a NATO Research Centre
un Centre de Recherche de l'OTAN

Reprint Series NURC-PR-2009-007

Collaborative multistatic ASW using AUVs: demonstrating necessary technologies

David T. Hughes, Francesco Baralli, Stephanie Kemna,
Michael Hamilton, Arjan Vermeij

December 2009

Originally presented at:

MAST 2009, Stockholm, Sweden, 21-23 October 2009

About NURC

Our vision

- To conduct maritime research and develop products in support of NATO's maritime operational and transformational requirements.
- To be the first port of call for NATO's maritime research needs through our own expertise, particularly in the undersea domain, and that of our many partners in research and technology.

One of three research and technology organisations in NATO, NURC conducts maritime research in support of NATO's operational and transformation requirements. Reporting to the Supreme Allied Commander, Transformation and under the guidance of the NATO Conference of National Armaments Directors and the NATO Military Committee, our focus is on the undersea domain and on solutions to maritime security problems.

The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to NURC and the Supreme Allied Commander Transformation.

NURC is funded through NATO common funds and respond explicitly to NATO's common requirements. Our plans and operations are extensively and regularly reviewed by outside bodies including peer review of the science and technology, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification.

NOTE: The NURC Reprint series reprints papers and articles published by NURC authors in the open literature as an effort to widely disseminate NURC products. Users are encouraged to cite the original article where possible.

Collaborative Multistatic ASW using AUVS: Demonstrating necessary Technologies

D.T. Hughes, F. Baralli, S. Kemna, K. LePage, M. Hamilton and A. Vermeij
NATO Undersea Research Centre.
Viale San Bartolomeo 400,
19126 la Spezia, Italy.
Contact: Hughes@nurc.nato.int

Abstract

Many research laboratories and several nations are showing an interest in the 'underwater networked battlespace' in which a combination of stationary and mobile underwater platforms communicate wholly or partially by the use of underwater modems. Scientific advancements and technological development have been shown in the arenas of environmental sampling, mine detection and classification and, more recently, in the field of anti-submarine warfare (ASW). In ASW, in particular, new operational paradigms are evolving for slowly moving systems which have low bandwidth communication between platforms, necessitating high levels of onboard processing and highly developed autonomous behaviours.

As part of NURC's ongoing research into collaborative ASW using autonomous underwater vehicles (AUVs) a major sea-trial has been held to investigate enabling technologies and to investigate the detection and localisation performance of such AUV-based systems.

We present results demonstrating

- **On board processing of active transmissions**. By implementing parts of NURC's existing signal processing chain we were able to produce contacts, detections or tracks which could be further processed on-board or passed over the underwater communication link.

- **Adaptive behaviour.** By taking the outputs of the real-time system - whether they be contacts (defined as a latitude and a longitude or range-bearing on a particular ping) or a fully formed track – it has been possible to investigate how an underwater system can be truly autonomous and to exhibit a behaviour which is relevant to active ASW.

We discuss how these demonstrated technologies have been integrated into a working autonomous system to provide realistic 'operational' type behaviours and how lessons learned are influencing future research directions.

Keywords: *NATO, ASW, sonar, multistatics, signal processing, AUV, underwater networks, acoustic communications, autonomy.*

1 Background

Traditionally the task of Anti-Submarine Warfare (ASW) is a person-intensive discipline with various levels of sophisticated sensors gathering large amounts of data, from towed array or sonobuoys for example, from which the relevant information, in terms of possible target or non-risk assessment can be made. From this inferred decision a consequent action is taken. Should the detection be ignored? Should it be passed on for further analysis? Or should it be acted on directly, by for instance, sending a helicopter with a dipping sonar as a step towards the ultimate prosecution of the target?

At NATO Undersea Research Centre (NURC) and several other labs in the world an alternative approach is being investigated in which the sensors and underwater assets themselves make the decisions and carry out the necessary change to behaviour or position to optimise the chance of detection and classification and to minimise the errors in localisation.

In particular the concept of use of underwater multiple vehicles interacting only by means of underwater communications is receiving a great deal of interest and prompting many areas of research including robotics, communication theory and in the field of multistatic tracking. The constraint of using predominantly underwater communications necessitates that the vehicles are expected to only receive minimal information from other systems and therefore carry out on–board 'reasoning'.

To this end NURC has initiated a project to investigate the use of AUVs as part of a networked system. The project as a whole incorporates research into both AUV control for ASW and the issues of how networking and underwater communications can be used to facilitate system wide detection and localisation as well as passing information back to a centralised command centre.

2 Approach to the autonomous ASW problem

The vision of *groups* of networked unmanned vehicles swimming around independently, carrying out high-level processing and sharing information between other members of the submerged fleet, ultimately carrying out detection and classification of enemy assets and passing the information to a command and control centre, or carrying out their own prosecution, is seductive and enticing. Such a capability would, in effect, exhibit levels of flexibility which would be of great use in at least three of the arenas of interest as quoted in the US's Navy Unmanned Undersea Vehicle Master Plan NUUVMP [1]:

- In Transit/'Protected Passage'
- Chokepoint/'Hold at Risk'
- Sea base/'maritime Shield'

And also it is possible to consider the role of a group of AUVs involved in
- Hunting

All of these capabilities share a core set of requirements
- Navigation;
- Detection/Localisation and Classification and Tracking processing;
- Autonomous adaption of AUV's path or trajectory;
- Intelligent task allocation
- Underwater communications for AUVs.

It is this 'toolbox' of capabilities that we are presently researching and developing at NURC. The goal in the next few years is to exhibit a fully networked system with multiple nodes in which an asset can be localised and tracked by several AUVs and the utility of such underwater systems demonstrated to the maritime community in general. We discuss this research within the context of a recently conducted at-sea experimental trial.

3 GLINT09

The GLINT09 sea trial was held between the 29th June and the 18th July 2009. The experiment took place on an area to the south-east of the island of Elba close to the Formiche islands off the coast of Italy. The area was ideally suited to an AUV based experiment with a relatively flat bathymetry at a depth of approximately 110 metres.

The objectives of the experiment were four-fold
- Gather data for off-line processing; to allow investigation of expected sonar performance for AUVs
- Demonstrate real-time signal-processing on an AUV;
- Demonstrate a truly adaptive behaviour on the AUV which uses the outputs of the signal processing ;

We now discuss and explain these objectives in more detail and give results from the sea-trial which demonstrate state-of-the-art capabilities, as well as indicating lessons learned. We begin by describing the relevant equipment deployed,

3.1 Equipment

OEX AUV with BENS towed Array

The main tool of research for the GLINT09 trial was NURC's Ocean Explorer (OEX) AUV used in combination with the BENS towed-array

The OEX is an untethered AUV of length 4.5 meters and a diameter of 0.53 metres. It can operate down to 300 meters – but for the purpose of the GLINT09 experiment it was operated at a maximum depth of 100 metres. It has a maximum speed through the water, when towing the array, of 3 knots. Battery constraints limit the lifetime of any mission to about 7 hours. The OEX is equipped with two independent modems. One of these is a WHOI modem which is used for communication of data with the command centre and for passing of information between vehicles.

In line with other efforts the approach for controlling communication, algorithmic functioning and platform control is carried out under MOOS-IvP (Mission Orientated Operating Suite Interval Programming). The software architecture which has been developed at MIT and Oxford University [2] allows each modules behaviour and requirement to be compartmentalised and to allow the scientist and developer to rapidly insert new algorithms and autonomous behaviours into the system whilst leaving MOOS to cope with interface and the avoidance of internal conflicts. The IvP helm component is itself a MOOS process that uses a multi-objective optimisation technique to determine platform motion. The so-called back seat driver paradigm [3] [4] allows low-level tasks such as depth-keeping and vehicle safety to be controlled by the vehicle's main computer, the MOOS-IvP messages coming from a separate payload. The algorithms developed at NURC have been implemented on PC-104 stacks. Signal, data and information processing algorithms already exist, having been developed under NURC's multistatic program in recent years.

The OEX is shown in Figure 1 with the attached BENS array. The BENS array is an adaption of the SLITA array [6] and as such based on the same underlying technology. The array has 83 hydrophones of which sets of 32 can be chosen to give a frequency coverage from 750 to 3400 Hz. Furthermore the array is equipped with 3 compasses and two depth sensors to aid with the reconstruction of the dynamics of the array.

Figure 1. OEX AUV being lowered into the water the towed source can be seen dangling behind the AUV and behind, that looping through the water is the BENS towed array.

DEMUS Source and Echo repeater

The DEMUS source is a programmable bottom-tethered high source level based on free-flooded ring technology. It has a maximum source level of 217 dB. It is equipped with a WHOI modem which allows it to be turned on and off remotely by means of another compliant acoustic modem. In this mode the source acts as a cueable stand off-source which can allow AUVs to change the overall system's mode of operation from, for instance, passive to active. The DEMUS source is equipped with a radio buoy so that the acoustic signals to be transmitted can be altered by means of a radio connection. It also has a GPS unit which allows a very accurate transmission time and position of the source. This level of information could be used subsequently to aid the AUV in determining its position more accurately.

In order to have a reproducible and controllable target in the experiment a towable echo-repeater was used. This gave us the flexibility to gather data and examine behaviours for targets with different speed and target strengths. Furthermore, a fixed delay can be placed on the signal which is retransmitted by the ER and a tag signal can be added to the end of the returned signal to help with unambiguous identification of contacts coming from the target.

3.2 Data Collection

Some data relevant to ASW processing has previously been collected in an earlier trial, GLINT08 (partially reported in [7]). Although those datasets allowed some useful and interesting insight into tracking possibilities and attendant localisation errors, the experiments were carried out at very short ranges and with very large target strengths applied to the echo-repeater (ER). In terms of data to be gathered for the GLINT09 experiment, discussed here, the goal was to show that detection of 'realistic' targets could be carried out at much greater ranges.

To this end data was gathered on the AUV acquisition system. One experimental set-up is shown in Figure 2. The AUV carried out a rectangular race-track (2km x 500m) whilst the ER travelled on a straight leg from shorter to longer distances. A pulse repetition interval (PRI) of 12 seconds was used with a 1 second simultaneous 200 Hz linear-frequency modulated (LFM) pulse near 3 kHz and a continuous wave (CW) transmission at 2500 Hz. The signal was produced by the DEMUS source which was transmitting at 210 dB. For the initial look at the data under investigation we have analysed only the LFM data to act as a comparison with the data analysed by the real-time system (see next section).

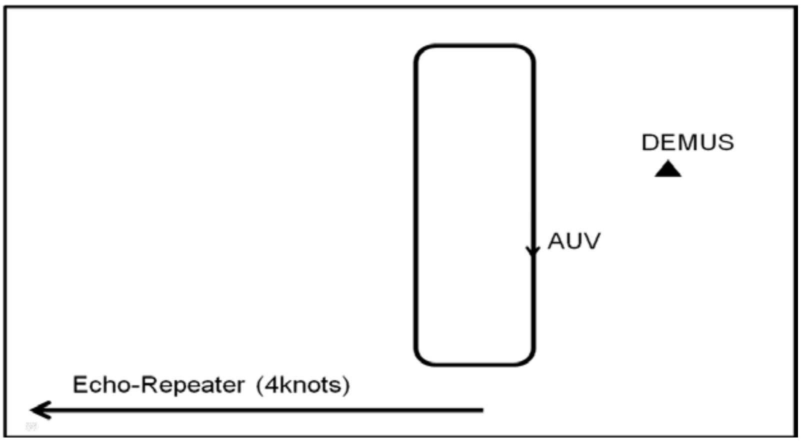

Figure 2. Schematic of run for Figure 3. The AUV carries out an approximately rectangular path. The DEMUS source is stationary and the echo-repeater, towed by the CRV Leonardo travels east-West at approximately 4 knots.

Figure 3 shows the corresponding processed data from the run as a beam-compressed display. This type of display is created by processing each ping of data separately to form contacts and then choosing the contact with the largest SNR for each range. This output is amalgamated over multiple pings to give the "poor man's tracking" shown here.

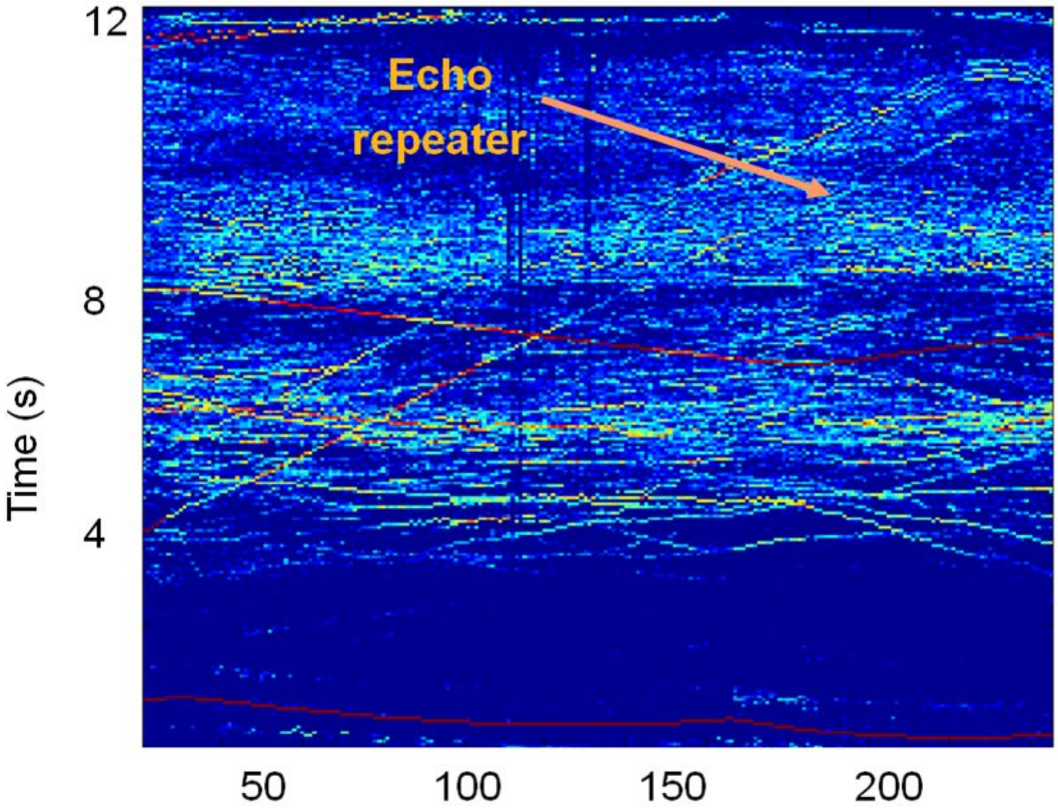

Figure 3. Beam compressed output from run shown in Figure 2. The ER signal can be seen clearly out to the furthest ranges. Other, consistent signals can be seen which require further investigation in a geographical framework to understand their origin.

The image is clearly rich in content and is worthy of some explanation. The red line near 0 seconds is the direct blast arriving directly from the DEMUS source, the slight variation across the display being due to the movement of the AUV on its track. The return from the ER is indicated. It is clear that the target is moving away from the receiver for the duration of the pings. Several other tracks can also be identified and are believed to be associated with fixed features on the bottom – which are consistent over the time of the run.(NB a ghost tag can be observed which is a artefact of the processing due to an out of band tag in the echoed signal).

Many tens of hours of data were gathered during the sea-trial which will be analysed to allow us to assess the efficacy of such AUV based systems in terms of false alarm rates, probability of detection and detection ranges. The detailed analysis of this data will allow us to, for instance, investigate the effects of beamforming while the AUV is manoeuvring – such as turning the corners in Figure 2.

Initial investigation of the data gathered over several days during the GLINT09 trial indicates that detections of a target with a target strength of 5dB could be consistently made at a range of 7km. As discussed previously in [7] this is the type of range that is of interest in these networked AUV type systems.

3.3 Real-Time Processing

Real-time sonar processing sits at the heart of our AUV based system. It can be thought of as acting as the bridge between the sensors and the more complex adaptive behaviours which make decisions on the basis of the sonar world picture. The AUV based processing chain which we have implemented is constrained to run on relatively low powered processing boards – in order to limit power consumption within the vehicle – and is designed to be robust, obviously requiring no human intervention and able to cope with occasional drop-outs of data and corrupted samples.

The approach is based heavily on the signal processing chain which has been developed at NURC for general array-based systems [5].The processing chain used is presently only implemented for FM waveforms. For speed and ease of implementation on the vehicle the beamforming and matched filtering is carried out in the frequency domain whilst the normalisation, detection and contact formation is carried out in the time domain. The contacts formed return position relative to the AUV in terms of an *(x,y)* co-ordinate relative to a pre-defined fixed point, as well as an estimate of the signal-to-noise ratio (SNR) of the contact. The linear array used necessitates that an ambiguous return is created for every true detection and this replication is mirrored in the display where true contacts have an ambiguous 'ghost' The tracking was carried out using a simple baseline one-step ahead Kalman-filter based tracker which has been developed as part of NURC's Multistatic Tactical Planning Aid initiative [12].

During GLINT09 the processing chain was implemented on the OEX AUV producing contacts and tracks. These data were passed via acoustic modem to the NRV Alliance where the information could be projected within the command and control centre on a screen which facilitated understanding of the geographical experimental space. Figure 4 shows a screenshot which was made during the trial.

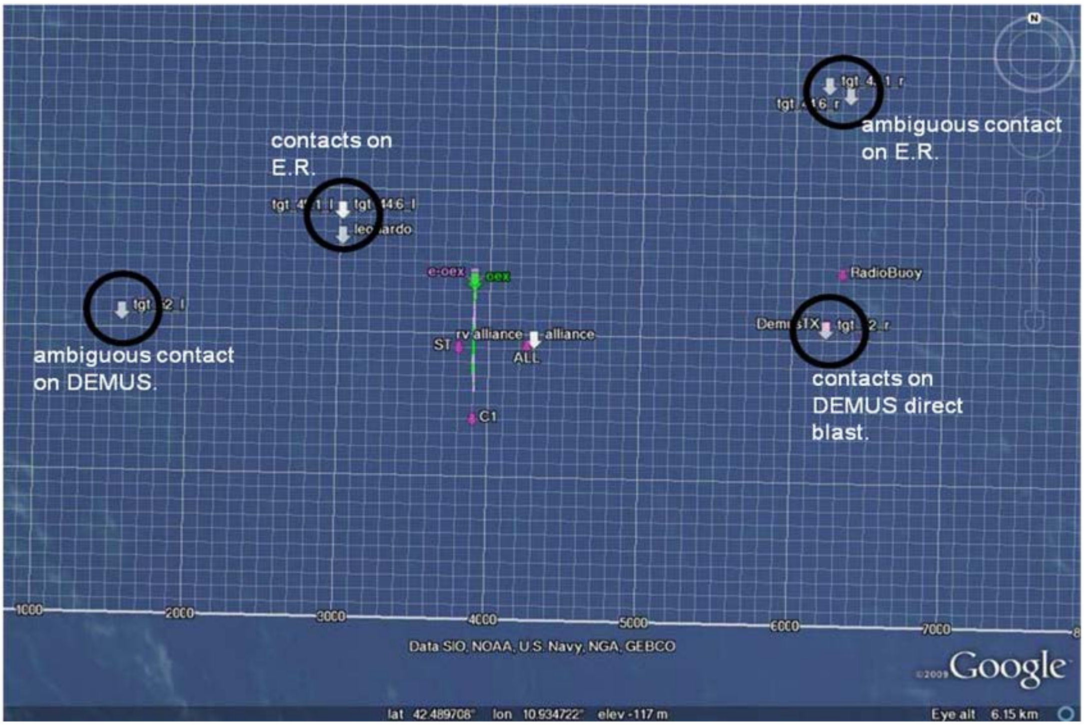

Figure 4. Screenshot, taken from command centre display produced during GLINT09. The display showed not only recent updates on the position of the AUV, shown in pink and green, but also the position of contacts, calculated on-board the AUV and passed back to the command centre by means of acoustic modems.

The green and purple overlapping lines running vertically near the centre of the image show the measured trajectory of the AUV at this part of the run, using the two independent acoustic modems. Slightly to the East (the units at the bottom of the image are in metres) is the position of the NRV Alliance which was acting as the command and control centre. The DEMUS source gives a clear return 2.2 km to the East. The (false) ambiguous return can be seen lying 2.2 km to the West. More interestingly the Leonardo with its echo repeater can be seen lying north-west of the AUV. Here the ambiguous return falls rather on the bistatic ellipse with the foci at the position of the AUV and the fixed DEMUS source.

3.4 Simulation

AUVs are not cheap and neither is time at sea. Consequently pre-testing by means of simulation is crucial before any effort is made to demonstrate behaviours at sea. The simulation which has been developed is advanced and gives a good level of fidelity of what may be expected both in terms of received acoustic time-series, signal processing, vehicle behaviour and vehicle dynamics.

The generation of synthetic times-series at individual hydrophones is based on simple expressions for bistatic reverberation intensity developed at NURC by Harrison for straight arrays [9] and on a more general theory for the target return on arrays of arbitrary geometry [10]. The overall consideration is one of the highest possible fidelity within the constraint of real-time stimulation for the hydrophone elements. At this time, the environment is assumed to be range-independent and isovelocity, although the second assumption may be relaxed at relatively little computational cost. The bottom scattering is assumed to follow Lambert's law, a separable scattering kernel which lends itself to fast simulation. Similarly the target is assumed to be a point scatterer, another assumption which allows for fast implementations. The source function is assumed to be an LFM.

For the stimulation of reverberation at the element level, the assumption of a straight array allows the sampling of the product of the grazing-angle vs azumith reverberation intensity density developed in [10] with the array wavenumber response for the N+1 wavenumbers resolved by the array, where N is the number of elements, 32 in the case of the BENS array. The N+1 wavenumbers represent waves from forward endfire through aft endfire, at cosine angle spacing. The weights of the intensity observed by the array at each of these wavenumbers is obtained by taking the product of the array wavenumber response with the theoretical reverberation intensity. The pressure amplitudes at each wavenumber are simply the square root of this intensity, up-sampled to the sample frequency of the data acquisition system, randomized to have Rayleigh envelope statistics, and convolved with the source waveform.

For the stimulation of the target echoes on the individual hydrophones, the straight array assumption is relaxed, and a general propagation model is used to generate the one-way Greens functions from the source to the target, and from the target to the hydrophone locations. These Greens functions are generated at the sample frequency of the data acquisition system, and are convolved with one other to obtain the impulse response of the target for each hydrophone. This impulse response is then convolved with the target impulse response and the source waveform to generate the required element level time series associated with the target response.

The simulated data on the hydrophones are the sum of the reverberation and target simulations which are then passed to the signal-processing module. This is an ***exact*** copy of the code which sits on the AUV. This exact replication of code and parameters is a crucial part of the checking and validation of ideas and algorithms before they are tested at sea. The configuration control, at sea, can become complex but is worth the effort to ensure well tested code is being used.

An exactly analogous approach is taken in terms of the code which controls the behavioural response of the AUV – in that the code used in simulation is that which is ultimately used on the vehicles. There is however a slight complication in that a model of the vehicle dynamics must be used; to that end we have used a relevant but simple dynamic model [13]. Future developments will allow us to incorporate a more specific and accurate model of the OEX.

Such, a detailed simulation then allows us to investigate and optimise against physical parameters as well as allowing us to carry out many re-runs of the simulation with different starting conditions and for different acoustical data sets (based on different random instantiations).

3.5 Autonomous Adaptive Behaviours

The ‘autonomous’ in AUV is a term which can leads to a great deal of confusion. For instance, a vehicle which is programmed to go out and execute a pre-defined lawn-mower pattern is called autonomous if there is no continuous updating of the vehicle’s plan by an exterior source (by underwater acoustic communications or even a cable – as employed by a remotely operated vehicle). What we were interested in during the GLINT09 experiment was several steps of advancement from this baseline autonomy. For our demonstration we wanted to show how an AUV could monitor its environment based purely on its own sensors, and convert the data obtained into information which could be used to alter the trajectory of the AUV to exhibit some form of ASW relevant-behaviour. As discussed in the previous section the observation and interpretation of the external world is carried out in the real time processing. The output can be either contacts with associated latitudes, longitudes, bearing and SNR, or fully formed tracks, with associated position estimates and error-covariance estimates. For the behaviour described here we used the former configuration although work is on-going to use tracks for adaptive behaviours (as discussed in [7] there remains the issue of whether contacts or tracks should be used as the best information packet for passing between vehicles).

It was shown in simulation in [14] that realistic operational constraints on an AUV following a target resulted in the vehicle keeping that target at or near broadside. To this end we have implemented an algorithm which keeps a target at broadside using the contact information which has been delivered from the real time processing.

The behaviour is conceptually straightforward (for details see [8]); the AUV makes an estimate of the position of the target, based on the output of the real-time system, relative to the direction of travel of the AUV. It is important to stress at this juncture that the system does not have any information about the position of the source – both range and bearing are calculated ‘on the fly’ by the signal processing. The heading the AUV must keep in order to maintain the target at broadside is calculated and the AUV commanded take this heading. The reality is rather more involved.

- To be sure of reliable contacts we do not want the vehicle to turn too quickly – so that the towed array does not become too distorted. Therefore we imposed a maximum turn-angle that limits the amount of change in the AUV’s heading within a PRI.
- The contact information obtained is actually only relevant to the orientation and position of the vehicle in the past because data acquisition and data processing take a finite period of time. For the experiment at hand this is approximately 24 seconds and therefore it is necessary to try and keep the target at a smaller angle than broadside, so less than 90 degrees
- The system must be robust to a loss of contact. To this end we implemented an SNR threshold on the contact, which was possible here because we know that the SNR of the contact from the DEMUS source will be high. If for a predefined number of contacts the SNR does not change or is too low, then the vehicle will move into another mode of operation: the so-called *adaptive loiter*.
- In the adaptive loiter mode the AUV traverses a predefined pattern, a square or a hexagon for instance, but the behaviour also ‘waits’ until contacts with high enough SNR have been found, upon which the broadside behaviour begins. This serves two purposes; a holding pattern which is used if the signal is lost, as described in the previous bullet point or as the baseline for a vehicle when there is no target present.

The selection of the correct contact is, generally, an issue but here we chose to keep the DEMUS source at broadside so that we can use the contact with the highest SNR on each ping. Consequently, the expected trajectory is a circle centred on the DEMUS source.

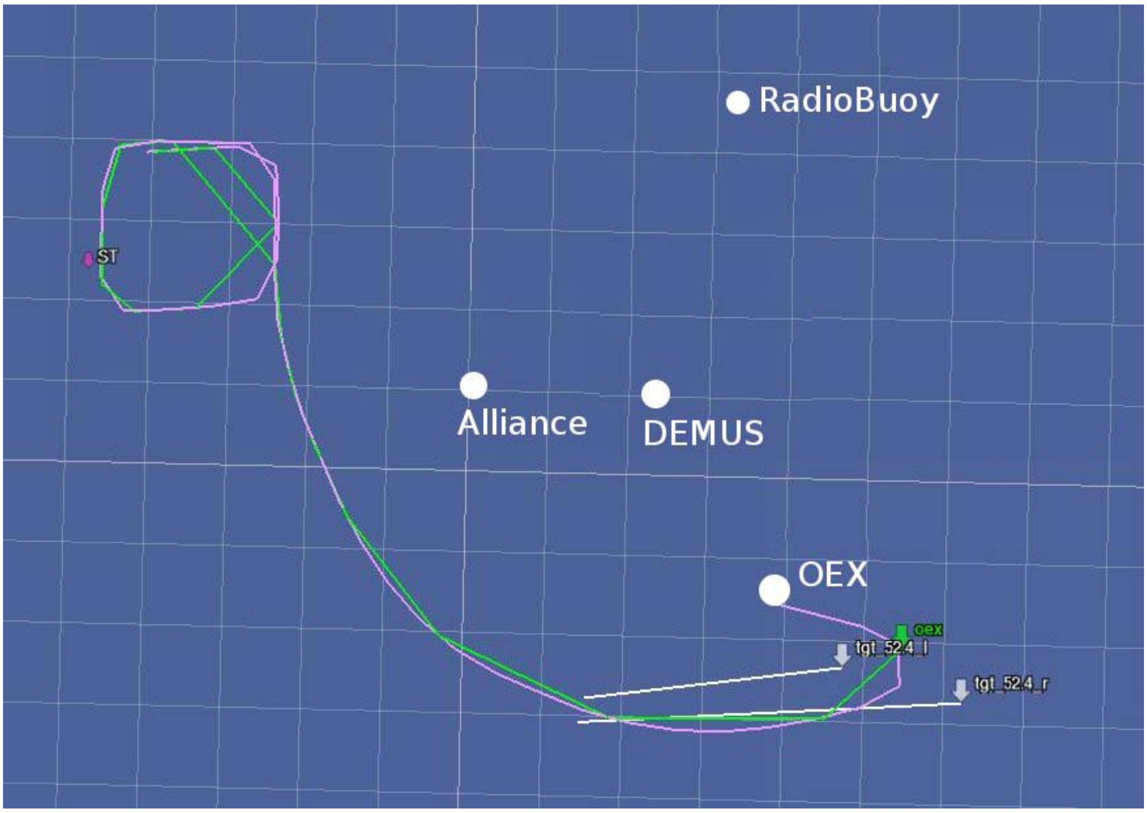

Figure 5. Screen capture showing the time progression of the AUV (pink and green lines) as it moves from adaptive loiter to broadside behaviour in which it, approximately circles the DEMUS source.

Figure 5 shows the result of a demonstration of the described behaviour. The path of the AUV is shown by the pink and green lines (showing the estimated position of the AUV passed back to the command centre by means of the 2 acoustic modems fitted to the vehicle). The AUV was deployed in the adaptive loiter mode with the DEMUS source turned off. During this phase the AUVs processing the data but, no strong signal is being detected. The AUV repeatedly moves around the square – tagged as Adaptive Loiter. At some point the DEMUS source is turned on and starts pinging with a PRI of 12 seconds. After several pings the AUV 'decides' that the contacts found are 'good' ones and, it changes its mode to keep the source at broadside, and consequently starts to move on a locus which is approximately a circle. The AUV was able to move through a quadrant of a circle before a safety timeout made the AUV switch back to a standard loiter at a pre-defined position.

The behaviour worked identically to what had been predicted in simulation. It was, to the authors' knowledge, the first demonstration of a fully functioning active ASW-relevant adaptive algorithm being operated underwater in real-time.

4 Conclusions

Multistatic undersea surveillance capability in water depths of less than 200 metres will continue to be one of the prime concerns of NURC. A relatively new approach to this field of research is the introduction of a fully networked capability.

At NURC, to give this concept an operational goal a heterogeneous network will be demonstrated with a cluster of non-acoustic sensors and a cluster of towed array fitted AUVs in conjunction with stationary and mobile sonar transmitters. It is the latter capability that we have investigated in the GLINT09 trial.

In this paper we have discussed some major milestones which have been achieved in the progress towards a fully functioning collaborative ASW system. In particular the demonstrated capability to

- Provide high levels of simulation prior to deployment of equipment to minimise risk and allowing testing of behaviours and algorithms in a greater range of environments and configurations than could be achieved at sea. (Ultimately, however, only at-sea demonstration can provide the proof of functionality!).
- Carry out real time processing. The implementation of a fully operational processing chain, taking data all the way from acquisition to tracking all in real-time gives the AUV the precise and accurate view of the real world which allows subsequent adaptive behaviours.
- Demonstrate adaptive behaviours at sea. We have detailed only one behaviour here, but the general approach is very similar for more complex behaviours with the MOOS architecture allowing rapid insertion of behaviours, testing by means of simulation and then implementation on an actual vehicle. The behaviour demonstrated, although apparently simplistic, demonstrates how autonomous ASW-relevant behaviours can be implemented.

This multistatic active sensor network has the potential for augmentation by other assets such as low-cost gliders; and this interaction with other assets will be addressed in subsequent demonstrations and experiments. In particular the GLINT10 experiment, to be held in the summer of 2010, will take the work described here to the next level with multiple AUVs carrying out autonomous adaptive behaviours.

The ultimate goal of this body of research will be a demonstration at sea with military participation in order to facilitate development of concepts of use and a transition of techniques to operational systems and to industry.

Acknowledgements

The authors would like to thank the crew of NRV Alliance and CRV Leonardo for their help in obtaining the at-sea data described and to Massachusetts Institute of Technology (MIT) and to the Naval Undesea Research Centre (NUWC) for their provision of some of the equipment used in the collection of data during the GLINT09 trial. The authors would like to thank Robert Been for his analysis of the data for the production of Figure 3.

References

[1] US Navy's 'Unmanned Undersea Vehicle Master Plan, 2004. See, for instance http://www.navy.mil/navydata/technology/uuvmp.pdf.
[2] *See for example oceanai.**mit**.edu/**moos**ivp/background.html.*
[3] Eickstedt D.P. and Benjamin M. R. IEEE Cooperative Target Tracking in a Distributed Autonomous Sensor Network. /MTS Oceans 2006. Pages 18-21, 2006.
[4] Eickstedt D.P, Benjamin MR, Schmidt H, and Leonard J.J. Adaptive Control in Heterogeneous Marine Sensor Platforms in Autonomous Sensor Networks. Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing China 2006.
[5] .Baldacci A and Haralabus G Signal Processing for an active sonar system suitable for advanced sensor technology applications and environmental adaption schemes. EUSIPCO 2006, European Signal Processing Conference, Florence. Italy. 4-8 September 2006.
[6] SLITA: a new Slim Towed Array for AUV applications. Maguer A., Dymond R., Mazzi M., Biagini S., Fioravanti S., Acoustics'08 pp 141-146, Paris, France 2008.
[7] Been R., Hughes D.T., and Vermeij A. Heterogeneous underwater network for ASW: technology and techniques. UDT 2008.
[8] Kemna S. Hughes D.T, Hamilton M, LePage A, Vermeij A, Baralli. A broadside behaviour for an autonomous underwater vehicle. International Conference on Robotics and Automation. Anchorage, Alaska. May 2010.
[9] Harrison C. Formulae for bistatic signal and reverberation. NURC Report: SACLANTCEN SR-370 December 2002. NATO Unclassified.

[10] LePage K. Reverberation and target time series generation for real-time ASW simulation applications. NURC report: NURC-SR-2009 September 2009. NATO Unclassified

[11] Freitag, L., Grund, M., Singh, S., Partan, J., Koski, P., Ball, K., The WHOI Micro-Modem an acoustic Communications and Navigation System for Multiple Platforms. *IEEE Oceans Conference, Washington DC, 2005.*

[12] Wathlet A., Strode C., Vermeij A. and Been R. Optimisation in the multistatic tactical planning aid (MSTPA). NURC report: NURC-FR-2008-013. May 2008. NATO Unclassified.

[13] A detailed description of the dynamic model used 'uMVS' can be found in http://dspace.mit.edu/bitstream/handle/1721.1/45569/MIT-CSAIL-TR-2009-028.pdf

[14] Hughes D.T., Been R and Vermeij A. Heterogeneous Underwater networks for ASW. MAST 2008.

Document Data Sheet

Security Classification		*Project No.*
Document Serial No. NURC-PR-2009-007	*Date of Issue* December 2009	*Total Pages* 11 pp.

Author(s)

Hughes, D.T., Baralli, F., Kemna, S., Hamilton, M., Vermeij, A.

Title

Collaborative multistatic ASW using AUVS: demonstrating necessary technologies.

Abstract

Keywords

Issuing Organization

NURC
Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
NURC
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int