

# BAUUV AUTONOMY

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## ABSTRACT

This paper discusses autonomous modules, developed under the SEA led UK MoD BAUUV programme, which provide higher levels of military AUV capability and describes their evaluation within recent water based trials.

BAUUV modules to address the key autonomy gaps include a military goal based user interface, an onboard replanning module, task based planning modules such as a transit planner and an autonomous swath planner, a collision avoidance module and a multiple vehicle planning module.

## INTRODUCTION

The UK MoD funded Battlespace Access Unmanned Underwater Vehicle (BAUUV) programme was a 3.5 year UUV technology research and assessment programme [Ref 1]. The initial phase of the programme aimed to assess the status of UUV technologies and to identify key technology gaps related to a wide range of future (2010-2015) UK military missions. Subsequent phases have involved focussed developments to move identified key technologies to Technology Readiness Level (TRL) 5/6 along with system engineering activities and work towards vehicle based trials.

The programme has assessed technologies within a range of areas. This paper is addressing some of the findings and resulting studies relating to the Command, Control & Mission Management (CCMM) technology area.

During the Technology Gap Assessment, the BAUUV team identified that one of the key technology gaps relates to the

*“provision of suitable levels of autonomy (and/or communications to human supervision) in order to perform long duration military missions”.*

The team found that CCMM strategies exist, based largely on detailed mission preplanning and extensive supervision, which are appropriate to many contemporary missions. However, such an approach would not be suitable for the execution of some of the envisaged future military missions.

The reliance on initial detailed plans will be unsuitable for some future missions as the characteristics of the mission; the vehicle and its environment may significantly differ from the situation known by the pre-mission planner. Some missions, environments and vehicles will have changing characteristics that would make an initial plan inappropriate. The vehicle may encounter unexpected threats or opportunistic events that significantly modify the remainder of the mission. Furthermore, with pressures on personnel numbers and limited communications opportunities within some missions, detailed tasking, retasking and supervision will be impractical or undesirable in some cases.

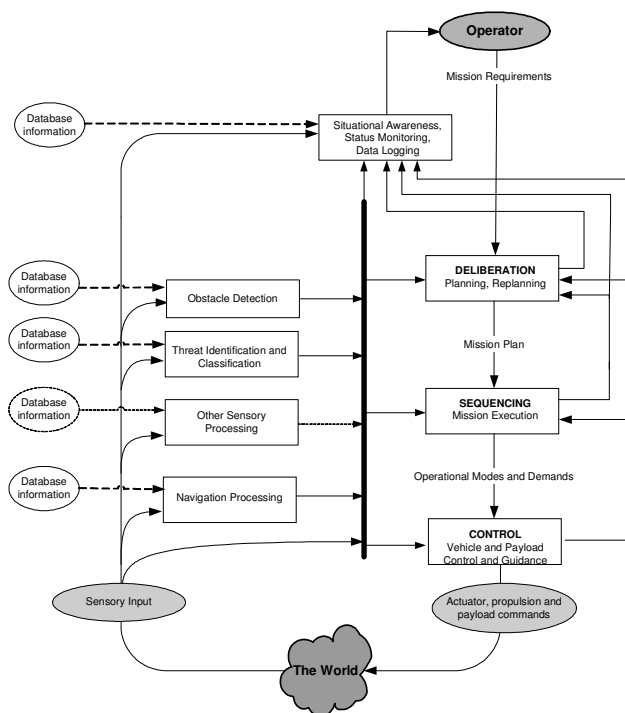
Therefore, some future missions will require vehicles that are more autonomous than existing platforms.

## FUTURE AUTONOMY ARCHITECTURE

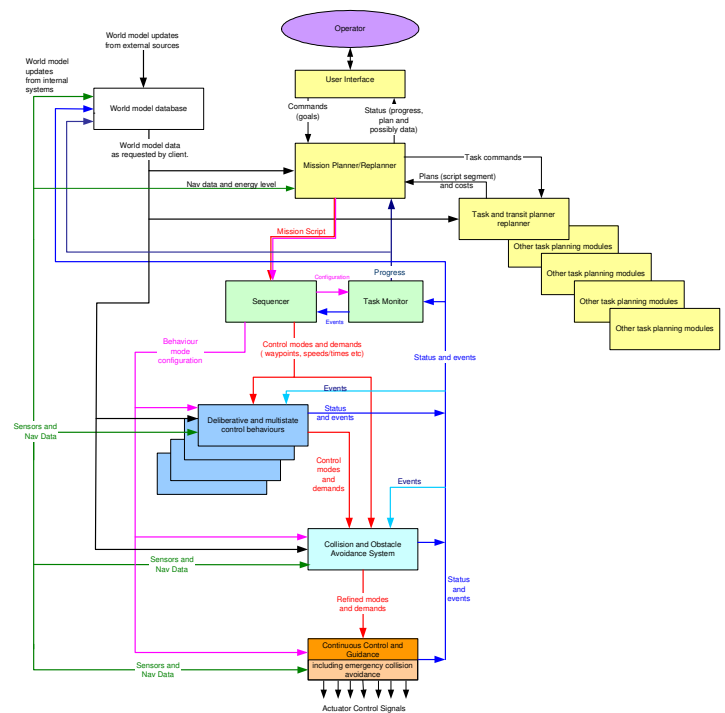
An outline UUV control system is shown in Figure 1. This includes a typical hybrid 3 layer control system [Refs 1-10] along with signal processing modules and associated databases and world modelling components.

The control system includes deliberative slow acting planning components, an intermediate sequencing layer and faster acting sensor based reactive control and guidance elements.

Within many conventional vehicles, deliberation and planning is essentially performed by a human supervisor who generates (and possibly updates) a mission script.



**Figure 1 Generic UUV Control Architecture**



**Figure 2 Example Future Architecture**

In a future UUV, some of this deliberation will occur on the vehicle. The user would therefore no longer need to manually plan a mission in detail but would instead specify military goals and constraints to autonomous planning replanning components within user tools and onboard components.

Such a goal based approach has previously been implemented for space based applications [Ref 11-20]. Whilst such applications operate in a different domain, they experience similar challenges to long duration UUV operations; both are restricted by an unknown and challenging environment, limited communications opportunities and supervision manning pressures.

An example future autonomy architecture is shown in Figure 2. Within the deliberative planning layer, an Intuitive User Interface allows the user to specify mission goals and constraints. These are passed to a Mission Replanner, which selects and orders the goals that can be achieved and calls the detailed task and transit planning modules.

The outputs of the deliberative planning layer (yellow in Figure 2) are updated mission plans. The sequencer (green in Figure 2) interprets these to generate control and guidance commands (orange in Figure 2). However, a future UUV may also contain additional task achieving behaviours and a collision and obstacle avoidance module [Ref 25] which can modify the output of the sequencing layer.

Key components within such a framework have been developed and under BAUUV as discussed below:

## BAUUV AUTONOMY MODULES

### User Interface

The user interface enables the definition of the mission goals and constraints and graphically displays the resulting mission script and displays UUV status updates.

A Windows based prototype user interface has been developed. To initialise the interface, the user first selects a vehicle configuration. Each vehicle configuration is retrieved from a Microsoft Access database and includes all the associated payloads and parameters for the selected vehicle. The vehicle configuration dialog is shown in Figure 3.

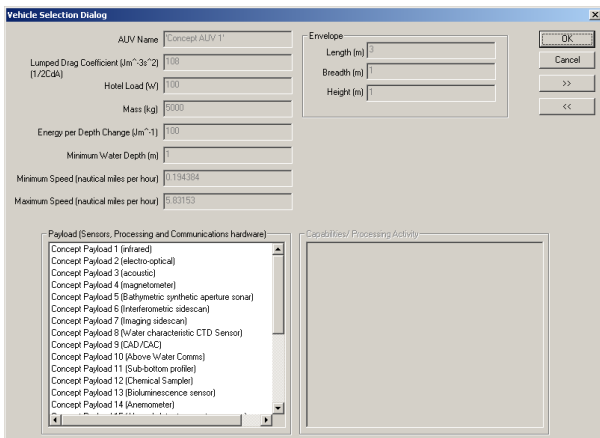


Figure 3 Vehicle Configuration Dialog

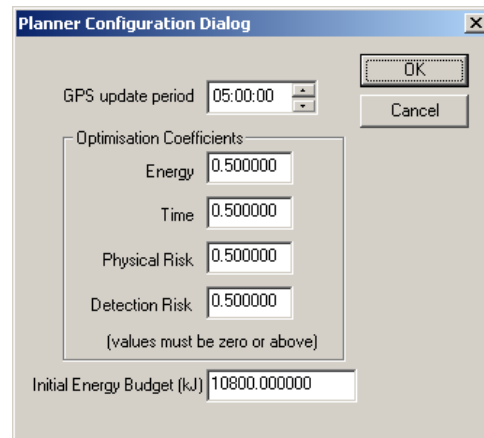


Figure 4 Planner Configuration Dialog

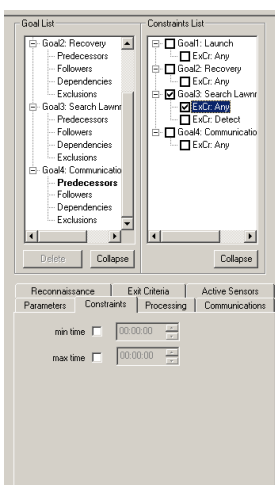


Figure 5 Defining Goal Constraints

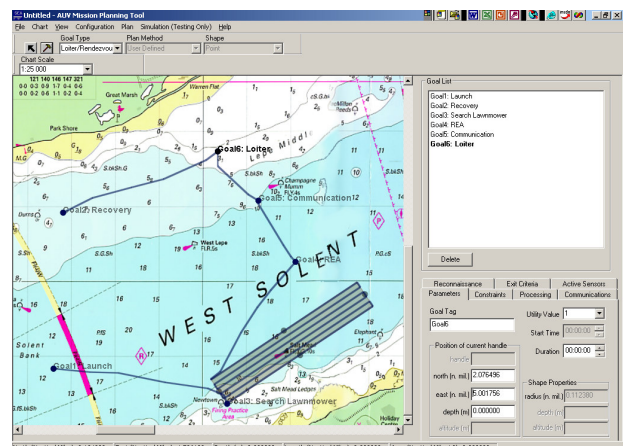


Figure 6 Defining a multiple goal mission

The user may also alter the default optimisation coefficients of the planning system, as shown in Figure 4.

To define a mission, the user is able to select a number of mission goal types, including Launch, Recover, REA, Reconnaissance, Communication, Loiter and Search/Survey. Each goal type also has a list of associated shapes, which may be added, deleted or altered using a digital navigation chart. Shape types include Point, Line, Polygon, Square, Rectangle, Hexagon and Circle.

After selecting a position for the goal on the chart, the parameters and constraints of each goal are entered in the property pages to the right of the display. The property pages include:

- Parameters: Goal Position, Utility Value, Duration
- Constraints: Minimum/Maximum time and constraining goals
- Processing: On-board processing activities that influence activated on-board sensors
- Communications: Data to be communicated and active communication payloads
- Reconnaissance: Repeatability parameters
- Exit Criteria: Goal exit criteria upon detect, timeout, command or complete
- Active Sensors: Active sensors listed upon processing techniques selected

The constraints selection dialog and the tabs for the other property sheets available are shown in Figure 5. Figure 6 displays a test plan containing multiple goals, including Launch, Recovery, Lawnmower Search, REA Point, Communication and Loiter.

The user interface uses its own version of the planning system to allow the goals to be validated before they are uploaded to the AUV. Following offboard validation, the goals can then be downloaded to the vehicle. However, when used with a contemporary UUV without onboard replanning, the mission plan is downloaded instead.

When communications opportunities exist, the user interface will display the current vehicle plan and status.

The User Interface (and optionally the vehicle onboard system) includes a version of the goal based planning and replanning software which is described below.

## Replanning

Mission replanning aims to respond to changes in information about the UUV and the world it is operating in from the “model” used to initially plan the mission. These changes include

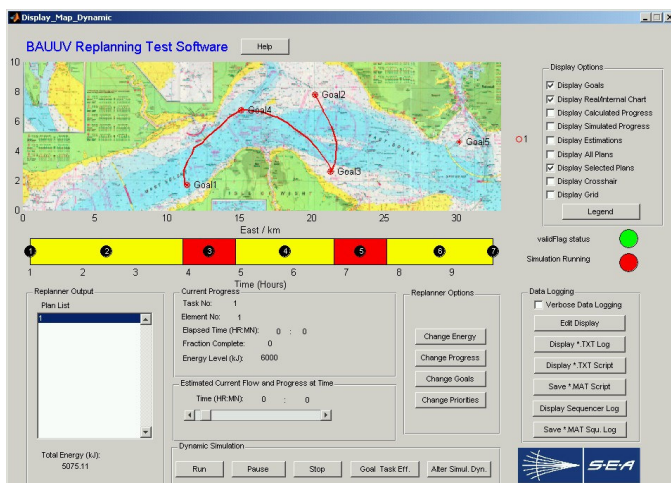
1. Sensed/deduced internal changes to the AUV
2. Sensed/deduced changes to the AUV’s world and mission
3. Directed changes to mission objectives.

In order to generate an initial plan the replanning system uses its plan building functionality to generate a new plan from the initial set of mission goals and its model of the UUV capabilities and environment.

During execution, the replanning system monitors progress, including energy usage and navigation data, and compares it to the plan. If a significant deviation from the plan is detected then a replan is instigated. A replan can also be triggered by changes in mission objectives or by unexpected events occurring.

Mission goals can be added, removed, or altered prior to a replan occurring.

In line with business and military planning and with many other autonomous replanning concepts [Refs 21-24], a hierarchical approach was adopted within the BAUUV replanning system. Such an approach allows an initial top-level plan to be quickly generated based on simple task models. Once an outline plan has been defined, this plan is then refined based upon more detailed task plans. Figure 7 shows a typical replanning test output.



**Figure 7 Replanning test output**

Within this test, goals 1 to 4 can be achieved but goal 5 to the east was rejected, as this was lower priority and required more energy than was available.

In addition to the core replanning module, a range of detailed task planning and costing modules have been developed by SEA. These include an autonomous transit planner and an autonomous swath planner.

## Transit Planning

The SEA Autonomous Transit Planner provides a key component within the BAUUV replanning system by planning and costing transit tasks.

In order to improve mission performance and reliability, environmental factors and risks are considered when planning a transit path. These include:

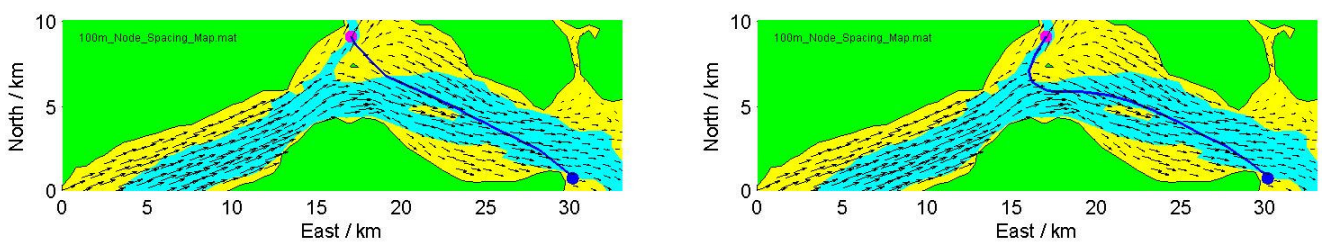
1. Time-varying and non-uniform subsurface currents
2. Time-varying water levels
3. Areas or times of high physical risk
4. Exclusion zones
5. Risk of detection.

Adapting to water currents is an important aspect to consider, as the limiting factor for AUV performance is stored energy. Water currents in the littoral zone can flow as fast as the operational speed of an AUV, and so reacting optimally to these currents is vital for mission success. When flying with the currents, UUVs can benefit from flying close to the surface, whereas when flying against the currents it is often advantageous to fly at depth or to take a longer route that avoids the main stream.

The military environment of an operational area has a strong bearing on the stealth (probability of detection) of an AUV. The detectability of the UUV will vary with position (eg relative to the coast line and military installations) and time. The physical risk (eg associated with grounding or collision) also varies with time and position.

The Transit Planner module considers the problem of finding the optimal 4-D (3-D position and speed) path through a time-varying, non-uniform directional field – composed of water currents and risks (both physical risks and risk of detection). Optimisation requires that a multi-parameter cost function be introduced.

The coefficients of the cost function are chosen by the user to reflect the vehicle “personality” as defined by the relative priorities given to energy, time, physical risk and risk of detection.



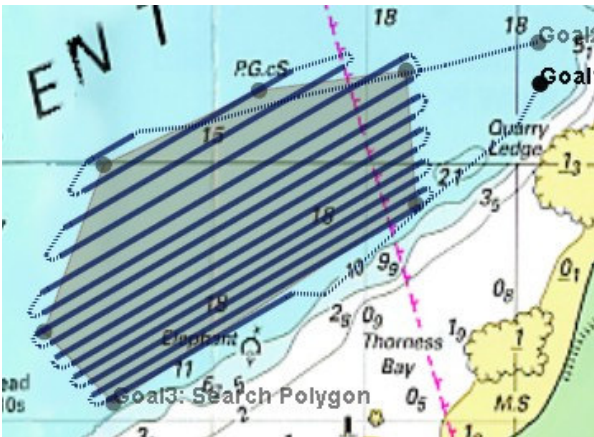
**Figure 8 Example transit plans (left plan is energy biased, right plan is risk biased)**

Example transit plans are shown in Figure 8. The left plan is biased to minimise energy, whereas the right plan with a more cautious risk settings avoids crossing the shallow water area.

## Autonomous Swath Survey Planning

The SEA autonomous swath survey planner aims to reduce operator workload and skill requirements relating to the definition of survey plans, to optimise the resulting plans and to facilitate onboard survey replanning.

The planner autonomously generates survey plans and costs based on the user defined survey area, resolution and sensor type. The planner takes account of the characteristics of sensors available on the vehicle along with the UUV manoeuvre envelope and any prior knowledge of currents and bathymetry. The resulting plan will include vehicle manoeuvre commands and sensor commands. For example, the planner can define when to transmit and the pulse repetition frequency (PRF) suitable to achieve the desired resolution whilst respecting vehicle speed and depth limits and sensor and acoustics limits.

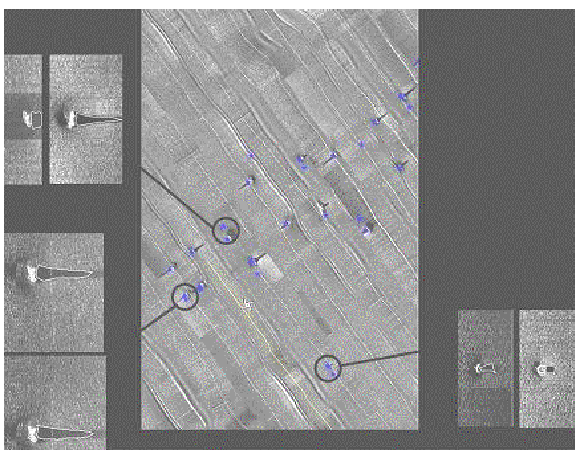


**Figure 9** Autonomously generated survey plan with varying swath width

If coverage data is available, the module can dynamically replan a survey to minimise gaps and overcautious overlap.

## World Modelling

Within a future UUV an onboard “world model” allows for evolving situational awareness knowledge to be stored and shared between autonomy and data processing modules. Under BAUUV, SeeByte considered this concept and developed a prototype world model architecture and supporting data fusion capability.



**Figure 10** The World Model facilitating autonomous fusion of multiple view CAD/CAC outputs

The world model was demonstrated with example planning and data processing clients and REMUS sidescan data. For example, CAD/CAC outputs from multiple runs were autonomously fused via the tool in order to reduce false alarms from duplicated targets (see Figure 10). The tool also fused the outputs of CAD/CAC and seabed classification clients in order to autonomously identify whether potential targets would be easy to hunt.

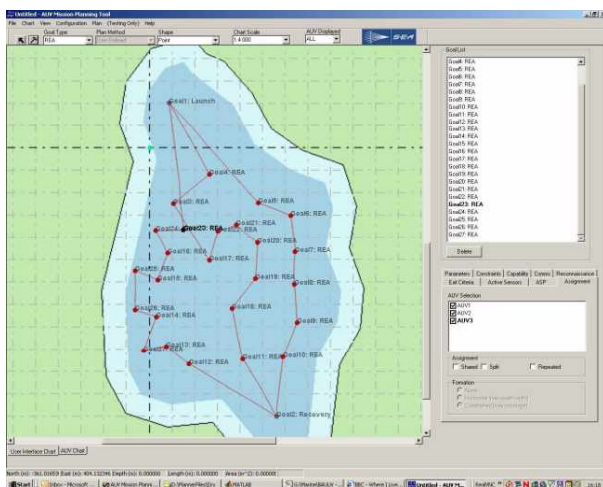
## Collision And Obstacle Avoidance

Under BAUUV, Heriot Watt University have developed a prototype collision and obstacle avoidance system [Ref.25]. The system includes both an emergency reactive component and also a novel deliberative component. This performs fast path planning to modify the vehicle path based on a vehicle referenced local obstacles map.

## Multiple UUV Operations And Planning

SciSys have addressed and compared concepts for multiple UUV operations within MCM missions [Ref.26]. Key elements have been simulated and also reproduced using University of Aberystwyth Aerobots.

SEA have extended their goal based planning and replanning software in order to handle multiple UUV operations. This reduces the significant human workload associated with generation of multiple vehicle plans and allows goals to be autonomously split or shared between vehicles in order to balance the mission cost (related to energy, risk and time) for each vehicle. For example, a large survey goal may be split into smaller surveys to be handled by different vehicles and many REA sampling goals may be shared between different vehicles.



**Figure 11 Autonomous sharing of goals between three vehicles**

Figure 11 shows an example whereby 27 goals have been shared between three vehicles.

## BAUUV INTEGRATED SYSTEM TRIALS

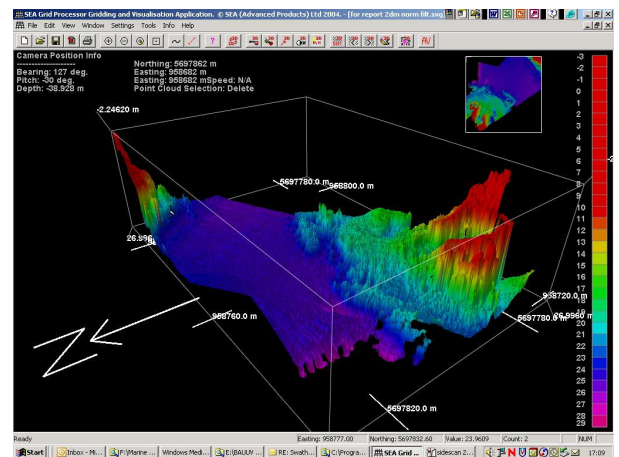
A series of vehicle based trails were performed during April and May 2006 in order to raise the Technology Readiness Level (TRL) of key BAUUV technologies and evaluate their in water performance. The trials took place in Portmore Loch near Edinburgh and at Vobster Quarry near Bath. Candidate technologies were hosted on the SeeByte RAUVER vehicle.

RAUVER was selected as its open frame construction and its Ocean Shell based networked system architecture simplifies the integration of candidate payloads.

The trails culminated in the execution of example mission elements which exercise the key BAUUV and guest technologies.



**Figure 12 RAUVER avoiding a net in Portmore**

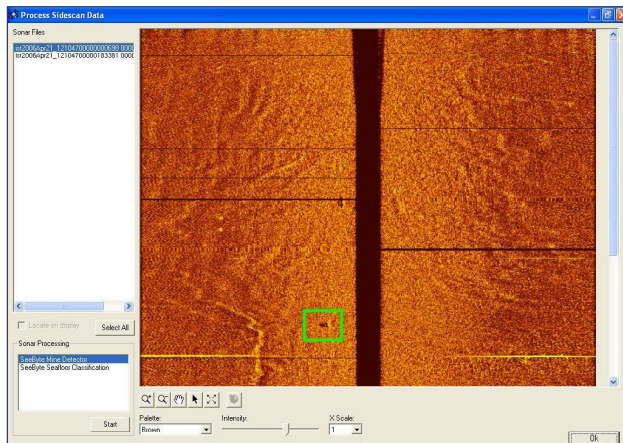


**Figure 13 Example bathymetry data**

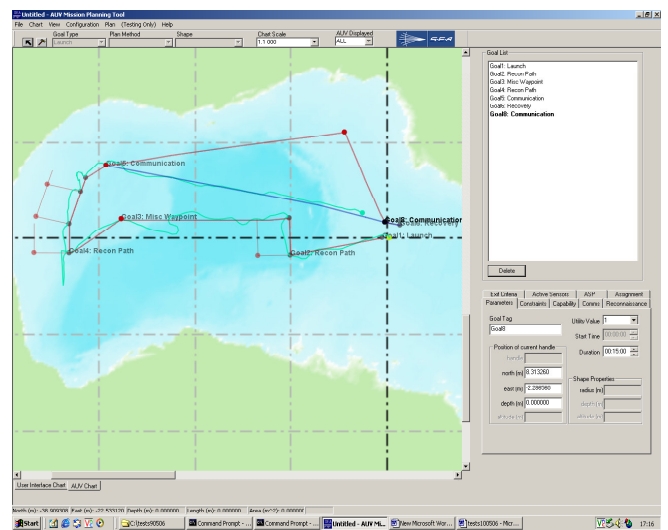
## MCM Mission Elements

Elements of an MCM mission were performed. This demonstrated the capability of the BAUUV Autonomous Survey Planner to generate survey plans which are suitable for coordinating a real UUV and sensor. The SWATH<sub>plus</sub> interferometric sonar generated bathymetry (see Figure 13) and sidescan data.

The data was used by a BAUUV CAD/CAC software module, developed by SeeByte, to locate and identify a mine like target (see Figure 14). The capability of an onboard replanner to replan a mission to include a reacquisition search at the position defined by the CAD/CAC software was also demonstrated during testing.



**Figure 14 Mine like target autonomously identified in sidescan data**



**Figure 15 Replanning and collision avoidance during a harbour penetration mission**

## Harbour Penetration and ISR Mission Elements

Elements of harbour penetration and ISR missions were also performed. The interaction of the goal based user interface and the onboard replanner was demonstrated. The vehicle replanned its mission in response to communicated goal changes, unexpected progress and an emulated unexpected change in energy use. Reconnaissance goals were planned and executed and the resulting video data was mosaiced by SEA MAVIS software.

The collision and obstacle avoidance and escape system was also successfully demonstrated. RAUVER was able to avoid multiple obstacles including a monofilament net with gear, a vertical pipe, a planer target and nested polypropylene nets with gear.

An example harbour penetration mission is shown in Figure 15. The red line is the pre-launch plan and the blue line represents mission replanned by the vehicle to accommodate a goal change. The green line is the onboard measured vehicle position; this shows the path deviations imposed by the BAUVV collision and obstacle avoidance system to avoid multiple nested nets.

## FUTURE WORK

BAUVV studies and trials have successfully demonstrated the utility and practicality of UUV goal based mission planning and replanning. Operational rules, constraints databases and modes of operation now need to be defined in order to foster user confidence and progressively examine the most appropriate use and level of supervision for the emerging autonomy capabilities. This should be carried out via the simulation and wargaming exercises in combination with military personnel along with trials in coastal waters.

The BAUVV obstacle avoidance system has also seen particular promise. Future work should involve the refinement of noise filtering and obstacle detection techniques, and the extension of the system to operate with wider range of vehicles, manoeuvre envelopes and avoidance sensor types.

The autonomous replanning system and the obstacle avoidance system have utility for other unmanned systems such as unmanned surface vehicles and crawlers.

## **CONCLUSIONS**

A future BAUUV CCMM system is likely to consist of:

1. User interface tools and deliberative on board planning and replanning modules
2. A world model database to store situational awareness information and support deliberative autonomy and sensor processing
3. A sequencing layer, which coordinates lower level behaviours based on planner/replanner outputs
4. Task achieving deliberative and reactive behaviours
5. Low level control modes

Key technologies within such a system have been successfully developed and derisked under BAUUV.

By enabling a UUV to plan and adapt to its environment and to avoid complex obstacles, such a system would facilitate the reliable execution of future missions where detailed planning and supervision is unavailable or unachievable.

As a short term “quick win”, some operator workload and mission performance benefits can be achieved by implementing a BAUUV type goal based mission planning within a user interface for a conventional UUV.

## **ACKNOWLEDGEMENTS**

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