Implementation of Autonomous Mission Control for Mine Reconnaissance AUVs

B. Evans, G. Davies, V. Myers, A. Bellettini, M. Pinto, P. Munk
NURC
Viale San Bartolomeo 400
19126 La Spezia
Italy

evans@nurc.nato.int

ABSTRACT

Whilst autonomous underwater vehicles (AUVs) are increasingly being used to perform MCM tasks, the capability of these systems is limited in terms of their ability to network and co-operate effectively with other manned or unmanned assets. This paper describes a processing system which is being developed at NURC to address this missing capability. In addition to describing the system approach and implementation progress, the underlying requirement for the system is analysed through a review of typical mission needs and the performance constraints of current technology.

1.0 INTRODUCTION

Prior to describing the autonomous mission control structure and details of the individual processing areas, the paper first provides a background analysis to examine the requirement for an autonomous mission control system. To do this the paper examines current MCM operations and limitations and uses these to identity the requirements for an MCM AUV. The extent to which existing technology (including current MCM AUV systems) meets this requirement is then briefly reviewed and the need for an autonomous mission control system is demonstrated.

2.0 CURRENT MCM SYSTEMS AND OPERATIONS

Maritime minewarfare has traditionally been performed by manned surface platforms which clear areas / lanes by performing either minehunting or minesweeping operations. For minehunting operations the surface ships are fitted with high frequency active sonars for target detection and classification, plus divers and remotely operated vehicles (ROVs) for target identification and disposal. For minesweeping the ships are equipped with towed signature generation / wire cutting equipment.

AUV systems have for many years been viewed as providing the basis of a future minehunting capability due to their ease of deployment, greater visual covertness and ability to position the sensor to improve performance within the hunting environment (for example to negate sound velocity profile (SVP) effects). Whilst their relatively low speed and limited energy storage capability has constrained their use in other military roles, the capabilities of current systems are becoming increasingly well matched to the needs of both

Evans, B.; Davies, G.; Myers, V.; Bellettini, A.; Pinto, M.; Munk, P. (2007) Implementation of Autonomous Mission Control for Mine Reconnaissance AUVs. In *Platform Innovations and System Integration for Unmanned Air, Land and Sea Vehicles (AVT-SCI Joint Symposium)* (pp. 8-1 – 8-14). Meeting Proceedings RTO-MP-AVT-146, Paper 8. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Implementation of Autonomous Mission Control for Mine Reconnaissance AUVs**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NURC Viale San Bartolomeo 400 19126 La Spezia Italy**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202416.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

MCM sensors and missions. This is reflected in the number of MCM AUV development programmes which are taking place around the world and the increasing number of AUV systems which are being brought into service. To date, in service systems have predominately concentrated around the introduction of small vehicles (especially the REMUS vehicle from Hydroid) to support divers in very shallow water (VSW) operations, although larger, wider area coverage vehicles such as HUGIN have also entered service.

3.0 UNDERSTANDING THE REQUIREMENT

The minehunting task is, by nature, relatively slow and painstaking, with sonar tracks being completed at regular spacings to achieve the required level of assurance that an area is free of mines. The number and spacing of these tracks is affected by the environmental conditions, with greater levels of effort having to be concentrated in more difficult areas. Detection of a mine-like object further slows the speed of the operation as extra effort (potentially including the use of divers and/or ROVs) needs to be expended in checking and confirming each of these contacts.

There are several areas where an AUV capable of finding targets and determining environmental conditions should benefit minehunting operations. Prior to the commencement of a full MCM operation, AUVs could be deployed to perform covert reconnaissance operations in an area. AUVs can provide information on contacts (both potential targets and clutter) and the minehunting environment (bottom type / water column properties etc.). This information can be used to enhance MCM planning, in terms of both quality (i.e. by planning the route around difficult areas) and accuracy (a greater knowledge of the environment / number of targets etc. can enable more accurate plans to be produced).

Once an MCM operation is started, then a networked combination of ships and AUVs should provide a flexible solution to finding, classifying and disposing of mines in a faster and lower risk manner.

There are several key requirements that need to be met by a future reconnaissance AUV as follows:

- provide high levels of location accuracy;
- deliver trustworthy data;
- deployability;
- reliability;
- area coverage / coverage rate;
- networked enabled.

Each of these areas is expanded below.

3.1 High level of location accuracy

A system needs to be able to find objects on the seabed to an accuracy which aids subsequent disposal operations and / or avoidance of the mine (i.e. accuracies in the region of 10m). In more complex environments where re-surveys may be required, then the system should also be able to provide a relative location accuracy between surveys that is sufficient to ensure that multiple survey information can be correctly matched (to improve ATR performance) and to allow successful change detection. Items of interest are likely to have a major dimension of 1m, suggesting that a relative location accuracy of between +/-0.5 and +/-1m would be required.

3.2 Deliver trustworthy data

The ability to deliver trustworthy data is a key requirement for any automated system, if it is to be used by an operator. For an MCM AUV there are two areas to consider. Firstly, the search performance must be 'good enough' in terms of the system's ability to find mines and reject false alarms. The level of 'good enough' is dependent upon the operation, but should be sufficient to improve the overall delivery of the capability.

Secondly, the system must be able to accurately report the search performance that has been achieved. The operator needs to understand the quality of the information that has been produced by an MCM reconnaissance AUV so that he can make informed decisions about the extent to which an area is safe and/or what further level of MCM effort is required.

3.3 Deployable

The vehicle must be deployable to the part of the world where it is to be used, and must also be deployable from a range of platforms so that operational flexibility is not compromised.

3.4 Reliable performance

In addition to providing a high level of system reliability, an MCM AUV needs to be able to consistently provide a useful MCM capability in different environmental and operational conditions in the same way as surface ships do. This could include[1], for example:

- not wasting time performing a search in an impossible minehunting area;
- being robust to changes in sonar performance within the environment;
- being able to adapt to non-critical system failures etc.
- suitable area coverage and area coverage rate;
- consistently operating in a safe manner.

The vehicle needs to be capable of covering an area that is meaningful in MCM terms. The area coverage rate and level of endurance must also be such that the autonomous systems do not result in a heavy launch and recovery overhead being placed on MCM forces.

3.5 Networked operation

Whilst standalone systems have a level of benefit, the move of future operations towards interoperable networked capabilities needs to be reflected in the performance of AUV systems. An MCM AUV therefore needs to be able to:

- disseminate the necessary information;
- update its role based on orders;
- operate as part of a cohesive group with other vehicles to deliver an effective capability.

4.0 CURRENT TECHNOLOGY

There are currently several different MCM AUVs available throughout the world. Recent tests at NURC have included several systems including Bluefin 12 and 21”, Hugin 1000, Sea Otter, Remus 100 and Remus 600 vehicles. These tests, amongst others, have indicated that many of the requirement areas are starting to be met. Accurate location of targets can be achieved even for extended underwater operations. Systems are generally deployable from a range of platforms, even if the range of acceptable sea states is limited. Enhanced deployment capability continues to be addressed on a case by case basis by manufacturers / system integrators. The data delivered by the systems is certainly useful, but the quality of the information can be limited by the environment and target type. This was demonstrated by the December 2005 SWIFT trial by the US CMWC platoon REMUS vehicle. Figure 1 shows three sonar snapshots of the same location taken from different tracks. It can clearly be seen that the search results are quite different in the three cases, depending upon: the combination of target orientation; the environment; and the range performance of the vehicle sensor.

Figure 1; Sonar snapshots at different aspect angles

The effects of this varying performance were analysed using the NURC planning and evaluation tool [2,3]. The tool was used to assess the performance of a classifier for each of the three survey directions [3], with the results provided in figures 2 and 3. These figures again clearly demonstrate both the benefits of performing multiple surveys, and the significant differences in performance which are observed when performing surveys in different directions.

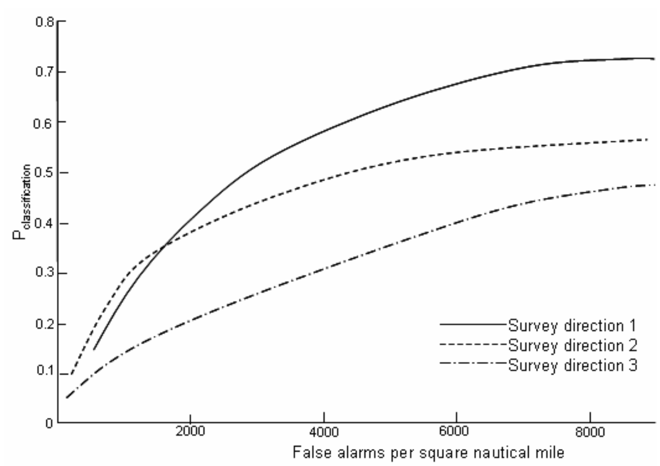

Figure 2; Search performance by survey direction

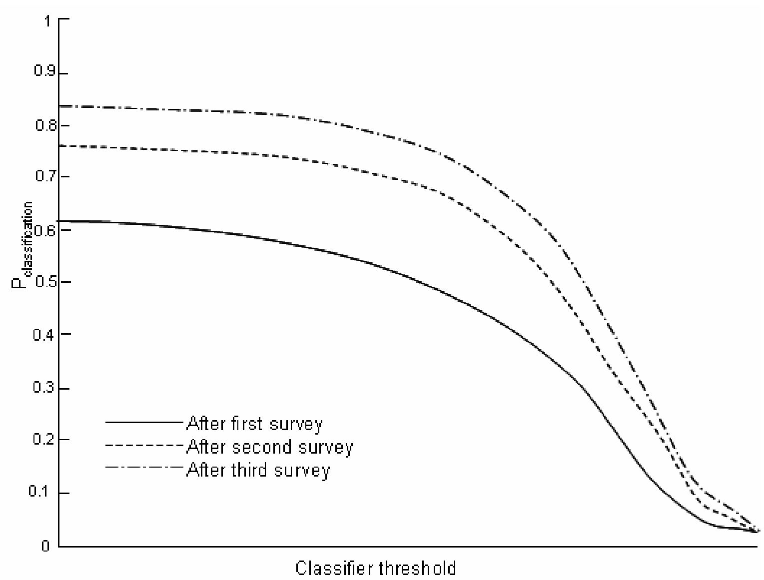

Figure 3; The effects of multi-aspect surveys on search performance

The vehicle systems are further limited in their ability to deliver information by a combination of the constraints of the available communications systems and the availability of effective onboard processing. At present the processing required to classify targets and provide bottom type information generally requires the support of the operator to deliver an output of the necessary quality, specifically to reduce false alarm rate [3]. To support this processing the operator will need to see at least elements of the sensor information which will require that sonar image information is passed back from the vehicle to some surface location. Typical performance levels for current communications equipment is provided in table 1.

System	Data rate (kbps)	Range (km)
HF	9.6	30 - 40
Commercial satellite	2.4 – 9.6	Coverage
Packet modem	1.2 to 115	Line of sight
WiLAN	2000	1km / Line of sight
Acomms (long range)	0.1	10km
Acomms (short range)	16	2km

Table 1; Performance of potential AUV communications systems

Standard operations with NURC's REMUS systems result in a 1.2MB (MSTIFF) file being generated for each 100 to 120m of survey distance, equating to a streaming data requirement of approximately 160kbps. For higher performance (range, resolution and dynamic range) synthetic aperture systems this can rise to data rates in the region of 4Mb/s. Communicating the high resolution SAS data is effectively unachievable, even over short ranges, and even communicating the short range sidescan information is unattractive due to the limited communications range, particularly as sea state increases and starts to interrupt line of sight. The implementation of image compression techniques (JPEG etc.) is similarly unlikely to reduce the data to a level where full communication is effective. The bandwidth requirements can be reduced by just communicating image snapshots, typically giving transmission requirements of between 1.8kbps (sidescan) to 7.1kbps (SAS). These rates could be accommodated by a range of different systems at short ranges, but transmission, even of just the snapshots over extended ranges (for example by HF or commercial satellite) would result in the vehicle spending nearly as much time on the surface transmitting data as it spends under the surface on a survey task. Although this problem could, at least in part, be alleviated by the use of other system alternatives (such as the use of relay buoys or unmanned surface vehicles (USVs)), the overall system complexity is increased and the operational covertness is likely to be reduced.

The delivery of information is therefore effectively constrained by need to recover the vehicle, download and then process the data, before the required MCM data is delivered. This further reduces the apparent coverage rate and prevents effective in-mission networking, as the results of the operation are not available when required. Thus, although in general most of the hardware required to deliver a non-networked capability is present, the processing chain required to enable the vehicle to: react; report; and provide reliable performance is missing and forms the focus of the NURC study.

5.0 THE NURC MCM AUV AUTONOMOUS MISSION CONTROLLER

NURC is developing an integrated processing system, as shown in figure 4, to enable the feasibility and performance of an autonomous mission controller to be assessed.

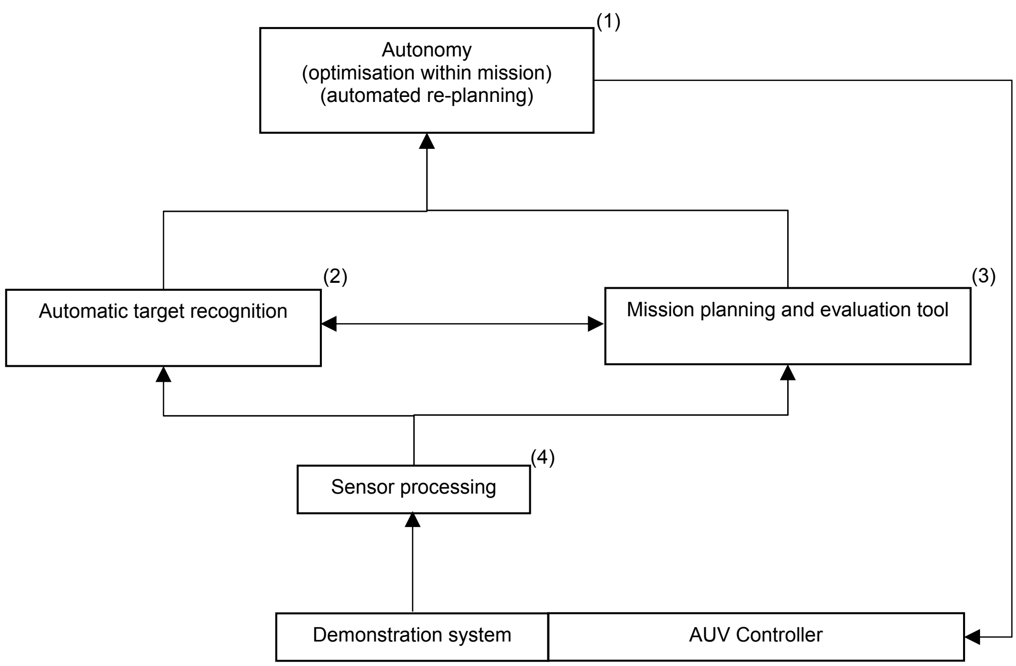

Figure 4: NURC MCM AUV autonomous mission control system

It consists of 4 main blocks, namely:

- autonomous mission planning / adaptation.
- automatic target recognition software;
- planning and evaluation tool;
- sensor processing;

Each of these elements is addressed in turn, with the paper providing a description of the requirement, approach and the current progress.

5.1 Autonomy

The implementation of autonomy needs to match both the environment and the task which is being implemented. For an underwater MCM task, there are several key considerations:

- communications can be intermittent and data rate is limited;
- system performance can be significantly affected by the environment (which may be unknown at the start of the mission and is also liable to change, especially for extended mission durations of 10h or more);
- the MCM effort is likely to be delivered by a number of different platforms and thus a level of co-operation is necessary.

Little work has been done to examine the specific autonomy requirements for an MCM AUV, for either home waters MCM or expeditionary operations (which, being a greater challenge for autonomy, forms the focus of this work). Expeditionary MCM is by nature a reactive type of mission. An initial plan will be formed based on the best available intelligence and overall mission needs. The plan will however need to be adapted based on the true conditions which are encountered as the mission progresses. An MCM AUV performing a reconnaissance mission is likely to have to adapt its mission based on changing environment (bottom type, SVP, current etc.), potential mine finds and changing mission needs. This could be either at a low level (i.e. changing the direction of survey to take account of bottom type) or at a more global level where the mission is moved to a different area to avoid particularly difficult or time consuming areas in an avoidance type strategy.

Several different levels of autonomy could be envisaged to meet these needs, including:

- pre-planned;
- command driven;
- adaptive mission re-planning;
- co-operation.

Pre-planned missions are the standard method of operation with most current AUVs. Missions are described by a series of defined movements which are the followed by the system, possibly with some deviations resulting from safety behaviours (i.e. prevention of maximum depth from being exceeded). To date this approach has worked well. The operator knows where the vehicle should be at any one time which provides re-assurance, and for relatively short duration missions where the environment is reasonably well known, the mission is likely to be delivered in an effective manner. Problems can still occur however, for example: changes in the current speed or direction can alter the effective vehicle survey speed, affecting the quality of the sonar data; and local bathymetry or sea structure effects can similarly reduce search performance. Pre-planned operation also limits the flexibility of the system within a networked environment since the mission cannot be altered to react to changing circumstances.

The next obvious change to make is to enable the vehicle to be re-programmed in-mission by the operator, based on information delivered by the vehicle, which, given the communications bandwidth limitations, underlines the requirement for effective, onboard processing. Whilst potentially effective, there are a number of potential problems with this approach, namely:

- the reaction speed of the system will be limited by the time taken to communicate the search results, develop an altered plan, and then communicate the updated mission commands;
- if communications are lost then the system will revert to a pre-planned behaviour, with the associated loss of performance as survey conditions change.

By providing the autonomous processing onboard the AUV, these final problems can be overcome, with the vehicle able to automatically re-plan its mission to reflect changes in the detected environment. Updates to the mission can still be achieved by operator communication, but the on-board automated processing delivers increased robustness, even in the event of communications failures.

This approach also forms the basis for the ability to properly co-operate between either groups of unmanned or groups of mixed unmanned and manned platforms. The ability of each platform to intelligently adapt its mission based on data received from other systems supports:

- the formation of local networks (where communications range is limited);
- a reduction in operator loading (by allowing vehicles to co-operate automatically to deliver the wider mission);
- more rapid optimisation of a group of vehicles with a minimum of communication (search results will have to be communicated but commands would not).

NURC is concentrating on techniques to deliver onboard autonomous decision making, coupled with co-operative behaviour in order to both address the area of greatest risk and to confirm the level of potential gain.

Autonomous control systems are commonly [4,5] grouped into 4 different types:

- hierarchical (an architecture where the task is decomposed in a top-down strucuture, where the higher levels are more complex and work at a more abstract decision making level, as well as supervising / controlling the lower level [6]);
- heterarchical (a flat architecture where control is provided by a series of behaviours which all make decisions at the same level of abstraction. There is no supervision, with individual behaviours negotiating with others to take command of the vehicle.[4]);
- layered or subsumption (an architecture where behaviours make decisions at the same level of abstraction, but are arranged in a hierarchy of importance, allowing more important tasks to subsume the behaviour of less important tasks. This architecture is often supplemented by a state machine which enables the importance of different behaviours to be adapted as the mission progresses [7].);
- hybrid architectures (an architecture where the tasks are broken down into layers, typically a slower update rate command layer and a higher data rate control layer [5], where each layer is formed from a different architecture).

Review of the MCM mission needs (as outlined earlier in this section) demonstrates that whilst solving the total problem is difficult, the approaches which could be applied to generate the overall mission plan are individually relatively simple, with the complexity of the solution being affected by how the different approaches are combined and different assets distributed. Similarly, whilst it may be challenging to model the effects of a combination of all aspects of the environment, modelling of each individual aspect is far more tractable, accepting that some techniques may be more heuristic than deterministic.

Since each approach (or strategy) to solving the MCM problem operates at a similar level of abstraction, the most suitable way of delivering an effective and intelligent MCM capability seems to be to use a heterarchical based controller, supported by a series of simple models to provide the necessary data analysis. This forms the basis of the approach being taken in the NURC autonomous controller, as shown in figure 5.

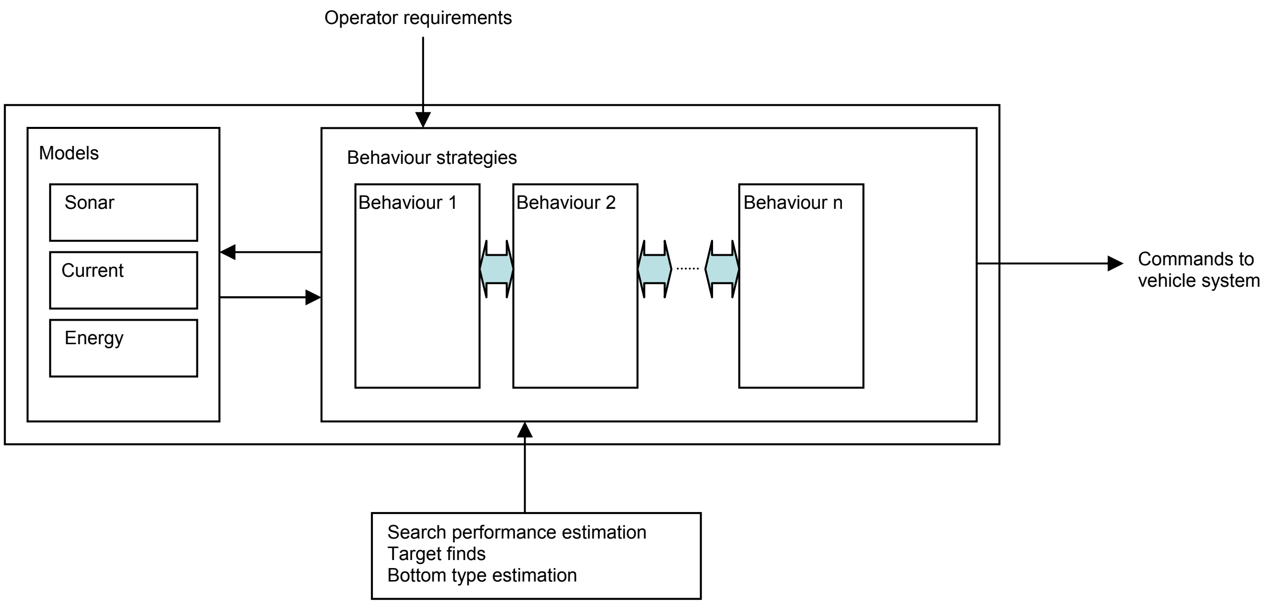

Figure 5; Details of the autonomous control function

The operator controls the function of the AUV by providing a mixture of geographical specifications and behavioural performance goals which describe the mission priorities, as follow

- available search area;
- size of cleared area + location requirements;
- clearance level;
- available search time;
- importance of comms;
- relative importance of speed, time and clearance.

These operator requirements are passed to the individual behaviours, along with the most up-to-date knowledge available on the environment. The individual behaviours then identify a proposed mission and generate a performance score (related to the ability of the strategy to deliver the desired performance goals) with the behaviour with the highest performance score winning control of the vehicle. Control will be maintained until either:

- changes in the beliefs / status / desires are seen to have altered (must be observed over some minimum time) in which case the overall behaviour will be reassessed;
- the measured performance of the vehicle falls beneath the predicted performance of the next best behaviour (again for some minimum time), in which case the next-best behaviour will take control.

In this manner the vehicle is able to adapt and alter performance as the overall mission progresses. At present the following behaviour types are proposed for implementation:

- search entire leg to most difficult standard;
- search entire leg to most general standard and re-survey as required;
- segment search by areas of similar search requirement;
- ATR active learning support;
- communications control;
- exploratory behaviour (target finds);
- exploratory behaviour (environment)
- safety behaviours (including return home functions).

As this work progresses it is proposed to examine the use of reinforcement learning type approaches to better specify the scoring of different behaviours, based on both simulated and real mission data. The approach will also be expanded to support co-operation between multiple vehicle systems based on the communication of key search results and the use of a common mission processing system, potentially with some additional behaviours which are only applicable to multiple systems.

As has been shown, all in-mission networking and autonomy is reliant upon the provision of on-board sensor processing which is able to:

- detect and classify targets;
- determine bottom types and bottom type effects;
- confirm mission performance.

The individual behaviours are also reliant on the use of a mission planning tool which can quickly and accurately plan vehicle tracks (based on a specific strategy) and produce the associated estimates of survey time and energy usage. These roles are fulfilled by the other aspects of the NURC autonomous processing system, as summarised below.

5.2 ATR

Accurate information on targets and clutter is a key requirement for any MCM decision process and inclusion of an effective automatic process onboard the AUV is key to supporting both single systems and co-operative performance. Many previous ATR systems have concentrated around the use of the image generated by sidescan sonars to support the decision making process. These techniques have generally struggled to provide a reliable and robust level of performance due to limitations in the quality of the sensor data and the reliance on the use of training data to develop the classifier. Modern wideband interferometric synthetic aperture sonars (SAS) provide far greater levels of information (high resolution complex images with a level of 3D information) and therefore offer the potential to improve the decision making quality. NURC is in the process of developing and implementing model-based adaptive ATR techniques which make use of the full range of available sensor data. Initial tasks have addressed comparison of high resolution images with a target model and demonstrate a high level of agreement.

5.3 Planning and evaluation

Whether planning individual or multiple system operations, an understanding of the level of search performance achieved by each of the systems is essential in order to assess the risk to follow on traffic. NURC is developing a software tool which enables the performance of AUV operations to be assessed by injecting synthetic targets into sonar data collected during missions and comparing the positions of contacts generated by an ATR algorithm with the positions of the injected targets.

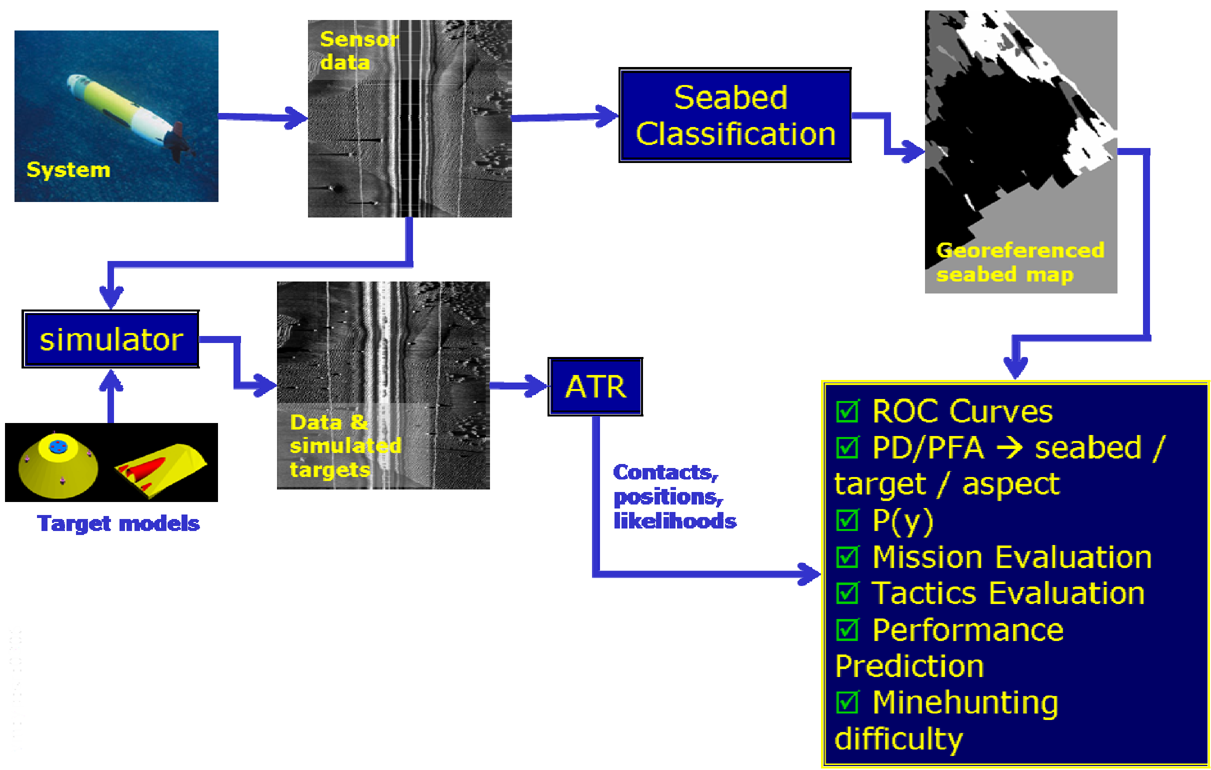

Figure 6; The NURC Planning and Evaluation tool methodology

The methodology [2], illustrated in figure 6, allows sonar performance to be assessed in terms of the probability of classifying a mine as a function of the number of false alarms (ROC curves) or as a function of across-track distance (P(y) curves). From these measures of effectiveness, the percentage clearance can be derived by applying probabilities associated with target reacquisition, identification, and disposal. Maps of percentage clearance can be obtained by segmenting the seabed by minehunting difficulty and calculating the sonar performance for each seabed class. Percentage clearance maps can be used to improve planning for further minehunting effort or to optimise the placement of routes. The software also has the ability to plan tracks based on a required percentage clearance across a channel, optimising track placement and minimising the number of tracks required.

5.4 Sensor processing

Although not covered in detail in this paper, the inclusion of real time sonar processing is both a key enabler and engineering challenge for the overall autonomous control system. As shown previously, the ability to produce high quality image data onboard the AUV is an essential pre-requisite for a networked autonomous system. Whilst this has been achievable for many years for sidescan sonars, robust real time processing for long range high resolution synthetic aperture sonar systems is far less mature. NURC has been examining different technology options for performing this task. Initial assessments examined the use of field programmable gate arrays (FPGAs) for the delivery of this capability as they were one of the few approaches which until recently had the potential to support the data throughput requirements of a streaming high resolution SAS. Whilst good progress was made in this area, it was decided to change the processing over to a PC based system since:

- the rapid developments in PC technology (such as the PCI Express standard) meant that PC boards are now able to handle the required data rates;
- the complexity of FPGA firmware development makes it a highly specialised process which results in changes and updates being more difficult to implement;
- PC performance is constantly improving and code can be relatively simply ported to new board designs.

At present the coding of the NURC SAS algorithms in C using the Intel Performance Primitives (IPP) library has been completed and integration with the proposed hardware is taking place.

6.0 SUMMARY

This paper has outlined the work being performed at NURC on the development of an autonomous mission control system for MCM AUVs. The requirement and technological gap has been identified and the progress towards achieving a solution has been described.

REFERENCES

[1] Antsaklis P, Passino K, Wang S, ‘An introduction of autonomous control’ Fifth IEEE International Symposium on Intelligent Control, Philadelphia, Sept 5-7, 1990

[2] Gary Davies, Vincent Myers, and Marc Pinto. Proposed way-ahead for project on planning and evaluation for MCM operations using AUVs. NURC White Paper (NURC-PR-2006-030), September 2004.

[3] Myers, V., Davies, G., Petillot, Y. and Reed, S. “Planning and evaluation of AUVS missions using data-driven approaches,” in Proceedings of the 7th International Conference on Technology and the Mine Problem, MINWARA assoc., (Monterey, California), May 2006

[4] Valavanius K, Gracanin D, Matijasevic M, Kolluru R, Demetriou G, ‘Control architectures for autonomous underwater vehicles’, Control Systems Magazine, IEEE, Volume 17, Issue 6, Date: Dec 1997, Pages: 48 – 64

[5] Hall W, Adams M, ‘Autonomous vehicle software taxonomy’, Proceedings of the 1992 Symposium on Autonomous Underwater Vehicle Technology, 2-3 Jun 1992, Pages: 49 – 64

[6] Smith S, ‘An approach to intelligent distributed control for autonomous underwater vehicles’, Proceedings of the 1994 symposium on autonomous underwater vehicle technology, 19-20 July 1994, pp 105-111.

[7] Bellingham, JG, Consi TR, Beaton RM, Hall W, ‘Keeping layered control simple’, Proceedings of the (1990) Symposium on Autonomous Underwater Vehicle Technology, 5-6 Jun 1990, Pages: 3 – 8.