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Autonomous networked anti-submarine warfare research and development at CMRE

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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.

Autonomous networked anti-submarine warfare research and development at CMRE

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***Abstract*—CMRE has been evaluating the potential of autonomous networked ASW using underwater vehicles through a program of sonar signal processing, underwater communications, navigation and robotic behavior developments and at-sea decision support tested through an ambitious seagoing experimental program and demonstrated during NATO ASW exercises. In this paper the various scientific aspects of the program are briefly outlined and some recent experimental results are shown.**

***Keywords*—ASW, robotic, autonomy, sensor networks, tracking, classification, data fusion, sonar, multistatic, UUV, AUV, DLCT**

I. Introduction

Anti-submarine warfare has the challenge to provide effective, flexible and affordable capability for force protection, area clearance and for holding hostile submarines at risk. Robotic solutions for these missions offer the potential to maintain or improve coverage and performance at a fraction of the price of traditional solutions. However, many fundamental problems in ASW including improving onboard detection, localization, classification and tracking (DLCT), as well as developing methods to apply machine intelligence to lower level adaptive track planning, higher level mission planning, and collaborative planning need to be solved before autonomous networks for ASW can become reality. The major hurdles to be cleared for making collaborative autonomous ASW possible include designing effective DLCT that allow robotic sensors to be robust to clutter and noise, enabling underwater communications in order for robotic networks to share information, and adding on-line decision support to help guide robotic ASW strategies. In addition to these scientific problems, there also remain significant ocean engineering challenges including launch and recovery in high sea states and improved energy capacity that need to be solved so that robotic networks are able to reach their full potential through operational agility and persistence.

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II. Approach

The Cooperative ASW programme at CMRE has thrusts in real-time embedded signal processing, including wide-band continuous active sonar waveforms with on-board classification, tracking, and data fusion; underwater navigation, underwater communications, local and network level robotic control, and at sea decision support. The objective is to develop a robotic capability for ASW networks based on relatively inexpensive and scalable underwater and surface vehicles that offers good performance by compensating for potentially lower individual sensor and platform performance through a combination of larger numbers, data fusion, and onboard machine intelligence for ASW.

The scientific areas of inquiry currently being actively pursued in the Cooperative ASW programme include:

A. Broad-band continuous active multistatic sonar

The use of wider bandwidths for improved classification combined with continuous waveforms that offer more detection opportunities per unit of time is being explored at CMRE. A new embedded beamformer and sub-band matched filter has been developed for these special types of waveforms that is capable of running on CMRE's underwater vehicles [1]. Experiments dedicated to evaluating the performance of these new types of waveforms are planned for 2015 and beyond, and a Littoral Continuous Active Sonar multination joint research project is being formed by interested nations.

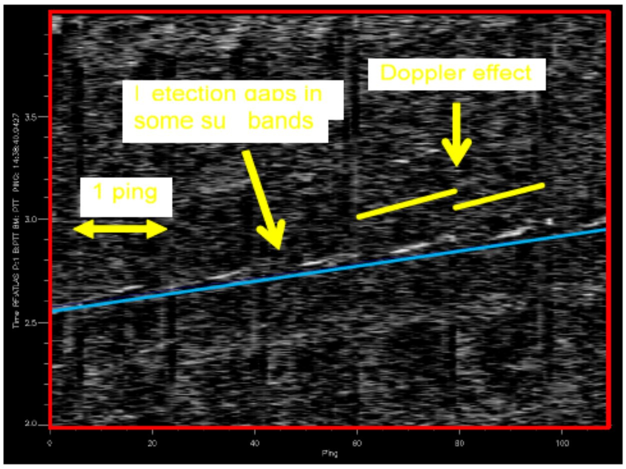

Fig. 1. Continuous active sonar detections of a vertical air-hose target measured during COLLAB-NGAS14.

In Fig. 1 we show subband detections of an air-filled target collected using a wide-band CAS waveform during COLLAB-NGAS14. 5 ½ consecutive pings are shown, with detections in each of 19 subbands (50% overlap) for each ping. Notice that detections are not obtained in each subband. However, the effective pulse repetition interval is much shorter for a CAS waveform than for an equivalent pulse active sonar, giving a much more rapid refresh rate leading it is hoped to more effective tracker performance.

B. *Onboard classification*

Contact and track-level classification has been extensively developed in recent years at CMRE. Effective classification is extremely important for controlling the false alarm rate of robotic sensors as the detection threshold is lowered. Robots rely on effective sensor performance in order to make reasonable and more optimal decisions, for this reason effective false alarm and non-target track rejection is a critical element of the CMRE ASW program.

In Fig. 2 the ability of an on-board track classification algorithm to classify echo repeater (E/R) tracks from the GLINT-NGAS11 experiment as target-like is shown. The green tracks generated by the AUVs for all contacts are shown, along with blue and yellow contacts associated to these tracks that have been classified by a Hidden Markov Model as belonging to the non-target class (blue) and the target class (yellow) [2]. Contacts that fall into neither category (remaining unclassified) are not shown.

C. *Multistatic tracking*

The ability to form effective tracks from intermittent detections of targets in high clutter environments is extremely important for all active ASW platforms. For collaborating autonomous vehicles, the importance is even higher as effective tracks make it possible for robots to evaluate the utility of future actions. CMRE has been actively involved in pushing forward the development of multistatic trackers.

In Fig. 3 the ability of a track to be formed by two cooperating AUVs in a high clutter environment is illustrated.

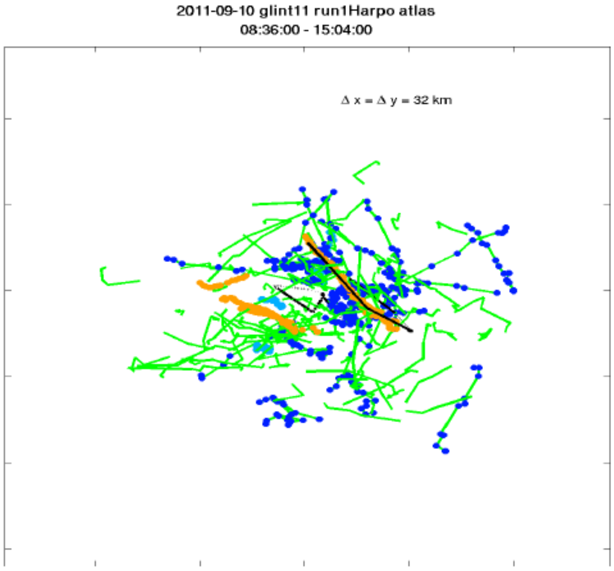

Fig. 2. Track level classification identifies tracks (yellow) associated only with the E/R. All other tracks are clutter-related tracks. Data collected during GLINT-NGAS11.

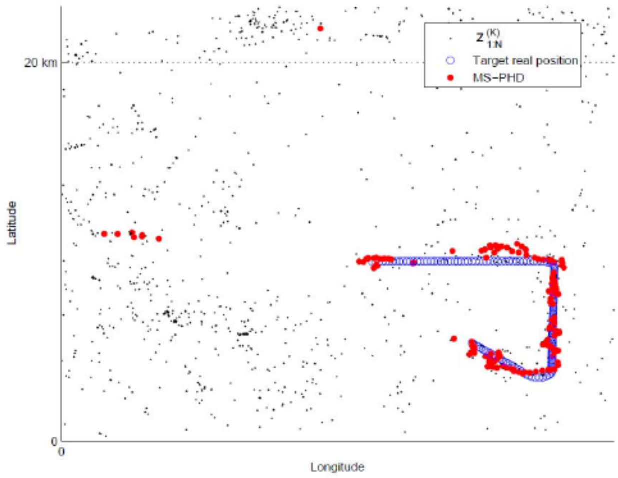

Fig. 3. Mode of multistatic particle hypothesis density filter (PHD) (red dots) obtained by combining E/R detections (black dots) from two AUVs during POMA12.

A multi-static probability hypothesis density particle filter has combined all the contacts shown by the small black dots into a probability surface whose mode is illustrated by the large red dots [3]. The fusion of information from two sensors allowed the rejection of incorrect port/starboard hypotheses for contacts generated by the vehicles sensors.

D. *Data fusion*

The affordability and therefore ubiquity of robot sensors makes possible significant data fusion gains from multiple observations. Data fusion also allows a required level of network detection and tracking performance to be obtained with less effective sensors as numbers are increased, allowing an optimum sensor-platform number tradeoff to be achieved.

The ability of data fusion to remove errors at the single-sensor level is shown in Fig. 4. During POMA13 two AUVs were deployed to track an E/R deployed from the NRV Alliance. One AUV sailed north-south while the second sailed east-west. Each AUVs on-board tracker generated two sets of tracks: one consistent with the actual location of the E/R and a second ambiguous track. Track to track fusion allowed the ambiguous tracks to be rejected [4].

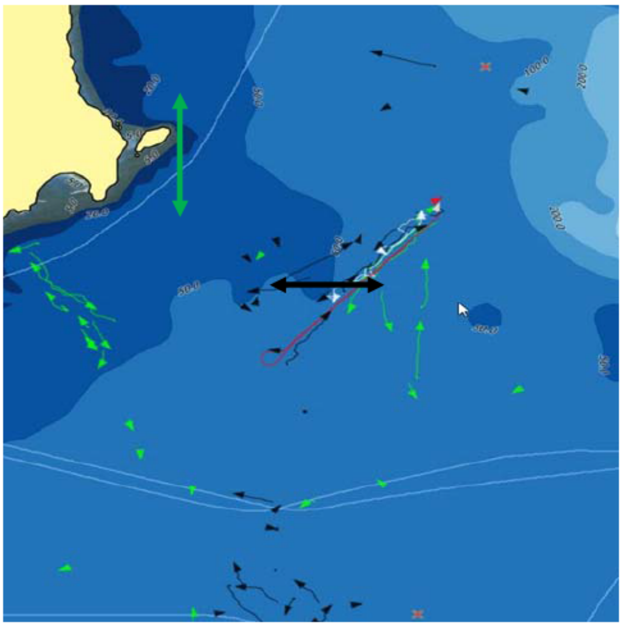

Fig. 4. Track-to-track fusion from POMA13 eliminates ambiguous and inconsistent tracks (green and black) generated by two AUVs and generating a single track (white) near known E/R trajectory (red). Grey tracks are AIS of passing ships.

E. Underwater communications

The ability of underwater sensors to collaborate, report, and fuse their findings relies on effective underwater communications networks. Within the Communications and Networking project a significant emphasis has been placed of the study of underwater communications network architecture and on standardization efforts to allow interoperability.

In Fig. 5 a block diagram for the Cooperative ASW programme's communications stack concept [5] for software-defined underwater communications is shown. As opposed to the standard serial OSI stack paradigm, CMRE's software defined open architecture modem (SDOAM) architecture is characterized by an inter-process communications (IPC) bus that allows access to cross-layer information necessary to inform policy decisions at each level. The architecture is also characterized by the concept of communications-enabled services such as network security management and navigation.

In order for underwater communications networks to be established, a first discovery protocol is required. CMRE has been developing the JANUS standard to make this possible [6]. The JANUS standard is based around a simple and robust FSK modulation scheme that offers good performance even in low SNR environments. The standard has been submitted to the NATO Standardization Office with the objective to make JANUS a NATO STANAG. The spectrogram of the JANUS communications protocol is illustrated in Fig. 6.

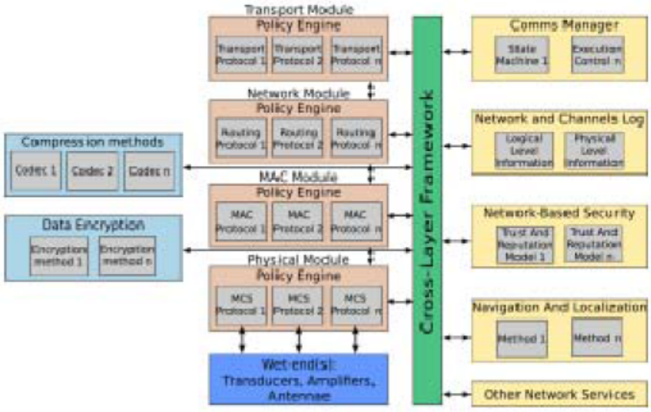

Fig. 5. Software-defined open architecture modem concept developed within the CASW Programme.

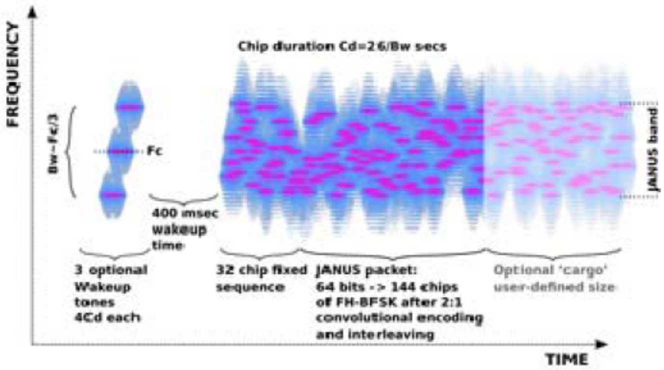

Fig. 6. Spectrogram of the JANUS underwater communications standard.

F. Underwater navigation

Underwater communications networks can provide localization services. In the past year CMRE has dedicated a significant effort towards allowing vehicle networks to self-navigate with a constellation of GPS enabled unmanned surface vehicles and gateway buoys [7].

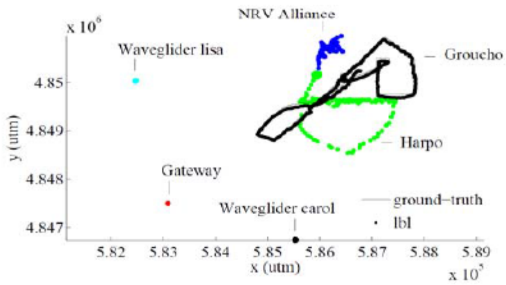

Fig. 7. Navigation of an AUV Groucho (thick black curve) using arrival times from surface gateways and Gound truth is shown by the black line.

In Fig. 7 the navigation of an AUV using inter-modem arrival times from nearby gateways (with GPS navigation) and collaborating underwater vehicles is shown. This type of long-baseline underwater navigation, also known colloquially as underwater GPS, is a critical enabling capability for underwater networks operating in absence of bottom-lock Doppler velocity logs and/or inertial navigation system.

G. Local and network level robotic control

CMRE has worked to define and implement several complementary paradigms for underwater vehicle control at the local and network level. The two approaches currently under active research are a cooperative Bayesian search behavior which is integrated with a probability hypothesis density (PHD) tracking filter and a Bernoulli target state estimator, and a collaborative non-myopic track covariance optimization controller for the vehicle trajectories.

In Fig. 8 the relative trajectories taken by collaborating AUVs tasked with minimizing the probability of a missed detection over a specified area is shown when those vehicles are combining detections to create a PHD of target presence over the area to be cleared. A Bernoulli Random Finite Set filter to estimate the target state and the probability of that target existing is run in conjunction with the PHD [8]. The blue symbols show vehicle trajectories optimized over 15 future pulse repetition intervals (PRIs) while the red symbols show vehicles trajectories optimized for the next ping only (essentially a Greedy optimization).

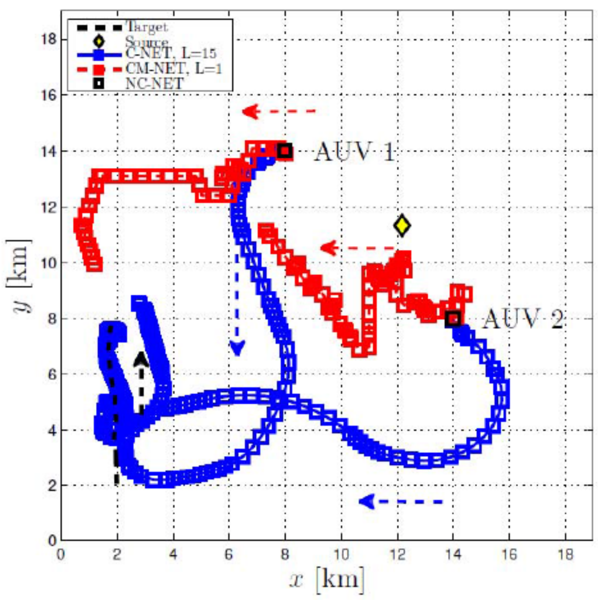

Fig. 8. Simulation of AUV trajectories when collectively minimizing the probability of missing a target detection based on observations and a P_D model Results obtained when planning 15 steps into the future are shown by the blue squares, while the results obtained when utilizing a Greedy approach are shown by the red squares. The Bernoulli RFS filter estimate of the known target position and probability was much superior for the non-Greedy path planner.

The vehicles that chose trajectories based on performance optimization over 15 PRI had a correct estimate of the probability of target presence (1.0, sailing north at the position [2.0, 2.0] km) much sooner than the vehicles performing the Greedy optimization.

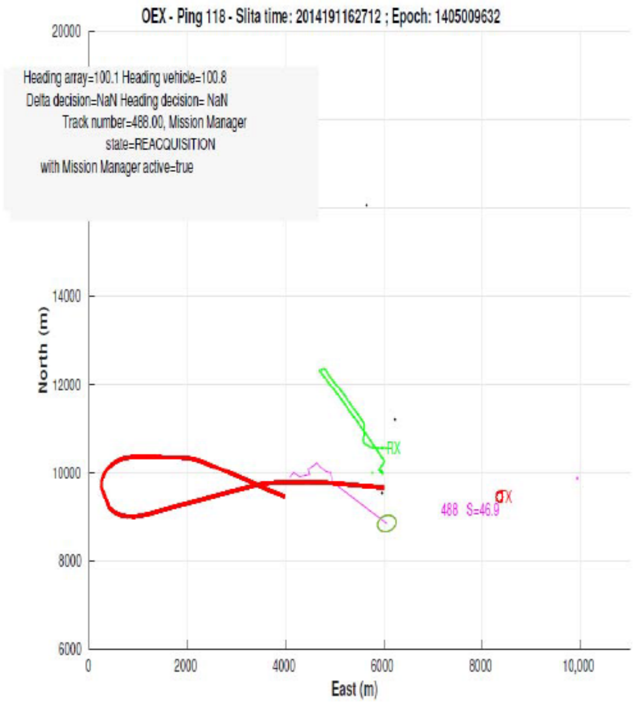

Fig. 9. Track covariance minimization trajectory of AUV (green) optimizing on E/R track (magenta) during COLLAB13. Red TX is source location..

A second method for optimizing vehicle trajectories has been developed based on minimizing the trace of the error covariance of the tracker running onboard the vehicles. Previous work has been based on either minimizing the localization error at the contact level or maximizing the SNR calculated using the bistatic sonar equations. The new approach is extensible to fusing contacts from cooperating vehicles and minimizes the resulting error of the fused track solution [9]. Results from the COLLAB13 experiment are shown in Fig. 9 where the vehicle is modifying its trajectory (shown in green) to optimize performance on the track generated on E/R contacts (shown in magenta). The actual trajectory of the E/R is shown in red.

H. Decision Support

The ability of robotic networks to make decisions at a track optimization level or in the Bayesian PHD construct described in the last section is currently only possible with an on-line decision support element. In the PHD context, the decision support element provides a probability of detection P_D that is used to accept or reject contact-level detections. In the track error optimization, the contact level covariance that is fed to the tracker and yields the track error covariance is also obtained using a model for the measurement SNR. These models are developed within the Decision Support project.

Another important element of the decision support project is real-time feedback to operators during NATO ASW exercises and to scientists working with autonomous networks. In Fig. 10 an example of a real-time performance prediction generated during the COLLAB-NGAS14 sea trial is shown. Real-time positions of the AUVs has been provided to the Multistatic Tactical Planning Aid (MSTPA) decision support tool through a connection to the robotic C2, allowing real-time estimation of detection performance to help guide understanding of detection performance observed by the ASW network and to shape command decisions to be sent to the robots in cases where fully autonomous behaviours are not activated.

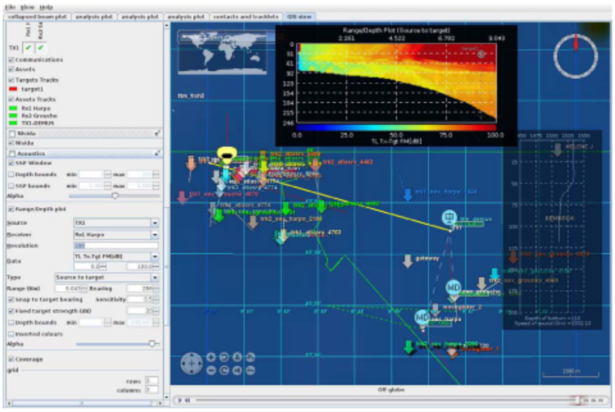

Fig. 10. Real -time decision support display during COLLAB–NGAS14.

III. Seagoing Experimentation and NATO Exercise Participation

The research areas outlined above are developed and validated through an extensive seagoing programme. An example for each area was given above in the context of the experiment in which the work was done. Below we enumerate the most recent experiments and exercises and briefly highlight the breakthroughs or novel aspects of each activity.

The autonomous ASW component of the Cooperative ASW programme typically goes to sea on the NRV Alliance more than one month a year, usually in one experiment with a partner nation providing a submarine target and a second activity with CMRE participating as part of a NATO ASW exercise. In both cases, extensive scientific data sets are collected to test the performance of the algorithms deployed onto CMRE underwater and surface vehicle network before the activities with submarine targets are initiated. In this way autonomous underwater vehicle networks for ASW are scientifically tested back-to-back with operational demonstration in relevant environments.

A. *GLINT-NGAS11 (multinational experimentation)*

This trial with the Italian Navy brought together members of the Next Generation Autonomous Systems (NGAS) JRP with the CASW programme to perform joint at-sea experimentation with AUVs and bottom sensors for the first time.

The NGAS JRP is directed to evaluating the feasibility of passive detection using autonomous (stand-alone) bottom sensors networked together with the Seaweb underwater communications network.

B. *POMA12 (NATO ASW exercise)*

Proud Manta 2012 was CMRE's first participation to a NATO ASW exercise with its autonomous AUV network and as such represents a milestone for the cooperative ASW programme.

C. *POMA13 (NATO ASW exercise)*

Proud Manta 2013 was the first exercise where CMRE's AUVs were deployed as part of an intensive ASW freeplay serial and the first time that CMRE's at sea network was connected in real time to a classified reach-back facility.

D. *COLLAB13 (national experimentation)*

The COLLAB13 experiment was the second CASW experiment conducted with the Italian Navy. It was also the second experiment after GLINT-NGAS11 conducted in a summer profile environment with significant bottom interaction. It was the first ASW experiment where the AUVs exploited depth separation for waterspace management (WSM) and where significant experimentation with collaborative adaptive behaviours was performed.

E. *DMON14(NATO ASW exerice)*

CMRE participation to DMON14 was limited to the deployment of a decision support element with MSTPA onto the command platform during the exercise, in preparation for full CMRE participation in 2015 with the NRV Alliance and the AUVs.

F. *REP14-Atlantic (multinational experimentation)*

This experiment was the first autonomous ASW experiment conducted by CMRE in the Atlantic Ocean, and the first collaboration with the Portuguese Navy. Significant testing of the JANUS protocol was performed.

G. *COLLAB-NGAS14 (multinational experimentation)*

This trial with the Italian Navy represented the final joint experimentation between the NGAS JRP and the CASW programme. It was also the first trial with significant testing of CAS waveforms and long-baseline navigation.

Future seagoing activities for the cooperative ASW programme include:

A. *DMON15(NATO ASW exercise)*

CMRE plans to participate to the NATO Dynamic Mongoose 2015 ASW exercise in Norway. This will be the CASW programme's first experimentation in northerly climes and will present unique environmental challenges.

B. *LCAS15 (multinational experimentation)*

In the fall of 2015 experimentation with the partners of the Littoral Continuous Active Sonar multinational project is planned. This experimentation will emphasis direct comparisons between pulse active and continuous active sonar to establish performance benchmarks.

IV. Conclusions

CMRE's Cooperative ASW programme has been undertaking work across a broad front of activities and research areas to develop the concept of autonomous multistatic active ASW networks. This work has so far concentrated on the research areas of improving DLCT for multistatic active sonar deployed from unmanned vehicles, improving underwater communications for command and control and data fusion, development of standards for underwater communications, implementing comms-enabled data fusion onto the vehicles and in reach-back, developing local and network level robotic behaviours to improve networked ASW performance, and developing an ASW decision support element capable of guiding robotic ASW decisions and providing real-time feedback and tactical advice to ASW operators during NATO exercises or during national experimentation. This spectrum of activities is closely tied to an extensive seagoing programme with experimentation in a national context and operational demonstration in a NATO ASW exercise context.

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Keywords

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