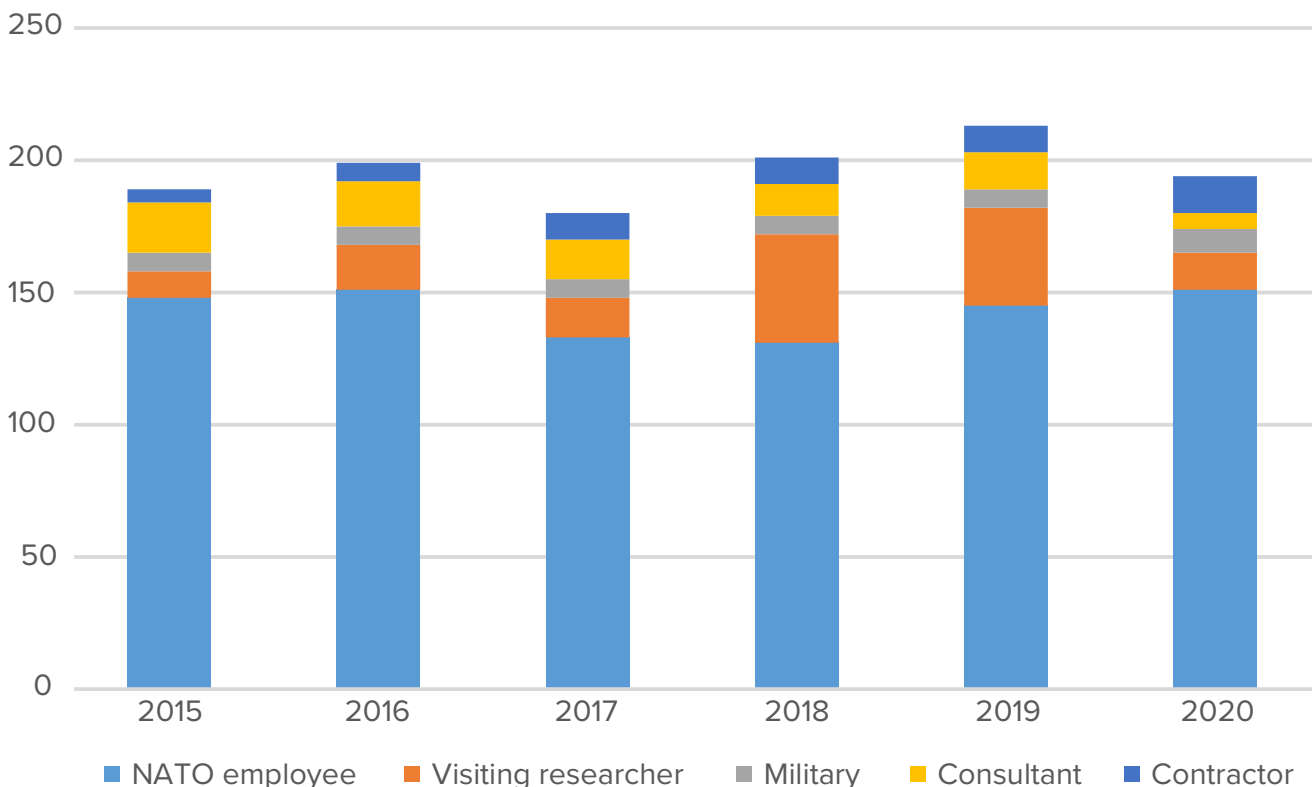
In response to the COVID-19 pandemic in 2020, HR tracked the movement of staff who travelled to different parts of Italy or other countries and provided advice on their requirements for quarantine and tests. Working with local medical authorities, HR streamlined the process for CMRE staff to obtain COVID-19 tests if needed, and HR tracked staff who were at home under surveillance due to possible exposure to COVID-19.

Despite the obstacles posed by the COVID-19 pandemic, in 2020 CMRE hired 13 NATO civilians with an average time to hire of nine months and an average time of 15 months to fill the position. At the end of the year, eight candidates had been offered NATO civilian positions but were waiting for their security clearances to arrive. At the end of 2020, CMRE had 151 NATO civilians, 8 military staff and 20 consultants of which 15 were visiting researchers. The average age of staff at the Centre is 49 with an average length of service of 9 years. CMRE staff represent 20 Nations and 24% of employees are female.

CMRE strives for a diverse workforce representing all NATO countries and has a programme to attract young scientists. More information about job opportunities can be found at:

[www.cmre.nato.int](http://www.cmre.nato.int)

Five-year workforce trend



# WORKING WITH CMRE

Founded in 1959 as part of the NATO military structure, the SAACLANT ASW Research Centre was common funded by the NATO Allies to carry out research and concept development and experimentation in the maritime domain, with emphasis on underwater warfare. In 2011, NATO Defence Ministers approved the NATO Implementation Plan for Agencies Reform, which resulted in the establishment in July 2012 under a North Atlantic Council (NAC) approved charter of the NATO Science and Technology Organization (STO).

The Centre for Maritime Research and Experimentation became an executive body of the NATO STO, with its mission 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, centred on the maritime domain. The STO charter as approved by the NAC required CMRE to be financed through customer funding; customers would be comprised of NATO bodies, NATO Nations and other parties, consistent with NATO policy.

Under the customer funding regime, CMRE has successfully provided since 2013 scientific and engineering products and services for a spectrum of customers on a break-even basis. Past and existing CMRE customers include: NATO bodies—in particular NATO Allied Command Transformation, which remains CMRE's largest customer by revenue; NATO nation government organizations; NATO nation industrial entities; and participation in consortia executing projects funded by EU grants. CMRE provides products and services for these different customers in different ways: for example, for NATO Nation industry, a commercial contract is used, usually supported by a non-disclosure of proprietary information agreement; whereas 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 multinational projects with customers and funding from several different nations.

## What CMRE offers

CMRE operates two research vessels, the Global-Class (and ice-strengthened) NATO Research Vessel *Alliance* and the Coastal Research Vessel

*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 seagoing sensors. 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 and experimental research. CMRE offers scientific research services in the fields of: signal processing; oceanographic remote and in situ sensing and ocean-atmosphere modelling; control theory; acoustic modelling; modelling and simulation; operations research and analysis; data analytics; data fusion; autonomy; and, algorithm development.

CMRE has a world-class ocean engineering capability which enables the rapid development of concepts and prototypes for scientific experiments and military exercises. Many prototypes of sonar arrays and unmanned systems in the fields of anti-submarine warfare, mine countermeasures, port security and environmental monitoring have been developed and tested successfully at sea. CMRE's expertise covers mechanical, electrical, software and ocean engineering. CMRE has developed test and calibration facilities, which ensure the acquisition of high quality 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 courses.

In summary, CMRE is open for business and stands ready to provide to customers cost-effective products and services centred in the maritime domain, and also more generic services such as data analytics and training.

## How to contact us

Please contact CMRE's Integrated Business Support team at [registry.cmre@cmre.nato.int](mailto:registry.cmre@cmre.nato.int) to discuss how CMRE may be able to work with your organization.



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