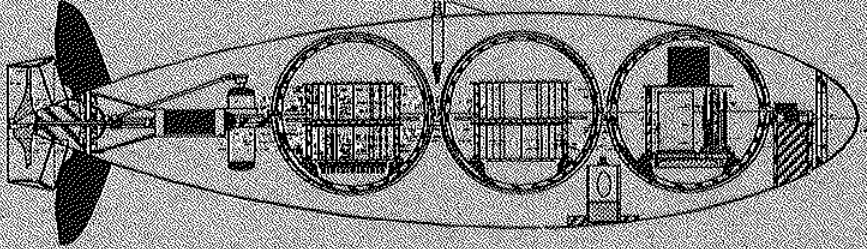


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The MIT Sea Grant Summer 1993 Undergraduate Workshop in Autonomous Underwater Vehicles

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**Applications for an Autonomous Underwater Vehicle:
A Case Study of Issues of Complexity
in Undergraduate Engineering Design**

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Quoc Tran

graphics by Clifford Goudey

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background

Long a pioneer in including research experience as part of undergraduate engineering education, MIT began the MIT Undergraduate Research Opportunities Program (UROP) 24 years ago, after the late Professor Margaret MacVicar, inspired by a memorable lecture presented by Dr. Edwin Land, championed the UROP concept within MIT. What was a radical and new idea then is now an integral part of MIT's undergraduate education.

One-on-one interactions between faculty and students fostered by UROP and NSF's Research Experience for Undergraduates are extremely important, but other dimensions to the research and development process are also important to the education of tomorrow's technological and scientific leaders. For example, most successful research and development problems require close interactions among engineers of many disciplines, yet we offer few such experiences to our undergraduates. We also recognize that marketing, research, design, engineering, manufacturing and sales cannot be compartmentalized in an era in which product cycles are short and reliability, functionality and style must be achieved at the lowest possible cost. Our conventional education programs offer few design opportunities and almost no construction of prototypes, much less manufacturing, for engineering undergraduates. Our Leaders for Manufacturing program, involving the Sloan School of Business and the MIT School of Engineering, addresses this issue, but primarily at the graduate level.

For the past three years the MIT Sea Grant Underwater Vehicles Laboratory (UVL) has been involved in an NSF and MIT sponsored experiment designed to address a critical issue in undergraduate engineering education — that of students working together organizing and managing a complex, multi-disciplinary, beyond the state-of-the-art project, involving a useful product that can be worked on as a team project for two, three or more years. As the test project, we have focused on the design and development of autonomous underwater vehicles (AUVs). AUVs are especially useful for introducing undergraduates to the problems and opportunities of working collaboratively on real systems. Our underwater vehicles employ a modular architecture for both hardware and software. This allows students to work together on an appropriately sized, manageable project involving a particular vehicle subsystem. At the same time, since all the software and hardware subsystems must function together in a working vehicle, a high degree of interaction and

(continued on next to last page)

the laboratory

The MIT Sea Grant Underwater Vehicles Laboratory (UVL) is dedicated to the development of fully autonomous underwater vehicles (AUVs) with diverse capabilities and equally diverse applications to oceanography, environmental monitoring and underwater resource utilization. Since its inception in 1989, the UVL has involved undergraduate and graduate students in all phases of AUV design, construction and testing.

Robotics has always been an exciting area of engineering research. AUVs are doubly exciting for students because they combine robotics with underwater exploration. The potential application of these vehicles to topical issues, such as pollution and global climate change, provides an additional strong motivation.

Robotics is an interdisciplinary field, combining elements of mechanical engineering, electrical engineering, computer science, artificial intelligence and, in our case, ocean engineering. Each student enters our lab with a particular interest and major, and his or her project is usually centered about that interest. Each, however, must closely interact with students and staff with expertise in other areas in order to integrate the results of the project into the vehicle. As a result of this interaction, all our students quickly acquire a baseline of AUV knowledge crossing all fields. For example, our electrical engineering students have learned many of the fundamentals of ocean engineering, while our ocean engineering students have learned how to design and program microprocessor-based systems. We encourage further intellectual cross-fertilization through student presentations, lab meetings and seminars.

A key element of our design philosophy is to build small and inexpensive, yet capable and reliable vehicles that can be easily and quickly applied to real-world problems. This has the advantage of producing vehicles ideal for use by students. For example Sea Squirt, our first fully operational AUV, weighs 35 kg and can easily be deployed by two students. Sea Squirt has been the focus of numerous student projects and theses. Our major efforts are now focused on Odyssey, a long-range, deep-water survey vehicle. Odyssey is two meters long, weighs 150 kg and is the smallest and lightest vehicle with 6,000-m ocean-depth capability in the world. Despite its more ambitious capabilities, Odyssey is designed for easy deployment with a minimum of support. In other words, Odyssey is "student friendly."

At the other end of the spectrum we have begun to develop a series of very small AUVs, which we call micro-AUVs. Two such vehicles are currently under construction — a 20 cm long, 3 kg wheeled benthic vehicle and a 70 cm long, 5 kg free-swimming micro-AUV. These vehicles are to be used in experiments in chemical sensing by AUVs.

workshop format

A problem associated with our first undergraduate education efforts was the students' varied skill levels and general lack of training in practical aspects of electronic and mechanical prototyping and construction. The Summer '93 Undergraduate Workshop in AUVs addressed this deficiency by adding a more formal education in practical prototyping.

The first day of the workshop was a time for orientation by Sea Grant Director Prof. Chryssostomos Chryssostomidis, UVL Manager Dr. James Bellingham and Workshop Organizer Dr. Thomas Consi. In addition, the MIT Safety Office provided a comprehensive seminar in laboratory and field safety. The students were then plunged into hands-on experience, with additional lectures, seminars and field trips supplementing the program. In the first week the students took a machine-shop course (run by the Edgerton Center) and started their projects, working one or two at a time with a project mentor selected from either the MIT Sea Grant UVL staff or from the MIT Department of Ocean Engineering. During the second week the students participated in a "How-to-Build with Electronics" course, run by the UVL and designed around electronics kits. This course gave them the skills required to build simple electronic devices, as well as providing them with the multi-meters and power supplies (built from the kits) they would need in their individual projects. For the remainder of the summer, the students immersed themselves in their projects. In addition, they participated in weekly laboratory meetings and seminar/lectures. Also weekly, each student had to hand in a progress report — no one got lost or was left to flounder.

Hands-on experience with the AUV Odyssey was an important element of the Workshop. Through working with Odyssey, the students learned about the problems associated with AUV deployment, operations and recovery. In addition, exposure to a fully operational AUV gave the students a "feel" for the total system and an appreciation for the power, size and reliability constraints placed on any system designed for use on an AUV. Every undergraduate was required to help operate the Odyssey at least once during the summer. Odyssey operations were coordinated by UVL graduate student Chris Smith, who (aided by high-school student Demetrios Zaphiris) directed a regular schedule of vehicle experiments.

The hard work paid off in the last week, when students met with each other and with the staff to show their accomplishments — presenting results in oral reports and formal write-ups. For the final lecture/treat, Dr. Consi headed a field trip to the New England Aquarium, where the students were introduced to the ultimate in AUV design — living marine creatures.

project 1

Mapping the bottom topography of the Charles River Basin using sonar and GPS

This project was intended to provide an accurate underwater map of the Charles River between the Harvard and Longfellow bridges. Knowledge of this underwater terrain is of particular significance for Sea Grant because this stretch of the river is used extensively for testing autonomous underwater vehicles and performing acoustic navigation experiments. The availability of the Coast Guard's differential global positioning navigation system (DGPS) and new, sophisticated mapping routines developed by the MIT Ocean Engineering Design Laboratory offered the opportunity to complete this project in a reasonable time with a level of accuracy never before attainable.

mentor: Donald K. Atwood
postdoctoral fellow, UVL

students: Jacqueline Brener
freshman
Molly Frey
sophomore, physics



Molly Frey and Jaqueline Brener set out for field testing in the Charles River

The two UROP students were responsible for all aspects of the bathymetry (mapping) project. First they integrated a depth sounder, a DGPS navigation system and a PC into a system to log depth and position (latitude and longitude) information into files that formed the raw data for underwater maps. Software to run this system was provided by Kurt Zala, an MIT Sea Grant UROP student. The data-acquisition system was installed on one of MIT Sailing Pavilion's power boats and methodical measurements were made over one week. Software developed by Seamus Tuohy (Ocean Engineering Design Laboratory) was then used to convert the depth readings into a three-dimensional grid, which represented the bottom of the Charles River. Portrayed in relief, with different colors representing different depths, these data have yielded remarkably detailed maps. In addition to maps that will benefit projects in the Charles, this project has developed a methodology for mapping ocean bottoms that will be used by Odyssey in future missions.

Donald Atwood

project 2

Development of an underwater, pressure-compensated digital imaging system

A prototype pressure-compensated underwater imager has been developed at the UVL. This system has the potential to become a small, light-weight digital camera for use on deep-water AUVs. A student was required this summer for further development and testing of this system.

mentor: James W. Bales
postdoctoral fellow, UVL

student: Eva Moy
sophomore, mechanical engineering



Eva Moy testing pressure-compensated imager on the dock of MIT's sailing pavillion

Eva Moy worked under my direction in advancing the development of a novel, pressure-compensated underwater imager. Eva took a prototype unit, designed and built by a graduate student during 1991-1992, and got it working again. She constructed a test facility in the lab, which allowed her to characterize the operation of the imager in water and under controlled lighting conditions. Based on her experiences with the prototype, Eva identified areas where the prototype could be improved, and performed a complete redesign of the mechanical housing and the focusing apparatus. She fabricated the new housing in a machine shop at MIT, and tested it in the laboratory. In carrying out her redesign of the camera, she worked closely with the MIT Sea Grant staff to ensure that her design was compatible with the small, low-cost AUVs being developed here.

James Bales

project 3

Development of a micro-AUV for studies in underwater chemical sensing

This project was intended to help develop small AUVs as test-beds for ideas in biological chemosensing behavior. A great variety of marine animals navigate using chemical signals to locate food sources, mates and spawning grounds. The sensory systems and behaviors exhibited by these animals are well adapted for robust operations in turbulent and chemically complex environments. The algorithms used by an animal to rapidly extract navigational information from a discontinuous and chaotic chemical signal are presently unknown and are the topic of current research. We are developing a small benthic robot which will be used as an algorithm test-bed for ideas in biological chemosensing behavior. The robot is designed to mimic the basic features of a lobster relevant to chemical sensing and associated behaviors. The lobster was chosen as a model system because its chemosensing capabilities are sophisticated and have been well studied.

mentor: Thomas R. Consi
UVL research engineer

students: Jamie Cho
freshman
Jude Federspiel
sophomore
aeronautics and astronautics



Jamie Cho keeping an eye on RoboLobster

Our robot is a small, wheeled vehicle with the size, speed and maneuverability of an adult lobster. Two students worked on the project during the summer. One student, Jude Federspiel, designed and built a test apparatus to calibrate a small gyroscope that will be used to monitor the rate of turning of the vehicle. Another student, Jamie Cho, developed the basic software to control the sensors and motors of the vehicle. Jamie is continuing his work in the fall '93 semester as a UROP student. He is currently writing the overall control code for the vehicle and is also porting a multitasking operating system to the vehicle's onboard computer.

Thomas Consi

project 4

Operation of FLASH EEPROM-based memory cards at high pressures

Memory cards, using FLASH memory chips, are now reaching data storage capacities that make them attractive for mass storage of data from AUVs. The cards offer a number of advantages over hard disk drives as mass storage media: they are rugged (no moving parts), run on low power and at high speed, and data can be rapidly transferred out of the vehicle (simply remove the card).

In order to be used in a deep-water AUV such as Odyssey, it is desirable to have the memory card and its interface outside the vehicle's pressure hull. This will reduce the need to open the pressure hull, an operation that could contribute to failure of the hull's seals. The memory card and interface must, therefore, be able to operate at the high pressures associated with deep water operations, up to 10,000 psi, which corresponds to 6,700 meters. This provides access to more than 95 percent of the earth's surface. To accomplish this we will mount the device in a filled oil container with a flexible bladder to equalize the inside and outside pressures. This pressure-compensation method is routinely used with deep-water instrumentation. The main question this project was designed to answer was: *Can a memory card and interface survive and operate reliably immersed in oil at 10,000 psi?*

mentor: Thomas Consi
UVL research engineer

student: James Uzdarwin
Worcester Polytechnic Institute
senior, electrical engineering

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mentor: Thomas Consl
UVL research engineer

student: James Uzdarwin
Worcester Polytechnic Institute
senior, electrical engineering



(from left) James Uzdarwin, Jared Bibler and Andrew Billings pressure testing memory cards

The student (James Uzdarwin) first had to learn about the structure of memory cards and their component FLASH memory chips. A commercially available memory card interface, designed for use with an IBM PC computer, was purchased. Jim wrote a C program to make test data files exactly the size of the memory cards tested (512K byte). Using software supplied with the interface, Jim could then test the integrity of every byte of data in a card by writing a test data file to the card, reading the data off of the card and verifying it against the original test data file on the PC. This was the method used to test the function of the memory cards and the memory card interface under pressure.

Jim disassembled the memory card interface and replaced the components that could not withstand 10,000 psi with pressure-resistant, epoxy-potted components. Sea Grant engineer Clifford Goudey designed a housing for the interface built, with Jim's assistance, by Jared Bibler, another undergraduate in the group. The memory card interface with a memory card inserted was mounted in the housing, which was then filled with mineral oil. Jim tested the card repeatedly over the next few days to confirm that the system worked immersed in oil.

Jim pressure tested the cards in a pressure test chamber at the Billings Co. in North Falmouth, MA. Three cards were tested at 1000 psi intervals from sea level (15 psi) to 10,000 psi. Jim was assisted by two undergraduates from our group, Jared Bibler and Yannick Trottier, and also by Andy Billings of Billings Co. They confirmed that the memory cards and interface could withstand high pressures (10,000 psi).

Thomas Consi

project 5

Mechanical design of a long-range, deep-water survey AUV

AUV Odyssey, the Lab's deep-diving, long-range robotic submarine, has been operational for approximately 15 months. In waters ranging from the Charles River to the Bellingshausen Sea off Antarctica, we have learned a lot about ways to improve the vehicle.

Several challenging missions planned for 1994 have prompted us to design and build an improved version of Odyssey. The key features of the original Odyssey — such as the spherical glass pressure housings and the floodable streamlined fairing — will be retained. However, the structural materials, external wiring, propulsion and control of the vehicle will be changed to improve the ease of operation and the robustness of the system. Improvements in the vehicle's electronics and software are also being made.

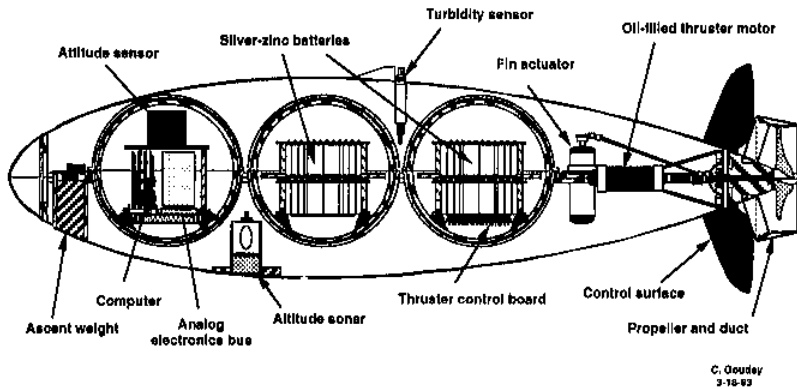
Cliff Goudey, a research engineer at Sea Grant, is responsible for the mechanical and hydrodynamic design of Odyssey II. Several design-and-build tasks were identified as being suitable for undergraduate involvement. In addition to helping the lab, the student would be interacting with experts from a variety of disciplines during the design process. The project offered an opportunity to make a measurable contribution to a complex engineering system.

mentor: Clifford A. Goudey
MIT Sea Grant research engineer

student: Dean Frank
sophomore, mechanical engineering

AUV Odyssey

Length = 66" Diameter = 23"



Schematic diagram of AUV Odyssey

The mechanical design of AUVs presents some unique challenges. Reliability, water-tightness and resistance to the pressures of ocean depth must be considered. Dean Frank, now a junior in mechanical engineering, worked under my supervision on several key pieces of hardware for the Underwater Vehicle Lab's next generation AUV. Dean accomplished the design and fabrication of two actuators to control the rudders and elevator fins of the vehicle. Built around D.C. brushless motors, the units are oil-filled for pressure compensation and accommodate all the electronic boards and components that control the motor's speed and position. The size of a soda can and made of plastic, stainless steel and O-rings, Dean's actuators will become a part of history when the lab's Odyssey II takes part in a scientific mission this spring under the Arctic ice cap.

Clifford Goudey

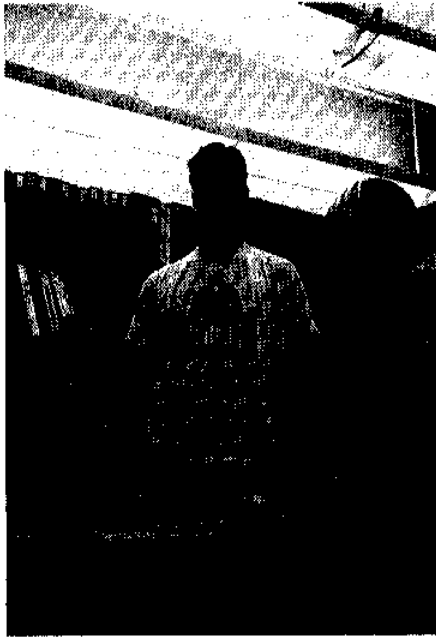
project 6

Development of an efficient propeller for use on the AUV Odyssey

The objective of this project was to design a high-efficiency propeller for a small AUV, using the latest available technology. Propeller efficiency is of major importance for this type of vehicle, since any improvements will result in direct gains in operating endurance with a fixed energy source.

mentor: Justin E. Kerwin
MIT professor of ocean engineering

student: David Brann
junior, aeronautics and astronautics



*David Brann examines
Odyssey's propeller*

David Brann worked under my supervision during the summer of 1993. While David had a background in basic aerodynamics, he needed to make a major effort to become familiar with the computational tools available for marine propeller design.

His first step was to develop the preliminary design parameters for the propeller using a design program recently developed in the Ocean Engineering Department under Navy sponsorship. In addition to his extensive use of the program, David interacted continuously with the Odyssey group to obtain realistic limits on size, power and shaft speed.

His next step was to develop a detailed design using a program that accounts for the interaction between the propulsor and the viscous boundary layer of the vehicle. Since this program is still under development, David's work was hardly routine! By the end of summer, a reasonable design had emerged.

It is planned that the blades for the new propeller will be machined at MIT using numerically controlled tools. In anticipation of this, David interacted with the Ocean Engineering Design Laboratory on the issue of translating the hydrodynamic design data to a form suitable for machining. This work is continuing during the Fall term.

Justin E. Kerwin

project 7

Imaging and obstacle avoidance sonar systems for the AUV Odyssey

The remarkable acoustic sensing capabilities of dolphins provide one inspiration for employing sonar on an underwater vehicle such as Odyssey. This project was intended to develop software for and perform experiments with an underwater sonar imaging system. The device is being integrated into the AUV Odyssey as a mission sensor for mapping ice cover and bottom topography. Given the difficulty in employing conventional sensors, such as cameras, underwater, sonar offers a valuable tool for such tasks as navigation, obstacle avoidance, and bottom-following.

mentor: John J. Leonard
postdoctoral fellow, UVL

students: Jared Bibler
freshman
Jean Nam
senior, electrical engineering



Jean Nam testing the sonar system in water

Jared Bibler's primary responsibility this summer was construction of an apparatus for positioning our Tritech sonar system in the MIT ship-model testing tank. The apparatus he constructed has been invaluable in our experiments and he now wants to do work he can publish in a paper for a conference. Jared picked up a lot of machining experience and obtained a lot of informal knowledge on how to get things done at MIT — from interfacing with technicians to ordering parts.

Jean Nam's accomplishments included some MATLAB simulations of sonar detector circuits, and one computer program to control our sonar sensor and another to interface to our digital oscilloscope. These will directly support our lab's efforts to integrate the Tritech sonar with the Odyssey II vehicle (currently under construction) for its upcoming Arctic ice-mapping mission. Jean also provided invaluable assistance in the tedious task of sonar data collection. With the summer's experience under her belt, she has taken a research assistantship in the MIT Department of Ocean Engineering.

John Leonard

project 8

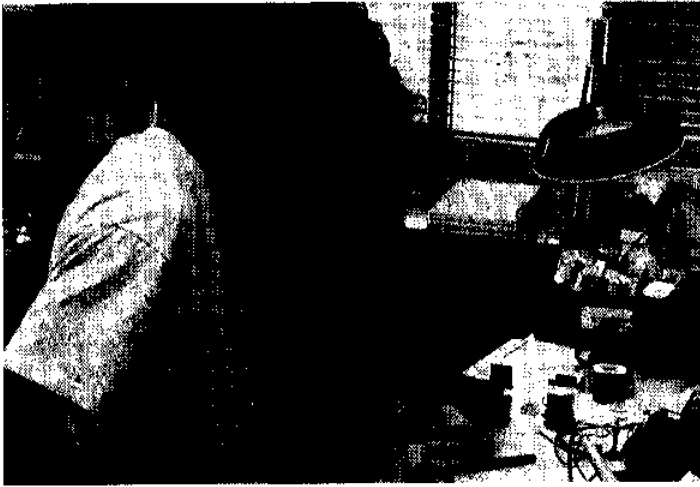
An underwater spectrometer for diver-held and AUV applications

The purpose of this project was to develop an instrument for making spectral measurements that could be implemented on the Odyssey AUV. The instrument was primarily intended to measure fluorescence emission spectra, but could also be used to measure ambient light spectra.

The project was divided into several facets, with responsibilities assigned to the project participants: 1. interface (hardware and software) of the Ocean Optics S1000 Spectrometer to the TattleTale 7 computer (Charles Mazel); 2. experimentation with means of coupling light into the fiber optic spectrometer input (Quoc Tran); 3. development of an appropriate fluorescence excitation source (all); and 4. design and construction of underwater housings for the various subsystems (Lydia Chan).

mentor: Charles H. Mazel
research engineer, ocean engineering

students: Lydia Chan
sophomore, mechanical engineering
Quoc Tran
sophomore, mechanical engineering



Quoc Tran and Lydia Chan checking circuits

At the start of the summer both Lydia and Quoc participated in the machine shop training, gaining experience vital to carrying out their projects. Quoc undertook the investigation into gathering light into the input fiber. He spent a great deal of time investigating optics and then designing and constructing several different light collection approaches using a variety of lenses and mirrors.

Lydia Chan undertook the design and construction of the housings. She spent much of the summer making construction drawings using a CAD package, machining the housings and endcaps, and dealing with outside vendors for penetrators and other pieces.

Work on the fluorescence excitation source was a shared undertaking among the students and the supervisor. Due to the time scales involved and the level of work on other tasks, only rudimentary progress was made on this aspect. A commercial flash unit was acquired and successfully connected to the computer, but the design was not finalized.

At the close of the summer the students had succeeded in constructing an instrument capable of making spectral measurements autonomously (though not yet of fluorescence). Besides accomplishing useful work, the students learned much about the reality of doing a real project, not a canned experiment, and for which success is not assured. The value of the students to the project is demonstrated by the fact that both have been kept on into the fall as UROPs to continue the development of the instrument.

Charles Mazel

(background, continued)

communication among the student project groups is required, strengthening the need for interdisciplinary communication.

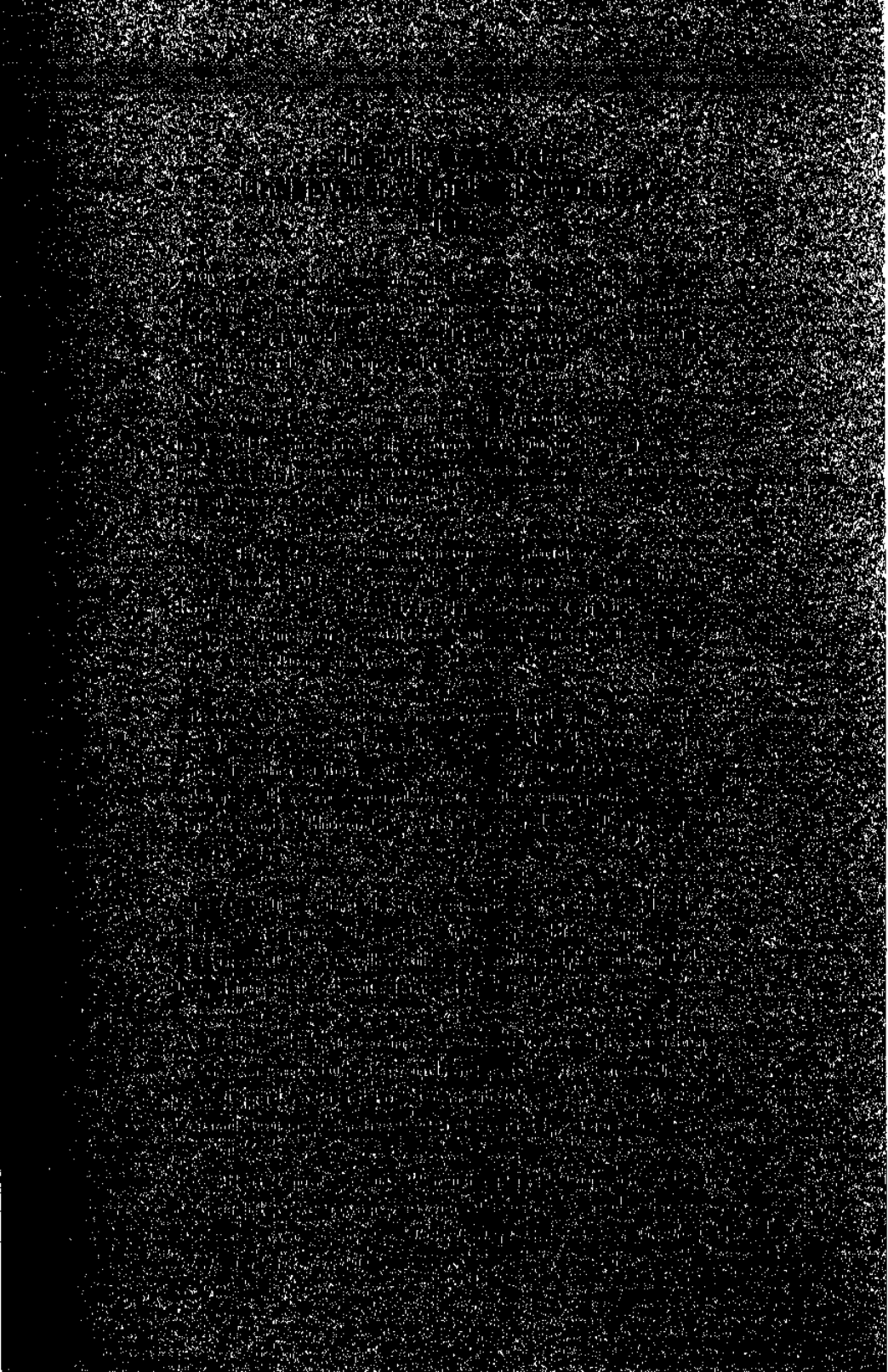
In the first phase of this experiment, from September 1991 to May 1992, 12 students participated in our program and pursued specific projects under the close supervision of laboratory staff. Several opted to continue their projects by doing their senior theses in our laboratory.

From June 1992 to May 1993 we continued and expanded our efforts to give undergraduate students solid experience with working in interdisciplinary teams developing autonomous underwater vehicles. The diversity of our student group had increased significantly to include more women and minority students, and we also opened our program to selected non-MIT students, including one high-school student. During this period we supported 12 students, eight continuing and four new students.

The culmination of this project occurred in the third year in the form of The MIT Sea Grant 1993 Summer Workshop in Autonomous Underwater Vehicles, involving 12 undergraduate students. We added a more formal educational element to the summer program, while continuing our successful model of individual student projects, one-on-one relationships with staff researchers and experience with working in a multi-disciplinary team on a complex engineering project. In addition, one high-school student joined the UROP group, bringing the total to 13 students. Of the 13 students and one undergraduate assistant, six elected to continue their research with us.

The Summer '93 Workshop in AUVs was very successful in both educating students and inspiring future workshops and courses of a similar nature. As a result of the Workshop we are developing collaborations with the new Edgerton Education Center. We are currently sponsoring one Edgerton Center Freshman Advisor Seminar in the design of an autonomous surface boat for use in big-fish tracking. We have also attracted the attention of scientists and engineers outside of the UVL who wish to mentor students in advanced AUV-related projects.

A total of 29 students have participated in this three-year program; about 50 undergraduates have been involved in the MIT Sea Grant Underwater Vehicles Laboratory since its inception in 1989. It is this solid and extensive base of experience with non-traditional "hands-on" undergraduate education that we present here.



The MIT Sea Grant Underwater Vehicles Laboratory Fleet

AUV Sea Squirt — Our first AUV, Sea Squirt is a 35 kg, three-foot-long autonomous underwater vehicle and has been used as a test-bed for software and instrumentation for more than four years.

AUV Odyssey — This pioneering prototype is 2.15 m long, 0.39 m diameter autonomous underwater vehicle capable of operation to 6,000 m and a variety of high-endurance missions.

Robo-Lobster — Our autonomous underwater wheeled vehicle is 13 cm high, 20 cm wide and 20 cm long. It was developed as a bio-mimic to test benthic animal behavior algorithms such as chemical detection and plume following.

Micro-AUV — This swimming vehicle is 9 cm in diameter and 65 cm long. It is under development to be a three-dimensional version of Robo-Lobster for plume following and ultimately locating point sources of pollution. It will be capable of 3 knots for ten hours.

Odyssey II — This is the second AUV in the Odyssey class. Its design stresses manufacturability and robustness. Odyssey II will be completed in early 1994. Its planned 1994 mission is in the Arctic.

ASC I — This autonomous surface craft is 1.37 m long with a beam of 0.38 m and is capable of 3 knots. It was developed for tracking and following an underwater sound source, but it can carry a variety of payloads.

R/V Penelope — Our 22-foot research support vessel is capable of carrying any of our underwater vehicles and a crew of up to six. Penelope was donated to the lab by the Gerson family.

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