At-sea NATO operational experimentation with interoperable underwater assets using different robotic middlewares

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Abstract. Autonomous Underwater Vehicles (AUVs) are offering new capabilities for a wide range of military and civilian applications. The interoperability of heterogeneous AUVs with different skills is critical to accomplish such complex tasks. Indeed, the proliferation of AUVs with their own mission control interface and communications protocol makes it difficult to operate them within operational experimentations, which requires joint management and coordination. This problem was approached in the preparation of the ASW-ODC17 (Anti Submarine Warfare - Operational Deployment of Concepts) sea trial, which, among its objectives, aimed to demonstrate the interoperability of an external AUV (the Folaga WAVE) within the CMRE heterogeneous robotic network during a NATO operational exercise in ASW. The different hardware and software architectures were integrated by configuring an asset of the CMRE network (a gateway buoy) to act as a bridge between the two robotic systems. All the AUVs were successfully operated during the joint NATO exercise through the same mission control station, unconcerned by differences in acoustic modems and robotic middleware.

Keywords. Autonomous Underwater Vehicle, unmanned vehicles interoperability, NATO joint exercise, robotic middleware frameworks

1. Introduction

Autonomous Underwater Vehicles (AUVs) are relatively new systems but they are growing quite fast both in types and in autonomous skills for military and civilian applications ([1], [2]). Despite the growing maturity and availability of the technology, there is still a lack of standardization about interoperability of heterogeneous platforms. Then, joint management and coordination of complex marine operations are dramatically difficult for the end-user.

This problem was approached in the preparation of the ASW-ODC17 (Anti-Submarine Warfare - Operational Deployment of Concepts) sea trial exercise, held in October 2017 and partly conducted off the coast of La Spezia (Italy). The sea trials

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activities were organized in the context of the CMRE project MUS (Maritime Unmanned Systems) for ASW, in cooperation with NATO Naval Units and the Italian SEALab consortium (the joint laboratory between the Naval Experimentation and Support Centre of the Italian Navy and the Italian Interuniversity Center of Integrated Systems for the Marine Environment). The final objective of the MUS project is the development and test at sea of a heterogeneous autonomous ASW network based on unmanned underwater vehicles implementing a multistatic active sonar system. From the Italian partners' point of view, the goal was to demonstrate the interoperability of a national AUV (the Folaga WAVE [3]) within the CMRE robotic network for ASW [4] during a NATO operational exercise involving assets of different NATO Navies.

The paper is organized as follows. An overview of the whole exercise is presented in section 2. The high-level architectures of CMRE ASW Network and Folaga WAVE software are described in section 3, along with their respective middleware. Then, specific interoperability experiments and related results are described in section 4 and the conclusions are drawn in section 5.

2. ASW Operational Deployment of Concepts '17 Experimentation

The ASW-ODC17 sea trial was led by CMRE and held in the period 12 October - 1 November 2017 in collaboration with NATO naval units. The interoperability tests described in this paper were conducted for four days (in the period 12 – 17 October).

The ASW-ODC17 experimentation mainly aimed to:

- Improve CMRE's capability to **integrate** a multi-static ASW hybrid manned-unmanned network into a NATO exercise / operational experimentation;
- Augment the CMRE ASW active multistatic sonar network by applying bistatics with the aid of other sonar sources;
- Demonstrate **interoperability** of a National underwater robot (the Folaga WAVE hybrid AUV) within the CMRE heterogeneous Manned/Unmanned network for ASW applications.

In CMRE's multistatic active sonar hybrid network, multiple more sonar sources (i.e. transmitters installed on a buoy or towed by NRV Alliance) transmit a sonar signal (ping). When the pings are scattered by objects, receiving hydrophone arrays can collect those echoes from different positions, including the arrays towed by autonomous platforms (in particular two OEX AUVs). Another receiver array, the new triplet SLICTA array, was towed from NRV Alliance. Mobile and moored gateway buoys build the communications infrastructure of the network and allow command and data exchange among all nodes (manned and unmanned). This way, a system operator can interact remotely or in real time with the underwater network using firstly the gateway buoys and then multi-hop acoustic communications.

3. CMRE Network for ASW and Folaga WAVE Software Architectures

3.1. MOOS-IvP vs ROS: Robotics Middleware Outlook

This subsection contains a brief overview of the two middleware used in this experimentation, MOOS-IvP (Mission Oriented Operating Suite – Interval

Programming) adopted by CMRE and ROS (Robotic Operating System) used by Folaga-WAVE, aiming at underlining similarities and differences.

The MOOS-IvP is a combination of two components: IvP Helm and MOOS. MOOS and ROS are publish-and-subscribe systems, which provide the communication of arbitrary data throughout a network. However, in order to complete mission objectives, a robotic system also requires a deliberative component in addition to its reactive aspects (e.g. avoiding obstacles) [5]. This is the goal of the MOOS process IvP-Helm, which act as an autonomous decision-making engine that executes in the backseat of the robotic platform. In fact, a MOOS-IvP environment is composed of several processes, which communicate using the MOOSDB database as a broker.

The rate of interactions across information channels, called topics, is controlled tightly by the MOOSDB, occurring synchronously at a predefined rate. Therefore, MOOSDB is relatively rigid, and each topic is bound to a startup-defined data type.

On the other hand, ROS processes (called nodes) communicate directly with each other, with no central broker. A central node (called master) exists, but only to manage node startup and shutdown. This is the main differences between MOOS and ROS: while all data within a MOOS system is transmitted through the MOOSDB, in ROS data are transferred using peer-to-peer communications.

The basic unit of interaction in ROS is a message, which is typically exchanged on a topic: from a node's perspective, messages are published synchronously and read from a subscription asynchronously.

The development of MOOS-IvP in the research community is continuous and ongoing, while its usage in the industry is very limited. While MOOS has historically been popular within the underwater robotics community, ROS is now by far more pervasive in a multi-domain context (ground, sea, air).

CMRE still prefers MOOS-IvP mainly because of the IvP part, which allows the vehicle to work autonomously towards a goal, while it operates within mission requirements, operating an efficient de-conflicting of the tasks.

Anyway, due to their many similarities, there is almost a one-to-one correspondence between ROS and MOOS system calls, and the path forward for the Centre is the integration of the two middleware.

3.2. CMRE NEMO Framework

NEMO is the software framework developed at the CMRE to support CASW experiments using AUVs with acoustic communications. This section gives an idea of NEMO as a whole, while the interested reader may find more information in [4], [6], [7]. The CASW research at the CMRE uses two middle-weight OEX AUVs, and the Centre adopted MOOS as its robotic middleware on those vehicles. The most important MOOS process is called pAcommsHandler [7]. In 2011, in order to extend the acoustic range of the vehicles, the CMRE decided to integrate an additional back seat acoustic modem, the EvoLogics S2C R 8/16.

In addition, it was therefore decided to redesign pAcommsHandler, opening up the driver to become broader interoperable. The new process is now known as NEMO, and its general architecture is shown in Figure 1. Each circle is a MOOS application, while the square represents a physical modem, accessible through the appropriate MOOS application. Each solid arrow represents a flow of data between two MOOS applications via the MOOSDB.

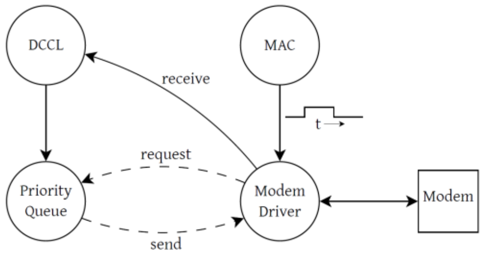

Figure 1. Nemo's high-level architecture.

The dashed arrows represent a client-server relationship. Any message received from the modem is published into the MOOSDB, from where the DCCL (Dynamic Compact Control Language) reads it and starts the decoding process. The DCCL MOOS application subscribes to those MOOS variables that are needed to compose outgoing messages. Once composed, the outgoing message is encoded and published into the MOOSDB, where it is read by the Priority Queue MOOS application.

The MAC MOOS application tells the Modem when it is allowed to access the acoustic medium. The current implementation uses a rigid TDMA (Time Division Multiple Access) scheme, where specific nodes are assigned specific time slot.

The migration from pAcommsHandler to NEMO has given the CMRE greater flexibility in modifying and extending the acoustic communication network with the OEXs and other research AUVs. The next ongoing step at CMRE is the development of a cognitive communications architecture (CCA) that will allow other channel access scheme beyond TDMA.

3.3. WAVE Mission Control System (WMCS)

The Italian WAVE project aims at studying and prototyping a hybrid oceanographic glider/AUV with energy conversion and recharging capabilities exploiting wave motion and solar energy. The project is funded by the National Research Projects of Military interest (PNRM) and it is conducted by the University of Pisa and GraalTech (Folaga vehicle manufacturer), under the supervision, steering and control of the Naval Experimentation and Support Centre of Italian Navy (CSSN). The WAVE Mission Control System (WMCS) integrates the modules specifically developed for the project with those already existing into the AUV, and it guarantees a high level of abstraction for the user set-up of an autonomous mission of the WAVE vehicle. The term "high level" means that the user does not have direct control of the hardware installed on the vehicle (both sensors and actuators), but interacts with them through an easily interpretable request-response mechanism made available by the WMCS.

Three basic functionalities are considered into the planning an autonomous mission through the WMCS:

1. Management of mission payloads: the user can switch on and off the additional sensors (CTD - Conductivity Temperature and Depth - probe and Side Scan Sonar), verifying their operating status and acquired data;
2. Control and Supervision of the mission: the user can communicate with the Guidance, Navigation and Control (GNC) system of the Folaga, giving new navigational tasks and monitoring the navigation status;

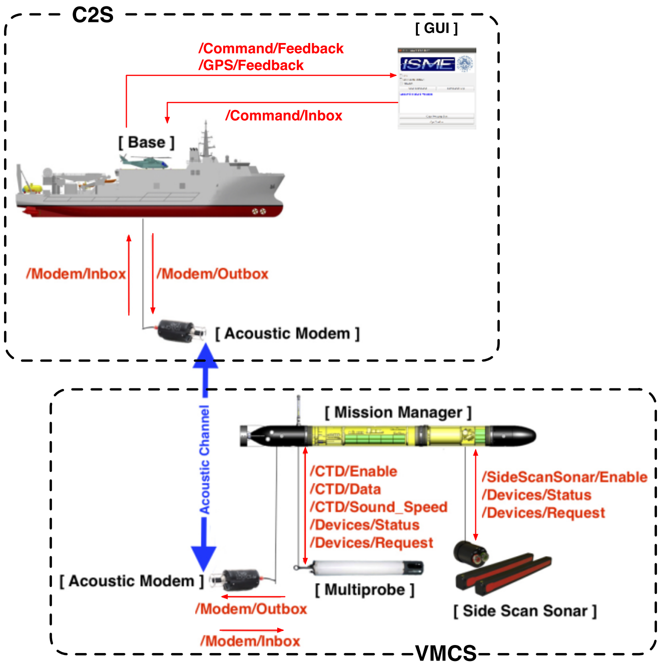

Figure 2. Conceptual scheme of the WAVE Mission Control System (WMCS).

3. Management of the operating mode: the user can control the operating mode of the vehicle (selectable between gliding, underwater navigation, surface navigation and surface recharging) depending on the available information and payloads.

In order to be effective, efficient and reliable, the SCMW has been designed and implemented in compliance with two main requirements:

- Modularity and scalability, thanks to the division of the system into different elementary modules. Each module has a specific task, favoring easier re-engineering of the system to cope with new needs and hardware changes;
- Reconfigurability: the system keeps the same general interface architecture independently by the vehicle configuration (addition, removal or change of payload), which depends on the mission to carry out.

3.3.1. ROS (Robotic Operating System) Implementation of WMCS

The WMCS consists mainly of two subsystems:

- The Folaga Mission Control System (FMCS) onboard the vehicle, responsible for the management of mission payloads and interaction with the low-level control system of the Folaga vehicle;
- The Command and Control Station (C2S) on the base station (which can be placed on the ground or on a support vessel), which provides a graphical user interface with all the tools to carry out mission supervision and control.

Although the two systems are physically separate, they interact through the acoustic channel using the EvoLogics 18/34 modems mounted both on the base station and on the vehicle. This way, the user can send commands to the vehicle and receive proper notifications and information. To meet the requirements described before, the WMCS has been implemented in C++ language taking advantage of the features offered by ROS, explained in section 3.1. All its features were crucial to the success of the general project and of the interoperability tests.

The conceptual scheme of the WMCS is illustrated in Figure 2. The two main subsystems (FMCS and C2S, dashed boxes in the figure) consist of several elementary modules. Each module corresponds to a ROS node, indicated in square brackets, with a specific goal. The different applications communicate with each other exchanging information through the red highlighted topics: the arrows indicate the direction of the data flow between nodes. Within a topic, the data is encoded with a particular message structure specific to the considered topic.

4. Interoperability Tests and Results

4.1. Trial Overview

Interoperability capability was demonstrated by integrating the Italian unmanned vehicle Folaga WAVE into the described CMRE heterogeneous network by exchanging both commands and data. As it is now clear, Folaga WAVE vehicle and CMRE network have different robotics middleware. Therefore, a ROS-MOOS bridge software was installed on a moored buoy acting as a gateway between underwater assets. The gateway was equipped with acoustic modems working on different frequencies, due to the peculiarities of the different AUVs (OEX and Folaga WAVE).

To have representative operational information, the Folaga WAVE was equipped during the trial with a CTD probe, the data of which was shared with the CMRE Environmental Knowledge and Operational Effectiveness (EKOE) team [9]. In addition, CTD data were made available for periodic updates of the environmental map in the area and for insertion into the MSTPA (MultiStatic Tactical Planning Aid) decision support tool [10], in which the onboard processed sound speed can be a valuable information. In particular, interaction with EKOE program allowed visualizing the positions of all the underwater assets (CMRE OEX AUVs and Folaga WAVE) on the EKOE C2 station. Furthermore, the Folaga WAVE position was available on board the NATO partners’ Flag-Ship and at NATO Allied MARCOM (Maritime Command) command and control stations. Figure 3 shows the information as they were seen on board NRV Alliance.

4.2. Specific Tests and Results

The planned interoperability tests started with a mission-planning phase, in which different parameters (e.g. waypoints, operating depth, and timeout) were sent from the CMRE C2S to the vehicle through the gateway buoy. After the vehicle started its mission, it automatically (at a selectable frequency) sent to the CMRE C2S its position and CTD data during profiling operation. Another test was the asynchronous request from the CMRE C2S to the vehicle of its position and CTD data. All the tests rely on acoustic communications between the gateway buoy and the vehicle.

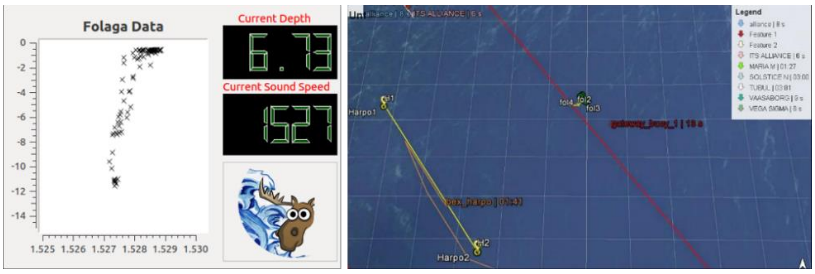

Figure 3. Screenshot of real data during the experiments. On the left, the sound speed received in real time during the Folaga WAVE profiling. On the right, the CMRE C2S with the AUVs' positions displayed.

The complete mission done for all the considered experiments is shown in Figure 4. It is important to recall that it was possible to remotely add, start, stop or abort different tasks on the AUV during the mission.

In particular, the vehicle was moving in gliding mode for about 250 meters in the first path between the starting point (red diamond) and the first dive point (orange asterisk). Then, it started doing four profiling tasks to characterize the water column down to 12 meters depth on a rectangular area of 5000 square meters. As it can be seen, it was present a strong Northeast sea current so that the vehicle resurfaced about 25 meters away from the diving points. In Figure 5, the gliding navigation and the following profiling tasks are shown. At the end of the last resurface, the vehicle was planned to autonomously reach a recovery point. Indeed, the mission timeout was achieved due to the tight operational schedule of the day. Hence, the vehicle did not complete the last profiling task and autonomously navigate to the mission final point.

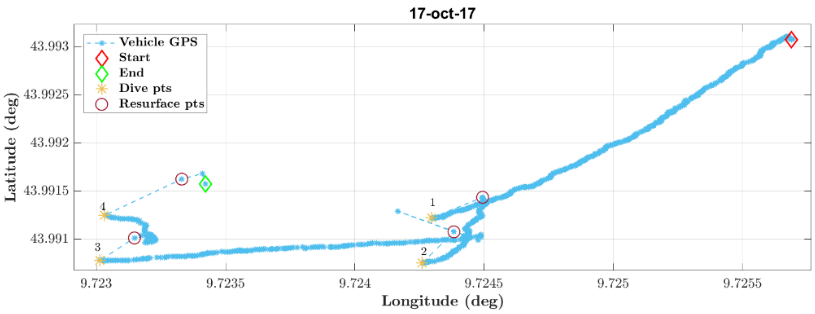

Figure 4. Interoperability test mission.

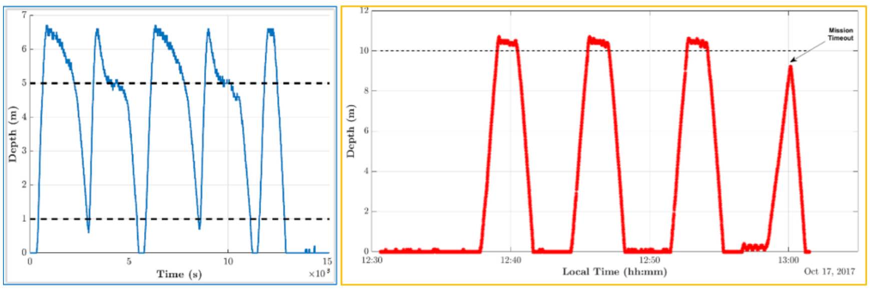

Figure 5. Time versus Depth plots. On the left, the initial gliding phase. On the right, the four profiling tasks, autonomously interrupted by the vehicle.

5. Conclusions

In this paper, we described interoperability tests between the innovative Folaga WAVE AUV, equipped with oceanographic sensors, and the CMRE network C2S onboard NRV Alliance, using a gateway buoy as a ROS-MOOS bridge. Their integration has been evaluated and validated through at-sea operational experiments off the La Spezia coast (Italy). This successful interoperability experimentation between different autonomous systems, with their own acoustic modems and middleware, is an important step to improve maritime situational awareness with respect to underwater assets during a joint NATO exercise. The WAVE software modularity makes possible to incorporate a new AUV in the existing CMRE network, which in turn demonstrated its flexibility to integrate newly available assets thanks to its decentralized architecture.
Future work might involve JANUS [11] language for underwater acoustic communication to make a first reliable handshaking between swarms of similar AUVs and the gateway node. After this contact, the interested assets can autonomously switch to a more appropriate communication protocol in order to maximize data rate.

Remarkable recent bridging applications are presented in [5] and [12]. According to the authors' knowledge, however, no National interoperable approach had ever been fully tested and demonstrated before in an operational exercise involving NATO manned and unmanned assets.

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