Rapid Environmental Picture Atlantic exercise 2015: a field report

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***Abstract*— The paper describes the sixth edition of Rapid Environmental Picture Atlantic exercise (REP15-Atlantic) which took place in July 2015 off the Portuguese islands of Azores to demonstrate coordinated operations of unmanned underwater, surface, and air vehicles contributed by participants coming from Europe and the United States of America. REP-Atlantic is a yearly demonstration exercise targeted at advancing the state of art in networked vehicle systems through large scale experimentation in real-life operational scenarios.**

Keywords*— *Networked vehicles; Autonomous Underwater Vehicle (AUV); Unmanned Surface Vehicle (USV); Unmanned Air Vehicle (UAV); Europtus; TREX; and, Azores.

I. INTRODUCTION

The sixth edition of the Rapid Environmental Picture Atlantic (REP15-Atlantic) exercise took place in July 2015 off the Azores Islands, Portugal (Figure 1). The exercise was jointly organized by the Portuguese Navy, the NATO Centre for Maritime Research and Experimentation (CMRE), the University of Porto through the Laboratório de Sistemas e Tecnologias Subaquáticas (LSTS), and IMAR-DOP from the University of Azores. The participants in the REP15 Atlantic exercise included, in addition to the organizers, the Norwegian University of Science and Technology (NTNU), the Royal Institute of Technology (KTH) from Sweden, the Naval Undersea Warfare Center (NUWC) and NASA-Ames from the US, University of Plymouth from the UK, and Oceanscan Marine Systems and Technologies, a spin-off from Porto University in Portugal. Each participant had specific objectives which had been carefully melded together for an ambitious field campaign that began with deployments from shore, which moved off-shore on the Portuguese Navy research vessel NRP Almirante Gago Coutinho, with support of vessels from IMAR-DOP, and then returned to shore to continue with shore based operations all based out of Horta, Faial Island, Azores.

Fig 1. Operation areas in the Azores islands, Portugal.

The paper is organized as follows. Section 2 describes the assets used in the exercise. Section 3 discusses the goals and organization of the exercise. Section 4 discusses selected results of the exercise and Section 5 presents the conclusions.

II. Assets

The REP15-Atlantic exercise included several USVs (2 Wave Gliders from CMRE), AUVs (6 LAUVs from LSTS, 6 eFolaga from CMRE, 2 LAUV Seacons from the Portuguese Navy, and 2 Ivers2 from NUWC), UAVs (6 Skywalker X8 based unmanned air vehicles from LSTS and NTNU) equipped with different sensors and acoustic communication payloads, buoys equipped with acoustic modems and environmental sensors from CMRE, as well as Manta gateways from LSTS.

The LAUV is an AUV designed by LSTS and targeted at innovative standalone or networked operations for cost-effective oceanographic, hydrographic and security and surveillance surveys (see Figure 2 and Figure 6). A robust and reliable vehicle for oceanographic upper water-column or bathymetric measurements, the upper water-column configuration can operate for more than 24 hours. It comes with WiFi, Iridium, GSM, and acoustic modems to enable operations over inter-operated networks and includes a host of sensors for specific oceanographic or security applications and is now built and marketed by OceanScan MST [1].

The X8 Skywalker is a low-cost COTS (Commercial Off-The-Shelf) vehicle, modified at LSTS, which allows for quickly deployable monitoring and surveillance missions (Figure 4). It is perfected for low altitude reconnaissance scenarios, with live video feed. The vehicle controller has been modified to work with the LSTS software toolchain for advanced concepts in ocean science and engineering.

The Manta box is a low-cost portable communications gateway that supports wireless and acoustic communications allowing multiple communication protocols to be used seamlessly, including Iridium, 802.11, acoustic modems and GSM for networked operations over land or sea.

The eFolaga is a torpedo-like vehicle, consisting in two fiber-glass water-proof cylinders, which compose the main hull, and one or more additional modules that can be mounted at mid-vehicle to host a mission-driven payload. The two main cylinders are connected to two wet ends where are located jet-pumps for steering and the propeller for the motion in the surge direction. Yaw, sway and heave thrusters are distributed both fore and aft. The forward section contains ballast for buoyancy control. At the surface, the vehicle has GPS and land-station contact through a multi-radio link allowing on-line modification of mission requirements and data transmission.

The Iver2 AUV from NUWC and the Wave Glider from CMRE are respectively manufactured by OceanServer and by Liquid Robotics. The Iver2 run MOOS-IvP software [2].

The vehicle systems from the Portuguese Navy, NTNU, and LSTS were deployed with the Neptus/Dune/IMC software tool chain developed by LSTS [3]. The software tool chain provides a uniform command and control system with support for inter-operated wireless and underwater communications and disruptive tolerant network protocols. Neptus is a Distributed Command and Control Infrastructure for the operation of all types of unmanned vehicles [4]. Neptus supports the different phases of a typical mission life cycle: planning, simulation, execution and post-mission analysis. Neptus can be adapted by operators to fit mission-specific requirements and extended by developers through a comprehensive plug-in framework (lsts.pt/toolchain/neptus). The Inter-Module Communication Protocol (IMC) [5] defines a common control message set understood by all types of vehicles and computers nodes in networked environments (lsts.pt/toolchain/imc). DUNE, Unified Navigation Environment, is the embedded software at the heart of the vehicle: modules for control, navigation, simulation, networking, sensing, and actuation (lsts.pt/toolchain/dune). The Teleo-Reactive EXecutive (T-REX) is an advanced Artificial Intelligence based software controller that synthesizes, refines and executes abstract temporal plans to command the LAUV vehicle [6]. T-REX uses concepts previously flown by this group on two NASA spaceflight missions, Deep Space 1 Remote Agent 65 Million miles from Earth in 1999 and as the Mixed-Initiative human-in-the-loop controller for the two 2003 Mars Exploration Rovers (MER) mission. The Open Source automated planner at the heart of T-REX was designed and built at NASA Ames Research Center. The LSTS software also allows the integration of other vehicle systems and control stations, as long as they are compliant with the IMC communications protocol. This was demonstrated at sea with vehicles from NUWC with the help of SAE JAUS [7].

The web-based situation awareness tool Ripples, also from LSTS, was used in connection with the Missions Tool Suite from NASA-Ames for dissemination of data and remote visualization.

The control system of the eFolagas and Wave Gliders from CMRE is based on the backseat-driver paradigm: a backseat computer executes the processes managing the mission and produces commands for a front-seat computer in charge of the low-level vehicle control [2]. This was implemented using MOOS [8] as the main software infrastructure of the backseat computer. MOOS is an open source C++ framework that provides autonomy to robotic platforms. MOOS is based on the publish/subscribe paradigm: a community of processes subscribe to receive and publish variables from/to a central collection point (MOOSDB). To control the vehicles, MOOS processes run on the backseat computer receiving data from/issuing commands to the front-seat computer.

These vehicle systems were deployed from Portuguese Navy ships NRP Gago Coutinho and NRP João Roby and also from research vessels Águas Vivas and Pintado from IMAR-DOP, University of Azores.

III. Organization

The exercise was organized into 3 phases.

A. *Phase I*

During phase I, operations took place on shore and near shore close to islands of São Miguel, Pico, and Faial (Figure 1), to ensure scientific and cultural alignment with various groups working on the exercise. Mine sweeping and harbour protection experiments conducted mainly by the Portuguese Navy took place at São Miguel Island. A search for a submerged contact near the island of São Jorge was conducted by the Mine Warfare unit from the Portuguese Navy with the help of an LAUV. NUWC and the LSTS demonstrated SAE-JAUS enabled AUV/UAV interoperability. In this demonstration, an UAV from LSTS tasked an AUV from NUWC. CMRE conducted underwater communications and positioning experiments mainly in the Pico-Faial channel from NRP Gago Coutinho (Figure 3). This was done mainly with Wave Gliders, moored buoys, and AUVs from CMRE and LSTS. The mapping of marine eco-systems close to the Pico Island were conducted with AUVs from Porto University with the support of vessels from IMAR-DOP. Flight operations from shore with UAVs from Porto University and NTNU were conducted for training and also to evaluate hyperspectral cameras mounted on-board the UAVs from NTNU.

Fig 2. One LAUV from LSTS being recovered from water.

Fig 3. CMRE equipment on the NRP Gago Coutinho. eFolaga vehicles are shown on the left, the two Wave Gliders on the right. The Wave Rider buoy is shown behind the rightmost Wave Glider.

B. Phase II

In phase II, operations were conducted from NRP Gago Coutinho, off-shore of Horta (Figure 4). Driven by engineering goals, the objective was to use AUVs, UAVs, and drifters to collect data which would allow the characterization of wakes of whales and sample transects along S. Mateus and Azores banks (red zone Figure 1). Acoustic communications and positioning experiments were also conducted by CMRE from the same ship with the help of a moored buoy. Operations took place 24/7 and also included multibeam surveys by NRP Gago Coutinho and CTD stations over the São Mateus bank by researchers from the PO Navy Hydrographic Institute.

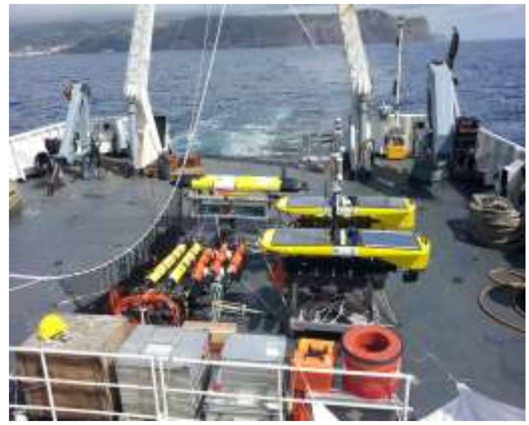

Fig 4. AUVs and ASVs from LSTS and CMRE onboard NRP Almirante Gago Coutinho.

Fig 5. UAV take-off and landing from NRP Gago Coutinho.

C. Phase III

For phase III, the operations took place close to shore. Here the objective concerned mapping shallow vents in Faial/Pico channel, operating several vehicles simultaneously. Multibeam and side-scan sonars, as well as video cameras mounted on the AUVs from LSTS were used in these surveys. In addition, long range flights between the islands of Faial and Pico were performed to test low cost high-bandwidth communications.

IV. Selected results

A. AUV-UAV inter-operability

LSTS and NUWC performed several technical tasks with the goal of supporting AUV re-tasking from a Command and

Control (C2) node and data exfil from AUV to a C2 node: i) deploy SAE-JAUS open architecture Core Service Set to LSTS' Skywalker X8 UAV and NUWC's OceanServer Iver2 and C2 nodes using both MOOS and Dune frameworks; ii) use HF radio for bidirectional UAV-AUV and UAV-C2 afloat communication with Combined Force platforms and architectures; and, iii) extend Command and Control with cross-domain AUV/UAV systems. MOOS-IvP autonomy architecture was deployed alongside LSTS Dune by leveraging LSTS' Inter-Module Communication (IMC) protocol.

The following goals were demonstrated with one LSTS' X8 UAV and one NUWC's OceanServer Iver2: SAE-JAUS Vehicle Status messages were received at C2 node from UAV directly and from AUV via UAV relay, extending effective C2 range of AUV control station; environmental (thermocline) data exfiltration from AUV via UAV relay for display on AUV control station enabled by NUWC-developed SAE-JAUS Client Provider service; and, SAE-JAUS messages used to re-task AUV mission from AUV control station via UAV relay.

B. *Ecosystem mapping*

The primary goal of IMAR-DOP/LSTS/NTNU during this phase of the exercise, was to produce detailed underwater habitat maps for Pico island south shore, from 0 to 40 m. IMAR-DOP scientists were in charge of these missions. The detailed habitat maps included high resolution bathymetry and video to study depth, relief, substrate type and possibly dominant biotopes. Water column biological and physical parameters were concurrently acquired by the fleet of LAUVs, equipped with a suite of hi-tech acoustic, optical and imaging sensors, such as a holographic camera. UAVs fitted with hyperspectral cameras mapped the coast line and shallow areas down to 10 m, where it's not safe to operate AUVs. The hyperspectral high resolution miniature imaging spectrometer, Dronespec, owned by Norut and made available by Prof. Fred Sigernes at UNIS, was integrated into an NTNU X8 fixed wing UAV and the Neptus command/control system. The imager was used to detect chlorophyll-A and phytoplankton as well as other suspended matter. Chlorophyl-A concentration is closely linked to the primary production in the ocean while other suspended matter or algae concentration can be quantitatively determined given that inherent optical properties are known. Data from both aerial and underwater sensors is being integrated to produce habitat maps to support conservation and management decisions and the design of marine protected areas.

Fig 6. AUV operations between Faial and Pico islands.

C. *Cetacean tracking*

The main goal of IMAR-DOP/LSTS/NTNU for Phase II concerned the characterization of physical and biological oceanographic processes driving foraging behaviour of cetaceans. This experiment would assess feasibility of different imaging sensors mounted on UAVs and AUVs to detect pelagic predators and obtain biometric and bio-energetic data and to investigate couplings between surface and deep-ocean processes. The experiment built on experience on integrated monitoring of sunfish behaviour in space and time [9,10,11].

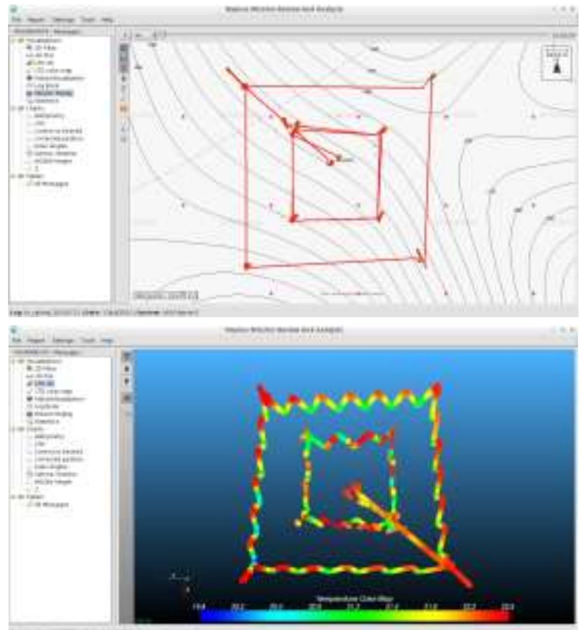

Fig 7. AUV surveys encircling one whale and corresponding CTD 3D plot.

The engineering components supporting tracking and characterization of the waves of cetaceans performed flawlessly. The problem was that the Azores front had moved north of the operations area, and so did the whales. Only one whale was spotted during the whole week at sea. In spite of this, engineering experiments were conducted both with that whale and with virtual whales to exercise the whole whale tracking and environmental sampling framework. Whale spotters on board NRP Gago Coutinho were on watch during the day. One whale was tagged with a radio transmitter allowing to track positions at the surface. UAVs were launched from NRP Gago Coutinho to search for whales and to conduct aerial imagery with IR and hyperspectral cameras. Multiple AUVs were also deployed from NRP Gago Coutinho to sample the area. This required a careful coordination of operations. The ship used Dynamic Positioning to align into the wind for air ops, while AUVs were being thrown overboard to start the surveys. The ship would have to manoeuvre in between UAV launches to re-align while other assets were in the water. A typical tracking operation would take several hours with AUVs at distances over 4 Km from the ship and multiple UAV launches. All of this was supported by the Neptus/IMC/Dune toolchain with the assistance of the new planning tool for mixed initiative interactions, Europtus [12]. Europtus not only tasked AUVs to perform CTD surveys, but also invoked the help of human operators under some pre-defined conditions. Europtus also interacted with the T-REX deliberative planning tool running on the AUVs for high level coordination. Netpus was used for situational awareness over a ship-based network offering a unified view to all operators on board. Iridium and underwater communications were used to interact with the AUVs at long distances. The poor quality of the communication links, especially the acoustic links, was compensated by the on-board T-REX deliberation capabilities.

Figure 7 presents results from one experiment where 2 AUVs were tasked to sample the environment where a whale was spotted. The 3D plots display CTD data taken by the 2 AUVs. Concurrently, two X8 UAVs from NTNU and LSTS were tasked to search for the whale.

D. Modulation schemes

CMRE tested new coded modulation schemes that could potentially extend the JANUS standard [16] towards including fast rate acoustic communications.

An equalizer receiver that copes with platform motion and multipath effects was tested in the Azores for the first time. Data was processed from two links: One with 500 m range, little motion (channel A) and another with 800 m range, motion of 2-3 knots (channel B). Channel A could support 2-PSK modulation at a rate of 4 kbps but not higher level modulation like 4-PSK/8-PSK). On the other hand, channel B could easily support 8-PSK at a rate of 12 kbps. From the results, we can firmly conclude that the choice of the transmitted scheme should be dictated by the channel multipath and Doppler fluctuations (assuming sufficient SNR). This work is the foundation for the development of a smart and adaptive policy engine for physical layer signalling tailored to the dynamics of the underwater channel.

CMRE conducted tests towards validation and evaluation of novel MAC solutions (ALOHA with carrier sensing [1] - ALOHA-CS). The idea is to have additional solutions to be employed in scenarios where the Time Division Multiple Access (TDMA) protocol, currently implemented and used within CMRE’s software stack, can result in low performance. ALOHA-CS is a simple solution which does not require any node synchronization and any knowledge about the rest of the network (number of nodes, distances among nodes, etc.). ALOHA-CS is fully distributed and it tends to be an aggressive solution. This can improve the network throughput and packet delivery ratio in configurations where the maximum propagation delay is much longer than the actual transmission delay. During the first part of the MAC experimentation, for all the considered scenarios and experiments, ALOHA-CS has obtained a normalized throughput similar (or higher) to the ones of TDMA. Although for both protocols the performance in terms of throughput is limited, we have to remember that the considered scenarios (small node count and short range due to the high frequency modems used) are much more fitting to TDMA than to the ALOHA-CS one. In a scenario with more nodes and a larger area, the offered load for TDMA has been much less in respect to ALOHA-CS with a capability to deliver bits to at least one other node in the network, being higher for ALOHA-CS.

E. Constellation adaptation for positioning of AUVs

Following the initial work developed and implemented in 2014 for autonomous constellation adaptation, CMRE tested the latest developments during REP15-Atlantic. The concept is that of having a surface constellation that autonomously adapts its geometry according to some optimization criteria driven by a cluster of AUVs operating in the area. The primary objective is to have a dynamic constellation of surface vehicles that can adapt its geometry in order to minimize the localization error (in an LBL setting) of the AUVs, maximize the communication opportunities or a mix of both

The main equipment used during the REP15 constellation optimization experiment is shown in Figure 3. This equipment constitutes the CMRE autonomous sensor network, which for the purpose of this specific experiment was set up to keep into account inputs from CMRE CASW project which deploys an ASW multi-static autonomous network.

The eFolaga AUVs, equipped with an additional module to accommodate either one Evologics acoustic modem or the Evologics USBL were used in this experiment. The surface nodes of the network were realized through Wave Gliders, as autonomous surface vehicles, and Gateway buoys. The Wave Glider's mobility was used to position it in favorable locations to improve the communication and localization with the rest of the assets. Finally, one Wave Rider buoy was also deployed to measure the wave height and period.

All the nodes of the network were acoustically connected creating an underwater acoustic network [13]. The physical layer of the network was realized using Evologics acoustic modems, working between 18 and 34 kHz. During the constellation optimization experiments two different Medium Access Control (MAC) protocols were used: the more traditional Time Division Multiple Access (TDMA) where different communication nodes share the same bandwidth and avoid conflicts transmitting at different times; and, the ALHOA MAC, where nodes probe the channel to verify its availability before transmitting.

All the nodes, when on surface, communicated via radio to the NRP Gago Coutinho, and had access to GPS for self-localization. When underwater, the eFolagas sent messages containing navigation data and information related to their operative state using acoustics. Throughout the experiment, the network-based long-baseline described in [13] and the clock-synchronization algorithm presented in [14] were also activated, creating additional messages circulating in the

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[1] The carrier sensing does not follow the traditional approach used for terrestrial networks where a node listens to the channel for some time before transmitting. Due to the long propagation delay of acoustic transmissions in water, listening to the channel before transmitting would not provide the required level of knowledge on the status of the channel. Therefore carrier sensing in this case is mainly checking if the acoustic modems is currently busy - transmitting/receiving - an acoustic message.

network. Finally, more messages were artificially created to emulate the network load typically present within the CMRE ASW network, where messages are produced to share information on detected contacts and/or tracks. All the assets were deployed from the NRP Gago Coutinho, which also acted as the Command and Control (C2) Centre during the experiments.

The constellation optimization experiment was successfully conducted in a variety of scenarios, with a number of different vehicles. LSTS LAUVs were integrated into CMRE's network, and a constellation composed of eFolagas, Wave Gliders, and Gateways was used as a supporting infrastructure, showing an increased level of flexibility and interoperability.

F. JANUS use cases

CMRE addressed and tested two uses cases of the JANUS protocol [15][16]: broadcast of situational awareness messages (a.k.a. underwater AIS) and first contact and language switching. These use cases draw significant benefits from employing a standard language that can be used in multi-national operations (military and non-military) where heterogeneous surface and underwater assets are employed. This can potentially reduce the probability of collisions between underwater and surface assets, since the submerged vehicles benefit from a surface situational picture.

V. Conclusions

REP15-Atlantic was focused on collaborative experimentation with multi-domain unmanned vehicles in real-life operational scenarios to advance interoperability, autonomy, underwater communications and networking capabilities. Deliberative planning techniques were used for the first time to support coordinated off-board planning and execution control of AUVs and UAVs.

The REP-Atlantic exercises allow a core group of participants to test, evaluate, and refine novel concepts of operation for networked vehicle systems [17]. Each edition builds on experience on collaborative work on lessons learned in previous editions to minimize risk and maximize the potential outcomes of each new edition.

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