AUTOTRACKER: REAL-TIME ARCHITECTURE FOR PIPELINE AND CABLE TRACKING ON AUVs

Jonathan Evans, Yvan Petillot, Paul Redmond, Mark Wilson and David Lane
{j.evans ; y.r.petillot ; p.redmond ; mark.wilson ; d.m.lane} @ hw.ac.uk

Ocean Systems Laboratory, Heriot-Watt University,
Edinburgh, EH14 4AS, SCOTLAND, UK

ABSTRACT

As the underlying vehicle technologies for AUVs mature, increasing attention is being paid to the development of "smarts", onboard systems used to enhance and extend the range of autonomous operations that can be undertaken. These include advanced navigation, onboard CAD / CAC techniques (Computer Aided Detection / Computer Aided Classification), mission self-reconfiguration, and detection / recovery from onboard system failures.

This paper concentrates on one of the fastest maturing, and probably most immediately significant, commercially: Cable and Pipeline Tracking. A modular approach to this problem has been adopted for the technologies developed as part of the autonomous pipeline and cable tracking system. The AUTOTRACKER project is partially funded by the European Union and companies within the offshore industry. The system will be demonstrated and evaluated on real pipelines and cables using a commercial Survey-AUV.

This paper describes AUTOTRACKER's modular, distributed software architecture. It then outlines the sensor and processing techniques used for real-time control of the AUV to perform tracking and obstacle avoidance. In addition, details of the system tests and practical trials used in the development process are outlined.

1 INTRODUCTION

Probably the most mature of AUV applications is the use of survey-class vehicles (non-hover capable) for seabed survey. The main aim of using AUVs is to improve the quality of the survey data (for instance, by decoupling the motion of the sensor platform vehicle from the surface), and reduce the reliance on costly surface ship support. However, if low-altitude, high-resolution data is required, or the operating range of the sensors is limited, existing control systems on AUVs are unable to maintain the vehicle's trajectory within the narrow "survey" corridor.

The aim of the AUTOTRACKER project is to create a prototype system capable of on-board detection of seabed pipelines and cables, and demonstrate the real-time control of a survey-class AUV to perform surveys in realistic offshore environments.

To perform low-altitude, high-speed inspection over the extended ranges necessary for pipeline and cable survey it is essential to combine the two "smart" AUV technologies:

- **Real-time, embedded Detection and Tracking:** Detect the pipeline, and follow it to gather as much useful information as possible on the pipe condition (burial, corrosion, span) including possible re-acquisition phases.
- **Obstacle Avoidance and Path Planner:** Enabling low-altitude survey, in variable, unstructured and changing terrain.

The **tracking** component is essential to continuously manoeuvre the vehicle over the structure (e.g. pipeline), maintain optimal sensor coverage, and prevent the vehicle from falling out of the narrow (because of the altitude) pipeline survey corridor. It is not sufficient to simply navigate using the pre-programmed legacy data for the structure. Instead, the on-board systems must, in real-time, process the sensor data and issue the various course corrections to maintain the vehicle's track. In addition, if the pipeline or cable is lost (for instance, due to burial) the intelligent tracking system must be able to reliably detect this condition and navigate the vehicle to reacquire further along the known route of the pipeline.

The **obstacle avoidance system** is a key technology if the AUV is to swim very close to the seabed (~2m altitude), and not strike the numerous known and unknown objects (both natural and man-made) that are found all over the seabed, and particularly close to structures such as pipelines.

A modular approach to this problem has been adopted for the technologies developed as part of the autonomous pipeline and cable tracking system. The AUTOTRACKER project is partially funded by the European Union, and various companies within the offshore industry.

The consortium combines a range of expertise in AUV vehicles, embedded AUV "smarts", intelligent task planning, and a wide range of sensor processing and end-user knowledge:

- Heriot-Watt University
- National Technical University Athens
- University of the Balearic Islands
- Innovatum International Ltd
- Alcatel Submarine Networks
- Subsea7
- BP

The system prototype, including the embedded detection and tracking algorithm described here are currently under integration with Subsea7's GEOSUB AUV. Shallow water testing will begin soon, with first sea trials planned for early 2004.

2 PIPE DETECTION & TRACKING

Considering that a pipeline is a very distinctive man-made structure on the (typically) unstructured seabed, and considering the high availability of prior information about the pipe (max curvature, max and min diameter), a model based approach has been chosen. The pipe is detected on side-scan sonar images and tracked on MBE (Multi-Beam Echo-sounder) profiles. In each case, we use the *a-priori* information available to constrain the model.

Section 2.1 presents the pipeline detection and tracking algorithm on side-scan sonar images, while Section 2.2 concentrates on tracking in multi-beam echo-sounder profiles.

2.1 Side-Scan Sonar Pipe Detection

Man-made objects such as pipelines produce distinctive shadow regions in Side-Scan Sonar imagery, which can be used for detection and classification purposes. However, while the detection of these shadow regions is not difficult, assessing the results to determine whether a pipe is present can prove more problematic.

The SIDESCAN TRACER module within the AUTOTRACKER system, in real-time, analyses the incoming side-scan data, and determines the probability of one, two or three pipes being present in an image simultaneously.

Side-Scan Sonar images are generally very noisy, making analysis of the raw image very difficult. To overcome this, an unsupervised Markov Random Field (MRF) model is used to segment the image into regions of shadow and non-shadow (Figure 1). The resulting binary image is then split into horizontal sections, which are individually searched through for pipe-like shadow regions (Figure 2) using an adaptive non-linear filter. This introduces the idea that a pipe can be described simply as a collection of pipe-segments.

Although the movement of the AUV (or more classically, the sonar fish) can induce curves in the pipeline shadow, the system assumes that the pipe can be described as a linear line. To robustly fit multiple trajectory lines to the pipe-segments, a Least Median Squared algorithm was implemented. Outliers for each fitted line are removed as suggested, after which a Least Squares algorithm is fitted to the remaining inliers.

The model has been tested on multiple Side-scan images containing one, two and three pipelines. The results in Figure 3 show the resulting "trajectory" solution overlain on the side-scan data. The probability results for the various numbers of pipes being present in each of the images are in Table 1. As can be seen from the probability figures, the model predicted the correct result in all cases.

2.2 Multi-Beam Echo-sounder (MBE) Tracking

Once the pipe has been detected in the sonar image, the vehicle can be driven to a position above the pipe where multi-beam data can be gathered. For reliable, high-resolution data this might be as close as 2 metres altitude.

Due to the large variety of possible scenarios (pipeline partially exposed, span, pipeline in trench – for example see Figure 4) it is very difficult to design a filter that will cover all possible cases. However, there is a common denominator to all those scenarios: the pipeline or the trench are circular (or elliptical) profiles of an approximately known size. If we can model this property together with the accuracy of the fit between the model and the observed data, it should lead to a robust tracking system.

The problem can be stated as an optimisation task, with the parameters of the model that we wish to estimate. The pipeline profile is modelled as a segment of an ellipse. Other parameterisations are possible, and do not change the principle of the algorithm.

Currently the parameter set is composed of:

- Centre of the pipeline
- Bottom depth
- Burial depth
- Major and minor axis of the ellipse

A typical plot of a pipe and seabed profile obtained by a multi-beam echo-sounder is shown in Figure 4.

Table 2 shows the highly accurate relative positions obtained from the MBE Tracer process. On the vehicle, these results are then fed to the sensor fusion, and task planning control systems to dynamically alter the vehicle's trajectory and keep the sensor in its optimal position – plus simultaneously recording the pipeline's position.

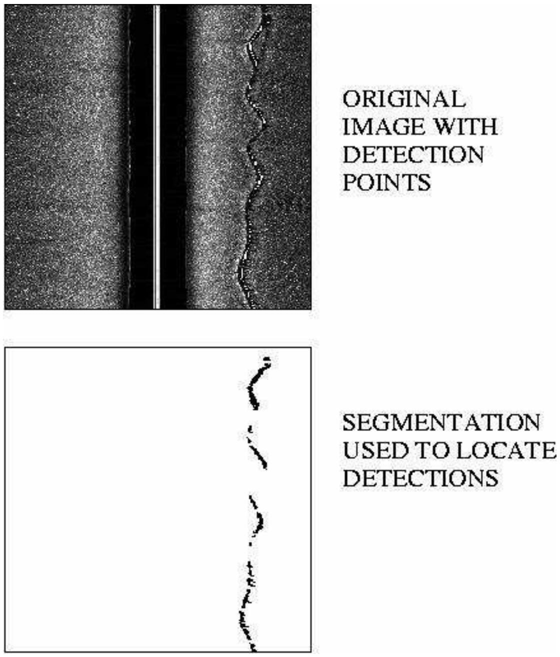


Figure 1: (a) Raw, ungeoreferenced side-scan image; (b) Output of segmentation process showing the disjoint pipe sections.

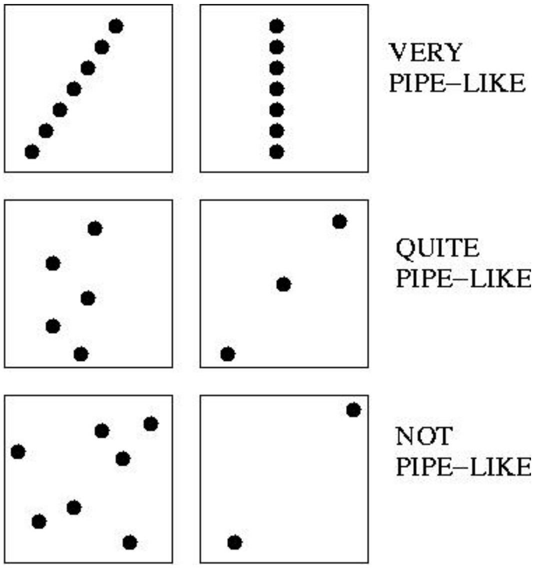
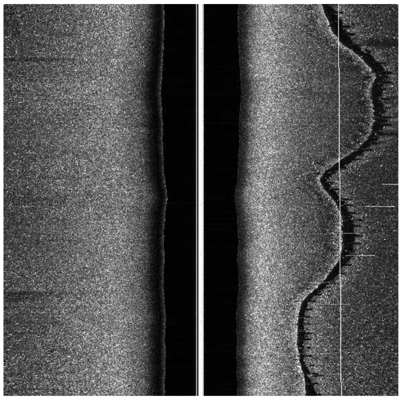
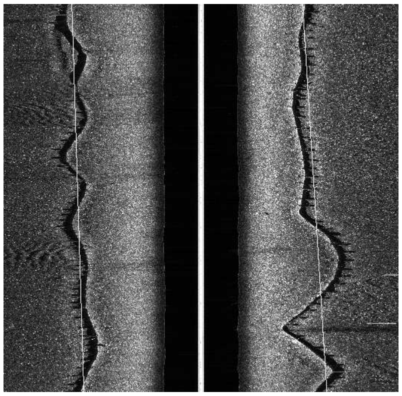


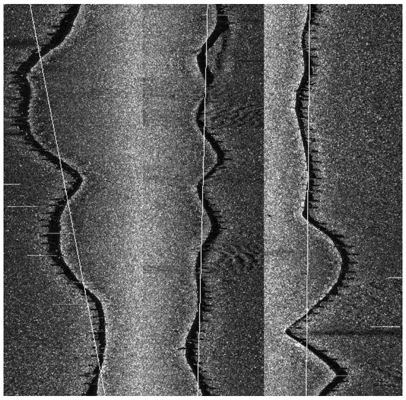
Figure 2: Examples to demonstrate how a pipe can be described as a series of closely spaced and aligned segments



(a) One Pipeline



(b) Two Pipelines



(c) Three Pipelines

Figure 3: Displaying the most likely outcome as predicted by the model for images containing 1, 2 and 3 pipes respectively

Table 1 : Probability Results for the 3 possible scenarios for each of the 3 images presented

OVERALL PROBABILITY	1 pipe image	2 pipe image	3 pipe image	Correct Solution ?
P(1 pipe)	0.751	0.600	0.304	YES
P(2 pipes)	0.122	0.713	0.632	YES
P(3 pipes)	0.005	0.145	0.787	YES

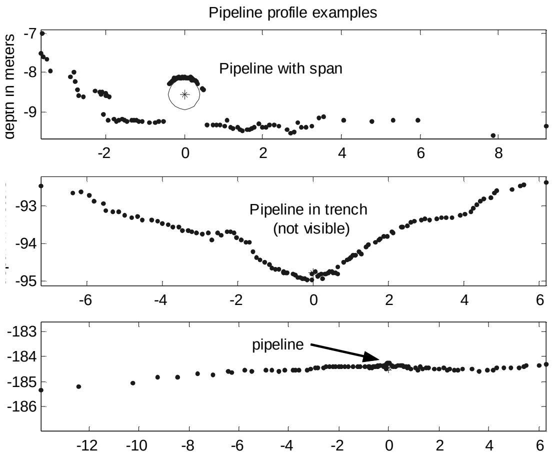


Figure 4: Examples of raw MBE profiles for various different pipelines.

Table 2: Mean and Standard Deviation of the Error in position of the pipe estimate in metres on 100 pipe profiles for each scenario in tracking mode. The PD (Probability of Detection) is %

PIPE TYPE	HALF-BURIED	TRENCH	SPAN
Mean Err (m)	0.0104	0.16	0.08
Std. Dev.	0.0092	0.12	0.14
PD (in %)	100	91.2	96.0

3 OBSTACLE AVOIDANCE AND PATH PLANNING

Obstacle avoidance systems are a key technology needing further development if AUVs are to work close to the seabed or submerged structures. Previous research work at HWU (Lane, and Stoner., 1994; Lane, *et al.*, 1998; Petillot, *et al.*, 1998; Smith; Petillot, *et al.*, 2002) led to the development of a real-time, 2D OAS (Obstacle Avoidance System). The specific requirements of AUTOTRACKER demand the extension of this technology to three dimensions – allowing the AUV to “rise over” obstacles, as well as “pass round”.

The OAS is required to enable the AUV to perform low-altitude (~2m), high-speed (~3knts) survey, and is capable of detecting unknown (and known!) objects - both natural and man-made. The aim is to determine in real-time the avoiding course, while minimising loss of sensor data.

Figure 5 shows the sonar configuration for the OAS – two imaging sonars are used to scan both down and forward simultaneously. An interesting feature of this configuration is that the “downward-looking” sonar is swept to the horizontal providing an estimate of the forward bathymetry.

The approach uses an analogy to charged particles moving with an electric field, called Potential Fields (Latombe, 1991; Petillot, *et al.*, 2002). This permits the simultaneous solution to the basic Obstacle Avoidance problem (i.e. preventing a collision), together with the more advanced problem of Path Planning (re-establishing a route to the goal or waypoint following a deviation).

3.1 Potential Field Method

The concept of the potential field method is to model the vehicle as the equivalent of a charged particle in an electric-field which represents the feature space. Any obstacles (the seabed itself is treated as an obstacle) are regarded as having a charge of the same potential, with the magnitude of the field decreasing with distance from the obstacle. The approach exploits the physics of the repulsion of similar charges – the aim being that the vehicle avoids any obstacles, just as similarly charged particles avoid each other.

To apply this concept to navigation through feature space, a potential map is created. This involves allocating zero potential to the desired goal point and increased potentials to the other points in the map based on their distance from the goal point. The relationship between distance and potential is often parabolic or conical in nature creating a “potential well”. Sonar data is then interpreted and mapped into the potential map. Any point on the map which is thought to contain an obstacle is allocated an infinite potential and surrounding points allocated a progressively smaller potential. The number of and extend to which surrounding points are affected can be altered to suit a particular system.

This leads to the situation where the goal point is the global minimum i.e. it has the lowest potential of any point in the map. Since the potential field is essentially a ‘well’ (see Figure 6) the most sensible way to search for a path from start to goal points is to follow the steepest gradient of the potential well. This is achieved by examining the neighbouring points at any position, and selecting the point with lowest potential. This is commonly known as the “depth-first”, or “gradient-decent” algorithm.

3.2 Depth-First Algorithms

Such an algorithm can, however, become trapped in local minima. This is the condition (illustrated in Figure 7) where the algorithm follows the steepest gradient into an area surrounded by obstacles from which there is no escape. Local minima results in complete failure to plan a path, and must be avoided. Consequently, an alternative algorithm, the “best-first” algorithm was adopted. This algorithm operates in a similar manner by following the steepest gradient, but crucially stores the points which it has visited in a tree. When an area of local minima is encountered, the algorithm can search back through the tree and choose an alternative path which is the next steepest gradient, thus allowing local minima to be escaped. When the goal point is found the tree is optimised to reveal the path without the unnecessary transit into the area of local minima (see Figure 8). Once a suitable path is found, it can output to the vehicle mission controller.

3.3 Vehicle Dynamics

A key issue in path planning is to produce a path which the vehicle is actually capable of following and hence the dynamics of the vehicle must be incorporated. Since the best first algorithm traditionally works by examining the potentials of neighbouring points, the grid resolution must be of sufficient resolution so that the vehicle would be capable of reaching any of the neighbouring points. Such an approach would result in a very large potential map, unsuitable for real time applications. An alternative would be to use a coarse grid, but perform repeated searches until a path which satisfies the dynamic constraints is found. This would, however, result in inconsistent search times - again unsuitable for real-time applications.

To overcome these problems a “look-ahead” sampling approach was identified. This involves the best-first algorithm searching the potentials of not the neighbouring points in the potential map, but points a distance ahead of the present location. These points are calculated based on the turn radius and turn rate of the vehicle (so that they are achievable). The distance from the present location to each search point is not less than the vehicle turn radius. In the limit, this allows the planner to calculate the path necessary to perform a complete U-turn. This is the most extreme “avoidance” manoeuvre, and is necessary as the GEOSUB AUV (like most non-hover, Survey-AUVs) does not have the capability to reverse.

The limitation of this look-ahead sampling method is that an obstacle can be present in-between the present location and the search points and so may not be detected when planning a path. This may be overcome by creating a safety zone around obstacles or by extending the scale and influence of the potential field around obstacles. The exact implementation of this strategy depends on the dynamic capability of the vehicle in question but it offers a way to find a valid path in real-time.

3.4 Potential Corridor

An additional key constraint in AUTOTRACKER is the need to stay (whenever possible) above the pipeline, and not drift to too far left or right where the magnetic or acoustic sensors may not sense the pipeline. It is therefore desirable to prioritise the “go over” route (Figure 9), compared to the more usual “go around” (Figure 10) of most obstacle avoidance systems (hence the need for 3-D obstacle avoidance). To satisfy this requirement a potential corridor has been integrated into the potential map. This involves simulating obstacles to form a narrow corridor from start to goal points, the width of this corridor is such that the magnetic sensors will not loose track of the pipe if the vehicle remains within the corridor.

A search for a suitable path is conducted within the corridor, and if no path can be found, the corridor is removed and another search conducted, accepting that this may result in the temporary loss of the pipeline.

3.5 Map Management

Due to the real-time processing requirements, the Potential Map must be fixed in size, and this size is related to the range capability of the on-board obstacle avoidance sonars. The overall start and goal points are likely to exist outwith this map and so a local goal (waypoint) is identified along with the AUV’s present location. A suitable path is then planned from the current location to the local waypoint. During the transit along this path, the map is regularly updated with new sonar images. Depending on the configuration of the on-board sonars and the vehicle’s pitch and yaw, these images will install more of the AUV’s environment into the map, and will update existing areas. The “new” potential field can then be calculated as each new sonar frame is received. An updated (or completely new if obstacles require) path can then be calculated from the present location (obtained from navigation data) to the local goal. Typically this happens every few seconds.

Once the vehicle has progressed half way towards the edge of the map, the map is redrawn with the vehicle at the centre of the new map, and a new local goal defined. The relevant sonar data from the old map must be loaded into the new map otherwise the information uncovered thus far will be lost. This is an important aspect of the map management.

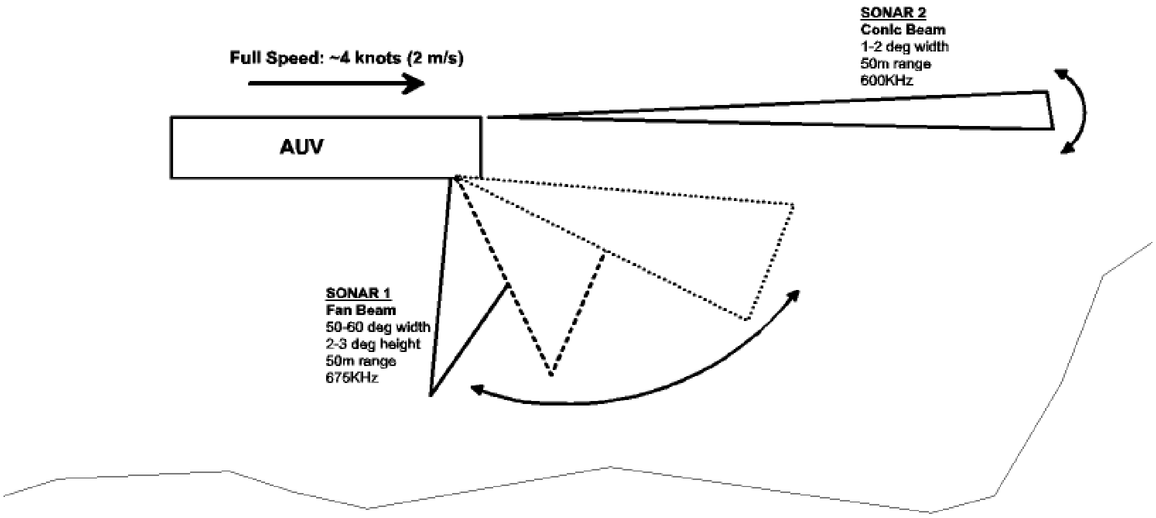


Figure 5: The dual sonar configuration used for the 3D OAS and Path Planning system

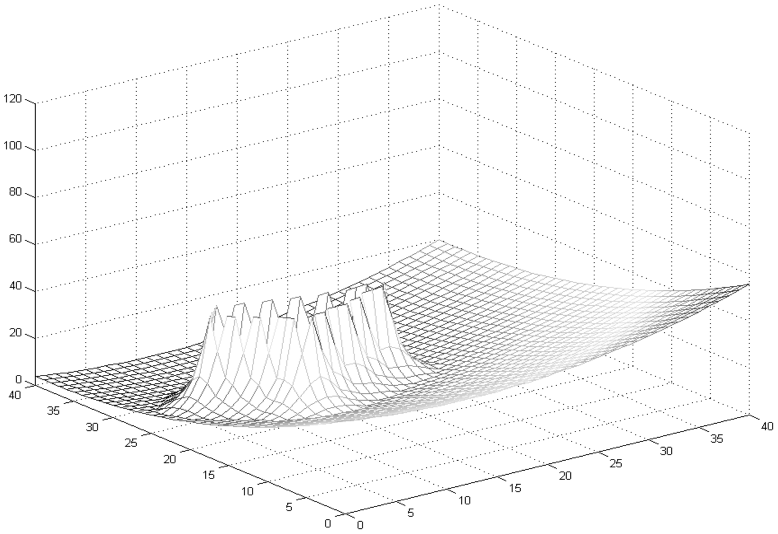


Figure 6: 2-D potential well with obstacle - height indicates magnitude of potential

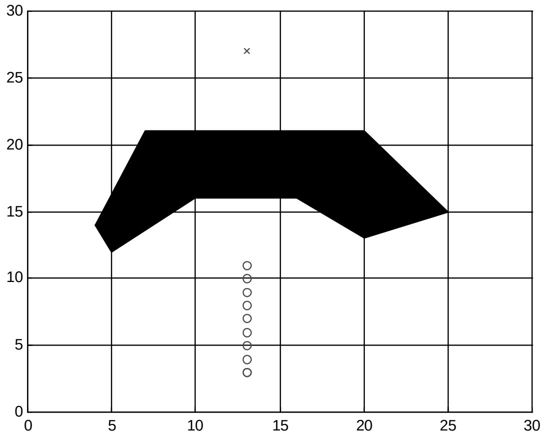


Figure 7: Depth first algorithm trapped in local minima

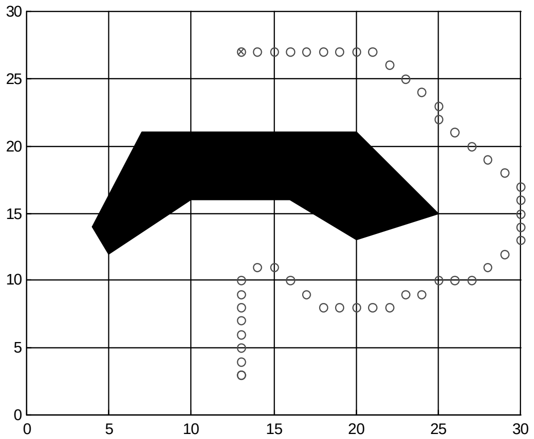


Figure 8: Best first algorithm avoiding local minima

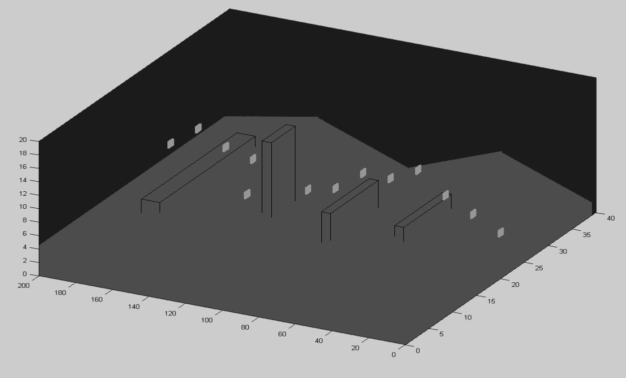


Figure 9: Example of 3D obstacle avoidance, including "rise-over" motion

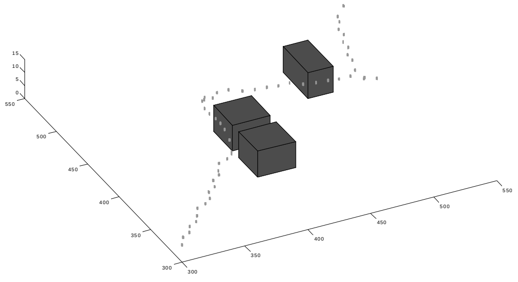


Figure 10: Further example of avoidance motion where vertical ascent is impossible

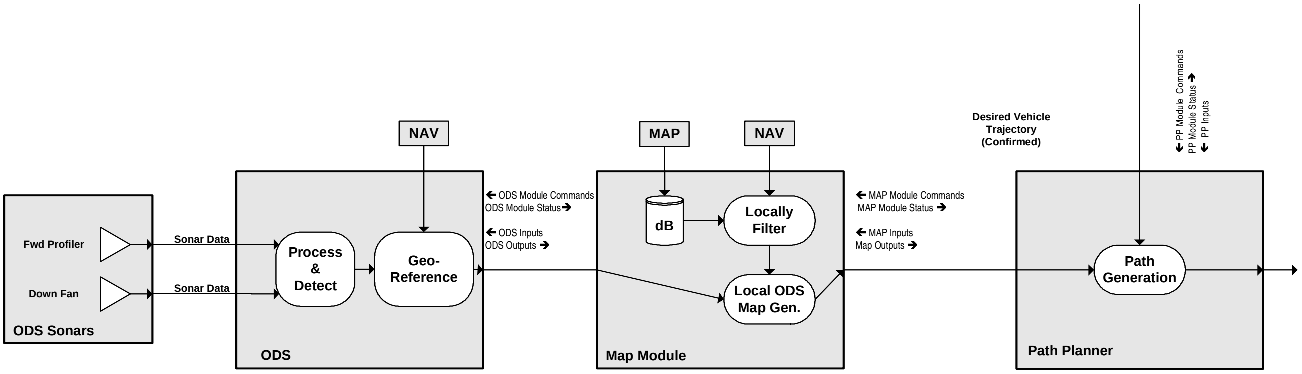


Figure 11: System diagram of the OAS components of the AUTOTRACKER system

4 SYSTEM ARCHITECTURE

The AUTOTRACKER system comprises of a number of software modules all constructed from a common module framework. This framework is a suite of C++ Programming Language Classes which can be viewed as ready to use application shells, simply waiting to be filled with an algorithm at a known point. Inter-Processes Communication (IPC) is inherited by the Module in the form of another HWU designed component, the shared memory. The shared memory manages data-structures, encapsulating them in messages, sending them out over a communications link when they are updated, and conversely updating the relevant data-structures when new messages are received. The particular communication link used is a UDP (User Datagram Protocol) over IP (Internet Protocol), and distributed in a broadcast fashion over a small Ethernet LAN.

Common behaviour in response to a set of generic Command messages e.g. OFF, STANDBY, and RUN, is inherited by the modules. The behaviour for the OFF command is to enter a silent, non-active state with no initialised sub-systems. STANDBY, results in the initialisation of any particular sub-systems necessary for the full functionality of the specific module. RUN, sets the module into full functionality, again this is specific to the particular module. Additionally the reporting of the module's state in a Generic Status message is also inherited by Framework Modules.

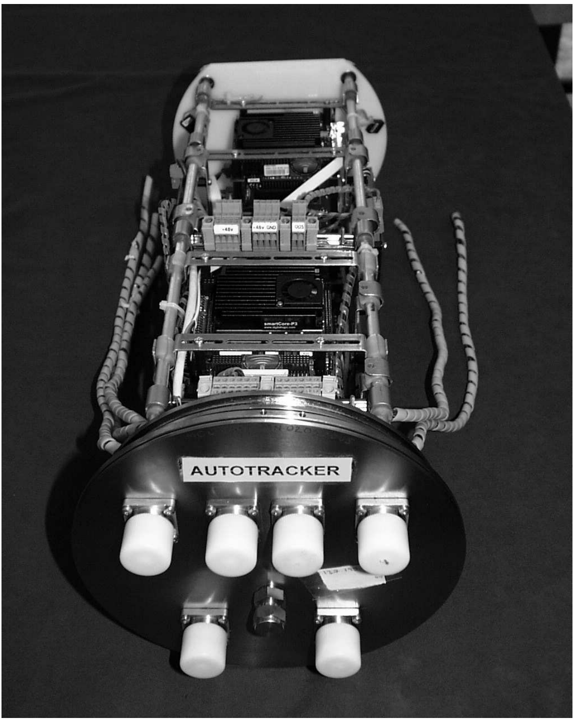
Modules in the Tracking System are structured in a hierarchy, providing a "chain of command" type arrangement. For example, there is module responsible for the construction of a map containing geo-referenced obstacles (see Figure 11). In order to function, the Map Module needs to receive data from an Obstacle Detection System Module (ODS). The Map Module will send to the ODS, STANDBY, RUN and OFF commands as required. It will also monitor its Status message to ensure the ODS module is in the correct state. The Map Module itself is controlled and monitored in an identical fashion by a Path Planner Module which uses Map Module output along with the output of other Modules and Systems to create a Vehicle trajectory which follows pipes/cable whilst avoiding obstacles. Another hierarchy of modules links sensor processing modules, a data fusion module, and an expert system module.

The Module Framework and its inherited IPC, has simplified the software engineering task. The use of the common module framework across the Tracking systems modules allows confidence in the consistency of the behaviour of numerous modules. Engineers and Researchers can focus on core implementation issues with respect to the specific module they are working on. The Module framework has also been adopted by HWU's project partners, NTUA, and UIB to host their fusion algorithm, and expert system modules.

The highly reusable nature of the Module Framework is demonstrated, by it use in the EU ALIVE project, and by its adoption as the software framework for HWU's internally developed RAUVER AUV.

5 AUTOTRACKER HARDWARE

The AUTOTRACKER hardware is designed to be an intelligent payload ("pod") that can be hosted on any Survey-AUV. The internal modules of the AUTOTRACKER are independent of the host AUV – the AUV specific interfaces are contained and maintained within a "Personality" or Interface Modul.e



.

Figure 12: Photograph of the AUTOTRACKER "pod" – with its four high-performance PC104-based computers

Physically the "pod" is a distributed real-time processing platform hosted on 4 high-performance LINUX-based PC104 computers (see Figure 12), working as a computing cluster. Additional software on the "pod" supports real-time fault detection, and process reorganisation to maintain mission critical components.

6 GEOSUB AUV

Subsea7 (www.subsea7.com) is the AUV partner within the AUTOTRACKER consortium. They provide expertise in the commercial operation of AUVs for the offshore oil and gas markets.

The Geosub AUV has been developed by Subsea 7 for commercial applications in the oil and gas and subsea cable markets. Geosub addresses the increasingly demanding requirements for high resolution geophysical survey allied with high accuracy positioning in ever-deeper waters.

Geosub is designed to operate in water depths to 3000m and has a mission time of between 30 and 60 hours depending upon payload configuration. The power source is based on environmentally friendly, state of the art battery technology providing excellent power density. The vehicle dimensions are 6.82m in length and 900mm in diameter, and weighing in at 2400kg (shown in Figure 13), the vehicle is an ideal stable platform for operating a comprehensive range of survey sensors close to the seabed. A schematic overview of Geosub is given in Figure 14.

7 CONCLUSIONS

The AUTOTRACKER project is one of "next generation" development projects underway around the AUV community. As AUV vehicle technology (for example, thrusters, guidance, batteries etc.) matures, there is a growing demand for "intelligent" payloads which can emulate functions previously done by human pilots - or perform functions previously impossible without embedded control systems.

By combining real-time, embedded tracking together with autonomous Obstacle Avoidance and Path Planning techniques, the AUTOTRACKER system will significantly advance the state-of-the-art for "intelligent" AUV applications – and will hopefully find real commercial service in the pipeline and cable service industries.

The Geosub modifications are underway to host the AUTOTRACKER system, including the magnetic tracking sensors. Full sea trials of the complete system are due in Spring 2004.

Figure 13: Recovery of GeoSub AUV

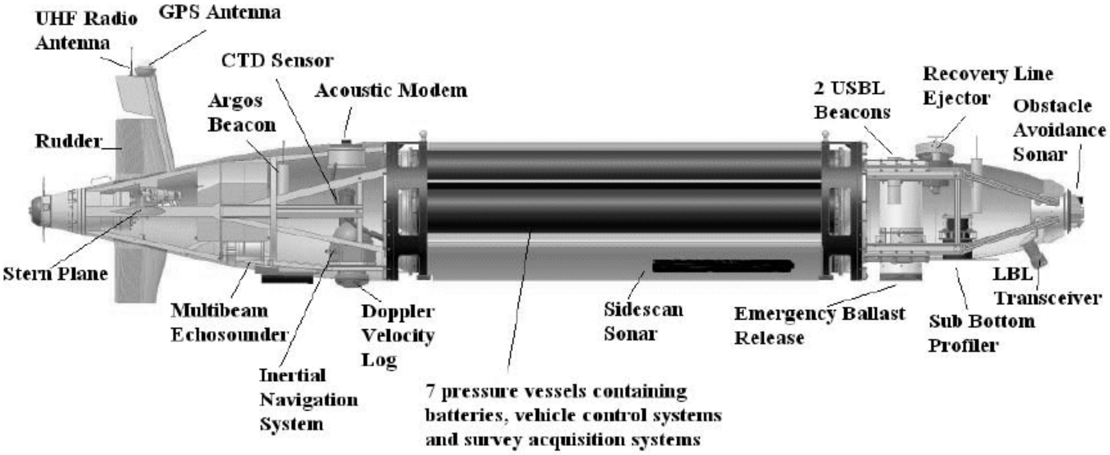


Figure 14: Schematic overview of the GeoSub's mechanical design

ACKNOWLEDGEMENTS

We would like to thank and acknowledge the important contribution all our partners have made to the project. The AUTOTRACKER research programme is supported by the European Union under the AUTOTRACKER project (Framework V G3RD-CT2001-00265).

Finally we would like to thank all the people, too numerous to mention, at the Ocean Systems Laboratory who have contributed in any way to the research and engineering developments described here.

REFERENCES

Lane, D. M. and J. P. Stoner (1994), “Automatic interpretation of sonar imagery using qualitative feature matching”,, IEEE J. Oceanic Eng., **19**, pp. 391–405.

Lane, D.M., M. J. Chantler, and D. Dai (1998), “Robust tracking of multiple objects in sector-scan sonar image sequences using optical flow motion estimation,” IEEE J. Oceanic Eng., **23**, pp. 31–46.

Petillot, Y., *et al*, (1998), “Underwater vehicle path planning using a multi-beam forward looking sonar”, in Proc. OCEANS’98, vol. 2, Nice, France, Sept. 1998, pp. 1194–1199.

Petillot, Y., I. Tena Ruiz and D. M. Lane (2001), “Underwater Vehicle Obstacle Avoidance and Path Planning Using a Multi-Beam Forward Looking Sonar”. IEEE J. of Oceanic Engineering, **26**, pp 240-251.

Latombe, J. C. (ed) (1991), "Robot motion planning", Boston: Kluwer Academic Publishers.