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# Research on Autonomous Underwater Vehicles at the Naval Postgraduate School

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## Abstract

This article describes the past accomplishments, presents status, and future areas of concern for research at NPS in mission planning, mission execution, and post mission data analysis to meet the needs of future Naval Autonomous Underwater Vehicles. These vehicles are unmanned, untethered, free swimming, robotic submarines to be used for Naval missions including search, mapping, surveillance, and intervention activity. This project is joint between the Mechanical Engineering, Computer Science and Electrical and Computer Engineering Departments at the Naval Postgraduate School and is focused on a long range program to develop **control technology** for these vehicles. The approach taken combines computer simulation, real time robust control theory, computer architecture and code development, vehicle and component design, sonar data analysis and data visualization.

Started in 1987, the major thrusts are in the areas of **mission planning**, both off-line and on-line, **mission execution** including navigation, collision avoidance, replanning, object recognition, vehicle dynamic response and motion control, real time control software architecture and implementation, and the issues of **post mission data analysis**.

## Introduction

This article focuses on systems having to do with the Navy's use of Autonomous Underwater Vehicles (AUVs). AUVs are a class of underwater vehicles that are independent from mother ship support with respect to power and control. AUVs are – **untethered-free swimmers** – with sufficient on-board intelligence to perceive uncharted and unplanned situations and take action in response. We are interested in these vehicles for a variety of military and/or commercial missions where direct human intervention is difficult or dangerous, and where the use of power cables and fibre optic data links are cumbersome. These vehicles will be used to gather data, provide surveillance, and possibly perform tasks in hostile areas. Research at NPS is focused on the issues of advanced controls for mission execution, and the post mission analysis.

Interest in intelligent **untethered underwater vehicles** has been growing recently. University groups include Texas A&M University, (Mayer et. al., 1987) who have developed a knowledge based real time controller, hosted on SUN 4 computers with particular attention paid to hardware and software reliability; University of New Hampshire, who under the guidance of D. Blidberg (Chappell, (1987)), have built and operated EAVE East vehicles since 1977 with ever increasingly complex computer architectures. EAVE III has a modular, hierarchical architecture using Motorola 68000 series computers running separate PSOS operating systems allowing for multi-processing operation. Lower level tasks are run in "C" while upper level tasks have been run in LISP, with the NIST RCS-3 real time control system (Albus, 1988). At MIT the Sea Grant Program has funded work conducted by Bellingham (1990a), who is exploring the demonstration of intelligent behaviors with a vehicle running on a GESPAC computer having a 68020 CPU with the OS-9 operating system and control code written in "C". Their behaviors are hierarchically prioritized using the "Layered Control" concept (Brooks, 1988), although more recently, (Bellingham, 1990b) has seen fit to introduce a state based layered control to coordinate mission specific behavior. The University of Tokyo has recently developed an underwater vehicle for bottom contour following using neural network techniques, (Ura, 1990). At the Naval Postgraduate School, we have developed an underwater testbed vehicle that is specifically designed to test and verify developments in control technology. It is run in the NPS swimming pool as an environment for experimental mission demonstration using a GESPAC computer with a Motorola 68030 CPU a 2MByte RAM card with control code written in "C". The mission planning interface with the vehicle control computer is embodied in a GRiDCASE laptop MS-DOS machine containing mission details in the form of way points and run times that are obtained from an external pre-mission planning analysis. The NPS AUV II, shown as a sketch in Figure 1, is 84" long displacing about 380 lbs. having 2 propellers, 8 control surfaces, 4 thrusters and, at present, 4 single beam sonar channels (Healey and Good, 1992). Many

**Figure 1.**

*Sketch of the NPS AUV II*

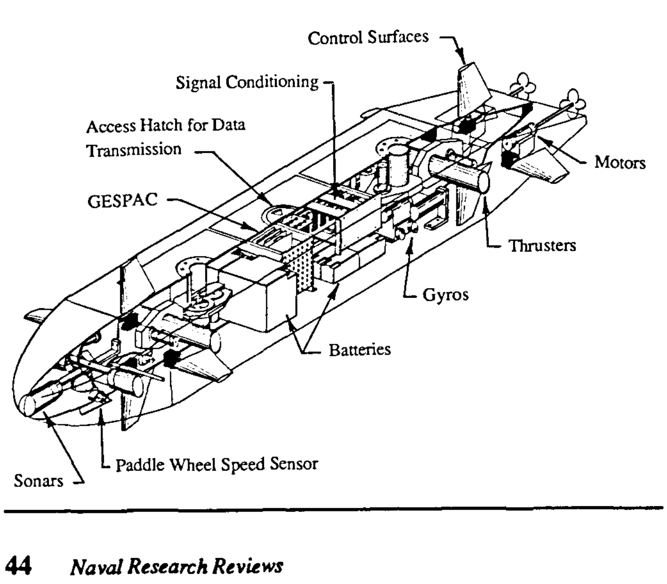
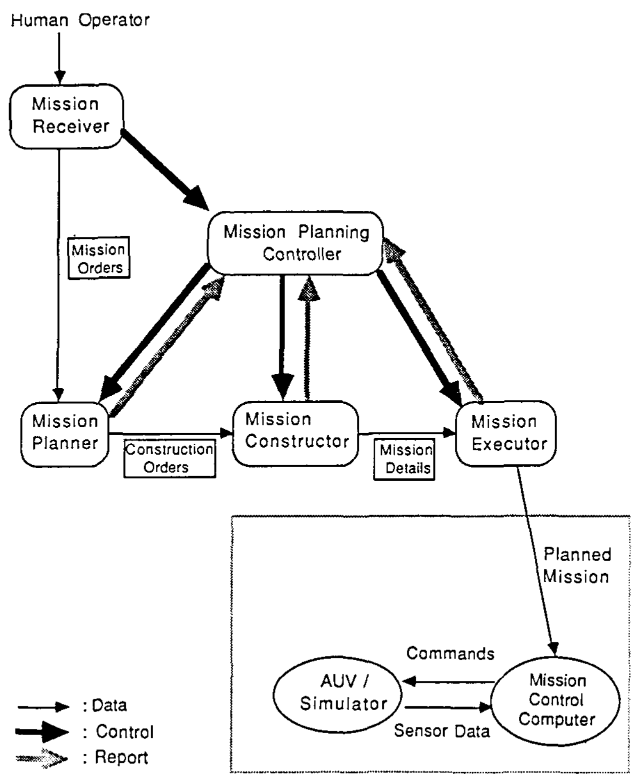



**Figure 2.**

*Mission Planning Expert System*




industry groups as well as Navy Laboratories, DARPA and the DRAPER Laboratory have work ongoing in this area.

While no formal control system structure has been adopted by all – in fact there are as many as there are investigators – our opinion is that a structure will be necessary that includes the ability to first perform extensive (if time permits) simulations to verify that the predictable aspects of any mission will be executed in a feasible way. This would be regardless of the mission details. In our structure, this is done with the **Mission Planning Expert System** as shown conceptually in Figure 2. The output is a planned series of geographic way points that avoid charted problem areas and lead the vehicle to its operational site(s) with task descriptors at each target point. This plan encompasses launch, transit to the area, operating in the area, returning to home and recovery.

The **Mission Execution** phase is shown by the structure of activity in Figure 3. **Mission Execution** after launch is conducted between the **Mission Executor** and the **Guidance System** by breaking down the planned mission into a sequence of intermediate way points defined on a finer grid possibly having an adjustable spacing. In more critical areas the spacing would be suitably refined. The **Guidance System** thus interpolates the baseline grid to provide a refined series of way

**Figure 3.**

*Mission Execution System Diagram*

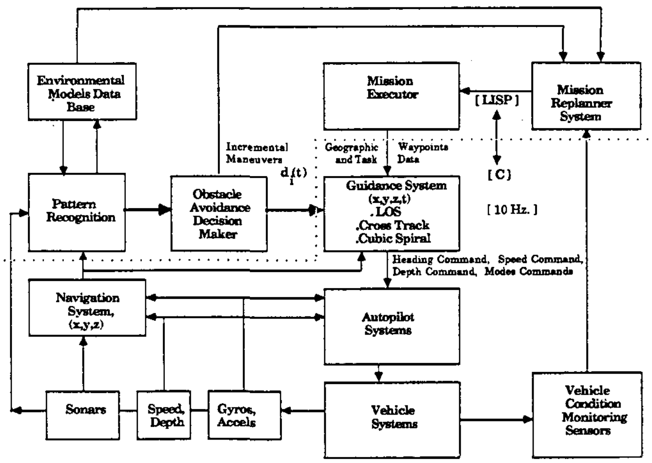
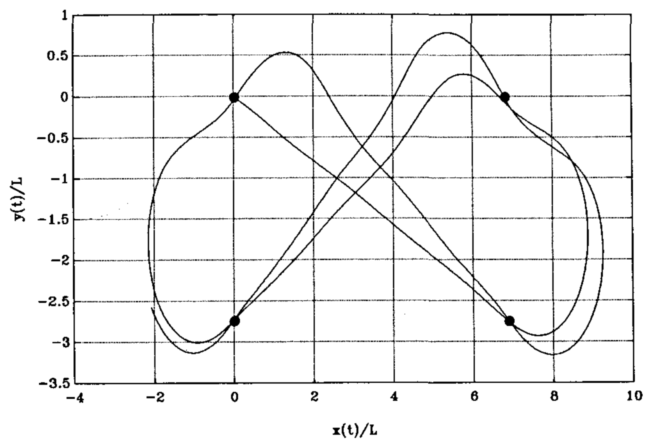



**Figure 4.**

*Line of Sight and PD Steering Autopilot: Experimental Results*




points which are passed to the vehicle **guidance law** and selected according to the degree of precision in path tracking desired by the mission plan. The **guidance law** generates the commands for vehicle's heading, speed, and depth. These commands are then sent to the vehicle **autopilot systems.** Three autopilots are installed for control over the vehicle's speed, heading, and depth. The servo levels of the vehicle's controller then provide final commands to the vehicle's propulsion plant, control surfaces, and thrusters to drive the vehicle to its planned path.

Obstacle avoidance and reflexive maneuvering logic are to be built into the vehicle's guidance system as a command override structure to respond to signals from the **Obstacle Avoidance Decision Maker (OADM).** The **OADM** receives input from **Pattern Recognition** software which correlates information from the sonars and estimates of present location and attitude from the **Navigation System** with an **Environmental Data Base** within the **Mission Executor**. The impending presence of an obstacle is thus flagged. At that time, status as to whether the object is stationary or moving, is to be reflexively avoided, or gradually outmaneuvered (either slow down, speed up, change course, which direction, etc.) is computed. Incremental modifications, $\mathbf{d_i(t)}$, to the planned way points and time are then made. Note that for all $d_i(t)$ moves, $d_i(t)$ will be said to tend to zero as t tends to infinity so that the originally planned path will be finally joined. Status signals are sent to the Mission Replanner from internal sensors concerning the condition of the internal equipment such as motor and battery status, motor controller system status, servo power and signal conditioning equipment, and power and internal temperature of the main CPU/Data Acquisition/Data Storage hardware.

Post mission data analysis is accomplished by down loading data that is stored in onboard RAM storage and displaying it on the data post processing computer. The post processor at this time resides in an IRIS graphics workstation containing graphics modules that replicate the environment in which the vehicle is operating together with models for analysis of the vehicle motion data and the sonar sensory data obtained from the mission run (Brutzman et. al., 1992). The results of the planned mission are both simulated prior to mission approval using an IRIS workstation as the environment and vehicle simulator, and then displayed at mission completion. Details of the sonar imagery, or the bottom contour, or other mission specific results would be output in a user-friendly format.

# Mission Planning Expert System

The details of our Mission Planning Expert System were given recently by Kwak (1990) and in more detail in Ong, (1990). Basically the system shown in Figure 2 is hosted on a stand alone Symbolics 3675 Lisp Machine. Conceptually it resides off-line from the vehicle where only the results of the planning process (in terms of geographic way points and task level instructions) are to be downloaded to the vehicle's on-board computer. The Mission Planner has been developed entirely within the KEE expert system shell with a corresponding knowledge base detailed by Ong. The mission planner is essentially hierarchical, patterned after the progressive phases of a mission, namely, the initiation by the human operator, the planning, construction, and the mission execution. In this software architecture, the planning operation is supervised by a mission planning controller which is a system devised to oversee the entire process and enforce orderly transition to each phase. There are four role players, the Mission Receiver, the Mission Planner, the Mission Constructor, and the Mission Executor. The Receiver is the human interface and is embodied in the workstation screens with which the user defines the nature of the mission to be planned. Details such as mission type, location parameters, and planning horizon are entered. The information received is then given to the mission planning controller which initiates all subsequent actions. The mission planner decides on the basis of the data given and its internal knowledge base, which planning algorithm to use. A system of **voters, knowledge processors** and **decision makers** operating on three different rule sets interact with the planner until an acceptable choice is made. The mission constructor then solves the path planning problem with the selected constraints and algorithm. Part of the problem is to select a grid of coordinates on which the plan is based. It should also be noted that the knowledge base will in fact be extensive and contain all necessary known features concerning the mission arena. Maps, bottom contours, current data, charted objects such as subsea wells and offshore platforms, and harbor profiles if needed, must all be represented. Three algorithms are presently active; A*, best first, and a heuristic search. The mission constructor then sends the plan to the mission executor which acts as the interface between the planning system and the vehicle on-board system. The plan is embodied in a sequence of way points with target points and work task parameters identified.

# Mission Execution Systems and Results for the NPS AUV

The execution of the mission begins with downloading the mission plan to the on-board **Mission Executor** followed by the vehicle launch. A time delay must be built into the executor to allow for the launching delay. It has been found important that during this launch phase, and especially with a fully autonomous vehicle, some indicator that the internal systems are functional is desirable-we have used a small movement of one of the control surfaces as this indicator. Upon program initiation, the mission execution plans (defined in terms of a series of way points with instructions at target points), are contained in an MS-DOS GRiDCASE laptop computer which is connected via serial link to the vehicle onboard GESPAC MPU30HF single board computer (based on the Motorola 68030 CPU, at 25 Mhz. with 2 Mb of RAM and a 68882 math coprocessor) running with the OS-9 multi-tasking operating system and 2 GESDAC-2B 8 channel 12 bit DA/AD converter cards. Control code is written in "C" language. The GESPAC system is the interface between the mission planning phase and the vehicle hardware, and it houses the **Guidance System**, the **Navigation System**, and the speed, diving, and steering **Autopilot Systems**, each of which operates under robust Sliding Mode Control. Figure 3 shows a diagram of the execution functions. Details of the theory and design of Sliding Mode Controllers are available in Healey, Papoulias, and Lienard, (1990) and Papoulias and Healey, (1990) and in Healey and Marco, (1992). The major interfacing in the execution phase is between the **Mission Executor** and the **Guidance System** and some interplay with the **OADM**. These systems, (in their future embodiment) are to be hosted in Prolog or C++ language on an Intel 80386 processor based single board computer running MS-DOS within the GESPAC card cage while the **Guidance System** runs in "C" on the current 68030 processor board.

## Guidance, Control, and Navigation

The fundamental breakdown of the motion control functions between guidance and autopilot relies on the notion that

**Figure 5.**

*Experimental Results for Speed, Steering, and Depth Control Autopilots*

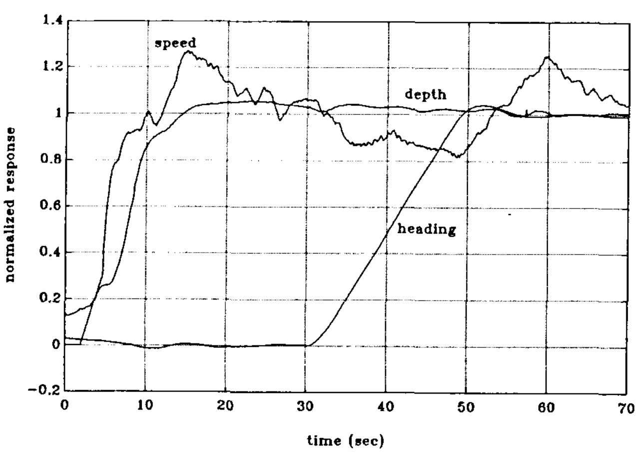
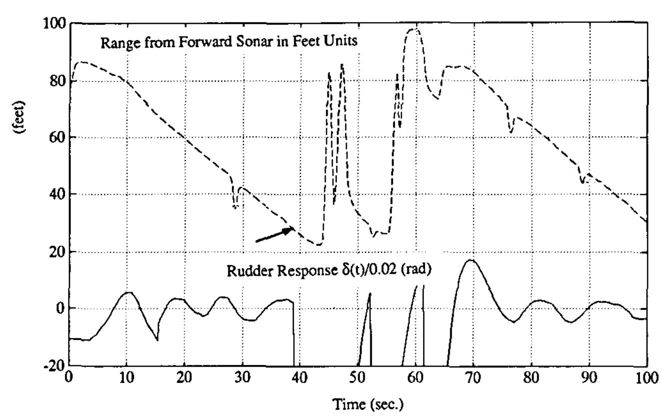



**Figure 6.**

*Obstacle Avoidance Sonar Range and Vehicle Steering Response*



an autopilot is responsible for stabilizing the motion dynamics of the vehicle in terms of its speed, heading, and depth. The guidance law combines commands for the path and position to be followed and other attitude requirements with navigational estimates of true position and orientation, to generate the speed, heading, and depth commands for the autopilot. In this manner, **Guidance** is responsible for dealing with **geometrically and/or kinematically** based relationships, while the **Autopilot** is responsible for control of the vehicle **dynamics**. Such a distinction between guidance and control offers the advantage of analyzing the behavior of different schemes and allows for great flexibility in the design and final selection. An example of a line of sight guidance law with a proportional-derivative heading autopilot is shown in Figure 4, from experimental results in the NPS swimming pool. The commanded path, a figure eight maneuver, was discretized into 4 way points and it can be seen that the results are repeatable after two loops. More way points, provided they are appropriately selected, would result in improved accuracy and a smoother path. Questions pertaining to dynamic interactions between guidance and autopilot laws for accurate path keeping are very important for AUV's for the following reason: due to the fact that an AUV suffers from significant dynamical lags, satisfactory response characteristics of a combined guidance and control law are not guaranteed unless proper care is given in their design. Analysis of this problem revealed regions of stability loss and the emergence of self sustained oscillatory modes. Experimental validation of the theoretical results is scheduled.

Stabilization of the vehicle dynamics was achieved by the independent design of three Sliding Mode autopilots for propulsion, diving, and steering. The added robustness that Sliding Mode Control laws provide was proven sufficient to stabilize the vehicle when operated in full coupled fashion under all six degrees of freedom. An experimental verification is presented in Figure 5, where the response of the vehicle is evaluated under simultaneous speed, heading, and depth change commands. The guidance law in this case was selected to simulate a basic obstacle avoidance maneuver; heading change commands were issued based on the distance from the front wall of the swimming pool as recorded from sonars.

As a result of the vehicle's enhanced maneuverability, in particular the existence of independently controlled bow and stern rudders and dive planes as well as plans for four vertical and horizontal thrusters, considerable effort has been devoted to issues surrounding precise motion control in transition from cruise to hover and dynamic position modes. This was achieved in simulation by means of multiple sliding mode control combined with linear quadratic regulator techniques. Appropriate functional relationships of the weighting factors on different system states in terms of the vehicle forward speed enables smooth transitions between cruise and hove modes and efficient use of the various vehicle actuators.

**Figure 7.**

*Sonar Signature from Pool Maneuvering Run*

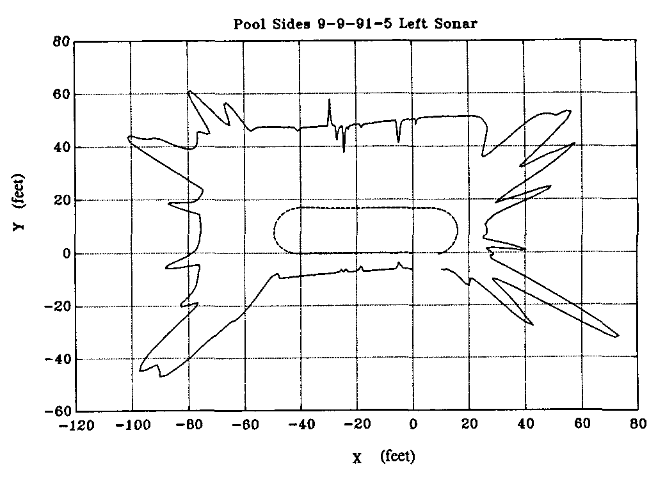



**Figure 8.**

*Segment Identification Result from Post Processing*

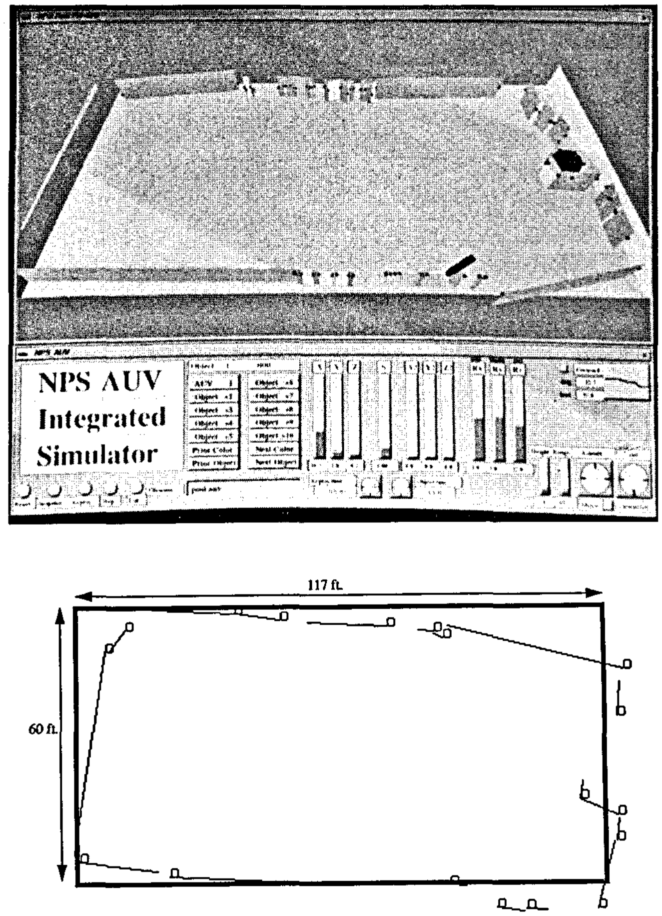
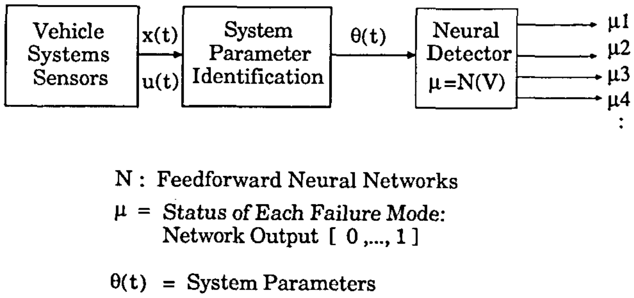


**Figure 9.**

*System for Neural Network Failure Detection and Diagnostics Neural Diagnostic Decision Surface*




Naturally, vehicle guidance and control cannot be accomplished unless reasonably frequent updates are provided by the **Navigation System** which is responsible for estimating where the vehicle is located. This is accomplished by an enhanced dead-reckoning system that takes into consideration vehicle forward speed over the water, heading angle, and heading rate; and provides through the use of an observer an estimate of the side slip velocity. The system has been calibrated based on sonar information from the swimming pool walls as discussed later in the next section.

## Obstacle Avoidance

While the **Obstacle Avoidance Decision Maker** is a system that has yet to be defined to its fullest extent at the time of this writing, the vehicle has four sonar ranging systems on board that have been providing mapping data to the pool sidewalls. One of the most important obstacle avoidance issues is to prevent the vehicle from running into a solid object in its path. The use of a forward looking sonar to provide range to such an object has been demonstrated in pool tests where a limit of 25 feet has been set after which a hard turn to the starboard is triggered. The quality of the range signals from the Datasonics PSA 900 200 KHz. is shown in Figure 6 where it has been clearly shown that an obstacle avoidance maneuver was triggered at the correct time to turn the vehicle away from the pool end wall. Working with sonar signals in the underwater environment for autonomous control is not easy and will be the subject of future research.

## Underwater Object Recognition using Sonars

Object recognition for the AUV is an important task for its intelligent behavior. We used sonar range data interpretation for this task. Especially, regression analysis was adopted to extract linear features from sonar signature. This linear feature extraction enables the system to perform pattern matching with the environmental database to allow navigational position updating, or, unknown obstacles can be added to the environmental database if they are not previously registered.

The method we have investigated is able to represent line segments in the most general form. That is, even lines which are perpendicular to the X-axis are uniformly representable. Figure 7 shows an example of sonar signature taken by a mission in the NPS pool. Figure 8 is the result of a regression analysis. Another advantage of this method is that the end points of each segment are explicitly obtained. These segments are matched to the environmental model to identify the AUV's position and orientation which in turn corrects possible dead-reckoning errors, (Floyd, Kanayama, and Magrino, 1991).

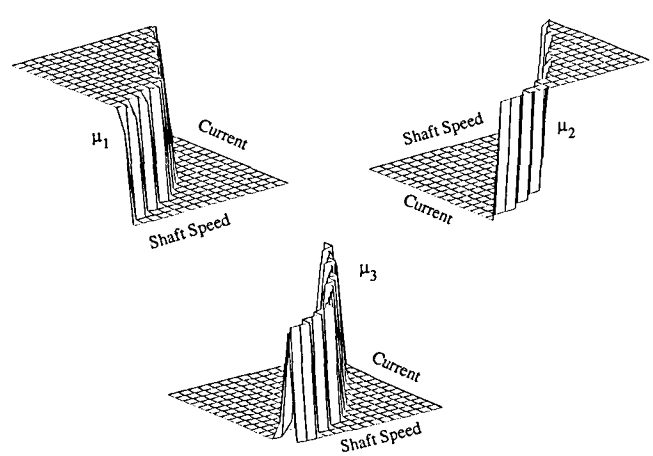
The terrain-following altitude controlling algorithm using a down-looking sonar was also tested in the NPS pool. Using a filtered signal from the bottom sonar, the controller maintained the AUV at a height of 3.0 feet from the pool bottom.

This sonar interpretation technique has been proven to be extremely effective both for real-time underwater object recognition and for post mission data analysis. An expert system which combines geometric analysis with sonar classification heuristics is successfully able to classify walls and objects in the NPS pool (Brutzman, Compton and Kanayama, 1992).

Further work on sonar detection of objects in the pool and the problems of dealing with noisy sonar data is ongoing. It is planned to investigate the use of a 750 KHz. 1 by 30 degree sector scanning sonar together with a 1 degree conical beam profiling sonar to provide higher resolution images and enhance the development of obstacle avoidance controls.

**Figure 10.**

*Motor 'Failure Decision Surface' as a Function of Rotation Speed and Current; $\mu_1$ = 1 Indicates Shaft Friction Too High; $\mu_2$ = 1 Indicates Normal Operation; $\mu_3$ = 1 Indicates Loss of Loading*



## Vehicle Condition Monitoring

Vehicle component reliability is a major issue for any operational AUV system. This problem is being addressed at the time of this writing by NPS, the Naval Coastal Systems Station and the Draper Laboratory. It has to do with monitoring the health status of equipment so that intelligent decisions may be made in software to at least continue the mission in a partial way if failure occurs. Additional sensors dealing with the monitoring of motor currents and voltages, computer systems temperature and cooling needs, servo controller card status, battery voltages, and servo motor currents are now planned to provide input to computer based models of the internal components so the anomalous operating data can be sensed and either corrected or mission adjustments can be made by the mission executor software. The basis of the failure diagnostics system is a Kalman filter system parameter identifier coupled to a neural network diagnoser that is trained to determine the operating mode of the vehicle sub systems. (illustrated in Figure 9). The design of systems of this type is complicated by the need to recognize discrepancies in the inner correlations between system variables, and to link those changes to particular failure modes. Research is needed to define the performance possible from these systems. A neural network has been designed to identify whether a propulsion motor is operating in normal, under or overload conditions with the decision surface shown in Figure 10. More details are given in Healey, (1991).

# AUV Integrated Simulation and Post Mission Visualization

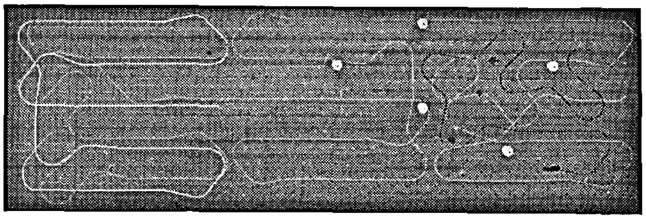
The developments and testing of AUV hardware and software is greatly complicated by vehicle inaccessibility during operation. Integrated simulation remotely links vehicle components and support equipment with graphics simulation workstations, allowing complete real-time, pre-mission, pseudo-mission and particularly, post-mission visualization and analysis in the lab environment.

High resolution three-dimensional Silicon Graphics Inc. graphics workstations can provide real-time representations of vehicle dynamics, control system behavior, mission execution, sonar processing and object classification. Use of well-defined, user-readable mission log files as the data transfer mechanism allows consistent and repeatable simulation of all AUV operations.

The flexibility, connectivity and versatility provided by this approach enables sophisticated visualization and analysis of all aspects of AUV development (Brutzman, 1992, Compton, 1992, and Brutzman, Kanayama, and Zyda, 1992). Figure 11 shows an example visualization of an extended minefield search. The bright track is at shallow depth, the grey track is at intermediate depth and the dark track shows commencement of a deep-water minefield search.

**Figure 11.**

*Minefield Search Pattern From The Integrated Simulator*



# Conclusion

Much more work needs to be done in this community to continue, with appropriate overlap from sufficiently diverse points of view, to illuminate the range and trade-offs of possible structures and technology, hardware and software, needed for precise, reliable control of AUV's in the future. In particular, during the next few years, we plan to

1. Develop techniques for design of mission planning software using a simulator that has realistic run times and vehicle motion dynamics constraints,
2. Develop technology for understanding multiprocessor real time computation with transputers for mission control execution,
3. Understand the precision to which slow speed control can be accomplished in the presence of ocean currents,
4. Understand how to incorporate high resolution imaging sonar into vehicle guidance and control functions to enhance the ability of vehicles in gaining acoustic imagery of potential targets,
5. Understand how to integrate a GPS/INS suite into the vehicle's mission planner and navigation systems,
6. Further the understanding of the design of system diagnostic reasoners using neural networks to increase vehicle operational reliability.

# Biographies

Dr. Healey was graduated from London and Sheffield Universities with the degrees B.Sc. (Eng.) and Ph.D. in mechanical Engineering in 1961 and 1966 respectively. He has taught at The Pennsylvania State University, MIT, The University of Texas at Austin, and in 1986, he assumed his present position as Professor and Chairman of Mechanical Engineering at the Naval Postgraduate School. His areas of specialty include Mechanical System Dynamics, Vibration, and Control Systems, and he is presently the leader of the multidisciplinary project in Autonomous Underwater Vehicles at NPS.

Dr. Robert B. McGhee received his Ph.D. in Electrical Engineering at the University of Southern California in 1963 and taught at Ohio State University until 1986 when he joined the Computer Science Department at the naval Postgraduate School. He currently serves as Chairman of that Department. His specialty areas are in Robotics, Walking Machines and Artificial Intelligence.

Dr. Yutaka Kanayama received his Ph.D. degree from University of Tokyo in 1965 and has taught at the University of Electro-Communications in Tokyo and the University of Tsukuba in the areas of Robotics and Computer Science. He was an Adjunct Professor at the University of California at Santa Barbara 1986-1988 and since 1988 has been a professor in the Computer Science Department at the Naval Postgraduate School holding the Grace Murray Hopper Chair 1989-1990. His specialties are in Mobile Robotics and Algorithm Theory.

Dr. Roberto Cristi received his Ph.D. degree in Electrical Engineering at the University of Massachusetts in 1988 and is currently associate Professor of Electrical and Computer Engineering at the Naval Postgraduate School. His specialty is in Adaptive Control, Signal, and Image Processing.

Dr. Fotis A. Papoulias received his Ph.D. degree from the University of Michigan in 1987 and is currently an Assistant Professor of Mechanical Engineering at the Naval Postgraduate School. His research interests are in Dynamics and Control of Mechanical Systems, Guidance and Autopilots for Marine Vehicles, Bifurcation and Chaos.

Dr. Shridar Shukla received his Ph.D. in Electrical and Computer Engineering from the North Carolina State University in 1990. He is currently an Assistant Professor in Electrical and Computer Engineering at the Naval Postgraduate School. His current research interests are in parallel real time computing and fault tolerant distributed computing.

Se-Hung Kwak received his Ph.D. degree in Electrical Engineering from Ohio State University in 1986. He worked as a Post Doctoral Fellow in Electrical Engineering at Ohio State University and since 1987 has been an adjunct Professor in the Computer Science Department at the Naval Postgraduate School. His research interests are in robotics, artificial intelligence, real-time systems, and computer architecture.

Yuh-jeng Lee received a Ph.D. (1988) in Computer Science (Artificial Intelligence) from the University of Illinois at Urbana-Champaign. He is currently an Assistant Professor of Computer Science at the Naval Postgraduate School. His research interests include automatic programming, intelligent systems, real-time systems, and model-based reasoning.

Amr Zaky received his Ph.D. in Computer Science in 1989 from The Ohio State University. Since September 1989, Dr. Zaky has been an Assistant Professor with the Department of Computer Science at the Naval Postgraduate School. Dr. Zaky's research interests are in the areas of Parallel Computing, Computer Architecture, and Real Time Systems.

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