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Recent technological advances in underwater autonomy

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About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

Recent technological advances in Underwater Autonomy

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Abstract— **Underwater Unmanned systems (or more precisely systems of systems) will definitely play an important role in future maritime surveillance and environmental data collection. For many years, the NATO Centre for Maritime Research and Experimentation (CMRE) has deeply invested in developing Artificial Intelligence algorithms to allow robots to perform unmanned missions. These scientific efforts have always been based on these robots' capability to localize themselves, to communicate reliably, and to continuously operate for many days or even weeks or months. This paper describes the recent technological advances performed at CMRE for solving these challenges, in particular the work done on increased persistence, deep-water navigation, communication and launch and recovery.**

Keywords—persistence, deep-water navigation, cognitive underwater communication, launch and recovery, unmanned systems

I. INTRODUCTION

As part of the Science and Technology Organisation (STO) of NATO, the Centre for Maritime Research and Experimentation (CMRE) has been actively involved in Maritime Unmanned Systems (MUS) S&T for almost twenty years. The next-generation of Autonomous Underwater Vehicles (AUVs) currently being developed at CMRE is equipped with a comprehensive suite of sensors. For many years, a strong effort has been put in CMRE to equip such AUVs with advanced on-board signal and data processing capabilities and artificial intelligence-based autonomy engines capable to adapt to the environment in order to achieve high level mission tasks without human intervention. Considerable scientific effort was also dedicated to the collaboration and cooperation of unmanned assets that is a necessity for solving complex missions.

However, despite the encouraging results, the capability to perform successful autonomous scientific and operational missions still heavily depends on solving the technological challenges that exist for such underwater systems.

The objective of this paper is to describe the work done in the latest years at CMRE towards the development of the future unmanned system-of-systems for the maritime domain and in particular elaborate on the technological advances made in the following domains:

- Persistence
- Deep water navigation
- Cognitive underwater communication
- Launch and Recovery

The first section addresses the issue of persistence which is the prime limitation for maritime autonomy. Navigation of AUVs, is presented in the second section, and is still a challenging task, requiring a trade-off between performances, cost and operational time. The third section elaborates on the very important underwater communications challenge CMRE has been investing in for the last few years. The lack of standards and common interfaces for underwater digital communications represents a significant bottleneck towards the effective deployment of cooperative networks of underwater assets. The last section is dedicated to the technological solutions implemented at CMRE in order to upgrade the Centre's operational ability to deploy and recover AUVs from their mother vessels, improving safety and reliability while mitigating weather constraints.

II. PERSISTENCE

This section addresses the issue of persistence which is the prime limitation for maritime autonomy. For this reason CMRE developed a hardware interoperable and scalable Wireless Power Transfer (WPT) system. The system is named "hardware interoperable" since it is easily scalable and adaptable to different AUV sizes. For instance, the first 21" prototype was re-sized to fit in a man-portable AUV (an eFolaga) and a CMRE docking station.

A. Technical description of Wireless Power transfer system

The Wireless Power Transfer (WPT) system is capable of transferring 500W continuously without contact through an inductive coupling. A feedback system, integrated inside the coils, guarantees DC voltage stability at the load, independent of load and coupling conditions. Overall efficiency from the power supply output to load is around 90% at full load. Ferrite, windings and auxiliary feedback control are molded into a hockey-puck shaped housing, with a diameter of 78mm and a height of 62mm, connecting to the electronics by means of a special underwater cable (including litz wire). Maximum allowed gap in salt water is 10mm.

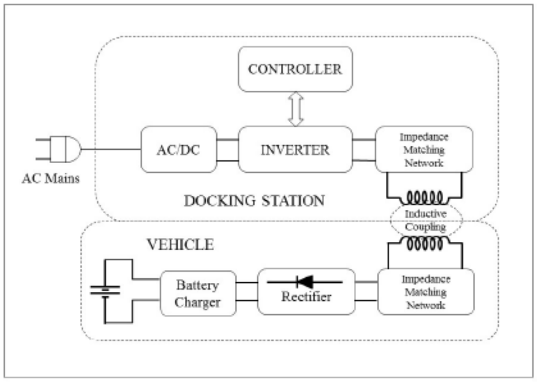

Fig. 1. Wireless Power Transfer Architecture

The WPT is composed of two components: the primary side being part of the docking station while the secondary side is the one integrated in the AUV.

The primary side is based on a variable frequency half-bridge resonant converter with series compensation of both primary and secondary leakage inductances. It is using the zero-voltage-switching (ZVS) technique that dramatically reduces the switching losses and EMI noise and efficiency is significantly improved. The primary side housing having the dimensions (240mm diameter by 350mm length) contains a power supply completely filled with resin, capable of providing 1kW @100Vdc and a bridge control, including a microcontroller and the feedback system

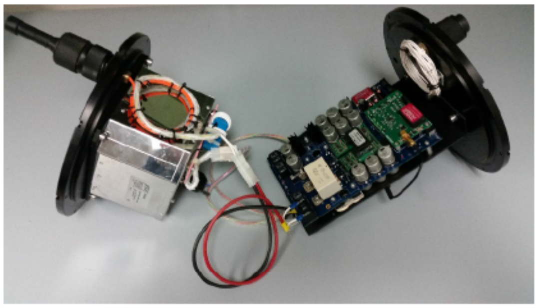

Fig. 2. WPT primary side bridge electronics and power supply

The secondary side (with the exception of the hockey-puck shaped coil that is external) is hosted inside the e-Folaga section (155mm diameter by 350mm length). The section includes a Motherboard with high-efficient synchronous rectifier and a 4 battery chargers. The motherboard hosts a microcontroller and can talk both to the AUV and to the battery charger. Each battery charger can be reprogrammed and adapted to any kind of battery. The 4 Polymer Li-Ion Battery Packs were recharged at 27V, 4x4A in less than 4 h. During those tests, it was verified that the Temperature inside the AUV is not critical thanks to the synchronous rectification design.

B. WPT Integration in the AUV and docking station

The proper mechanical integration of the AUV in the docking station, is essential to ensure high efficiency recharging as the minimum distance between the primary side and the secondary side of the WPT needs to be secure. Specific design effort and numerous tests were necessary to secure optimal performance of the WPT.

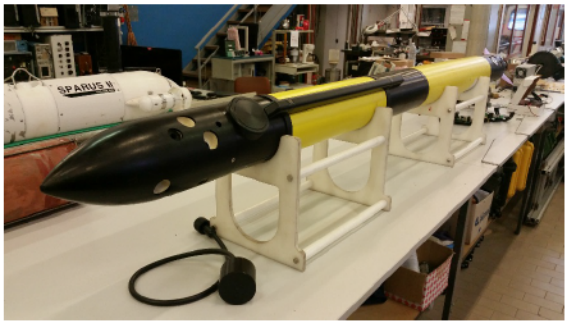

Fig. 3. WPT integration in eFolaga AUV with hockey-puck shaped housing in the AUV and on the bench

The *Dream Catcher* or AutoLARS [1] was developed to be either used in mobile or fixed modes. For the mobile mode it is equipped with propulsors allowing it to move with 6 degrees of freedom with the idea that after acoustically detecting the unmanned underwater vehicle it would move in the water to catch it as the equivalent of an aircraft in the air refueling system.

Fig. 4. AutoLARS or "Dreamcatcher" before its deployment in CMRE harbor.

The dream catcher mechanics has been modified in many parts, with respect to the original design, in order to facilitate the eFolaga entrance, obtain a more effective and precise clamping action from the two actuators, and have a better mate between the two halves of the WPT transformer.

Fig. 5. Dreamcatcher slide-in guide and IPT primary side coil receptacle and dreamcatcher actuator

C. *At-sea demonstrations*

The 2017 work culminated in a two-week continuous at-sea experimentation last November 2017 during which the AUV remained in the water for the whole period, switching from its science activities consisting of communicating with a farm of sensors fixed on the sea bed to its "survival mode" mission in which battery charge and on-board data storage capacity are restored to conditions that allow the normal scientific mission to be resumed.

For this experimentation, the docking station was used in a fixed mode meaning that the AUV was autonomously detecting its position through acoustics and adapting its navigation to enter in the catcher before being grabbed by the actuators.

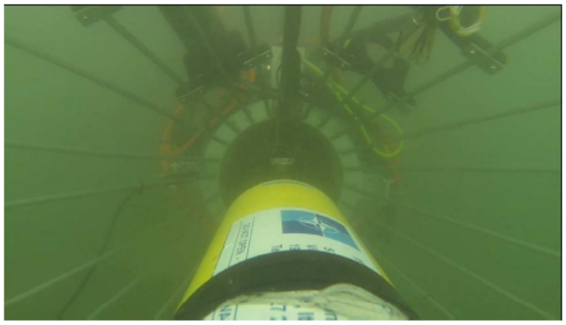

Fig. 6. AUV docking underwater for battery recharging and data exchage in CMRE harbor two-week continuous demonstration in November 2017

D. *Wireless Power Transfer Way forward*

Potential improvements for the WPT would be increasing power from 0.5 to 1kW by using larger coils (~120mm diameter). A new design could incorporate the rectifier inside the hockey-puck shaped coil by making it slightly longer. In this way the AUV should host only the battery chargers. Some tests suggest that it should be possible to design the coils including a Wi-Fi link. Primary side electronics could be redesigned in order to fit into a smaller space, provided that Wi-Fi link proves to be reliable enough in order to replace auxiliary feedback system

III. DEEP WATER NAVIGATION

Navigation of Autonomous Underwater Vehicles is still a challenging task, requiring a trade-off between performances, cost and operational time. In most scenarios, the AUVs represent the movable assets of a wider infrastructure (*i.e.* autonomous sensor network) or are immersed within a structured environment (*e.g.* supporting a vessel with HiPAP or USBL) that can be used to enhance the localization and navigation capability of the vehicles. To this aim, it is important to define the type of localization information that can be collected from regular network communication traffic to help the AUV to fuse navigation estimates from various data sources and increase the overall localization/navigation performance.

In the recent years CMRE has been working in order to enhance the navigation performance of AUVs in those scenarios where traditional means to bound navigation errors show their limits: *e.g.* deep waters where DVL bottom lock cannot be achieved, or operations in denied areas where the use of static and dedicated beacons is incompatible with the mission requirements.

A. *Technical approach*

The proposed approach is based on the investigation of using additional/alternative localization devices (e.g. HiPAP, USBL, network-produced range measurements, etc.) to be fused within a real-time Extended Kalman Filter (EKF) capable of combining kinematic exteroceptive data (when available) with vehicle odometry. The filter was integrated onboard the CMRE OEX AUVs applied for ASW missions, and tested at sea for the first time in deep water during the NATO exercise Dynamic Mongoose'17 off the South coast of Iceland (June-July 2017). During this experiment the filter, integrated in the back-seat onboard each OEX AUV, was devoted to fuse information, in real-time, available from:

- AUV GPS position (available only on surface);
- direction-of-arrival (i.e., bearing) estimates of other nodes equipped with an acoustic modem (data from the USBL installed on each AUV);
- Round-trip-time (RTT) measurements provided by the underwater acoustic modems linking the AUV with all the other network nodes (when available);
- AUV position from HiPaP data coming from the mother ship, when available;
- Through-the-water speed measurements from the DVL.

B. *Results*

The filter ran along all the different missions conducted in deep water configuration mode (up to about 11 h continuously). *Fig. 7* shows an example of localization error obtained during a 5hour mission of Groucho AUV when the HiPaP data were sent to the AUV only from time to time (with gaps lasting up to 1 h) in order to test the filter ability to apply opportunistic philosophy and work only with the remaining available measurements (i.e., USBL and RTT in particular).

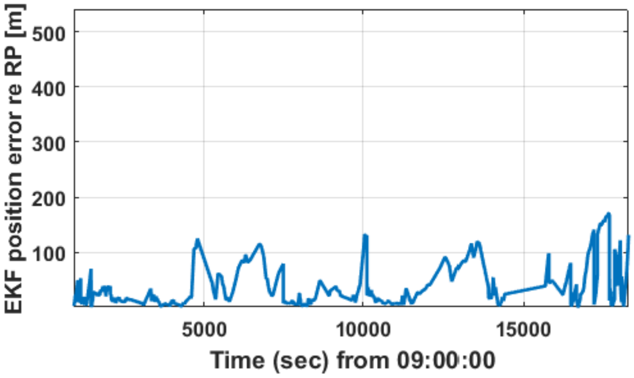

Fig. 7. Example of localization error of the EKF developed to make CMRE AUVs navigate in deep water.

The error is referred to the Reference Path (RP), the output of an instance of the filter which was running on our mother ship NRV Alliance and exploited, as observations, the AUV position measurements available at high rate through her HiPaP USBL system. The error is always less than 200 m even during unavailability of HiPAP measurements at the AUV.

An extensive description of the selected EKF-based approach, and a selection of experimental results are reported in [2].

The EKF navigation filter developed to allow deep water positioning and navigation of AUVs was an important enabler for the CMRE autonomous heterogeneous network implementing multistatic active sonar for ASW applications. The approach allowed the CMRE network to be integrated in the DMON17 NATO exercise off the South Icelandic coasts in June-July 2017. The filter was fully integrated in the control loop of the two CMRE OEX-C vehicles and it was running in their backseat during the duration of all the missions conducted in deep water configuration mode (up to about 11 h continuously). The integration among all the involved components demonstrated to be reliable. The data analysis provided the evidence that the adopted approach has led to a filter capable of working with heterogeneous time-irregular and possibly delayed measurements providing a navigation state estimation, in absence of DVL bottom-lock; it was capable to work on the basis of a variety of opportunistic data also when the high-accuracy HiPAP™ USBL system of the mother ship was unavailable for relatively long periods (up to about 1 h during the conducted experiments).

IV. SECURE COGNITIVE UNDERWATER COMMUNICATIONS

As seen above, some of the effectiveness of distributed underwater autonomous solutions comes from the fact that they can be deployed in large numbers and conduct cooperative tasks. In the case of underwater autonomous systems, cooperative techniques are typically faced with the bottleneck of underwater communications. In the underwater environment, both radio and optical signals are greatly attenuated, and acoustic waves remain the most efficient means to communicate underwater for ranges beyond about 50 m. Nonetheless, acoustic-based solutions suffer from long propagation delays and low data rates. Factors affecting the quality of the received signals such as multipath propagation, frequency dependent scattering losses, motion-induced Doppler, are difficult to model. It is therefore of high interest to develop a system that can intelligently adapt the transmission schemes to specific (measured) environmental attributes. Additionally, for short-range applications optics and electromagnetic waves can achieve data throughputs several orders of magnitude above those offered by acoustics. The previous adaptation idea can then be expanded to smartly select which communication modality to use (between acoustic, optical and electromagnetic) when more than one is available.

A. *Cognitive Communication Architecture (CCA)*

Adaptation is the foundation concept for the Cognitive Communications Architecture (CCA), developed at CMRE.

The CCA (Secure Communications is a C++ implementation or reference architecture of a Software Defined Modem (SDOAM) [3], which is intended to provide, simultaneously, improved flexibility while still maintaining some classical architectural organizing features of stacks that follow the Open Systems Interconnection (OSI) paradigm. The use of a layered structure enables to maintain a good level of separation among different layers, thus allowing the user to simply substitute the solutions to be adopted at a specific layer without affecting other layers. At the same time, the traditional OSI paradigm is enhanced with the support of more than one solution at each layer of the stack and the possibility to use cross-layering interaction among the various layers. This enables to have the entire stack exchanging relevant information in order to work in a coordinated and more effective way selecting the more suitable solution(s) to use at each layer. The selection of the specific solution(s) to use is driven by the presence of cognitive capabilities (policy engines), enabling the stack to autonomously reconfigure and adapt to the environmental or operational picture.

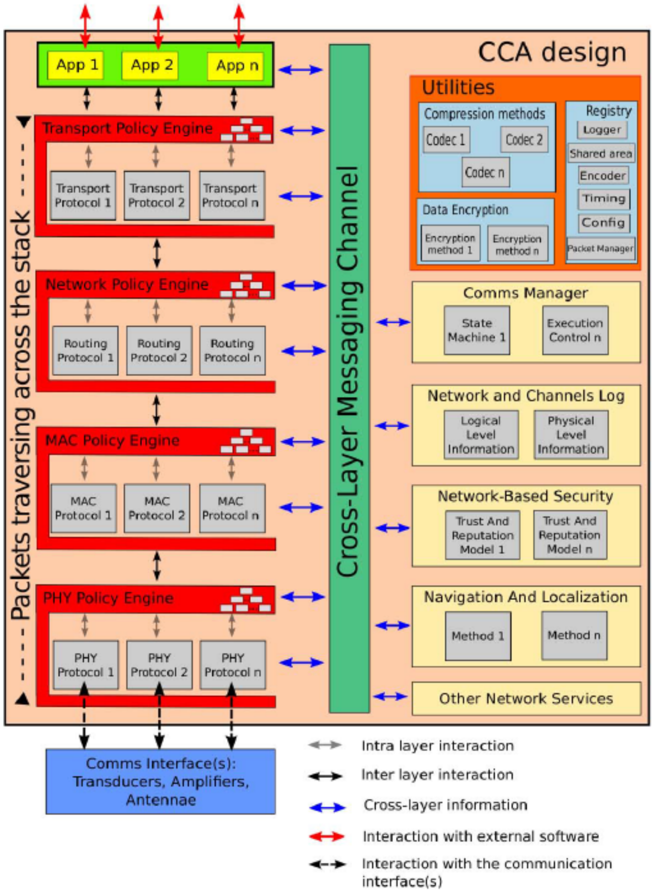

Fig. 8. The CCA design and its major components

The CCA works as a "skeleton" on top of which, protocols can be deployed in order to achieve a full underwater networking solution. The CCA is currently CMRE's architecture for all implementations of underwater communications. The software is dependable and has been used in different sea trials (REP16-Atlantic, REP17-Atlantic, Dynamic Monarch 17 and CommsNet17) in support of JANUS operations and to interface commercial modems. When used in support for JANUS, the CCA effectively implements the software component of a JANUS acoustic modem. When used with commercial modems, the CCA provides a driver and upper protocol functionality. For any of these applications the hardware demands are very humble. The CCA was successfully deployed in both cases on Raspberry-Pi and other ARM boards.

One of the next steps in the CCA development is to support more demanding modulation schemes. For this to be possible, specialized hardware capable of guaranteeing the required real-time processing needs is being pursued.

Several promising novel techniques to be used within the CCA for adaptive networking have been proposed and tested. These include: adaptation at the physical layer with a deep-learning based method to select (from a library of available waveforms) which one to use given the measured channel conditions [4] ; a dynamic address allocation method for pure ad hoc underwater networking [5] and a novel method for efficient cooperative localization based on exchange of acoustic communication signals [6].

B. Secure Communications

In terms of underwater communications security, the implementation of techniques "imported" from the terrestrial domain is, in some instances, considered. The peculiarities of the underwater acoustic channel and its limited available throughput motivate the careful decisions that must be made in that regard. The ability of the CCA to provide a framework for cross layer information exchange is being explored to propose novel solutions that can make use of the information available in the whole stack to better select the appropriate counter-measure to employ. Since the application of encryption and authentication techniques tends to increase message size, one must balance carefully the threat risk against the performance degradation imposed by the additional overhead. Integrity of communications in critical operations, protection against denial-of-service attacks, detection of malicious behaviors and identification of compromised nodes are areas of interest for CMRE [7].

C. Digital Communication Standardization

The CCA is also intended as a facilitator of interoperability (which is a core requirement for NATO) by providing a homogenized approach to protocol implementation and protocol switching.

Up until recently no digital underwater communications standards existed. The lack of interoperability in underwater digital communications represents a significant bottleneck towards the effective deployment of cooperative networks of underwater assets.

CMRE took the lead in an effort to establish the first-ever standard to break this interoperability barrier. As a result, JANUS [8] (known in formal terms as STANAG 4748) was promulgated as a NATO standard in March 2017.

The JANUS standard is deliberately robust. The digital coding technology that is used is well-known and can easily be adopted by a wide range of existing systems. The physical layer coding scheme is known as Frequency-Hopped (FH) Binary Frequency Shift Keying (BFSK). FH-BFSK has been selected for its robustness in the harsh UW acoustic propagation environment and simplicity of implementation. JANUS is unique in its open and public nature. It is available to all (academia, industry military, NATO and non-NATO). The specification of the signal encoding and message format is openly available and anyone can experiment with JANUS transmitters and receivers.

CMRE has been promoting the use of JANUS to deliver new services in the maritime world [9]. These include broadcast of Automatic Identification System (AIS) and Meteorological and Oceanographic (METOC) data to the sub-sea domain. JANUS usage as a possible support for automated SOS during submarine distress cases has been also proposed and demonstrated in the exercise Dynamic Monarch – the world's largest submarine rescue exercise.

V. LAUNCH AND RECOVERY

The last section is dedicated to the technological solutions implemented at CMRE in order to upgrade the Centre's operational ability to deploy AUVs from their mother vessels, improving safety and reliability while mitigating weather constraints.

A. *Problem statement*

In order to support its various research programs, CMRE operates a fleet of Maritime Unmanned Systems (MUS), ranging from Surface Vehicles (USV) to gliders, and Autonomous Underwater Vehicles (AUVs).

Up until recently all CMRE unmanned systems, and particularly the 21"-class AUVs – primarily involved in Anti-Submarine Warfare (ASW) and Mine Counter-Measure (MCM) programs – were deployed and recovered from support ships in a conventional manner, by means of a deck crane, with the assistance of a RHIB (Rigid-Hull Inflatable Boat). Recovery in this fashion is often the most critical and incident-prone phase of a maritime robotic experimentation, and may restrict operations to low sea state conditions (up to SS2) and daylight hours.

As CMRE maritime autonomous systems became more advanced, and were expected to operate for extended durations, in more challenging operational environments (NATO naval exercises, Arctic seas), the need arose to provide safer, RHIB-less operations, in moderately heavy sea conditions, and for a range of host vessels.

B. *Implementation*

The marine robotics community has proposed and demonstrated a variety of LARS technologies in recent years, at the surface or submerged, sometimes requiring sophisticated software and hardware developments onboard the AUV systems, and specific adaptations on the supporting vessel. CMRE has been contributing to the development of such advanced LARS systems, and continues its efforts in dedicated engineering programs.

For 21"-class AUVs, in order to enable short term operational readiness, preference was given to proven, state of the art technology, with focus on interoperability and portability, hence enabling AUV deployment not only from CMRE research vessels, but also from other ships of opportunity.

The result is a general-purpose LARS system for (up to) 21" AUVs. Its architecture is an articulated hydraulic ramp, sliding and tilting from the ship transom, as illustrated in Fig.9.

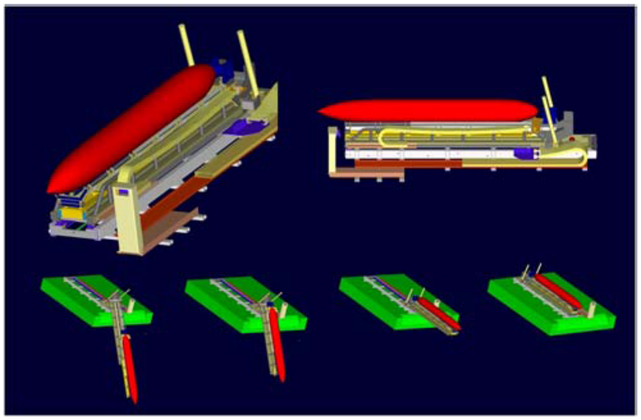

Fig. 9. LARS architecture and principle of operation

During the design phase, particular attention was paid to ensuring maximum multi-platform interoperability, considering key features such as on board hydraulic power pack, standardized deck fittings, variable geometry in ramp extension and tilting angle, interchangeable cradles, but also ship-independent lifting capability, allowing multi-AUV concurrent operations.

The LARS includes a base frame, that can be fastened onto Ship's deck directly or via an ISO Container interface frame, supporting the Hydraulic Power Pack, the Operator Control Station and allowing the longitudinal translation of a Trolley; a two-stage Chute is hinged at it, to be tilted up and down by means of two hydraulic cylinders. The Chute can be extended in and out with a hydraulic cylinder to allow the deployment of the LARS in close proximity to the water, compensating for different Ship's deck heights above water. A pull-in Winch is mounted at the inner end of the Chute to hoist the Vehicle onto the Chute. The main components of the LARS are shown in Fig.10

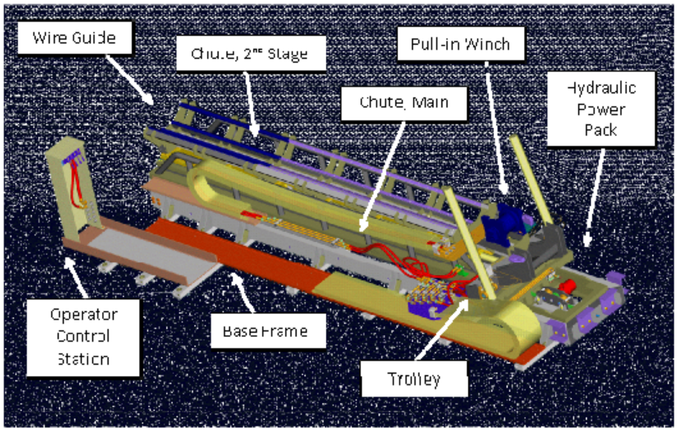

Fig. 10. LARS layout and main components

In order to hoist the AUV up and onto the ramp, the vehicle nose section is modified to integrate a releasable section, attached to the vehicle mechanical frame by a towline. Upon command to release, the float separates from the vehicle through wave motion, or by remotely commanding the vehicle in reverse. The towline is captured from the ship by means of a grappling hook or gaff, and the float brought onboard. Finally, the towline is engaged into the ramp hydraulic winch, and the AUV slowly pulled onto the ramp and onboard the Ship.

The main characteristics of the CMRE LARS are summarized in Table 1.

Table 1 - CMRE LARS Main Characteristics

Description	Unity	Value
AUV Maximum Mass	Kg	800
AUV Maximum Dimensions (Dia x Length)	m	0.533 x 6.0
LARS Mass	Kg	2500
LARS Dimensions (L x W x H)	m	6.3 x 2.1 x 1.5
LARS Electrical Power Requirements	V, Hz kW	380-440, 50-60, 7.5
Maximum Ship's Deck Height	m	5.0

C. *At-sea Results*

The LARS was operated for the first time in 2017, during NATO ASW exercise Dynamic Mongoose, in Iceland. The LARS was used to launch and recover 2 Ocean-Explorer-C (OEX-C) AUVs. It was immediately recognized as a major upgrade to CMRE standard operating procedures, providing reliable, safe and fast RHIB-less operations, even in Arctic seas. Although sea state conditions did not exceed SS2, reliable operations up to SS4 are deemed achievable in the future.

Fig. 11. LARS deployed from NATO Research Vessel ALLIANCE

Fig. 12. OEX-C AUV recovered from LARS

D. *LARS Way forward*

The LARS is now considered standard operational equipment for the Centre's ASW unmanned program, and is compatible for operations with all 21"-class AUVs. It can be readily installed and operated from a broad range of vessels equipped with ISO standard deck fittings or other fastening systems. To extend interoperability of the LARS, an additional upgrade is following in 2018, to integrate a small crane enabling ship-independent lifting and handling, and enabling concurrent servicing of several AUVs. Near-future engineering developments of the LARS are also planned at CMRE to support AUV expeditionary projection capabilities and the integration in ISO shipping containers.

VI. CONCLUSION

This paper described important technological developments made at CMRE in the last decade for enabling the future use of persistent, deployable and recoverable autonomous/unmanned underwater systems of systems. Results were shown that demonstrated the capability to efficiently recharge AUV while underwater through the use of a wireless power transfer docking station (an underwater "gas station"), dramatically increasing the AUV's persistence while avoiding the need to recover it. Other results were dedicated to demonstrating how new navigation techniques could allow AUV navigating and positioning accurately in a deep water environment. Further results dealt with work performed to provide an efficient, secure and adaptive inter-operable underwater communication capability that is critical for the future use of multiple AUVs that would be in large numbers and would be required to conduct collaborative and cooperative tasks. The last results demonstrated the development of a Launch and Recovery capability allowing AUV recovering up to Sea State 4.

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REFERENCES

[1] T.J Osse, S.Pai, A.Maguer, M. Chitre, M. DeBoni, P.Guerrini. J. Potter. Autonomous Launch and Recovery Systems (AutoLARS) for AUVs. Proceedings of European Conference on Underwater Acoutics. Istanbul. Turkey. 2010

[2] A. Tesei , A., Micheli, M., Vermeij, A., Ferri, G., Mazzi, M., Grenon, G., Morlando, L., Biagini, S., LePage, K., Costanzi R., Fenucci, D., Caiti, A. , Munafó, A. "Real-time underwater positioning and navigation of an AUV in deep waters," in Procs. Of MTS/IEEE OCEANS'18 Int. Conf., Kobe, Japan, May 2018.

[3] J. R. Potter, J. Alves, T. Furfaro, A. Vermeij, N. Jourden, G. Zappa, A. Berni, and D. Merano, "Software Defined Open Architecture Modem Development at CMRE," in Proceedings of the 2nd IEEE OES International Conference on Underwater Communications and Networking, ser. UComms14, Sestri Levante, Italy, September, 3–5 2014.

[4] K. Pelekanakis, L. Cazzanti, G. Zappa and J. Alves, "Decision tree-based adaptive modulation for underwater acoustic communications," *2016 IEEE Third Underwater Communications and Networking Conference (UComms)*, Lerici, 2016, pp. 1-5. doi: 10.1109/UComms.2016.7583461.

[5] R. Petroccia, "A distributed ID assignment and topology discovery protocol for underwater acoustic networks," in Proceedings of the 3rd IEEE OES International Conference on Underwater Communications and Networking, ser. UComms16, Lerici, Italy, August 30 – September 1 2016.

[6] J. Sliwka, R. Petroccia, A. Munafo, and V. Djapic, "Experimental evaluation of Net- LBL: an acoustic network-based navigation system," in Proceedings of MTS/IEEE OCEANS 2017, Aberdeen, Scotland, June, 19–22 2017, pp. 1–9.

[7] C. Lal, R. Petroccia, K. Pelekanakis, M. Conti and J. Alves, "Toward the Development of Secure Underwater Acoustic Networks," in IEEE Journal of Oceanic Engineering, vol. 42, no. 4, pp. 1075-1087, Oct. 2017. doi: 10.1109/JOE.2017.2716599

[8] STANAG4748 Digital Underwater Signalling Standard For Network Node Discovery & Interoperability - ANEP-87 Edition A. NATO Standardization Office, March 2017. Available at http://nso.nato.int/

[9] R. Petroccia, J. Alves and G. Zappa, "JANUS-Based Services for Operationally Relevant Underwater Applications," in IEEE Journal of Oceanic Engineering, vol. 42, no. 4, pp. 994-1006, Oct. 2017. doi: 10.1109/JOE.2017.2722018

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Abstract

Underwater Unmanned systems (or more precisely systems of systems) will definitely play an important role in future maritime surveillance and environmental data collection. For many years, the NATO Centre for Maritime Research and Experimentation (CMRE) has deeply invested in developing Artificial Intelligence algorithms to allow robots to perform unmanned missions. These scientific efforts have always been based on these robots' capability to localize themselves, to communicate reliably, and to continuously operate for many days or even weeks or months. This paper describes the recent technological advances performed at CMRE for solving these challenges, in particular the work done on increased persistence, deep-water navigation, communication and launch and recovery.

Keywords

Persistence, deep-water navigation, cognitive underwater communication, launch and recovery, unmanned systems

Issuing Organization

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