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Experiments in multi-vehicle operations: the Rapid Environmental Picture Atlantic exercise 2014

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***Abstract*—The paper describes the Rapid Environmental Picture Atlantic exercise 2014 (REP14-Atlantic), with special focus on the experiments with autonomous underwater, surface and air vehicles, and discusses how large scale experimentation in operational environments is contributing to advancing the state of the art in networked vehicle systems. REP14-Atlantic was also focused on collaborative experimentation to advance interoperability, underwater communications and disruption/delay tolerant networking (DTN) capabilities, automation and cooperation of unmanned underwater, surface and aerial vehicles. In addition some of these vehicles had deliberative planning capabilities onboard for unprecedented levels of autonomy. Deliberative planning techniques were also used to support coordinated planning and execution control of multiple vehicles.**

I. Introduction

Field experimentation is an important phase of the unmanned vehicle systems life cycle. First, the unmanned vehicles field is relatively new, but it is evolving quite fast, especially in some categories. Second, the distribution of cost across acquisition, operation, and support categories differs significantly from that of manned vehicles, making it difficult to transfer procedures and techniques used for manned vehicles to the unmanned vehicles field. Third, new concepts of operation, namely those involving coordination and cooperation of unmanned vehicle systems are still being developed, ([4], [9], [18]), and this cannot be done without an appropriate integration and evaluation framework. For example, the economics of coordination and cooperation of unmanned vehicle systems is still poorly understood. Fourth, a significant percentage of commercially available unmanned vehicles are closed systems, thus precluding integration and experimentation with heterogeneous vehicles. Field experimentation is even more difficult with ocean going vehicles. This is because access to the ocean is very expensive and highly dependent on weather-sea conditions. Collaborative experimentation is part of the answer to this problem. Once ships and other support assets are at sea, concurrent experiments can be typically supported for several weeks. In addition, multiple assets from different institutions coming from different countries can be tested in an integrated fashion and on a scale that is not typically accessible to any institution working in isolation. This is the main motivation behind the Rapid Environmental Picture (REP) exercise jointly organized by the Portuguese Navy and Porto University, through the Laboratório de Sistemas e Tecnologias Subaquáticas (LSTS), since 2010.

The first edition of the REP experiment took place in 2010 off the coasts of Sesimbra and Sines in Portugal. The experiment included, in addition to the Portuguese Navy and LSTS, the following: Naval Undersea Warfare Center (Newport, USA), SeeByte (Edinburgh, United Kingdom), OceanScan MST (Porto, Portugal), OceanServer Technology (Fall River, Massachusetts) and YSI (Yellow Springs, Ohio). The experiment was targeted at assessing the endurance and performance of the Light Autonomous Underwater Vehicle (LAUV) Seacon (developed by LSTS), evaluating and testing the coordinated operation of multiple Autonomous Underwater Vehicles (AUVs) from the Portuguese Navy (Gavias from Teledyne Gavia), NUWC (Iver2 from OceanServer) and LSTS (Seacon), extending the communication range of autonomous vehicles with fixed and mobile gateways, validating remotely sensed data, and testing ship and shore launching and recovery of AUVs. The 2011, 2012 and 2013 editions of the REP experiment took place in the same operational areas with additional participants from Norway and Sweden. The scope of the exercise has been extended to other areas and the complexity of the experiments has been evolving towards operational use ([5], [14]).

The fifth edition of the Rapid Environmental Picture Atlantic (REP14-Atlantic) exercise took place in July 2014 at the Lisbon Naval Base and off the coasts of Sesimbra and Sines in Portugal. The exercise was jointly organized by the Portuguese Navy, the CMRE (NATO STO Centre For Maritime Research and Experimentation), and the University of Porto.

CMRE is NATO's maritime hub for research and development. CMRE conducts relevant, state-of-the-art scientific research in ocean science, modeling and simulation, acoustics and other disciplines. CMRE also provides Science & Technology enhancements to unmanned vehicles and vessels, integrated defence systems, and autonomous intelligent systems that better enable operators to complete missions in hostile environments. In the particular scope of REP14-Atlantic, CMRE was involved in two main fronts: Testing of Anti-Submarine concepts employing networked autonomous vehicles and development of underwater communications technologies including testing of candidate standard protocols.

The Laboratório de Sistemas e Tecnologias Subaquáticas (LSTS) at the Faculty of Engineering from Porto University has been designing, building and operating unmanned underwater, surface and air vehicle systems for innovative applications with strong societal impact since it was established in 1997. In 2006 the LSTS received the national BES Innovation National Award for the design of the Light AUV. The LSTS has been involved in fostering and growing a world-wide research network in the area of networked vehicle systems with yearly conferences and workshops, and, more recently, with large scale exercises at sea. The LSTS has been organizing, in cooperation with the Portuguese Navy, the Rapid Environmental Picture (REP) annual exercise since 2010. Researchers from LSTS also participated in experiments, organized and hosted by collaborators, and taking place in the Pacific and Atlantic oceans, as well as in the Mediterranean and Adriatic seas. Currently, the LSTS team has over 30 researchers, including faculty and students, with Electrical and Computer Engineering, Mechanical Engineering and Computer Science backgrounds.

The participation of the Portuguese Navy was coordinated by the Naval Command. The Navy Clearance Diving Detachment - Mine Warfare (DMS3 MW) was in charge of field coordination, in addition to the operation of the autonomous underwater vehicles from the Portuguese Navy. The Portuguese Navy Clearance Diving Detachment - Mine Warfare (DMS3 MW) was created on June 12, 2008, by the Admiral Chief of the Portuguese Navy, to develop a new and modern Mine Warfare Capability in the Portuguese Navy. The DMS3 MW is dedicated to the search, location, classification, identification and neutralization of conventional submarine explosive ordnance devices, more commonly referred as mines, and for deep diving tasks, to a maximum depth of 81m. As a secondary role, can also be used in other EOD tasks in underwater environment, whether conventional or improvised, as well as other missions, like Search and Rescue (SAR) missions, when needed. To execute the assigned duties of mine counter measures (MCM), several equipments are normally used including search and survey equipments like ROV (Remote Operated Vehicle) and AUV (Autonomous Underwater Vehicles), for detection, location, classification and identification of explosive devices. DMS 3 operates two Gavia-Teledyne AUVs and three LAUV Seacon class AUVs, which were delivered by LSTS ([16]).

The participants in the REP14 Atlantic exercise also included, in addition to the organizers, the Royal Institute of Technology (SE), the University of Rome (Italy), the German Defence Research and Testing Agency (Germany), and the companies Evologics (Germany) and Oceanscan Marine Systems and Technologies (Portugal). There was an observer from the Navy Undersea Warfare Center (United States of America).

The paper is organized as follows. An overview of the exercise is presented in section II. The experiments are described in section III and the conclusions are drawn in section IV.

II. Exercise overview

A. Ships

The exercise involved three Navio da República Portuguesa (NRP) ships from the Portuguese Navy and one NATO research vessel.

NRP Arpão - Portuguese Navy The NRP Arpão was built in the shipyards of HDW (Kiel, Germany), the second of the two submarines of the Trident class. Since its rise to effective, in 22 December 2010, it has performed surveillance missions maritime area of national interest, participated in national and NATO exercises and incorporated in 2012, the Standing NATO Maritime Group 2, under which participated in operation “Active Endeavour”, taking place in the Mediterranean Sea under the aegis of NATO with the main objective of fighting against terrorism.

NRP Pegaso - Portuguese Navy This rapid surveillance speedboat is targeted at operations in the maritime areas under national jurisdiction in continental Portugal and Madeira. It is specially focused on patrol and surveillance of the waters under national jurisdiction with the highest traffic density of the Portuguese territorial sea. The vessel is equipped with a rigid hull inflatable boat.

NRP Auriga - Portuguese Navy NRP Auriga was developed and built in the Arsenal Alfeite, Base Naval Lisboa. This ship was specially built and equipped to perform hydrographic or oceanographic work. It has several scientific and technical capacity to meet the research and development activities. Usually performs scientific missions in support of military operations and the scientific community in national and international waters.

NRV Alliance - CMRE The NATO Research Vessel (NRV) Alliance is a specially designed vessel, built for the purpose of conducting underwater research and experimentation. The NRV Alliance is 93 meters long, offers 400 square meters of enclosed lab space and accommodates up to 25 scientists and engineers plus crew. The vessel is comprehensively equipped with a suite of deck handling ‘A’ frames, multi-purpose winches, cranes and workboats as well as with extensive laboratory and working deck space. During REP14-Atlantic the Alliance hosted scientists, engineers and operators from CMRE, FEUP, PRT Navy, WTD71 (Germany), Evologics (Germany) and University of Rome - La Sapienza and was the operational base for the autonomous assets.

B. Unmanned vehicles

The REP14-Atlantic exercise included several Autonomous Surface Vessels (2 Wave Gliders from CMRE), Autonomous Underwater Vehicles (2 OEX and 6 Folaga from CMRE, 2 Gavias and 2 LAUV Seacons from the Portuguese Navy, and 6 LAUV from Porto University) and Unmanned Aerial Vehicles (4 X8 based unmanned air vehicles from Porto University) equipped with different sensors and acoustic communication payloads in additional to buoys and moorings equipped with acoustic modem and environmental sensors. These systems were deployed from Portuguese Navy ships NRP Pegaso, NRP Auriga, and NRP Arpão and from the NATO Research Vessel Alliance. The vehicle systems from the Portuguese Navy and LSTS were deployed with the help of the Neptus-Dune-IMC

Fig. 1. NRP Arpão and NRV ALLIANCE

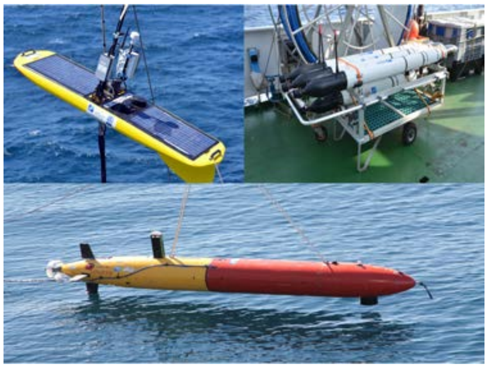

Fig. 2. CMRE Wave Glider, Folaga and Ocean Explorer

Fig. 3. Portuguese Navy LAUV Seacon

software tool chain developed by LSTS ([13], [15], [20]). 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. The IMC communications protocol allows IMC compliant vehicles and control station to interact in this networked environment. The software tool chain allows the integration of other vehicle systems. This was demonstrated at sea with the CMRE vehicles.

C. Operational areas

The fifth edition of the Rapid Environmental Picture Atlantic (REP14-Atlantic) exercise took place in July 2014 at the Lisbon Naval Base and off the coasts of Sesimbra and Sines in Portugal.

The Lisbon Naval Base is located in the Lisbon Harbor in Tejo River Estuary. This estuary is characterized by strong tidal currents, mainly in the narrow segments near the mouth, where currents can top 4 knots. The bottom type is mainly mud and sand, which contributes largely to reduce the underwater visibility during the low tides, due to the suspended particles. In the high tide the visibility can go up to 4 meters, in the calmest parts of the river. The predominant winds are from the

Fig. 4. LSTS LAUV Noptilus

Fig. 5. LSTS X8-based UAS

Fig. 6. South Area of REP-14 Atlantic

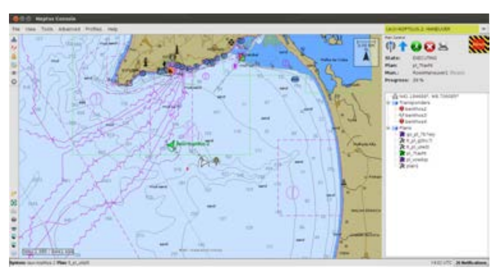

Fig. 7. LSTS Neptus command and control framework environment

North and West sectors. The bathymetry varies along Lisbon Harbor. In the river mouth and around Lisbon the river can go deeper than 30 m, but it will reduce to medium of 7 meters in the central section, which is the largest part.

Sesimbra is a small old fisherman's village in Sesimbra Bay, located in the south part of the Arrábida Natural Park, a few miles west of the Sado River mouth. This area is protected from the northern wind by the Arrábida hills, resulting in calm and clear waters almost all year. The bottom is mainly sand and gravel, with rocks near the coastline. The bottom currents, although low, are normally from west, and the bathymetry slope is around 5%, reaching the 100 meters mark in one mile from the coast line.

The South operational area for REP14-Atlantic was chosen with particular consideration given to expectable sea state and wind conditions for that period of the year. Attention was also paid to the vicinity to Lisbon the existing Portuguese Navy exercise areas, the presence of fishing and leisure boats and keeping an acceptable distance to submarine canyons and/or deep water where beaked whales forage. The area was selected to provide a relatively flat bottom between 40-200 meters depth to allow AUV navigation with bottom-lock Doppler Velocity Log. The selected area is depicted as a bright yellow square in Fig 6.

D. Goals

The REP14-Atlantic exercise is targeted at the operational evaluation and testing of heterogeneous multi-vehicle systems for maritime operations. Invited participants contribute with vehicle systems, sensors, and communication technologies for at sea experimentation of advances in networked vehicle systems and associated concepts of operation.

REP14-Atlantic concerned 6 operational vignettes: harbor protection, mine-countermeasures, anti-submarine warfare, rapid environmental assessment, search and rescue, and law enforcement. Harbor protection and mine-countermeasure experiments took place at the Lisbon Naval base, at the Tejo estuary and at sea, south of Sesimbra.

The LSTS and the Portuguese Navy focused on harbor protection, mine-countermeasures, rapid environmental assessment, search and rescue, and law enforcement. The experiments were targeted at demonstrating the operational use of multiple LAUV autonomous underwater submarines equipped with state-of-the-art side-scan sonars, video cameras and multibeam sonars in harbor and challenging estuarine environments under tight tidal constraints. The operational use of LAUV Seacon class autonomous underwater vehicles in combination with Tridente class Submarines was tested at sea by the Portuguese Navy and Porto University. Unmanned air vehicles and autonomous underwater vehicles were deployed from NRP Pegaso and NRP Auriga to demonstrate how unmanned vehicle systems can extend the capabilities of Navy vessels by providing not only sensor coverage for wider areas but also "bent" line-of-sight communications.

CMRE had two areas of focus: the first one dedicated to anti-submarine warfare (ASW) using autonomous sensor platforms, and the second devoted to acoustic underwater communications (ACOMMS). CMRE scientists on board the NATO Research Vessel Alliance tested collaborative autonomous behaviours of underwater vehicles for ASW applications, while also testing the performance of network-based solutions for vehicle localization and navigation. For underwater acoustic communications, CMRE scientists experimented networking and equipment capabilities, including Wave Gliders being used as autonomous gateways. The exercise included an assessment of the capabilities of JANUS, an underwater digital communication protocol, developed at CMRE, which is in the process of becoming a NATO standard and is currently being promoted in the maritime industry.

III. Field experiments and lessons learned

Highlights from the field experiments and associated lessons learned are presented below.

A. Integrated operations of air and ocean vehicles

LSTS and the Portuguese Navy focused on the integrated operations of air and ocean vehicles for maritime applications. This was demonstrated with the help of the vehicles from LSTS and from the Portuguese Navy, as well as the LSTS based control stations, and Manta gateways [1] to bridge air and underwater communication networks ([8]), while providing communications support for these networks. All of these assets were supported by the LSTS Neptus-Dune-IMC software tool chain. The AUVs run a full-fledged Dune implementation of the LSTS control architecture ([18], [20]) on the on-board primary computer. The X8-based UAS ([10], [11], [17]), developed at LSTS, implements the high levels of the LSTS architecture on a small form-factor computer board which interfaces with the Ardupilot auto-pilot. The X8-based UAS is capable of sending high-resolution video stream to a ground station equipped with a directional antenna. Maximum flight time is 1h. The networked operational environment allows Neptus trained operators to command and control multiple air and ocean vehicles in an mixed initiative environment ([6], [12]) from Neptus-enabled control stations 7. The LSTS AUVs had on-board planning capabilities. This was done with the help of a secondary computer running the deliberative planner TREX ([19]) that enables higher levels of autonomy and requires minimal operator's attention. These capabilities were put to test during a 24 uninterrupted run by one of the LSTS AUVs, which took place in Sesimbra. The same operational setup was first tested during night operations at the Lisbon Naval Base.

LSTS also run preliminary tests with the Networked Vehicles Language (NVL) [7]. NVL is fully integrated with the LSTS software tool chain to support programming of multiple vehicles. One single multi-vehicle NVL program is projected onto programs for each vehicle in the network. The NVL programming logic borrows concepts from parallel computing to allocate tasks to vehicles and to coordinate the concurrent execution of atomic or complex tasks (involving more than one vehicle). Execution steps through phases, at

[1]The Manta Gateway is a portable centralized communication hub supporting several types of wireless and acoustic networks. The system is capable of transparently route data between heterogeneous network links, balancing bandwidth and range. Additionally the device is capable of providing information about the localization of underwater vehicles and narrow band acoustic transponders.

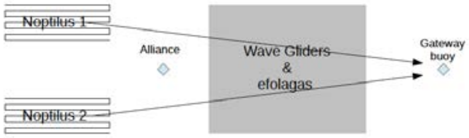

Fig. 8. Routing configuration

the end of which vehicles communicate and engage in tasks. NVL is extremely powerful because it allows one programmer to specify complex patters of coordination for multi-vehicle systems. The experimental runs showed that more advanced visualization concepts are needed to represent in an intuitive manner an execution of an NVL program.

The launch and recovery of an AUV from a manned submarine was done with the help of divers from the Portuguese Navy. In this concept of operation the AUV surfaces, after being deployed from the submarine, to get a GPS fix. The concept is simple, effective, and is a first step towards automated operations. Full automation requires tighter integration with the submarine systems.

B. Unmanned air vehicle control of a submerged underwater vehicle

CRME, LSTS and the Portuguese Navy demonstrated, for the first time, the use of an unmanned air vehicle controlling a submerged AUV with the help of a communications gateway (bridging WiFi and underwater acoustic communications) mounted on a Wave Glider. The unmanned air vehicles controlled the autonomous underwater vehicle with waypoint commands while receiving sensor data coming from the submerged AUV in real-time. These capabilities open new avenues for coordinated air-ocean operations.

C. Routing

CMRE, in collaboration with the University of Rome - La Sapienza conducted tests of a jointly developed underwater routing protocol [1]. The Routing testing was very successful and the algorithm proved to be mature for use and well adapted for the network scales used by CMRE. The testing scenario is shown in Fig 8 and involved a total of 8 assets: The 2 LAUV Noptilus (acting as data sources, issuing new packets every 40 seconds with destination Gateway Buoy); The Alliance, Wave Gliders and Folagas all available as relays for the algorithm; The Gateway buoy as the sink of information. We tested the MPR implementation against a baseline Flooding algorithm. Some initial results are condensed in Table I. Even if those results don't capture the differences in conditions of the acoustic channel between the Flooding and MPR tests, the benefits of MPR are clearly shown: at the cost of a slight decrease of Packet Delivery Ratio (PDR), MPR offers better energy performance by using on average less hops to route the message and incurring much less duplication of messages. This makes MPR a very fitting solution for scenarios where telemetry messages must reach a destination efficiently, travelling through a multi-hop network.

TABLE I. ROUTING RESULTS

Protocol	PDR%	Average Hops	Max. Hops	Average Duplicates
Flooding	74	2.72	5	1.1
MPR	65	2.02	4	0

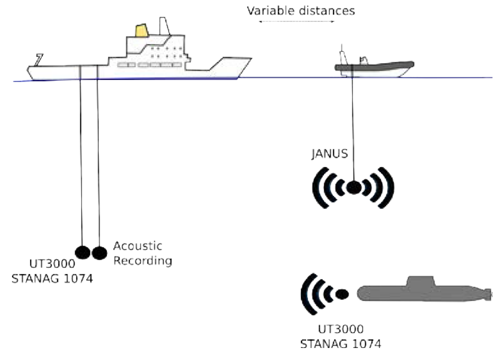

Fig. 9. JANUS experiment

D. JANUS

During REP14-Atlantic, a series of experiments were conducted with the goal of testing the JANUS protocol [2]. The objectives were, on one hand, to test and tune protocol parameters and on the other assessing the potential impact of JANUS when overlapping analog underwater telephone transmissions. The general setup of the JANUS experiments is depicted in Fig 9. All Underwater Telephone transmissions were triggered from the Portuguese Navy submarine NRP Arpão with pre-recorded sequences injected directly into the equipment. This allowed us to control the experiment at the transmission side. To do so, in the weeks preceding the experiments we asked 2 Navy Officers to speak to a recorder as if they were speaking on an underwater telephone equipment. We recorded the phonetic codes "alpha" to "zulu" and standardized list of rhyme words. The recorded sound files were then segmented and rearranged into randomly generated test sequences exported into 2 hour files and uploaded into a player that was later connected to the underwater telephone equipment of the NRP Arpão.

The JANUS experimentation was divided in:

- Interference tests with the Underwater Telephone using pre-recorded 3-letter code sequences: "The Message is" + "<word 1>" + "<word 2>" + "<word 3>";
- Interference tests with the Underwater Telephone using pre-recorded rhyme words: "The Word is" + "<rhyme word>";
- Back to back analog and digital transmissions without interference;
- MAC tests to tune protocol parameters.

The JANUS interfering signal was of varying intensity to provide a diverse data set. Also the repetition interval of the interfering signal was twice the repetition interval of the transmissions from the NRP Arpão so we could collect data with and without JANUS interference. The data sets collected are currently being processed and will be analyzed via objective and subjective testing. The subjective testing will be performed by operators from the Navies to which we will ask for support in filling in a questionnaire while listening to the recorded sequences. This will allow us to assess the impact that different levels of signal-to-noise-to-interference have on the ability of an operator to decode the vocal message arriving at the underwater telephone. The objective testing will initially be done by running the recorded sounds through the PESQ algorithms. PESQ, (Perceptual Evaluation of Speech Quality) is a family of standards comprising a test methodology for automated assessment of the speech quality as experienced by a user of a telephony system. It is standardised as ITU-T recommendation P.862 (02/01). Today, PESQ is an industry standard, applied worldwide for objective voice quality testing used by phone manufacturers, network equipment vendors and telecom operators. PESQ was not designed to cope with the typical distortions introduced by an underwater communications channel, so at a first instance it's output will not be regarded as of very high confidence. A by-product of this side-by-side analysis with objective and subjective testing will be how fitting is PESQ to analyze speech signals corrupted by an underwater channel in the operating frequencies of the Underwater Telephone. The results are currently being processed but the first empirical indication gathered during the trial and by a first non-structured analysis is that no significant impact on intelligibility is observed. This has mainly to do with the partial overlap in frequency bands and the fact that (some) operators tend to use no more than 1 kHz of band in their speech.

E. Waveglider Autonomy and dynamic constellation placement

The addition of autonomy onboard the Wave Glider was a major step forward for CMRE. Not only it is now possible to explore approaches that use the Wave Glider in autonomous mode but also it open the door for a different operational concept, relying only on local communications (rather than requiring an iridium link).

The dynamic constellation adaptation experiments, reported in [3] consisted in exploring the concept of having a constellation of LBL beacons that can dynamically re-position themselves in order to enhance the localization of one or more underwater vehicles (performing a survey or other task that requires an LBL service for navigation aid) . For this purpose, 2 wave gliders and one static buoy were employed as the beacon constellation while one Folaga AUV was used as the survey vehicle. First results show an effective operation of the algorithms in driving the network nodes to positions where the localization uncertainty of the survey vehicle could be minimized. This initial result will open the door for more collaborative deployments and future extensions of the concept to evolve towards multi-objective optimization including also communication quality and vehicle energy.

IV. Conclusion

Collaborative field experimentation is key to the development of networked vehicle systems and associated concepts of operation. It also contributes to bridge the gap between development and operational use. This is the main motivation behind the Rapid Environmental Picture (REP) exercise which had its first edition in 2010. The fifth edition of the Rapid Environmental Picture Atlantic (REP14-Atlantic), jointly organized by the Portuguese Navy, the CMRE, and the University of Porto was described with special focus on the experiments with autonomous underwater, surface and air vehicles. The experiments were targeted at inter-operability, underwater communications and disruption/delay tolerant networking (DTN) capabilities, on-board deliberation, automation and cooperation of unmanned underwater, surface and aerial vehicles. Lessons learned towards operational use and future trends are already impacting the development of concepts of operation by the Portuguese Navy.

The sixth edition of the Rapid Environmental Picture Atlantic experiment will take place during July 2015 off the Açores Islands. The exercise will be targeted at experimentation in near shore and off shore environments with deployments from several islands. Support will be provided by the NRP Gago Coutinho, an oceanographic vessel from the Portuguese Navy.

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Title

Experiments in multi-vehicle operations: the Rapid Environmental Picture Atlantic exercise 2014

Abstract

The paper describes the Rapid Environmental Picture Atlantic exercise 2014 (REP14-Atlantic), with special focus on the experiments with autonomous underwater, surface and air vehicles, and discusses how large scale experimentation in operational environments is contributing to advancing the state of the art in networked vehicle systems. REP14-Atlantic was also focused on collaborative experimentation to advance interoperability, underwater communications and disruption/delay tolerant networking (DTN) capabilities, automation and cooperation of unmanned underwater, surface and aerial vehicles. In addition some of these vehicles had deliberative planning capabilities on board for unprecedented levels of autonomy. Deliberative planning techniques were also used to support coordinated planning and execution control of multiple vehicles.

Keywords

Vehicles, underwater vehicles, testing, oceans, protocols, logic gates

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