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FULLY AUTOMATED MCM MISSIONS WITH HETEROGENEOUS AUTONOMOUS ASSETS DURING REP(MUS)22 AND DYMS22

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ABSTRACT

In September 2022, CMRE participated to the REP(MUS)22 and DYMS22 exercises in the Atlantic Ocean off the coast of Portugal. The CMRE ANMCM programme joined the exercises with the deployment of two MCM autonomous underwater assets: MUSCLE equipped with high resolution SAS for large area survey and BIONDo AUV equipped with a high resolution FLS for target identification. The CMRE MCM team aimed to demonstrate the full MCM chain from area survey, with automatic detection and classification, to target identification and reporting using autonomous vehicles. A strong emphasis was put on the collaborative aspect of a MCM mission and in particular on data sharing between heterogeneous systems. This paper will showcase all the recent CMRE advancements in autonomous MCM operations which were demonstrated during the trials. These advancements include automatic planning with or without prior knowledge, online adaptive automatic target recognition, online seabed characterisation and residual risk map computation, newly developed standardized messaging protocol to promote interoperability and interchangeability, automatic tasking and automatic human readable report generator.

Keywords: *MCM, AUV collaboration, ATR, P&E, interoperability.*

1. GLOSSARY

ACT	Allied Command Transformation
AIS	Automatic Identification System
ANMCM	Autonomous Naval Mine Countermeasures
ATR	Automatic Target Recognition
AUV	Autonomous Underwater Vehicle
C2	Command and Control
C3MRE	Command, Control and Communications system for Maritime Robotic Experimentation
CATL	Collaborative Autonomy Tasking Layer
CMRE	Centre for Maritime Research and Experimentation
CNN	Convolutional Neural Network
COTS	Commercial off-the-shelf
CSSN	Centro di Supporto e Sperimentazione Navale
DVL	Doppler Velocity Log
DYMS	Dynamic Messenger
FLS	Foward Looking Sonar
I2I	Interoperability and Interchangeability
MARCOM	Allied Maritime Command
MCM	Mine Countermeasures
MILCO	Mine like contact
MOD	Ministry of Defence
MUS	Maritime Unmanned Systems
MUSCLE	Minehunting UUV for Shallow waters Covert Littoral Expeditions
NMW	Naval Mine Warfare
P&E	Planning and Evaluation
REP(MUS)	Robotic Experimentation and Prototyping using Maritime Uncrewed Systems
ROS	Robot Operating System
SAS	Synthetic Aperture Sonar
STO	Science and Technology Organisation
UUV	Unmanned Underwater Vehicle
WTD71	Wehrtechnische Dienststelle 71

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2. INTRODUCTION

The REP(MUS)22 and DYMS22 trials took place between Monday 5th September and Friday 30th September in the Atlantic Ocean off the coast of Portugal between Sines and Sesimbra. The two consecutive trials were planned and organized by the Portuguese Navy, the NATO Maritime Unmanned Systems Initiative, and the Faculty of Engineering of the University of Porto (regarding REP(MUS) and MARCOM and ACT for DYMS22. The CMRE ANMCM programme [1] joined the REPMUS series for the first time in 2022 with the deployment of two MCM MUS assets.

We demonstrated the full MCM chain from area survey with automatic detection and classification to target identification and automatic reporting using autonomous vehicles. Underwater vehicle collaboration and interoperability was a key factor for the success of the trials. CMRE also demonstrated the newly developed CATL messaging protocol to promote interoperability and interchangeability between different assets and between different Nations. During REPMUS, CMRE collaborated with CSSN, WTD71 and the British MOD. In parallel, MCM products were demonstrated during the trials including automatic planning, ATR, seabed segmentation, residual risk maps and automatic reporting.

The primary scientific objectives of the NMW component of REPMUS22 and DYMS22 were to conduct autonomous MCM missions, testing and validating several sub-components linked to the ANMCM programme. The specific experimental objectives were:

- Demonstrate P&E products (including automatic computation of the residual risk map and automatic seabed segmentation) on board MUSCLE [2, 3].
- Test and validate planning capabilities, including newly developed survey and reacquisition strategies.
- Demonstrate an autonomous heterogonous vehicle network conducting detection, classification and identification using tasking protocol CATL from SCI-288/343 [4]. This task involved BIONDo and MUSCLE or BIONDo with at least one external collaborator.
- Demonstrate and evaluate the in-situ performance single-stage CNN [5] and the CNN-based ATR with auxiliary outputs [6] (incl. target type, image quality and seabed complexity) on board.
- Demonstrate automatic human readable mission reporting with ATR and P&E products.

3. MCM ASSETS

The following section describes the two MCM assets that were deployed during REPMUS and DYMS to perform the NMW serials.

3.1 MUSCLE

MUSCLE is a state-of-the-art mine hunting autonomous underwater vehicle, which uses multi-resolution, multi-aspect SAS to create detailed images of the sea floor. The vehicle is capable of processing sonar data onboard and uses neural-network software developed at CMRE to sense and adapt to the environment in order to achieve high level mission tasks without human intervention.

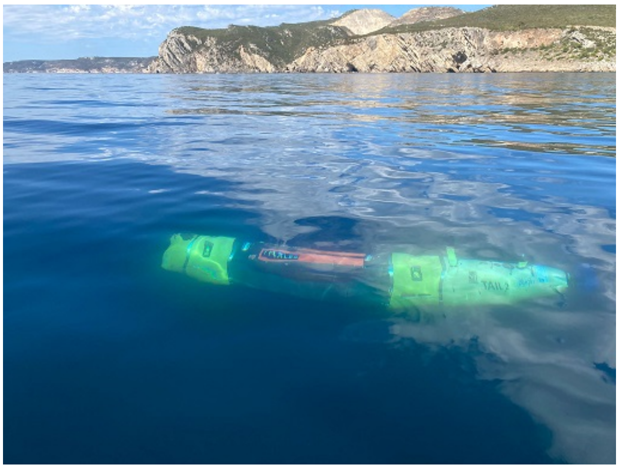


Figure 1. The MUSCLE AUV deployed off the coast of Portugal during REPMUS22..

Over the years, the system has been upgraded and modified to carry more processing power and a removable underwater storage unit. This allows MUSCLE to provide high quality SAS images of objects on the seafloor. The system has a high level of autonomy, thanks to its real-time processing software running on a dedicated high-end GPU-based system and advanced decision-making capabilities. In particular, ATR algorithms are running real time along side P&E products.

During both exercises, MUSCLE was sharing information to a top side C2 system including vehicle status, vehicle location and possible target detections to be handed over to other systems for identification.

3.2 BIONDo

The BIONDo AUV is a two-man portable system that carries, as the primary sensor, a COTS ARIS Explorer 3000 acoustic camera. The BIONDo is based on a commercial platform, the Sparus II from Iqua Robotics. The baseline vehicle uses a skid-steering arrangement (two off-axis thrusters in the aft) for heading and horizontal positioning control. A single vertical thruster approximately collocated with the centre of buoyancy provides heave control. Overall the system is under-actuated, without the ability to control pitch or sway independently.

Figure 2. The BIONDo AUV deployed off the coast of Portugal during REPMUS22..

The Sparus II software subsystem is built with a relatively open strategy — the vehicle ‘frontseat’ (the native vehicle controller) uses ROS with specific services built by the company to provide safety, piloting and mission features. This allows integrators (such as CMRE) to interact relatively directly with the vehicle subsystems to achieve a particular effect.

The acoustic camera can operate in two frequency ranges, resulting in short- and long-range modes. The maximum range for the short-range mode is 5 meters, while for the long-range mode the maximum range is 15 meters. In low-frequency, long-range mode the camera operates at 1.8 MHz, while in short-range, high-frequency mode the frequency is 3.0 MHz. The sonar is mounted in the forward direction of the vehicle, aligned with the vehicle’s longitudinal axis, and with a declination of approximately 20 degrees. The horizontal field of view is 30 degrees, and the vertical beam is 15 degrees.

CMRE has also integrated a COTS Phins Compact C3 inertial navigation unit, providing straight-line DVL-aided performance of down to 0.04% of distance travelled (e.g. 4 meters over 1 km).

4. ACHIEVEMENTS IN AUTOMATIC PLANNING

In 2022, we developed a novel planning algorithm for AUVs equipped with side-looking sonar sensors. The newly developed algorithm makes the full use of the P(y)-curve, taking into account the blind spot in the nadir and optimizing the planning for 2D maps. Additionally, it provides predicted performance maps besides a general predicted percentage coverage or clearance.

In the traditional planning algorithms used in MCM EXPERT for example, it is assumed that MCM operations are performed with one homogeneous channel. As such, only a one-dimensional cross-section of the channel is used in all analyses. In contrast, when we perform MCM operations within a box, or area of interest, performing the analysis on a two-dimensional grid is more appropriate. Therefore, planning the mission on a 2D grid allows us more freedom in planning our search pattern.

The algorithm optimizes the tracks based on potential prior knowledge (including previous area surveys) and a cost function that can, for example, quantify the average probability of missing a mine, or the level of uniformity in the coverage of the area of interest. The optimization method is based on generalized annealing which is an extension of the simulated annealing framework.

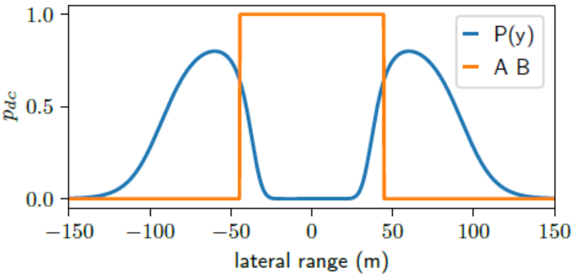
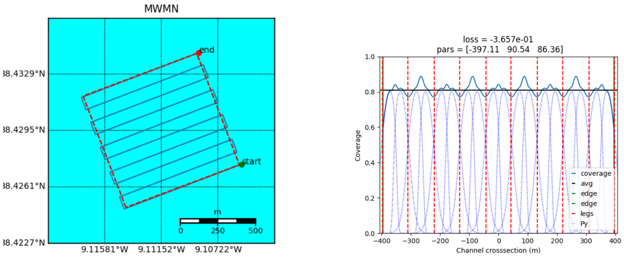


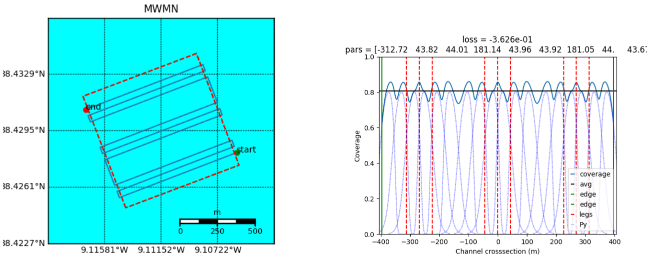
Figure 3. An example P(y)-curve, i.e. the P_{dc} values as a function of range.

The newly developed mission planning tool was systematically used for the planning of the MUSCLE AUV when tasked to inspect a specific box or boxes. Figure 4 displays the output of the mission planning when optimized for uniform tracks and for mean coverage. Figure 5 shows the output of the algorithm when the spacing between legs is not constrained.



(a) (b)

Figure 4. Mission planning output with constant leg spacing and mean coverage optimization.



(a) (b)

Figure 5. Mission planning output with free leg spacing and mean coverage optimization.

5. ACHIEVEMENTS IN MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE

The Centre has been developing target classifiers for SAS images for the last few years. Our current state-of-the-art algorithms are based on CNNs with carefully crafted architectures to adequately reduce the number of free parameters to be learned. The original CNN architectures only provide binary information on the inspected object: Mine or Not a Mine. Recently, we have demonstrated that the architectures of the CNNs could be modified to perform detection and classification simultaneously. We also demonstrated that additional information and auxiliary features can be extracted from the SAS images.

5.1 Auxiliary Features

We updated our classification CNNs to estimate other important parameters present in the SAS image [6]. Amongst these parameters, the SAS image quality estimation has proven to be a relevant and useful indicator to the reliability of the binary CNN prediction. To that end, we augmented the previously developed CNNs with additional auxiliary outputs such as image quality but also target type and target orientation.

During REPMUS22, we implemented the auxiliary feature CNNs into the MUSCLE AUV to run in real time. Although the implemented CNNs were not part of the full detection/classification chain, we demonstrated that this algorithm provides similar performance (in terms of probability of detection and classification) but gives more information about the MILCO. For instance, the quality feature can be used to filter MILCOs that come from a low SAS image quality. Doing so, we decrease slightly the probability of classification but also decrease by approximately 20% the number of false alarms. Moreover, it can also indicate the shape of the detected objects, which is accurate when the quality indicator is high. For instance, the shape of 64% of the Mantas and of 48% of the Rockans (given to the classifier) were identified correctly.

Figure 6 provides an example of the algorithm output for one of the trial areas. In that example, the algorithm found two targets and generated one less false alarm when compared with the binary CNN classifier.

5.2 Single Stage Detector/Classifier

In collaboration with the Direction générale de l'armement and the French mine countermeasures programme, we developed a single stage detector classifier. [5] The concept of this algorithm is to use the previously trained classification CNNs to perform detection and classification in one single step. A simple iterative algorithm is applied subsequently to return the positions of potential targets from the CNN outputs, called prediction maps. In particular, the eight CNN architecture was adapted to take as input the full SAS image (instead of a smaller image chip).

One downside of this new detector-classifier algorithm is its high computational cost. Using the eight CNNs on the

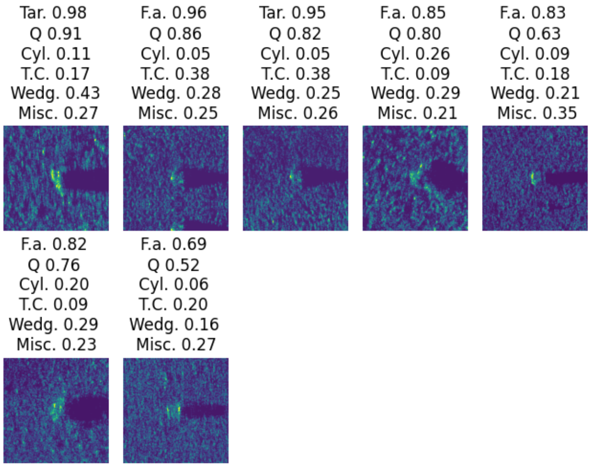


Figure 6. MILCOs in area H with the auxiliary feature classifier: global score, quality estimate(Q), cylinder, truncated cone (T.C.), wedged and miscellaneous object (Misc.) scores.

full sonar image is very costly in terms of memory or/and time. Unfortunately, the on-board GPU could not process the eight networks in real-time together with the SAS beamforming and the various SAS processing algorithms. However, the algorithm ran offline and we demonstrated a significant improvement when compared with the legacy detector: 56% of the targets were detected with a score higher than 0.5 (compared with the 28% detection rate of the detector). Figure 7 provides an example of the algotihm output for the inspected area MWH. The figure displays the 22 first MILCOs with a threshold of 0.5.

6. ACHIEVEMENTS IN INTEROPERABILITY

6.1 CATL

CATL is a product of the STO Research Task Group SCI-343 “Enabling Federated, Collaborative Autonomy”. This tasking layer is a draft standard that outlines a communications protocol that supports the distribution and allocation of tasks to unmanned assets. Though CATL is generically envisioned to support joint operations in a hybrid, heterogeneous domain, the principal initial use cases have been those that describe NMW scenarios. The essential CATL concept is the definition of standard types of tasks (for example, mine clearance or mine identification), and the definition of a minimal language to share those tasks among systems, and enable the task execution to be reported in-situ. CATL allows centralised planning approaches, where higher-level planning elements may assign tasks to systems directly, as well as decentralised ones, where assets themselves may elect to do specific unallocated tasks. An element of CATL involves also the design of specific encodings for environments that have significantly limited communications channels.

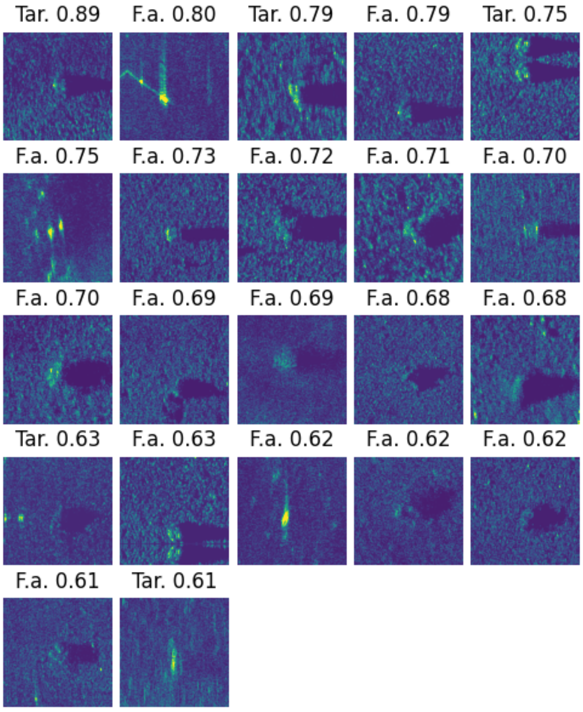


Figure 7. MILCOs in box MWH with the single stage detector classifier.

6.2 C3MRE

C3MRE is a metasystem that groups a set of services together to support communication, collaboration and general situational awareness between CMREs different seagoing platforms, as well as those systems of partners. Principally, the C3MRE network supports CATL-based messaging, to enable tasking of systems and collection of their resulting data products. Importantly, C3MRE relies on the accredited SCINET infrastructure, and allows partners to quickly and easily connect to the infrastructure, both for testing and for operations.

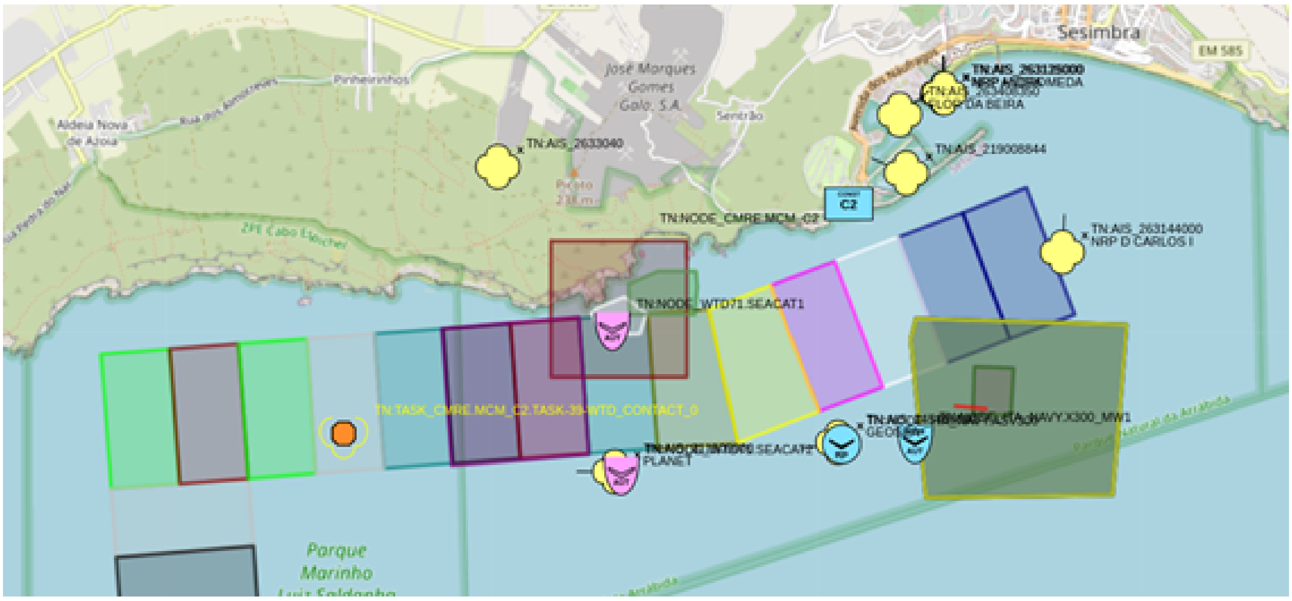


Figure 8. Snapshot of the local Common Operating Picture, as viewed through the C3MRE infrastructure on 21/09/2022. The translucent colored polygons depict the mine-hunting boxes of the exercise. The yellow 'flower' shapes are neutral AIS contacts (based on the AIS feed from NRV Alliance and also I2I network). The blue rectangle marked 'C2' is the NMW CTG. The foreground translucent boxes of irregular shape are task areas defined by CATL nodes. The pink half-ellipses ('SUBSURFACE' in APP-6(D)) marked 'AUT' are the SeaCat AUVs from WTD71.The corresponding blue subsurface node is one of the ITAN AUVs, while the blue circle is an ITAN USV. Finally, the orange hexagon on the left is a MILCO published by WTD71.

6.3 Interoperability at REPMUS/DYMS

During REPMUS22 and DYMS22, the CMRE team deployed the C3MRE infrastructure for the full duration of the exercises and for the benefit of all the participants. CATL messages from all participating Nations were then generated by the compatible assets or the associated C2 structures and transmitted to the C3MRE network via a MQTT broker. The standardized CATL messages and the common infrastructure enabled the feasibility of collaborative and complex MCM missions between heterogeneous assets without any extensive preparation or testing.

A sub-product of this centralized CATL/C3MRE implementation for interoperability has been the availability of a common operating picture of all CATL compatible assets in real time. Figure 8 pictures a snapshot of all assets including underwater assets operating within the exercise NMW areas at a given time.

7. CONCLUSIONS

REPMUS22 and DYMS22 offered the opportunity to test, validate and demonstrate to NATO partners the latest developments in AI, automatic planning and automatic evaluation. During these trials, we demonstrated the full automated MCM chain from large area survey to target identification using two heterogeneous assets. An important component of this trial has been the collaborative and interoperability aspect. In particular, we demonstrated the effectiveness of the newly developed NATO CATL messaging protocol for MCM multi-vehicle missions.

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