

# AUTONOMOUS AUV MISSION PLANNING AND REPLANNING - TOWARDS TRUE AUTONOMY

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## ABSTRACT

This paper discusses concepts developed under the SEA led UK MoD Battlespace Access Unmanned Underwater Vehicle (BAUUV) programme to provide higher levels of military AUV autonomy.

BAUUV aims to identify and assess the technology readiness relating to a range of future (2010-2015) UK military missions and to perform focussed technology development activities to address key technology gaps.

One key gap relates to provision of suitable levels of autonomy to allow a UUV to perform long duration military missions. Contemporary autonomous underwater vehicles generally execute a prescribed mission plan with simple branching. However, future military missions will require higher levels of autonomy such that the vehicle can operate with a minimum of supervision and adapt to changing military goals, onboard health and situational awareness.

In order to reduce onerous and often impracticable human supervision and communications requirements, future military vehicles will need to perform some level of autonomous mission replanning and decision making in order to adapt to changes in AUV situational awareness, changes in knowledge of vehicle status and energy availability and changes in military goals. Autonomous mission replanning algorithms that aim to provide

this functionality have been developed and evaluated. The resulting mission replanning software utilises a hierarchical iterative approach with initial rough planning based on goal selection and sequencing activities being followed by detailed task planning and plan tuning. Replans can be instigated by user defined changes in goal characteristics or priorities or by internal triggers such as an unexpected change in energy usage or task progress.

In addition to core mission replanning algorithms, software relating to specific task planning/replanning modules is being considered. For example, an autonomous transit task planner has been developed. This is capable of autonomously defining and costing a transit based on encyclopaedic knowledge of subsurface currents, detection and physical risks. The AUV "personality" is defined by the relative vehicle energy, risk and time priorities which drive the selection of a particular transit plan. Other task planners being considered include those relating to communications, survey, reconnaissance, REA and logistics goals.

Within a typical three-layer UUV hierarchical control architecture, the onboard mission and task replanning elements would form part of the top level deliberative elements and would typically interface to a sequencing layer via an updatable mission script. The sequencing layer would interface to task achieving behaviours and low level

autopilot modes, potentially via a collision and obstacle avoidance module.

In addition to onboard elements, this paper discusses associated concepts relating to intuitive user interfaces and planning aids. Goal based planning/replanning technology enables the user to specify a mission based on a series of military goals, constraints and priorities rather than having to define a detailed mission script. This should increase the speed for the definition, validation and modification of future missions and reduce the skill requirement for a future military UUV user. An example goal based user interface prototype is presented.

Finally, after describing current study results and status, the paper will touch upon ongoing trial activities to advance the technology from TRL 4/5 to TRL 6.

## INTRODUCTION

The UK MoD funded Battlespace Access Unmanned Underwater Vehicle (BAUUV) programme is 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 TRL 5/6 along with system engineering activities and work towards vehicle based trials.

The programme has assessed technologies within a range of areas including Energy and Propulsion, Navigation, Communications, Design & Integration, Sensors & Payloads, Platform Integration, Data Logging and Command, Control & Mission Management (CCMM). This paper is addressing some of the findings and resulting studies relating to the CCMM technology area.

During the Phase 1 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 to 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.

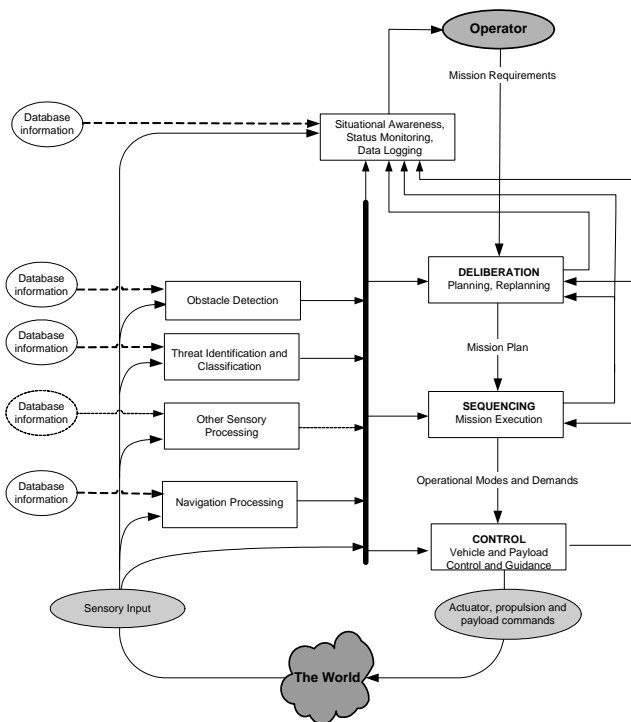
Therefore, some future missions will require vehicles that are more autonomous than existing platforms. Such vehicles can autonomously plan and execute a mission based on specified goals and constraints and autonomously replan a mission based on directed goal changes or changes to its situational and self-awareness. Under the BAUUV programme, algorithms and concepts to provide such autonomy and replanning capabilities are being examined.

## 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.

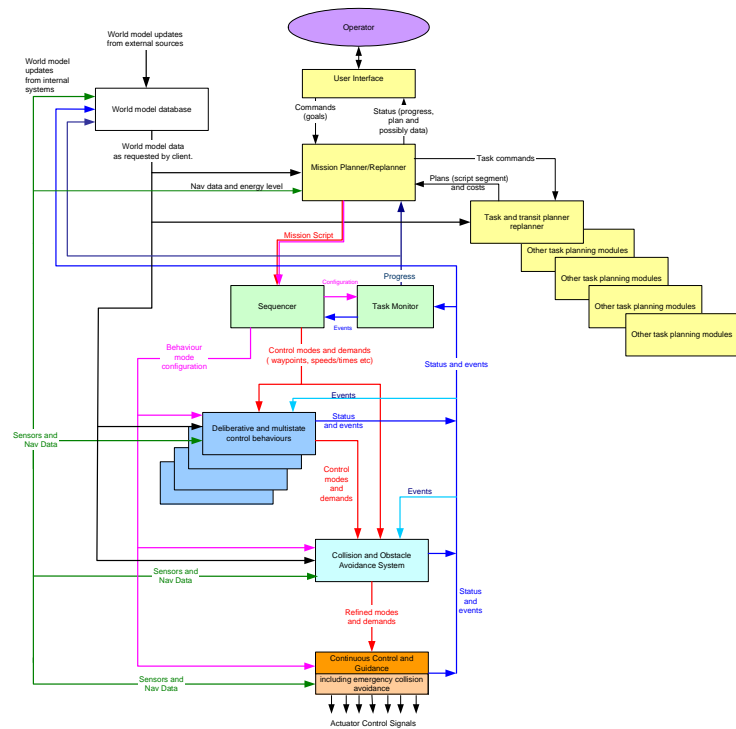


**Figure 1 Generic UUV Control Architecture**

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 which can be achieved and calls the detailed task and transit planning modules.



**Figure 2 Example Future Architecture**

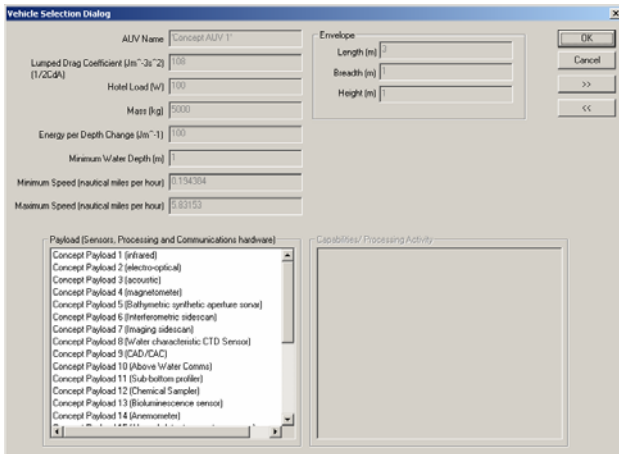
The outputs of the deliberative planning layer (yellow in Figure 2) are updated mission plans. The sequencer (green in Figure 2) interprets these to generate control and guidance commands (orange in Figure 2). However, a future UUV may also contain additional task achieving behaviours and a collision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

The key deliberative planning/replanning components being developed under BAUV are discussed below.

## USER INTERFACE

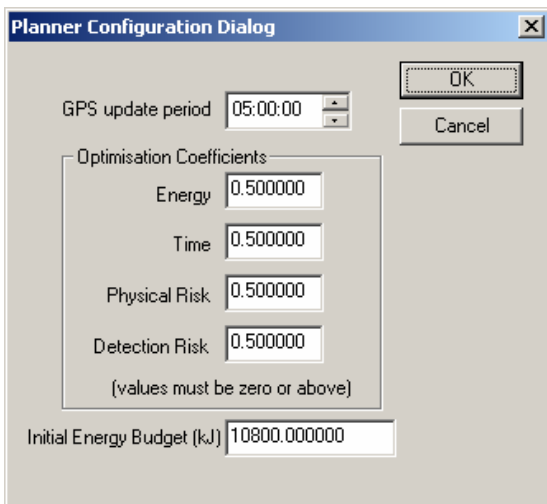
The user enables the definition of the mission goals and constraints, graphically displays the resulting mission script and displays UUV status updates.

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**

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



**Figure 4 Planner Configuration Dialog**

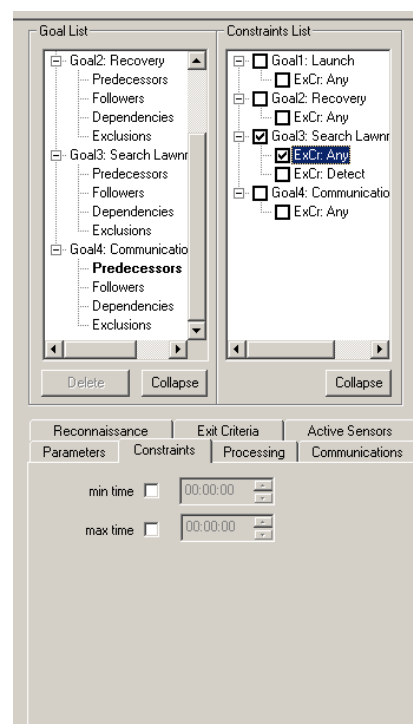
To define a mission, the user is able to select a number of mission goals types, including Launch, Recover, REA, Reconnaissance, Communication, Loiter and Search/Survey. Each goal type also has a list of associated shapes, which may be added, deleted or altered using a digital navigation chart. Shape 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 which 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 5 Defining Goal Constraints**

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. During the mission the User Interface planning system and AUV planning system will deviate due to deviations in progress or autonomous replanning activities.

When communications opportunities exist, the vehicle will communicate its location, progress and estimated battery levels. This information will then be used to estimate the current state and mission script of the AUV planning system. In a detailed supervision mode with available high bandwidth communications, the AUV may also be able to

communicate its current mission script, which will be displayed on the user interface chart.

Figure 6 displays a test plan created for a goal script, which contains a launch, recovery and Rectangular Lawnmower Search.

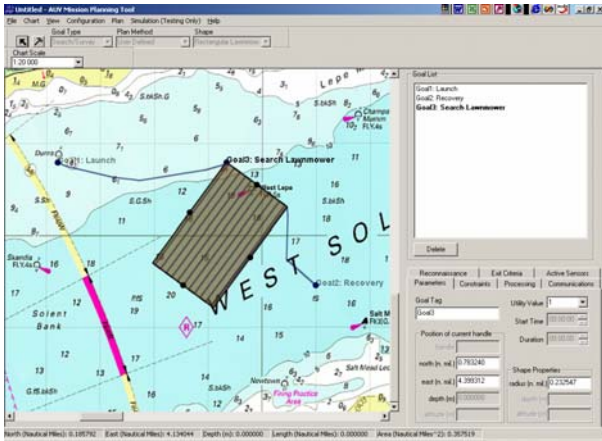


Figure 6 Defining a Lawnmower Search Goal

Figure 7 displays a test plan containing multiple goals, including Launch, Recovery, Lawnmower Search, REA Point, Communication and Loiter.

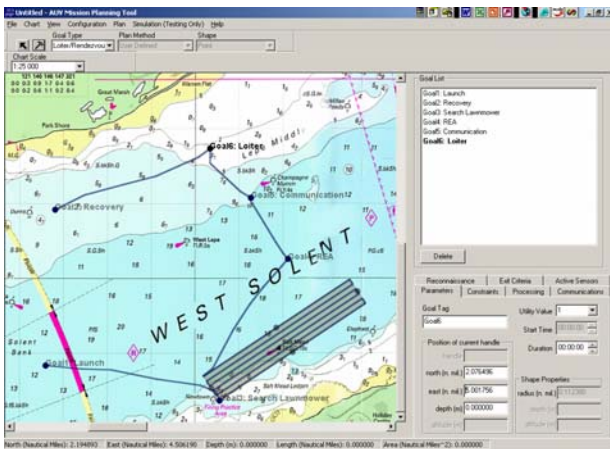


Figure 7 Defining a multiple goal mission

## 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.

The context of the replanning system is shown in

Figure 8.

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.

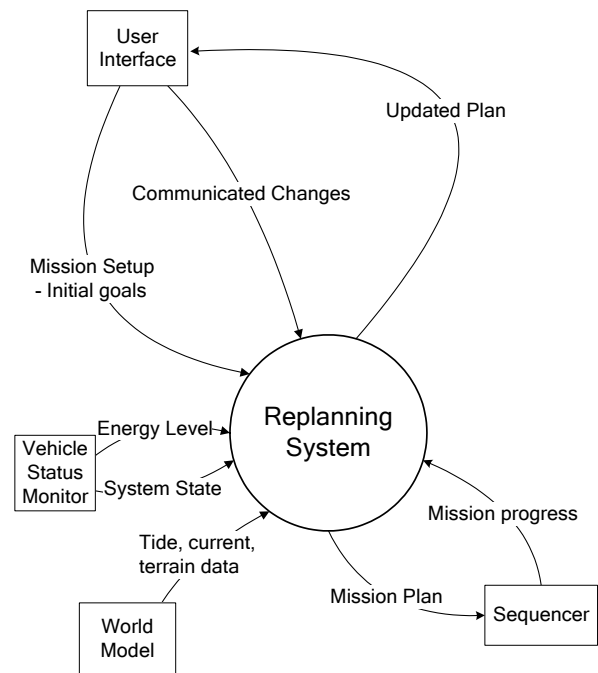


Figure 8 Replanning System Context

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.

This approach splits the replanning problem into at least two layers:

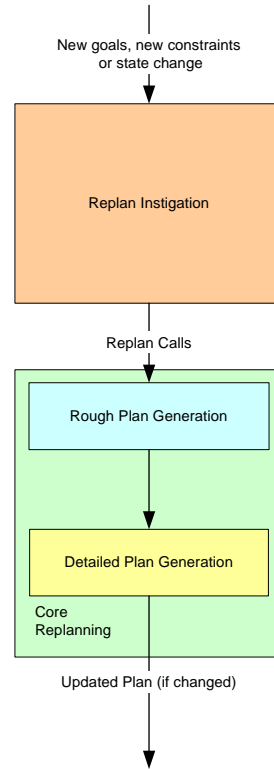
The **mission replanning layer** replans the existing mission plan to meet changing constraints and goals. Mission replanning involves determining a suitable sequence and schedule of tasks. Outline task cost estimates are taken into account during the mission replanning exercise, these estimates are subsequently refined during detailed task planning activities. The updated cost estimates may subsequently result in mission planning updates.

The **task planning layer** generates detailed plans and cost estimates for particular tasks based on the outline task description and time defined within the mission replanning layer. Task replanning may itself be layered (e.g. survey task planning may utilise route planning functionality). Planning modules have been prototyped for MCM, reconnaissance, REA, hibernation and loiter and communications goals. A transit is a specialised type of task.

In general the replanning system has the following simple sequence of actions:

1. Replan instigation – update goals and constraints and/or system state and, if appropriate, call replanning
2. Core replanning – search for valid and/or improved plan
3. If plan has changed then output new plan.

The core replanning function can be divided into two phases: rough plan generation (mission replanning layer) and detailed plan generation (task planning layer) as shown in Figure 9.

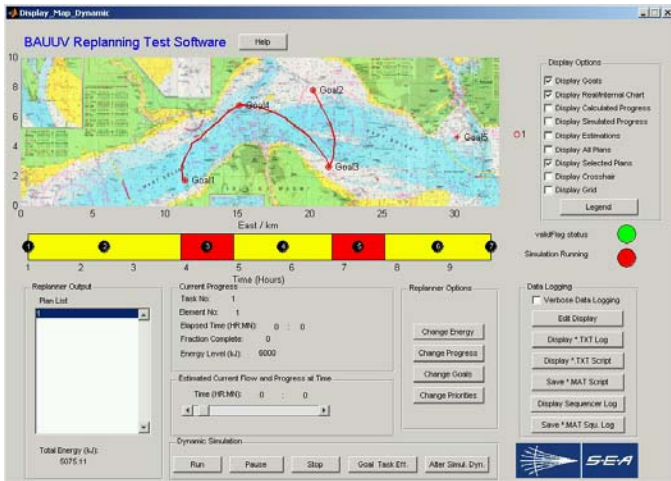


**Figure 9 General Replanning Sequence**

Rough planning aims to select the best order of goals that can be achieved based on the mission constraints and the available UUV energy level and resources. Rough time independent estimates of task costs are used at this stage.

Detailed plan generation involves the creation of detailed time specific task plans and, if necessary, revisits the rough planner to modify the task order and timing based on the detailed task values.

A software prototype of the replanning system was tested with a simulation based testbed. Figure 10 shows a typical test output/



**Figure 10 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.

The replanning software was subsequently integrated with the User Interface to allow for remission planning and onboard replanning.

### TRANSIT PLANNING

An autonomous transit planning module has been developed. This provides a key component within the BAUV 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

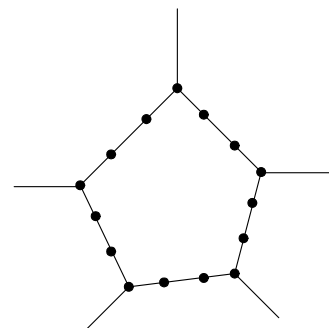
at depth or to take a longer route which avoids the main stream.

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.

A search based solution has been produced that is independent of the choice of cost function – other than that it will increase with time. Its choice must be driven by the application and map data available. In this instance a cost function is defined to be a linear combination of energy use, time taken, physical risk and risk of detection. 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.

The transit planner uses a predefined regions map area of operation. This is a tessellated map of convex cells (see Figure 11). The cells are sized such that the current is approximately uniform and constant across the cell over the time period for which the cell is occupied by the UUV. The cells also take account of boundaries such as coastlines and exclusion zones.



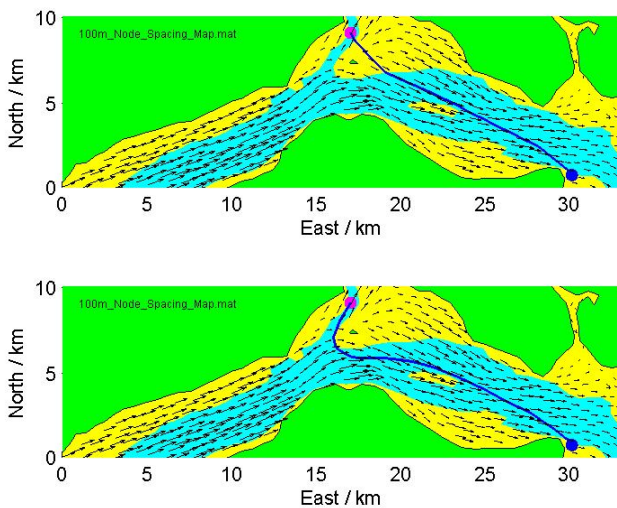
**Figure 11 Regions map cells and nodes**

A set of nodes are dynamically created along the edges of each cell. The definition of the node spacing is a tradeoff between plan execution speed and path resolution.

An environmental data server updates and interpolates time-dependant environmental and risk information for cells within the regions map.

The transit planner uses UUV parameters such as drag and hotel load, along with the regions map and data from the environmental server in order to calculate a path and speed profile between a given start and end point at a given time. Paths are generated for a particular combination of energy time and risk weightings. The transit planner also calculates the transit task cost to be used by the upper mission replanning layer.

Example transit plans are shown in Figure 12. The upper plan is biased to minimise energy, whereas the lower plan with a more cautious risk settings avoids crossing the shallow water area.



**Figure 12 Example transit plans (upper plan is energy biased, lower plan is risk biased)**

## FUTURE WORK

The mission and task level replanning software described above was initially implemented in Matlab and tested within a Matlab/Simulink test harnesses. The software has now been implemented in C++ flight code to allow for integration within the user interface and preparation for evaluation within the BAUVV Integrated System Trial. This is intended to take place during Spring 2006. The Heriot Watt University/Seebyte RAUVER Vehicle has been selected and upgraded for use as a test platform for these trials.

Other further activities may include the provision of further levels of task autonomy (e.g. autonomous swath planning and replanning) and the development of a goal based multiple vehicle planning and replanning tool.

Operational rules, constraints databases and modes of operation also 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.

The autonomous replanning system also has utility for other unmanned systems such as unmanned surface vehicles and crawlers.

## CONCLUSIONS

Autonomous mission replanning enables the AUV to adapt its mission based on updates to its situational awareness. An architectural framework and key modules have been developed to explore this concept and vehicle based trails are planned for 2006.

Key challenges remain, notably in defining operational rules, constraints and databases and additional planning modes. Implementation is likely to be progressive in order to foster user trust and acceptance. However, autonomy developments within BAUVV and other programmes are leading to the emergence of AUVs that are truly autonomous.

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