Sensible Behaviour Strategies for AUVs in ASW Scenarios

D. T. Hughes, S. Kemna, M. Hamilton and R. Been.
NATO Undersea Research Centre
Viale San Bartolomeo, 400.
La Spezia, Italy.

Abstract- **This paper discusses possible behaviours for single and multiple AUVs in bistatic and multistatic active sonar configurations respectively. With a mixture of theoretical exposition, simulation and actual sea trial results the possibility of making a mobile networked system which behaves in an optimal manner is discussed. For a single AUV it is shown that an information theoretic approach yields a result which can be simplified and was then actually demonstrated at sea. For a multistatic system with two AUVs we show how our approach leads to particular interesting behaviours and discuss the consequences for an at sea-trial to be held later in the year.**

I. INTRODUCTION

The NATO Undersea Research Centre (NURC) is currently conducting research investigating and demonstrating how multiple Autonomous Underwater Vehicles (AUVs) equipped with towed arrays can be used to assist in carrying out Anti-Submarine Warfare in littoral environments. The use of these vehicles in possibly hazardous scenarios will allow naval planners to release humans from the loop away from danger and to carry out human intensive tasks elsewhere.

The use of AUVs, however, introduces many technological and scientific research questions. The challenges include, how to increase battery life, how to achieve dependable and sufficient communication between platforms, carrying out signal processing of the acoustic data which has been acquired from the towed array on the AUV in real time, demonstrating adaptive and relevant behaviours both on individual AUVs as well as on multiple AUVs working collaboratively.

NURC has already had success in addressing some of these questions. This paper focuses, in particular, on the last two issues, investigating the question as to what one should do with AUVs which are in a tracking mode pursuing a target. The paper will provide a mix of theory, simulation and results from at-sea experimentation.

We have shown previously how consideration of localisation error for an AUV tracking a faster target leads to a simple 'heuristic' requirement that the AUV should follow a trajectory keeping the target at broadside [1]. In sections III and IV we expand on these observations and discuss how the theoretical understanding has been implemented on an actual vehicle, demonstrating adaptive behaviours at sea.

In section V we progress onto using a similar approach with two AUVs. Here the approach needs to be modified to include the contacts coming from both vehicles and the size of the error covariance matrix of the tracking Kalman filter is used as a metric for minimisation. We have focused, as a starting point, on a system in which the two AUVs can share all positional and contact information communications bandwidth.

In section VI we briefly consider the effect of the limited communications which are available for two AUVs underwater.

In section VII we conclude by detailing how some of these ideas for multiple vehicles will be demonstrated at-sea in the summer of 2010.

II. BEHAVIOURS

Fundamental to our approach is the use of the MOOS-IVP architecture (Mission Orientated Operating Suite) which has been shown to give great flexibility and has been used extensively in the underwater robotics community [2]. The approach is heavily built on the idea of subsumption [3] in which different layers (*behaviours* in our terminology) are active at the same time and it is their relative weighting which determines what the AUV actually does. Within our implementation of MOOS these behaviours are combined using an Interval Programming technique to obtain an 'optimum' solution or track.

Faced with how to make an AUV carry out missions independently and in a way which is relevant to ASW we have a set of low level behaviours on which we can rely. These include primarily safety behaviours which, for example, avoid obstacles, maintain the vehicle within a pre-defined geographical box or prevent the vehicle from turning too quickly. On top of this infrastructure we impose our more complex and performant behaviours. Work is going on in several areas for both single AUVs and for multiple AUVs

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working collaboratively (including for one system operating in a passive mode cueing another to become active).

In the following sections we shall consider the single AUV and multiple (in our case two) AUV case separately. Our approach will be a mixture of theoretical exposition, practical implementation and at-sea results.

III. What To Do With One Vehicle

To make the problem concrete we start with a description of the scenario in which we are interested. We consider an active bistatic sonar configuration in which a fixed source is present (shown schematically in Figure 1). We use a single AUV equipped with a towed array, acquisition system and on-board real time processing (For details of how this setup is mirrored by NURC's capabilities see [4]). The AUV, then, acts as the mobile receiver. We assume a straight-running target in what follows.

We assume that the source has a pulse repetition interval of the order of tens of seconds, that the speed of the AUV is of the order of 1 m/s and that it is travelling more slowly than the target.

The AUV is able to detect contacts as part of a bistatic sonar. We also have a tracker and some form of classifier on the AUV which can tell us unambiguously which track is the one we are interested in, or some system for cueing our system as to the likely presence and trajectory of any incoming vehicle (it is clear that some aspects of this scenario have yet to be achieved). What can and should we do with this track? It is clear that the answer to this question may well depend on the operational scenario in which we are interested. An obvious solution would be to approach the target as quickly as possible based on its present position or perhaps on some predicted position, estimated by the on-board tracker. Here we are into the classical world of pursuit theory [5]. We have, however, chosen to consider a more profound approach to the problem in which we consider the trajectories which minimize the localisation error associated with the target based on the measurements made by the vehicle. The approach taken has been explained elsewhere along with results from simulation [1]. We shall therefore only briefly describe the approach taken and explain how the results of the research have been simplified and applied on an AUV operating at sea.

The fundamental asumption is that the AUV is able to choose a single track which has sufficient history to have a well-defined estimate of target position and associated covariance matrix. This initial step leads to problems in a real system since in any realistic operational scenario we expect tens of false tracks to be formed per hour. It is to be imagined that the vehicle is able to choose the 'good' track by means of some kind of classification criteria, which may be physical or a 'cue' arriving from another node. Research is currently being carried out to consider how the approach could be made to work with multiple tracks, in which the AUV would manoeuvre in a way to optimize over several possible hypotheses of which is the correct target.

We assume that any given time t we know the position of the source and receiver and we have an unambiguous estimate of the position and velocity of the target. We choose a time in the future at which we want to have the best position and velocity of the AUV.

Rather than labour over the details of the Extended Kalman Filter, for the purpose of the simulation we shall consider the linearised form assuming that both measurements and estimates are provided in an xy space. The Kalman equations for the single AUV are then as standard:

$$\underline{x}(k+1) = \begin{pmatrix} 1 & 0 & \Delta T & 0 \\ 0 & 1 & 0 & \Delta T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \underline{x}(k) + \underline{v}(k) \quad (1)$$

Where $v(k)$ is the process noise and ΔT is the increment in time for the discrete filter, which for us is the PRI of the sonar system. $\underline{x}(k)$ is the state vector of the target given by its two-dimensional position and velocity. So for us

$$\underline{x}(k) = \left[x(k), y(k), \dot{x}(t), \dot{y}(t) \right]^T \quad (2)$$

and

$$\underline{z}(k) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \underline{x}(k) + \underline{w}(k) \quad (3)$$

Where $w(k)$ is the measurement noise and $z(k)$ is the measurement vector which is defined as the 2D observation of the position: $z(k) = \left(x_o(t), y_o(t) \right)$.

For any point on the AUV's trajectory there is a localisation error –which constitutes a part of the measurement noise which depends not only on the transmitter, target and receiver positions [6] and their associated uncertainties but also on the SNR of the target at the receiver and the beamwidth of the beam in which the target sits. through an expression [1][7]

$$\sigma_{Bearing} \sim \frac{Beamwidth}{\sqrt{SNR}} \quad (4)$$

With this information we are able to answer the question 'how should the AUV move to minimize the localisation error'.

To this effect we can use the state model which has been developed by the Kalman filter to provide an estimate of where the target will be and with what velocity it will be travelling. We make multiple hypotheses about regions of space which the AUV could reach. This region is clearly constrained by the maximum speed of the vehicle, how far ahead in time we predict the path of the vehicle and the maximum angle through which the vehicle can turn per second. Within the context of this paper the exact method for finding the best position and heading for the AUV is unimportant. We could carry out an exhaustive search or use some form of non-exhaustive optimisation technique. We chose to use the former to simplify the implementation of the algorithm. For the simulations that follow we shall use an exhaustive approach that is constrained to look 5 pings of the active source ahead. Possible paths of the AUV are further constrained since we only allow a limited turn angle per second. This would be necessitated by the real system in which we would not want the vehicle to turn too quickly because it is desirable to keep the towed array as straight as possible to allow linear beamforming and to minimize the risk of the vehicle getting entangled in the array. In fact with the subsumption approach this concept of '*maximum turn per second*' would be handled as a separate safety behaviour.

Each of the possible trajectories is then assessed by computing the sum of the traces of the localisation errors over the predicted trajectory.

The AUV is then instructed to take the trajectory – in the simulation the heading for the next time-step. At the end of that time-step we carry out the process again. This allows us to constantly monitor the latest, best, estimate of the target position.

Our original work [1] explicitly took into account the effect of the blanking effect of the direct blast – i.e. the region in which the energy arriving directly from the source obscures the returns from the target. In the present analysis we choose to ignore this factor. This can be thought of as being equivalent to using a very short pulse for the sonar (with a large bandwidth to maintain sufficient range resolution). In terms of a real system it is envisaged that a further behaviour could be incorporated into the subsumption architecture which would explicitly avoid putting the vehicle in the blanking zone for the system as a whole.

The error covariance matrix developed by the Kalman Filter is obviously fundamental to the optimization calculations. The exact details are unimportant in that the evolution of the covariance matrix for a tracker being fed 'correct' contacts is fundamentally the same irrespective of the implementation details of the filter. For completeness we mention here that on our vehicles we have implemented the multi-hypothesis tracker which has been developed at NURC and been shown to be robust and computationally efficient in a host of maritime applications [8][9]. In the present usage however we use the tracker in its basic mode with no latency before a tracking decision is made.

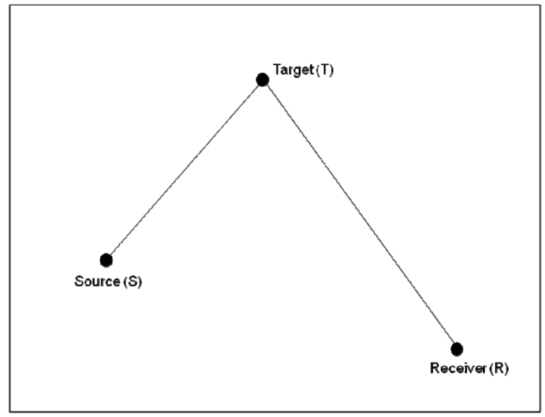

Figure 1 Single bistatic geometry. For all simulations the Source is fixed and the receiver is an array being towed behind a moving AUV.

For all simulations discussed here we have used a simple bistatic version of the sonar equation in which the received level is given by, (using the labeling of Figure 1)

SNR = *SourceLevel –15log10(ST) -15log10(TR) – NoiseLevel.*

In other words we have ignored absorption, any detailed propagation mechanisms and reverberation. The compromise spreading factor of 15 which lies between the cylindrical and spherical spreading factors has been used. In passing we note that this aspect could be much improved both in the simulation and on the vehicle. For instance measured Sound Velocity Profiles (SVPs) could be passed from gliders acting as part of the same mobile network and full propagation models could be utilized to give a better model of sound dynamics.

Figure 2 shows the output of such a simulation using a Pulse Repetiton Interval (PRI) of 60 seconds, an AUV speed of 1.5m/s and a target speed of 4 m/s, a maximum turn angle of 20 degrees/minute and a look ahead of 5 pings. The source position is at (-500, 500) and is modelled as 200 dB re1 μPa for a Sea State 1 noise background.

The target path is given by the continuous blue line while the measurements are given by red stars. The estimate of position is shown by the blue dots and the associated error by the ellipses. The ellipses are relatively small here since we consider short ranges and large source levels. For the first 5 pings the AUV is constrained to take a straight pre-defined path, during which the tracker initializes the (one) track under consideration. Even for this simple scenario the path of the AUV is not obvious *a priori*. It begins by approaching the estimated path of the before turning to follow a curve, increasing the expected SNR, but then the directivity index as expressed in equation (4) takes over and the AUV attempts to keep the target at broadside.

We have observed this type of behaviour many times with many permutations of parameters and starting positions [1]. Although no exhaustive search of the parameter space has been carried out, and indeed it is clear that for some starting positions the path could be very different but usually we observe a particular characteristic of the trajectory taken: *for an AUV trailing a target that travels more quickly than the AUV the trajectory taken should be for the AUV to keep the target at broadside to the vehicle* (more accurately to the towed array).

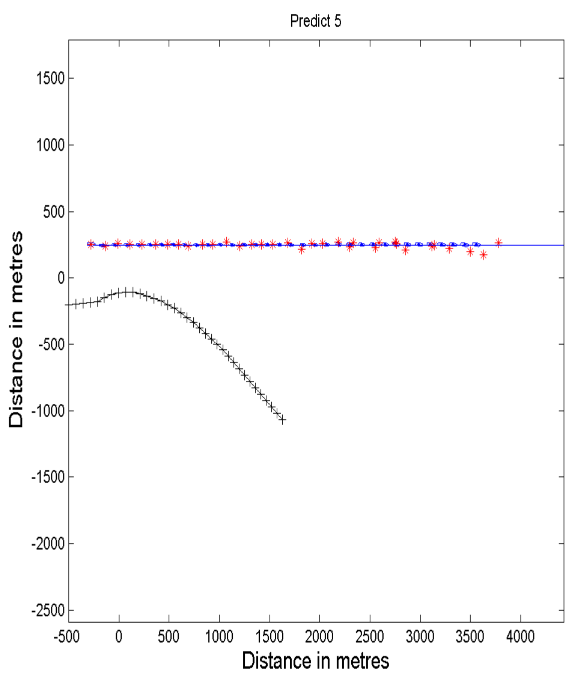

Figure 2 Path taken by an AUV marked by the black crosses. The continuous blue-line shows the path of the target. The red stars are the measurements and the blue ellipses show the estimated target position and the associated error matrix.

The understanding of how an information theoretic approach can be used to determine what path an AUV should take is interesting since it leads to a conclusion which is intuitively pleasing (in retrospect one may say obvious) and can be termed simply as the single statement given above. It is this simplified statement of intent that we chose to implement in an at-sea trial in 2009.

IV. AT SEA - GLINT 2009

After a rapid development push from the beginning of 2009 NURC was in a position to have both the equipment and technology and the theoretical understanding of what a single AUV should do and how to set up the internal reasoning to allow the AUV to do it independently of a human-in-the-loop, or without recourse to a pre-programmed trajectory as is usually the case in such ‘autonomous’ systems.

The demonstration was carried out in the Tyrrhenian Sea off the Coast of Italy. The experiment used NURC’s Ocean Explorer (OEX) AUV as a mobile receiver, the DEployable MUltistatic System (DEMUS) source as an active bottomed source with a maximum source level up to 217 dB re1 µPa. The area of the experiment was relatively flat with an average depth of 100m. Although a standard echo-repeater was used for other demonstrations during the experiment for simplicity and proof of concept we used the stationary DEMUS source as the ‘target’. This means that we expect the AUV to circle the DEMUS source at an approximately constant radius – keeping the source at broadside.

The source, echo-repeater and vehicle were all deployed at approximately 40 metres with the DEMUS source transmitting a combined 1 second HFM (Hyperbolic Frequency Modulation) and CW (Continuous Wave) pulse with a Pulse Repetition Interval (PRI) of 12 seconds. Here we consider only the processing of the HFM. We have in the past modified the MHT tracker to accept contacts formed from the CW (Doppler) processing [8]. Indeed to completely understand the ‘best’ dynamics for a system using both a large bandwidth and a Doppler sensitive waveform a more complex analysis would be required. This work will be presented at a later date.

Figure 3 shows the command and control centre display for the associated demonstration. The path of the OEX AUV is shown in pink and green, corresponding to two acoustic modems which are situated on the vehicle to allow us to monitor its position. It is important to stress that this information was being passed back to the control centre only for monitoring purpose: the vehicles was travelling completely autonomously, making its own choice as to when and how it should transfer from one set of behaviours to another.

The vehicles started in the top-left hand corner of the figure, carrying out an approximately square path, in what we call an adaptive loiter. In this mode the system is carrying out the real time signal processing waiting for what it believes to be a ‘good’ or ‘interesting’ target. When the DEMUS source is turned on the system detects something with a sufficient SNR and changes its mode away from the adaptive loiter and starts the ‘keep the target at broadside’ behaviour. At this point the target starts on a near-circular path centred on the DEMUS source.

At a point SSE of the DEMUS source the AUV breaks off from its circular trajectory and starts returning to the initial point –in response to a pre-programmed time-out safety behaviour. Although the behaviour implemented is relatively straightforward it was based on a great deal of pre-processing in terms of signal processing of the data acquired and acts as a demonstration of how an AUV system can respond adaptively to multistatic data (in this case bistatic).

At this point it is worth pointing out that although only a limited time could be dedicated to this kind of demonstration the performance of the real time system. However, the adaptive behaviour and the trajectory of the vehicle were tested many times before ever going to sea to prove that the vehicle would behave 'as expected'. This is achieved by means of a dedicated simulator. This simulator incorporates

- a hydrophone-level time-series generator for each of the hydrophones on the towed array, incorporating noise and reverberation;
- a model of the kinematics of the AUV;
- an exact copy of the signal processing and behaviour software which is actually used on the vehicle.

This level of detailed simulation allows us to have heightened confidence in how the system will behave when in the water and adds credibility to the limited number of runs which can be carried out at-sea.

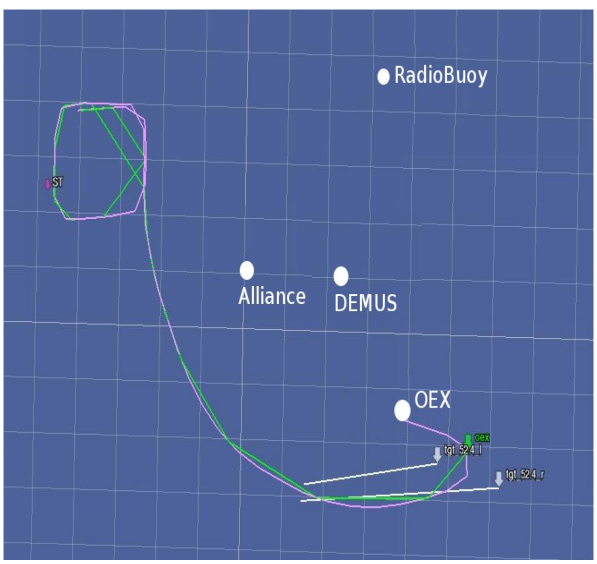

Figure 3 Command and control centre display taken from at-sea experiment. The pink and green lines show the path taken by NURC's Ocean Explorer AUV – passed over acoustic modem channel. The path is adaptively optimized to keep the DEMUS (target) at broadside.

V. WHAT TO DO WITH TWO VEHICLES

For two vehicles we take a similar approach. Here however the localisation error, although being well defined separately for each AUV individually does not carry over to the combined system of two AUVs. In this case a more general approach is to now consider the sum of the trace of the error covariance matrices coming out of the tracker for any hypothesized track. (We note that an alternative but essentially equivalent approach would be to maximise the inverse of the covariance matrix, corresponding to the Fisher Information Matrix).We assume that both AUVs have visibility of all the contacts from the other vehicle. Whether this level of communication between the vehicles would be possible or indeed desirable is doubtful but we treat the case here as a first step baseline to understand how such a system produces interesting behaviours.

The fusion of contacts or tracks across multiple vehicles and platforms has been shown to be a powerful technique in multistatics and here NURCs MHT has been shown to perform well [8]. For such a model although the observation vector has doubled in size the state-vector remains, obviously, of the same length. To be concrete, equation (3) above becomes

$$\underline{z}(k) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \underline{x}(k) + \underline{w}(k) \qquad (4)$$

Where, now $z(k) = \left(x_o^1(k), y_o^1(k), x_o^2(k), y_o^2(k)\right)$, with the superscripts denoting the AUV which made the observation at that timestep.

It has been pointed out in the literature that the 'standard' approach to the Kalman Filter for such a situation can be reformulated in terms of the Information Filter [10]. When the problem is couched in these terms an understanding of the problem becomes much clearer and when we have multiple observations becomes computationally more efficient [11]. Here, however, with only two vehicles, the computational advantage of using the Information Filter is not relevant and consequently we continue with our standard implementation.

Figure 4 shows a result from such a simulation for two AUVs. The continuous blue line shows the actual path of a target in the simulation travelling to the North-East. The source is located at a position (300, 200). The green and cyan stars show the detections made by the two AUVs. The paths actually taken by the AUVs are marked in red and black. For this simulation the speed of the target is taken as 2.8 m/s and the speed of the AUVs is 1.5 m/s. The underlying physical sonar model is as described in III with the spreading losses calculated separately for both receivers. The AUV's are started in approximately the same position with exactly the same velocities and allowed to 'run' for 5 pings in a straight line. From the 6th ping onwards the vehicles start to adapt their paths to minimize the overall uncertainty of the system. It is pleasing to note two features immediately from the results.

1. The trajectory taken by the 'black-track' AUV is similar to what was observed in the previous work with the path converging towards the keep-target at broadside trajectory.
2. The 'red-track' AUV, however, has a very different trajectory. This is worthy of more consideration.

Given the same starting conditions for the black and red AUVs it might be expected that both of the vehicles would traverse the same trajectory. Indeed this would be the case if there was no communication between the vehicles. This would correspond to the so called 'pathological-case' in which multiple vehicles all go to the same point because it is 'the best point'. Here, however, within the simulation there is the possibility of optimizing over the systems as a whole and this leads to new behaviours.

Thinking about the problem from an information point of view it is clear that having both AUVs 'see' the same world view continually along the track would be wasteful. The second AUV therefore sets off on a path which increases its own localisation error but contributes the maximum amount of independent information to the system as a whole.

The actual choice of which AUV goes to port and which to starboard is, of course, arbitrary and is a simple choice which comes out naturally from choices and comparisons made within the simulation. In a real world case it would be necessary to impose an ordering on the individual AUVs so that one of them would automatically take the dominant role.

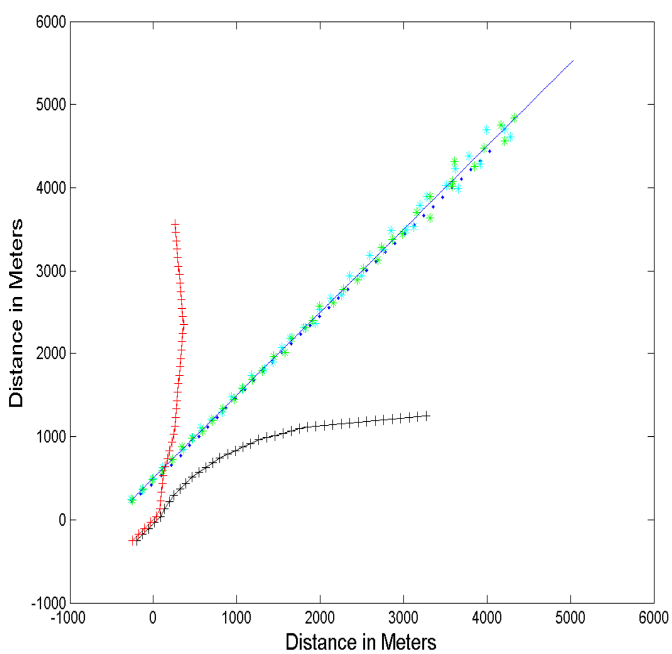

Figure 4 Result of simulation for 2 AUVs. The continuous blue line is the path of a target. The paths of the AUVs (red and black) are chosen to minimize the localisation error for the system as whole. Simulation assumes 'infinite' communications bandwidth between the two vehicles.

VI. COMMUNICATION

The results of section V are again very pleasing in that they provide an intuitively pleasing model of what two AUVs will do given a complete transfer of information between the vehicles. The level of communications that may be required for such systems has been discussed elsewhere [12] where it was pointed out that the possibility of passing all contact information on a ping-by-ping basis was very unlikely in a shallow water environment. It was also pointed out that the false alarm reduction provided by the tracker itself would allow the possibility of passing tracks between the AUVs. A 'track-contact' would incorporate, position, speed and time estimates as well as a description of the associated covariance matrix producing less than 50 bytes of information. Furthermore these tracks could be passed intermittently – dependent on acceptable latency and uncertainty.

Work is going on in parallel to the research described here to investigate robust acoustic communications as part of NURC's Collaborative ASW project. An overview of this work can be found in [4].

VII. AT SEA- GLINT 2010

Figure 5 the two OEX AUVs to be used in GLINT10. They have virtually identical set-ups and will be interchangeable within terms of the experiment.

In the summer of 2010 NURC will again go to sea. Part of the experiment will be to demonstrate some of the concepts that have been discussed within this paper.

Further to the equipment used in previous experiment in this year NURC will field a second AUV with on-board processing and a towed low-power source as well as directional arrays and improved timing and localisation units.

Figure 5 shows the two AUVs to be used. They will be used in conjunction with our multi-octave towed array (BENS array based on the previously reported SLITA array [13][14]) and our wideband on-board transmitter TOSSA (Towed Sound Source for AUV) [14]. Although it is not envisaged that the TOSSA source will be used for ASW it will be used as a method for transmitting acoustic communications signals directly into the towed-array of the other vehicle – where it can be demodulated by the real time system. This will be the first step towards an implementation of a software defined modem with reception of acoustic communication signals through the towed array.

As stated above the infrastructure to allow the AUVs to carry out a simple 'broadside' behaviour has been previously demonstrated. In 2010 the more complex minimization of localisation error will be demonstrated by minimizing the covariance matrices, based on the known receiver and source positions and the estimated position of the target, which will again be an echo-repeater.

More importantly we will attempt to demonstrate how the AUVs can be made to pass and share information between each other. This will act as the first step towards demonstrating a behaviour of the type shown in Figure 4 which is truly adaptive and truly collaborative.

VIII. Conclusion

We have shown how consideration of localisation error or more generally system information leads to a set of sensible behaviours for one or more AUVs. By means of simulations incorporating realistic levels of localisation error and propagation models we were able to show how the AUVs would be expected to travel as receivers in an active bistatic sonar system.

For one AUV we were able to show that such an approach lead to a simple 'keep the target at broadside' type of behaviour. This behaviour has been demonstrated at sea providing confidence in the adaptive infrastructure which will allow more complicated behaviours to be examined. In particular, this infrastructure will allow us to implement the approach, which has been discussed in this paper, in which the information theoretic content of the system is maximised in real-time. This approach will be demonstrated at-sea in the summer of 2010.

IX. Acknowledgements

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