II. REVIEW OF RELATED WORK

A. INTRODUCTION

This chapter reviews previous and current research pertinent to the creation of an underwater virtual world for an AUV. While no other underwater virtual worlds were encountered during this literature search, the diversity of the many components developed in this dissertation invite background examinations on a wide range of topics. Subjects examined in this chapter include underwater robotics, robotics and simulation, dynamics, networked virtual world communications, sonar modeling and visualization, and ongoing and future projects. In order to avoid becoming open-ended surveys of entire bodies of scientific literature, the following project reviews are limited to aspects directly pertaining to this dissertation.

B. UNDERWATER ROBOTICS

The AUV research community is small but steadily growing. Key papers in this field are primarily found in annual conferences (included throughout the accompanying list of references) which reach back over a decade. These include the IEEE Oceanic Engineering Society (OES) *Autonomous Underwater Vehicle (AUV)* symposia and *OCEANS* conferences, *Unmanned Untethered Submersible Technologies (UUST)* symposia, and *International Advanced Robotics Programme (IARP): Mobile Robots for Subsea Environments* workshops. A recent survey of previously unknown research submersibles and undersea technologies in Ukraine and Russia appears in (WTEC 93). Current capabilities in remotely operated vehicle (ROV) operations are described in (Newman 92-93). A survey of AUV capabilities emphasizing potential for commercial deployment appears in (Walsh 93-94). A detailed description of the NPS AUV appears in Chapter IV. This section provides an overview of several significant AUVs. For a dynamic view of underwater robotics, video segments of state-of-the-art AUV operations appear in recent video conference proceedings (Brutzman 93a, 94a).

A survey of all AUVs is not appropriate, but representative and pertinent AUV projects are summarized below.

1. ARPA/Navy Unmanned Undersea Vehicle (UUV)

The ARPA UUV program began in 1988 when the Charles Stark Draper Laboratories were contracted to build two large UUVs for tactical naval missions,

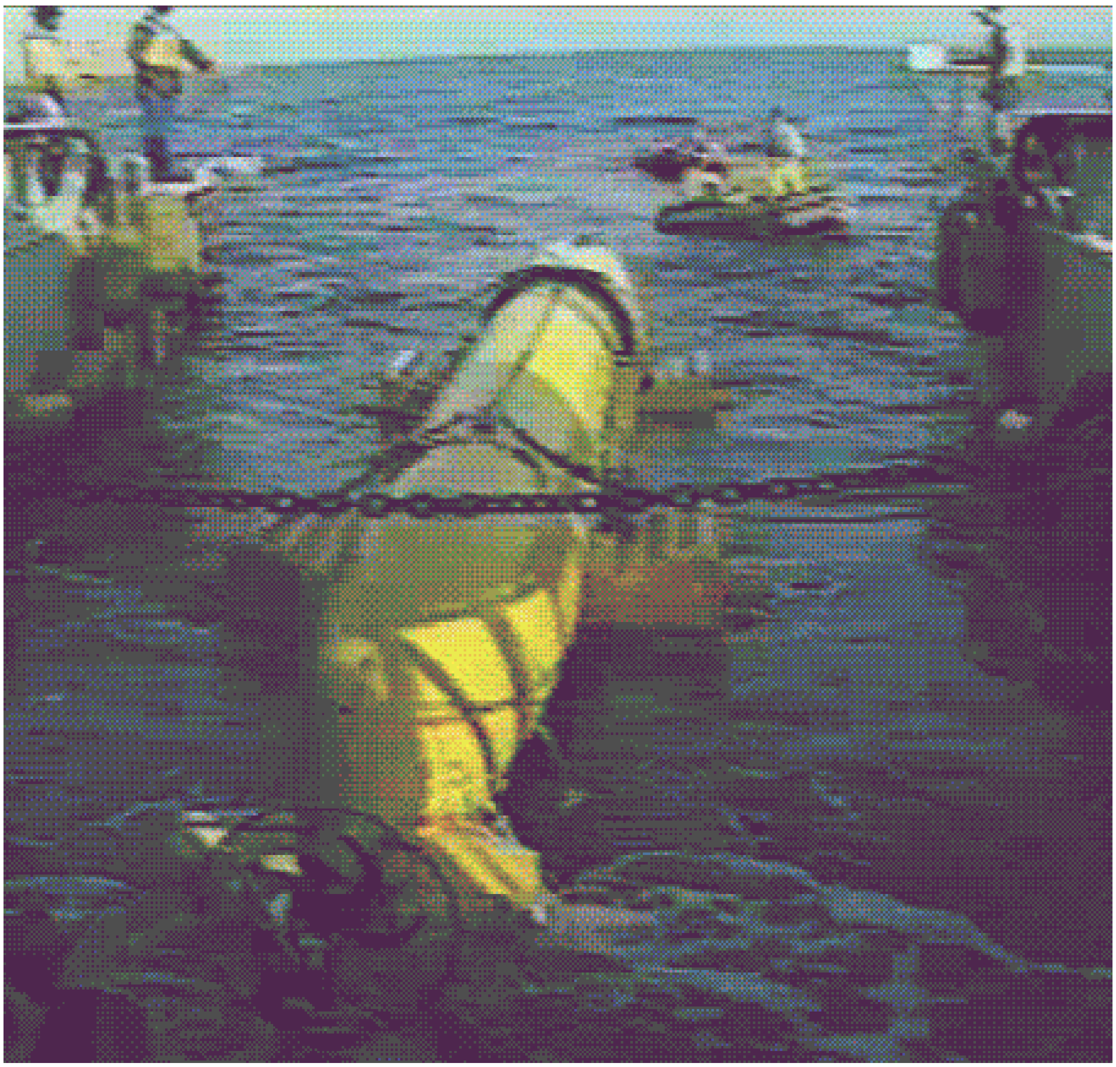

Figure 2.1. ARPA/Navy Unmanned Underwater Vehicle (UUV) being readied for launch during mission trials (Brancart 94) (Brutzman 94a).

particularly open-ocean minefield search. These vehicles are the largest, the most capable and (at approximately $9 million total) the most expensive AUVs built to date. The ARPA UUVs use high-density silver zinc batteries for 24 hours of operational endurance at 5-10 knots submerged. Weighing 15,000 pounds in air, the vehicles have titanium hulls which permit a test depth of 1,000 feet. The UUVs successfully deployed advanced sonar processors, laser communications and a variety of other advanced technologies in its 2000-pound-capacity payload section. Hybrid simulation techniques were used to test vehicle hardware and software prior to at-sea deployment. Simulation components included six-degree-of-freedom hydrodynamics and tether dynamics models, along with hardware subcomponent models and wireframe computer graphics. Vehicle overviews can be found in (Pappas 91) (Brancart 94), and extensive video footage of various testing milestones is included in (Brutzman 93a, 94a).

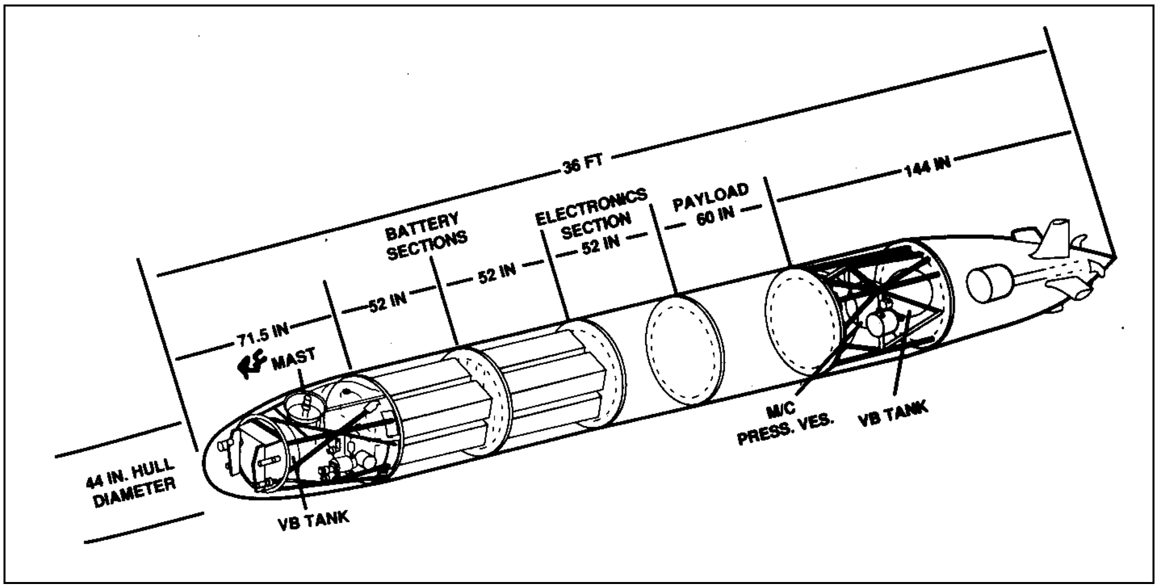

Figure 2.2. ARPA/Navy Unmanned Underwater Vehicle (UUV) internal layout (Pappas 91).

> "In March 1993, the [ARPA] Maritime Systems Technology Office successfully completed a series of at-sea tests that demonstrated the Mine Search System (MSS), a prototype minehunting system. In these demonstrations, a ship with the UUV in the lead repeatedly made safe transits through deep and shallow

mine fields. During these transits, bottom mines undetectable by ship-mounted sensors were readily detected by the UUV sensors optimally positioned with respect to the target mines... These demonstrations clearly showed for the first time the value of UUV sensors in a mine countermeasures role."
(from Brancart's ARPA abstract, Brutzman 94a)

The ARPA UUVs have been first to accomplish many important AUV tasks, but their cost is high and technical details remain out of the published literature. While they have been an excellent testbed for new technologies, the high cost of vehicle support and operations places them beyond the reach of most research efforts.

2. Massachusetts Institute of Technology (MIT) *Odyssey* Class AUVs

The MIT Underwater Vehicles Laboratory Sea Grant College Program has been building and deploying a series of low-cost AUVs for a number of years (Bellingham 94) (Fricke 94). The current *Odyssey II*, predecessor *Odyssey I* and

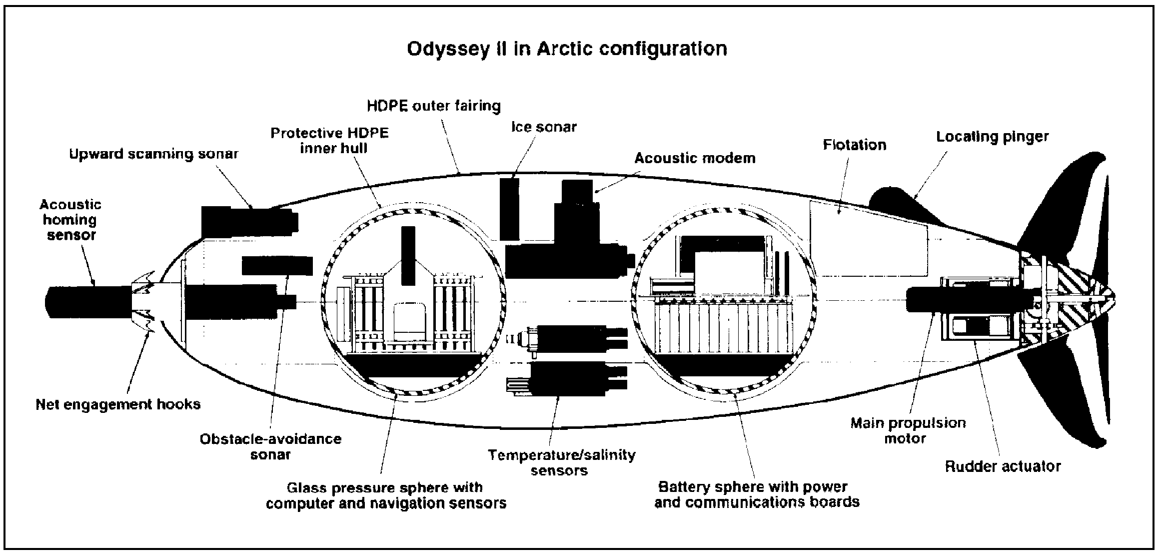

Figure 2.3. MIT *Odyssey II* in under-ice configuration. Deep-ocean configuration includes obstacle avoidance sonar, strobe light, altimeter sonar and video camera (Bellingham 94).

Sea Squirt vehicles are characterized by teardrop hull forms, 17" glass sphere internal pressure vessels, low power consumption, single 68030 microprocessor, single propeller and cruciform stern fin control. Vehicle control software uses state-configured layered control (Bellingham 90), an augmented form of subsumptive control (Brooks 86, 90) which provides a higher level of control in order to enable mission configuration. *Odyssey II* sensors include various scanning and homing sonars, depth sensor, temperature salinity and related sensors, video, inertial sensors, acoustic modem and acoustic navigation tracking pingers. Stable dynamic control is constrained by a minimum forward speed of 0.5 m/sec, and operational missions follow a cruise or survey profile. Maximum operating depth is 6,700 m. Unit costs remain low (under $75,000) even while each generation of vehicle has demonstrated significantly improved hardware and increased operational capabilities. Perhaps the greatest contributions of the *Odyssey* class vehicles have been in demonstrating operational missions in rivers, in open ocean and under the Arctic ice (Bellingham 94) (Fricke 94) (Brutzman 94a). Future work includes a variety of oceanographic missions using innovative sensors (Bales 94a, 94b) and ocean survey communications as part of a proposed Autonomous Oceanographic Sampling Network (AOSN) (Curtin 93) (Catipovic 93).

3. Marine Systems Engineering Laboratory *EAVE* Vehicles

The Experimental Autonomous Vehicle (EAVE) class of AUVs first started in 1978 when *EAVE I* demonstrated autonomous underwater pipe following (Blidberg 90) (Chappell 94). Subsequent missions have included navigation using acoustic transponders, submerged structure cleaning, underwater docking and parking, and multiple AUV submerged communication and mission coordination. *EAVE* class vehicles are constructed on open frames using large watertight cans for electronics and electrical components. Sensors include a variety of sonars, compass, temperature and pressure (depth) detector, inertial sensors, acoustic modem and video. The Marine Systems Engineering Laboratory (MSEL) was initially located at University of New Hampshire and moved to Northeastern University in 1994. Notable contributions of *EAVE* research include implementing multiple level software architectures, multiple vehicle interaction protocols, low-bandwidth acoustic communication languages, and

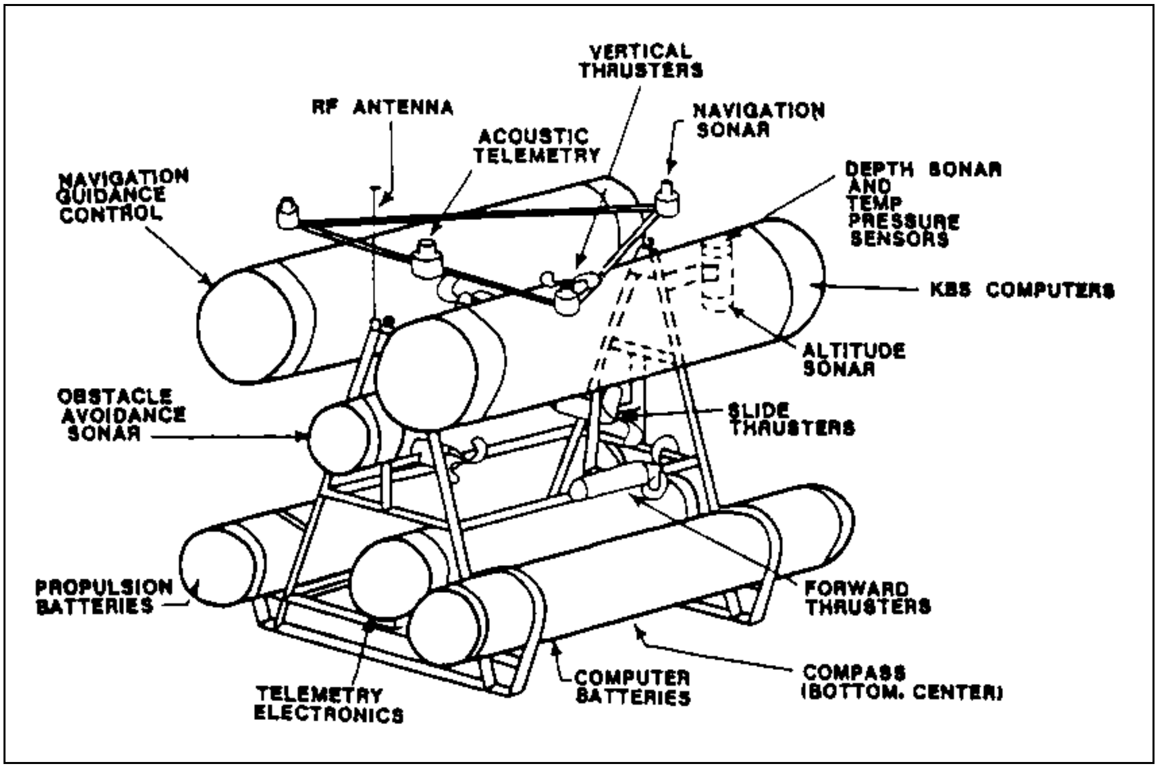

Figure 2.4. Marine Systems Engineering Laboratory (MSEL) Experimental Autonomous Vehicle *EAVE II* equipment layout (Blidberg 90).

unique missions such as rapid-response oil spill underwater survey (Brutzman 93a).

4. Florida Atlantic University (FAU) *Ocean Voyager II*

The ***Ocean Voyager II*** is a long-range AUV designed for coastal oceanography, classifying bottom types by flying at a constant altitude above the sea floor while measuring bottom albedo, light absorption and other parameters (Smith 94) (Brutzman 94a). Results of large-area surveys will be used to calibrate satellite measurements which currently have few correlation checks available with ground truth. The possibility of rapid response means that this AUV mission is also suitable for tactical oceanography. Vehicle hull form is similar in size and shape to the MIT *Odyssey* vehicles, as are most components. Navigation is by ultra-short and long baseline acoustic networks, doppler water velocity log and differential global

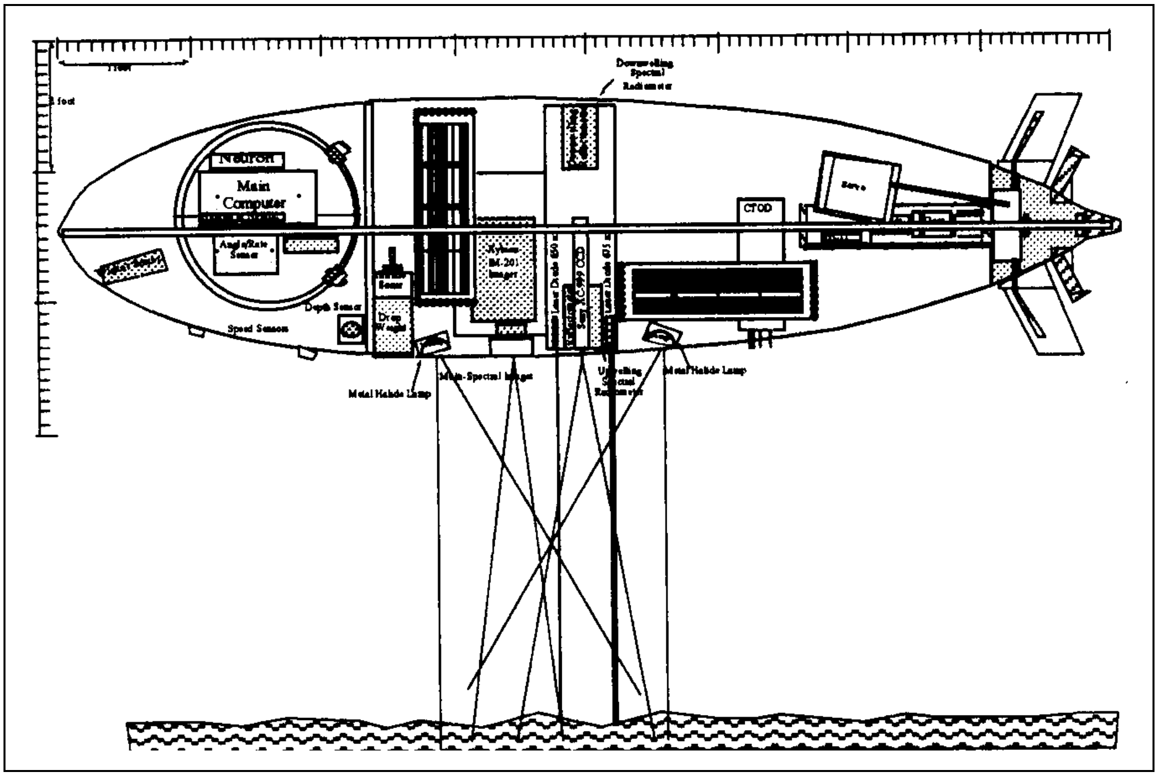

Figure 2.5. Florida Atlantic University Ocean Voyager II (Smith 94).

positioning system (DGPS). Communications are by 2400 Kbps acoustic modems or a towed float radio frequency (RF) antenna when near the surface. Vehicle endurance is 50-100 km, depth rating 600 m, and speed is 3-5 knots. Vehicle design required 1 year and $100,000 initial expense, with sensor payloads comprising over half of the total cost. Collection, correlation and evaluation of large oceanographic datasets are good candidate applications for an underwater virtual world.

5. Monterey Bay Aquarium Research Institute (MBARI) Ocean Technology Testbed for Engineering Research (*OTTER*)

In 1994, Monterey Bay Aquarium Research Institute (MBARI) and the Stanford Aerospace Robotics Laboratory built the Ocean Technology Testbed for Engineering Research (*OTTER*) AUV as a testbed for vision-based servoing for vehicle control while constructing video mosaics of the ocean floor (Marks 92, 94a, 94b) (Brutzman 93a, 94a). Stereo video cameras provide high-bandwidth streams which are

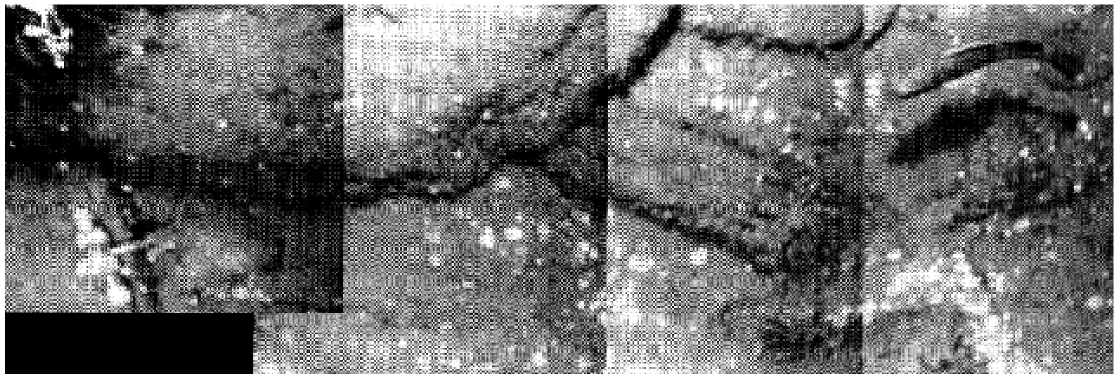

Figure 2.6. Video mosaic from Monterey Bay Aquarium Research Institute Ocean Technology Testbed for Engineering Research (*OTTER*) (Marks 94a, 94b) (Brutzman 94a). Note fish, upper right corner.

subsampled and filtered using vision-processing hardware for real-time response. As demonstrated by (Marks 94a), sequentially applying a signum function, a Laplacian function and a Gaussian correlation function produces images which can be adjusted for stereo disparity and correlated between subsequent frames. This result produces an optic flow output which can then be used for feature tracking. Once a feature has been identified, dynamic feedback to thrusters/planes/propellers controllers permits the *OTTER* vehicle to follow that object or navigate relative to the bottom. The same correlation algorithm can be used to match physically adjacent images into a large-scale video mosaic in real time, often providing a better match than is possible using manual methods. Acoustic transmittal of video mosaics is possible in real time, while transmittal of unculled video is infeasible due to excessive bandwidth requirements. Both object (e.g. sea creature) tracking and bottom mapping are extremely valuable oceanographic capabilities, and are also essential if AUVs are to be practical tools for ocean exploration. Video mosaic mapping and observation of undersea creatures *in situ* are fundamental behaviors for automatic data collection and underwater virtual world database construction.

6. **Woods Hole Oceanographic Institution (WHOI) Autonomous Benthic Explorer (*ABE*)**

The Woods Hole Oceanographic Institution (WHOI) has designed and constructed a special purpose AUV for long-term surveys of the deep ocean floor

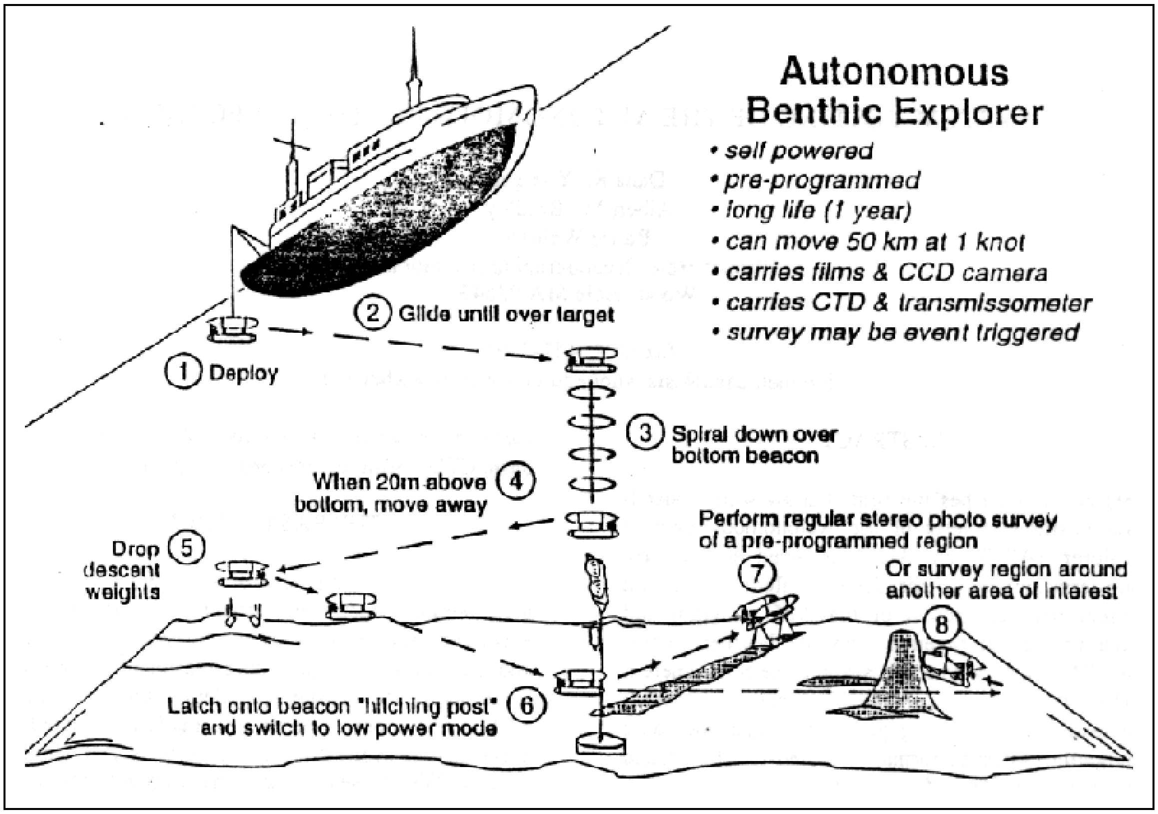

Figure 2.7. Woods Hole Oceanographic Institution (WHOI) Autonomous Benthic Explorer (*ABE*) mission profile (Yoerger 94).

(Yoerger 91, 94). The Autonomous Benthic Explorer (*ABE*) can moor at a fixed location for long periods of time in a "sleep" mode and periodically awake, perform a local survey by navigating within a short baseline acoustic transponder field while measuring water parameters and taking low light charge-coupled diode (CCD) camera photographs, then reattach to the mooring. Power consumption is extremely low in order to support 16 hours of maneuvering endurance spread over missions lasting up to a year. Science missions include observation of deep ocean hydrothermal vents and benthic biologic communities. The vehicle is retrieved following an acoustic command to drop ballast and return to the surface. *ABE* operational ranges and endurance can be significantly increased by attaching the mooring to a magnetic induction power transfer device and acoustic communications relay. Potentially high data rates and the possibility of making geologic measurements with real-time importance make *ABE* deployments a natural application to be networked with an underwater virtual world.

7. Explosive Ordnance Disposal Robotics Work Package (EODRWP)

The Lockheed Explosive Ordnance Disposal Robotics Work Package (EODRWP) is a UUV designed to assist divers in locating, classifying and neutralizing underwater mines (Trimble 94a, 94b) (Brutzman 94a). Although tethered in order to provide power and controller communications, the EODRWP has a sophisticated suite of rule-based behaviors to intelligently perform signal processing, classification, dynamics control, mission planning and mission execution with minimal human supervision. Shore-based graphical simulation connected to vehicle hardware in the laboratory is considered an essential capability and is used to visualize and test the EODRWP prior to at-sea testing. Particular contributions of this project include guidance, navigation, control and mission task integration of human and robot. Use of an underwater virtual world combined with EODRWP and externally-controlled synthetic humans has the potential to improve mine neutralization tactics while reducing risks to navy divers and ships.

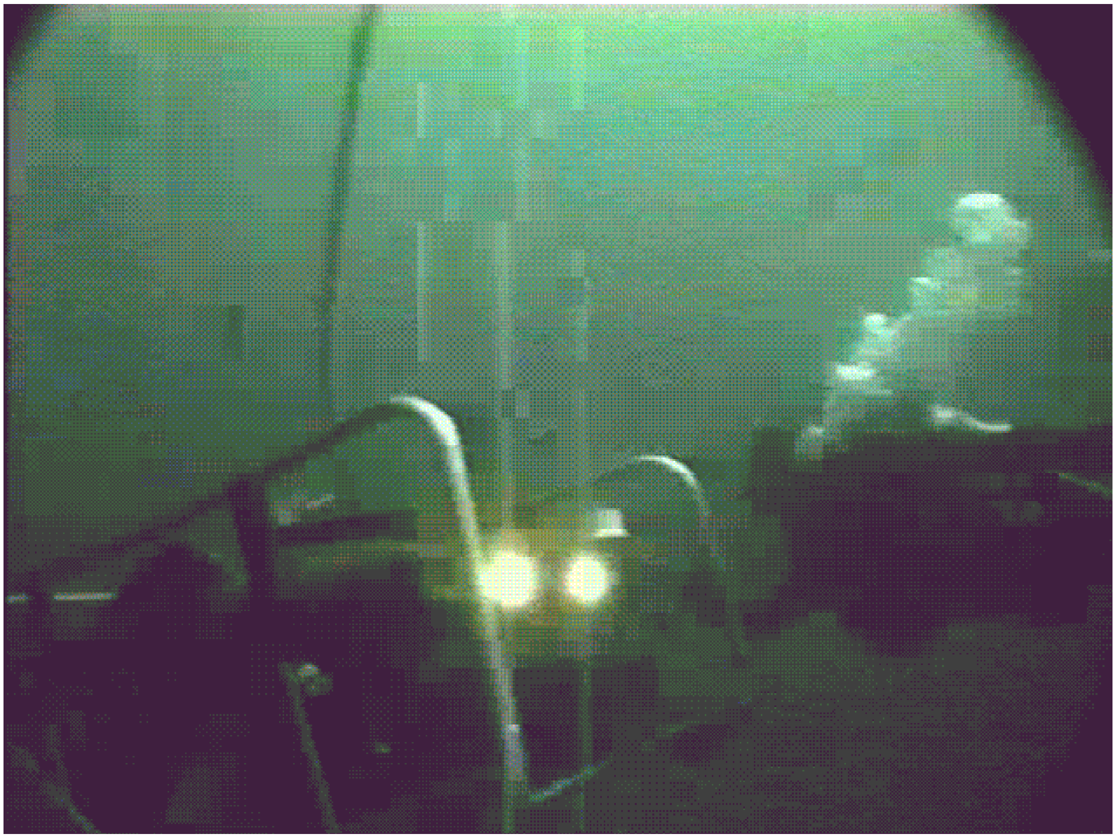

Figure 2.8. Lockheed Explosive Ordnance Disposal Robotics Work Package (EODRWP) and diver (Trimble 94a, 94b) (Brutzman 94a).

8. Miniature AUVs

With exponentially improving price/performance ratios in computer microprocessors, it is natural to expect that miniature AUVs might provide capabilities that avoid the power and propulsion handicaps of larger vehicles. The Smart Communications System (SMARTCOMMs) (Frank 94) is representative of such efforts. As fundamental AUV problems of low-power sensing, low-level dynamics control and high-level mission control are resolved, miniaturization and optimization of vehicles becomes cost effective. It is likely that large numbers of inexpensive and moderately capable AUVs will become available in the near future. Communicating with and coordinating these vehicles in the context of massive environmental datasets, numerous data streams and large ocean areas will be a significant challenge. Networking large numbers of these vehicles within an underwater virtual world can be a practical solution.

C. ROBOTICS AND SIMULATION

A very great number of robotics-related simulations have been produced, but few involve mobile robotics. Those simulations which are available are typically restricted by common limitations of simulation: problems and solutions are approached in a piecemeal and fragmented fashion. Thus simulation results remain susceptible to failure when deployed in the real world due to the untested complexity of multiple interacting processes operating within the hard real-time constraints of unforgiving environments. There is no safe and complete "practice" environment for AUVs, since test tanks cannot reproduce the variability of critical parameters found in the ocean, and since any in-water failure may lead to vehicle damage or loss due to flooding. Known simulation efforts pertaining either to AUVs or construction of robot-centered virtual worlds follow.

1. NPS AUV Integrated Simulator

Research preliminary to this dissertation established "integrated simulation" as a necessary tool for AUV development (Brutzman 92a, 92c, 92e) (Compton 92). Integrated simulation was identified as a suite of simulation tools to assist in the design and testing of all vehicle hardware and software components. An integrated simulator was built that provided real world functionality and visualization for a variety of AI-related tactical software programs. Integration of simulation throughout the software design process was shown to have tangible benefits in producing results that might otherwise have been impossible. Pertinent work preceding that thesis includes (Jurewicz 90) (Zyda 90) (Healey 92a). Confirmation of integrated simulation conclusions were subsequently reported following the successful development of the Multi-Vehicle Simulator (MVS) with the Twin-Burger AUV (Kuroda 94) (Brutzman 94a).

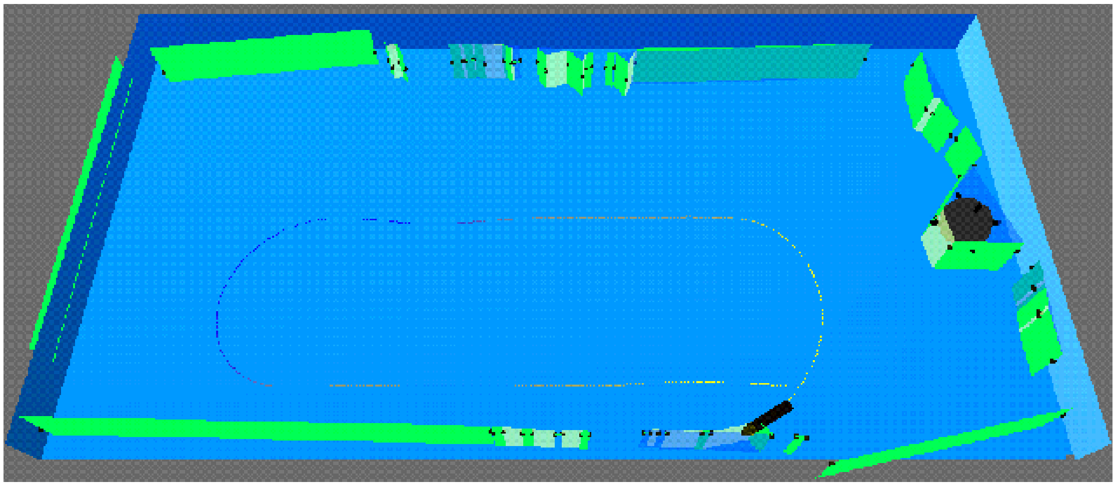

Figure 2.9. NPS AUV Integrated Simulator showing playback of pool mission with autonomous sonar classification expert system results (Brutzman 92a, 92c, 92e) (Compton 92).

Integrated simulation differs significantly from the virtual world produced in this dissertation in that robot-specific hardware and software were completely off-line, real-time response was not required, simulation models were not connected or networked, simulations were single user programs and vehicle hydrodynamics response was only available by playing back in-water test results. Developing and implementing the concepts involved in integrated simulation were important prerequisites to conceiving the notion and defining requirements to build an underwater virtual world for an AUV (Brutzman 92d).

2. ARPA/Navy UUV Hybrid Simulator

The ARPA/Navy UUV development lab at Charles Stark Draper Laboratories includes a simulator which consists of a mainframe computer, models of hydrodynamics and sensor response, and highly detailed component-level models of individual UUV internal equipment (such as motor electrodynamics models) (Pappas 91) (Brancart 94) (Brutzman 93a, 94a). A Simulation Interface Unit (SIU) provides a custom hardware interface between mainframe computer and vehicle.

Mechanisms are also provided to test individual vehicle components. At-sea test dive profiles are first undertaken in the laboratory prior to operational testing. Wireframe graphics provide a simple rendering of vehicle posture during hardware-in-the-loop testing.

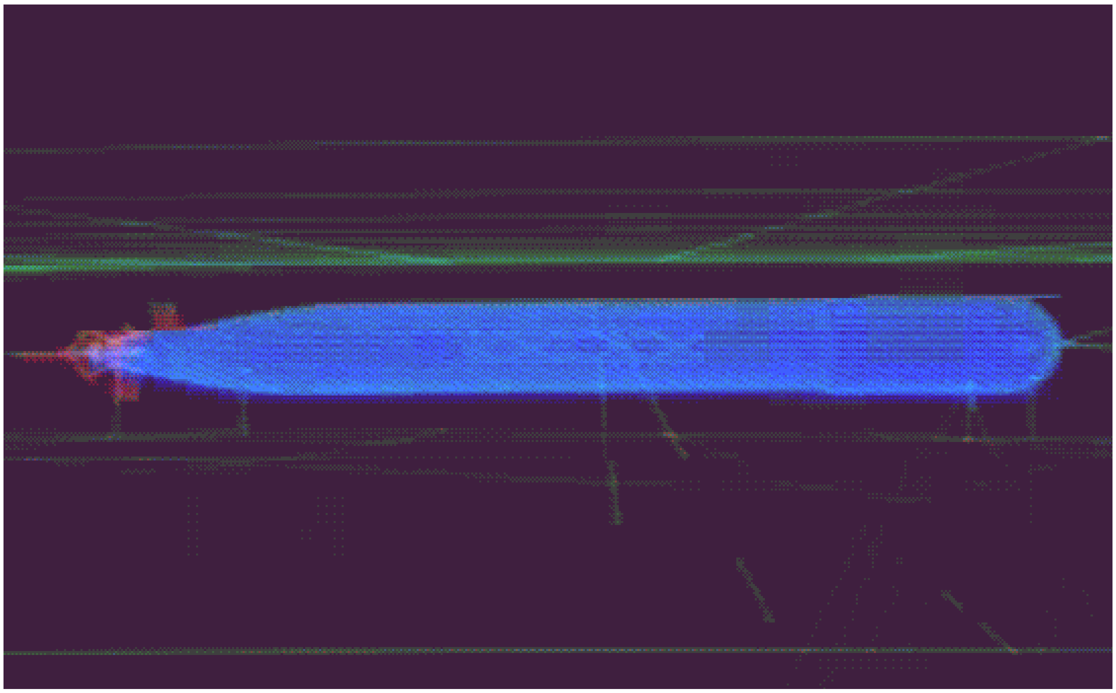

Figure 2.10. ARPA/Navy Unmanned Underwater Vehicle (UUV) Hybrid Simulator wireframe graphics rendering of hardware-in-the-loop laboratory vehicle tests (Pappas 91) (Brancart 94) (Brutzman 93a, 94a).

The ARPA/Navy UUV Hybrid Simulator has much of the functionality needed for a robot-based underwater virtual world, but several important capabilities are missing. The algorithms and source code for the hybrid simulator are not publicly available and many equipment components are proprietary. Since all software components (including computer graphics) are in a single loop on a large mainframe computer, the software architecture cannot scale up indefinitely with the addition of new world models. Graphics are particularly bound since the frame rate of screen updates are tied to the timing of the robot/simulator loop. No mechanisms are