The MIT/Marine Industry Collegium
Opportunity Brief #36

MIT Underwater Vehicle Research: Recent Advances and Future Programs

A Project of
The Sea Grant College Program
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The MIT Marine Industry Collegium

MIT UNDERWATER VEHICLE RESEARCH: RECENT ADVANCES AND FUTURE PROGRAMS

Opportunity Brief #36

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Preface

This Opportunity Brief is based on a workshop entitled "MIT Underwater Vehicle Research: Recent Advances and Future Programs" that was held at the Massachusetts Institute of Technology on December 5, 1983. The workshop was sponsored by the MIT Marine Industry Collegium, which is supported by the National Oceanic and Atmospheric Administration Office of Sea Grant, by MIT and by more than 100 member corporations and government agencies. Any opinions or conclusions expressed herein are those of the author and do not necessarily reflect the views of the MIT Sea Grant Program or of MIT.

The topics reported here include the latest applications of supervisory control to underwater vehicles, the design and demonstration of a novel parallel link manipulator arm, of a fiber optic touch sensor and of an underwater stud welding gun. Also included is a discussion of controlling a vehicle using constraints.

Through workshops and Opportunity Briefs, the MIT Marine Industry Collegium brings university researchers together with potential users of that research. If you would like any additional information, please call Margaret Linskey or Norman Doelling at (617) 253-4434/7092 or write to MIT Sea Grant Program, 292 Main Street, Cambridge, MA 02139.

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1.0 INTRODUCTION

The MIT Marine Industry Collegium members have participated in workshops on Underwater Technology Research at MIT since 1976. Recently workshops and Opportunity Briefs on Underwater Technology have been an annual event.

During the past year the research at MIT has accelerated and now includes a broader set of important research projects. The availability of an unmanned underwater research vehicle provides an opportunity to integrate these research projects and to field test concepts and systems which had previously been tested only in the laboratory. New cooperative efforts between MIT and the Woods Hole Oceanographic Institution assure rapid development and testing of concepts and systems which are needed by both institutions.

This Opportunity Brief and the accompanying workshop updates earlier research programs and describes new research activities at MIT.

2.0 BUSINESS PERSPECTIVE

As marine resource developers move from the shallow shelf waters into deeper waters in search of oil, gas, and mineral reserves, the costs of exploration and production coupled with the risk to divers have increased exponentially. In addition, the demand for knowledge about mineral resources in the deep ocean requires new systems to allow oceanographers and other marine scientists to search the ocean floor much more rapidly.

Although most of the actual offshore oil production comes from waters less than 400 feet deep, exploratory drilling has been conducted in water depths of 6,000 feet as seen by the recent Baltimore Canyon activity. At such depths, inspection, maintenance and repair of structures based on the sea floor require vehicles that can maneuver easily in and around complicated structures, along pipelines and in strong sub-surface currents.

Remotely piloted, remotely controlled, unmanned, or robot vehicles - whatever the name - are here to stay. About 25 service firms operate undersea vehicles and there are about 20 vehicle manufacturers. New technology is needed to provide less expensive, safer, more reliable and more capable systems for the deeper frontiers.

The work presented herein is an overview of some of the advances and developments made by MIT researchers over the last decade. Brief descriptions of their projects are presented in the report. For more elaborate details and background on the topics discussed, refer to the bibliography.

3.0 SUPERVISORY CONTROL FOR REMOTELY OPERATED SYSTEMS

3.1 Overview

The definition (and implementation) of a supervisory control system involves a local system of input and output devices supported by a local computer system communicating with a remote teleoperator, which also has input and output devices supported by another computer. Some form of communication link connects the two.

Most current remotely operated vehicles (ROV's) used offshore today have the basic characteristics of teleoperators with supervisory control systems. The inputs on the local system are typically joysticks and/or switches, and the outputs are on/off lights, alpha-numeric displays, or video displays. Microcomputers in the local system provide some flexibility in communicating with the ROV (the teleoperator). The ROV itself has inputs which sense the environment (for example, pressure gauges, attitude sensors, thermometers, cameras, etc.) and outputs which affect the ROV or its environment (thrust from motors, lighting, manipulators and the like). In some cases, the ROV itself carries a small computer.

When we talk about supervisory control systems, however, we generally imply that the inputs and the outputs in the remote vehicle are tied together in some degree through the remote computer. Thus, for some operations the remotely operated vehicle is more or less capable of autonomy. For example, automatic positioning is possible by connecting attitude sensors to the motor controls via the remote computer. Similarly, in the local system some of the inputs and outputs may be connected through the local computer so that one could model the result of a maneuver without actually carrying it out.

In the extreme case, as the remote system becomes "smarter" the communication between the local operator and the remote system becomes less and less frequent until the remote system becomes almost autonomous. The operator keeps track of the remote system through the local model.

Thus, we view direct manual control systems, supervisory control systems and autonomous systems as essentially the same thing. They differ only in the degree of communication that is necessary between the local and remote system. The degree of communications required is in turn a function primarily of the sensors, effectors, and "intelligence" of the computer systems.

Supervisory control allows a human operator to plan and teach tasks to a computer, monitor the automatic execution, intervene when necessary to update the computer, take over control or abort the action, and learn from experience. Making no attempt to eliminate human operators, it augments their capabilities by computer aids in order to improve performance or extend the capabilities of the system.

With supervisory control a human operator plus a computer can work more accurately, more quickly, with less variation and with more consistent movements than a human operator alone. Led by Professor Thomas Sheridan, members of the MIT Man-Machine Systems Laboratory explore how humans communicate with and teach computers, how people use computers to assist in making decisions, and how additional functions like touch can be added to the system.

In the supervisory control mode, a person gives the computer commands in a broader sense by presenting goals, available motions and constraints. For undersea applications a person on a ship will communicate with one computer, which will signal to another computer deep under the ocean to command a robot to carry out tasks. Supervisory control on submersibles could potentially follow instructions to respond as a function of what it sees somewhere else, or according to what it feels with its manipulators. These motions could be transformed into tasks such as cleaning, assembly, and inspection which must now be done laboriously by machines or even by divers working in dangerous circumstances.

For a tethered underwater vehicle with high bandwith telemetry to and from the surface, a supervisory control system would begin with a basic manual control mode, possibly allowing the operator to interact directly with the actuators on the remote system. The human operator could select any of several levels of automatic control, and could also choose from various programming options which combined with the automatic control elements provide the remote system with various degrees of autonomy. A corresponding computer system on the surface allows the human operator to plan and teach the actions of the remote system, monitor the remote system's progress and intervene when necessary.

Sheridan has perceived certain trends in supervisory control over the past five years: humans are being used less for purely manual tasks and more for cognitive tasks; greater authority and autonomy is now relegated to the computer that directly controls the machine; and to a much greater extent the computer that interacts with the human is shared among different subsystems.

The computer has shown itself to be useful not only as a subordinate in carrying out well specified decisions by the human operator, but also as a thinking aid for the human operator before the operator commits himself to do something. In earlier versions the computer was a slave that followed direct commands such as, "Go shovel that pile of coal." Now it is progressing to an assistant that investigates the situation and reports to the supervisor how many piles of coal it sees, how heavy are they, and how long it will take to shovel them using all the different means available.

3.2 SEAGRANT 1

Thanks to the loan from the Perry family of Recon-V, rechristened SEAGRANT 1, mechanical engineering students working under Dr. Dana Yoerger have a unique opportunity to rebuild and redesign a working submersible. Yoerger is a Lecturer in the MIT Department of Mechanical Engineering and Visiting Investigator in the Deep Submergence Laboratory at Woods Hole.

Designed for inspection, SEAGRANT 1 is a tethered electrohydraulic vehicle with five hydraulic thrusters and the systems to support a manipulator (Figure 3.1). Once it is fully functional, the submersible's first task will be to demonstrate remotely controlled undersea stud welding. The many movements involved in the welding process will test the vehicle's ability to navigate to the work site, maneuver close up and accomplish precise movements with the welding tool.

Another plan for SEAGRANT 1 is to have it be used for untethered vehicle simulation by making it behave as if it were controlled through an acoustic link. The operator would see all the data delayed and sampled as it would be on an acoustic link, but the experimenter could follow all vehicle subsystems in real time and observe the system as it mimics an acoustically controlled system.

As Yoerger's students spend months tearing the vehicle apart and building it back up in a redesigned form, they receive valuable practical experience and learn about problems ranging from reconditioning hydraulic systems to debugging computer programs. SEAGRANT 1 will be a testbed for the students and faculty researchers to try out their ideas of supervisory control, manipulator systems, and work tools.

3.3 Argo/Jason

Working with the WHOI Deep Submergence Laboratory, Yoerger is in charge of the supervisory control system for the Argo/Jason project. This large project involving several institutions will create an unmanned dual system in which the towed Argo carries the remotely piloted Jason. Operating as deep as 20,000 feet, Jason will transmit data a short distance to Argo which in turn will send it to the

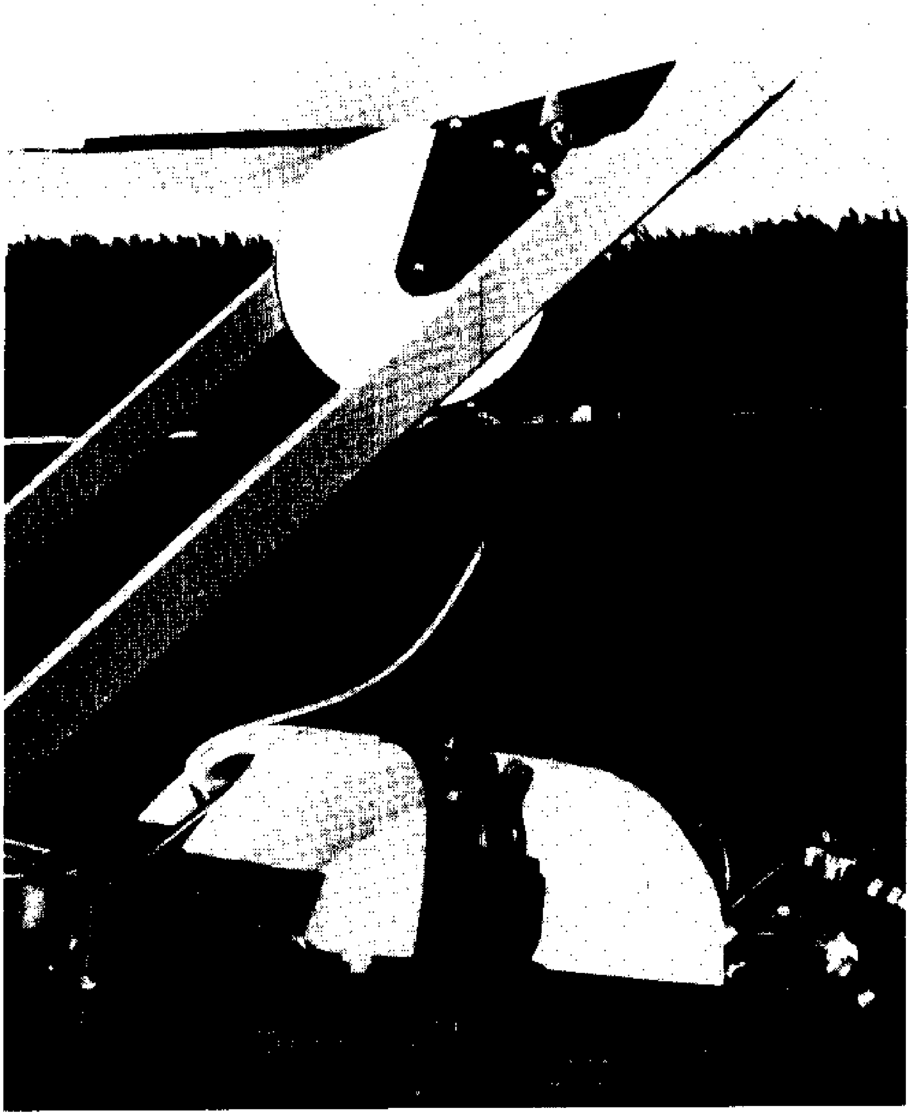


FIGURE 3.1: SEAGRANT 1

surface ship. Since the Argo/Jason systems can stay down for weeks at a time it will vastly increase the amount of information collected during research cruises. (For a sense of scale, the world's most productive deep submersible currently accumulates the equivalent of 25 days of continuous operation per year.)

The prototype Jason is a Benthos RPV-430 with a Deep Ocean Engineering manipulator arm. Yoerger and colleagues at MIT and Woods Hole are adding a more advanced manipulator with sensors and power system, and a new advanced supervisory control system for both the vehicle and the manipulator. Having a higher level control system enables the operator to regard the vehicle and arm as one unit, rather than being forced to calculate available movement options for each singly. If the operator wants to move the hand forward, the computer would choose the best combination of the vehicle thrusters and manipulator actuators. This concept will later be extended to include two manipulator arms working together.

Yoerger is interested in how to make a control system as transparent as possible, trying to create the illusion of operating directly in a remote environment. The Benthos RPV with the manipulator is currently in the water for initial trials integrating the manipulator control with the vehicle control.

3.4 Underwater Vehicle Control Systems Incorporating Mechanical Constraints

An underwater vehicle engaged in close-up inspections, cleaning, welding, assembling or disassembling must somehow fasten itself to the structure where it will be working. Generally its own thrusters cannot maintain the required positioning accuracy, especially in the face of the large forces generated by a moving manipulator arm or by currents flowing past the vehicle.

Sometimes a special grabber arm holds the vehicle at a fixed distance. However, because of the high inertial and ocean current forces, this arm may not be able to hold the precise angular orientation between the vehicle and the object it grabs.

Homayoon Kazerooni, a doctoral candidate in mechanical engineering, is developing a generalized stable positioning system to position and orient any object in the presence of constraints. An underwater vehicle using cables or grabbers to connect with the work piece can be controlled with this positioning system. After connecting the vehicle to the structure by cables or grabbers with the help of the manipulator on the vehicle, the cables can be tightened by utilizing the vehicle thrusters in the necessary directions. Maintaining the cable tension between the structure and vehicle will help give more definite position and orientation. The objective is to control the vehicle position and cable tension in any mission where the number of cables and location of their attachments to the structure are not known in advance.

Control in these circumstances leads in a more general sense to the idea of mechanical impedance control for the manipulator/vehicle system. This more general investigation has very important implications for the control of all types of teleoperator systems and leads to more controllable robots that will interact more comfortably with the environment. The robots will be less likely to damage or be damaged by constraints in their environment.

Kazerooni has developed a computer simulation with a graphic display to show the application of impedance control to almost any type of interaction between a teleoperator and its environment. A robot that tears a door off its hinges because it doesn't take into account the constraints of the door is the antithesis of Kazerooni's system.

3.5 Touch Sensing for Underwater Manipulators

Monitoring how well robotic arms or manipulators perform their assigned tasks is difficult when not enough information is returned to the operator to tell him what the manipulator is touching - or how hard. In a new technique to extract more information, John Schneiter, a PhD student in the Department of Mechanical Engineering, is outfitting a manipulator arm compatible with underwater requirements with tactile feedback to report forces and patterns of touch.

Touch sensing would be especially valuable in situations where the usual video link is impossible, such as in turbid or silt-filled water, or where the arm or environmental objects block the camera. With good touch sensing, a person might be able to recognize objects through "feel." Alternatively, the arm could be "taught" to recognize objects through artificial intelligence techniques. This could help in rescuing items which have fallen out of sight, for example.

The problem is to represent a solid surface in a way that is very concise and unique to the object. A good representation scheme would allow for successful matching or hypothesis generation from partial or degraded sensor information. Work is progressing toward representing objects in terms of connected lists of features, with the features being high curvature regions. Since properties such as curvature are based on second order derivatives, the effect of noise and measurement error on surface data becomes pronounced and can invalidate the calculations. It is therefore necessary to obtain some method of fitting a best mathematical surface representation to the collected data. Options include a spatial filter to smooth the data or use some of the methods from approximation theory for fitting surfaces to scattered data.

In order to investigate the effectiveness of the touch sensor, Schneiter is using a simulation system. A human operator directs the master manipulator, which is an input to the computer, and the same motions are displayed on a graphics terminal. As the human moves, the simulated manipulator in the display touches a simulated box, for example, which produces a grid of dots on the CRT (Figure 3.2). When the pad touches an edge, the output is a thin horizontal line of dots, while pressing against the side of the box would light up the whole grid (Figure 3.3).

The program can change sensitivities, and adjust the spatial resolution from coarse to very fine. Eventually Schneiter hopes to put the sensing pad on an actual arm and test the control ideas which appear most promising in the simulation.

Schneiter proposes that a finite element analysis be performed of a sensor pad with different material properties and under various loading conditions. The goals of the analysis will include determining how truthfully the sensor transduces the input, and determining the spatial frequency of such a sensor using various material properties and sensing element placement schemes.

The tactile sensor in this work functions as a surface data gathering tool as well as an indicator of where a hand should be positioned relative to an object. In addition to supplying surface information, sensor data will be used in an inner, immediate control loop for determining the absence or severity of contact between sensor and object.

3.6 Novel Manipulator Design

Most manipulators on submarines are serial link manipulators, meaning that each moving joint is attached to the proceeding part like in a human arm. In a parallel link manipulator each actuator is directly connected to the working end of the arm, much as strings from each of a puppet's joints are connected to a single stick. Sam Landsberger's Masters thesis in the Department of Mechanical Engineering concerns the design and construction of a parallel link manipulator which will eventually have six degrees of freedom.

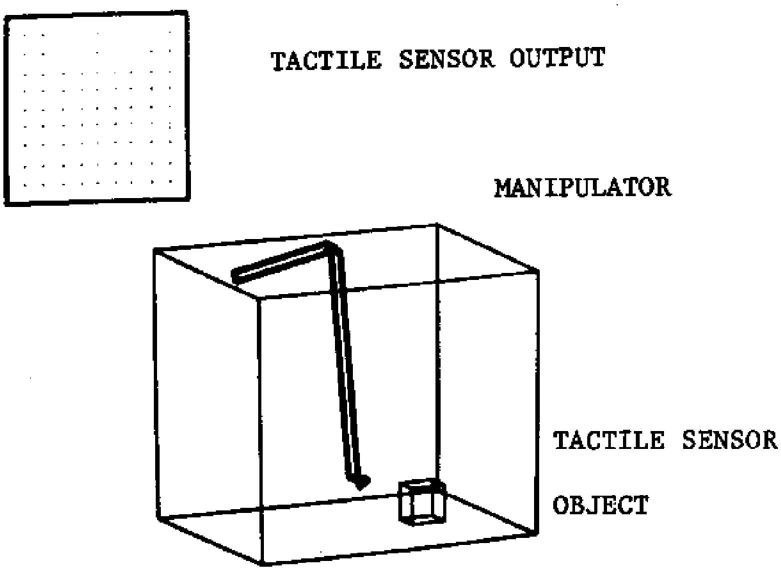


FIGURE 3.2: SENSOR APPROACHING OBJECT

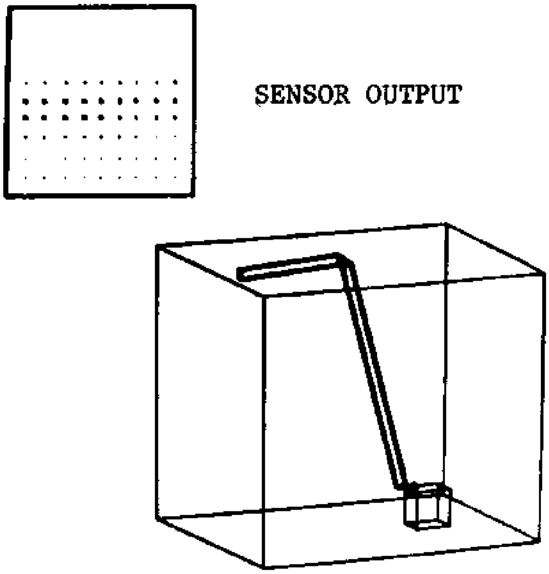
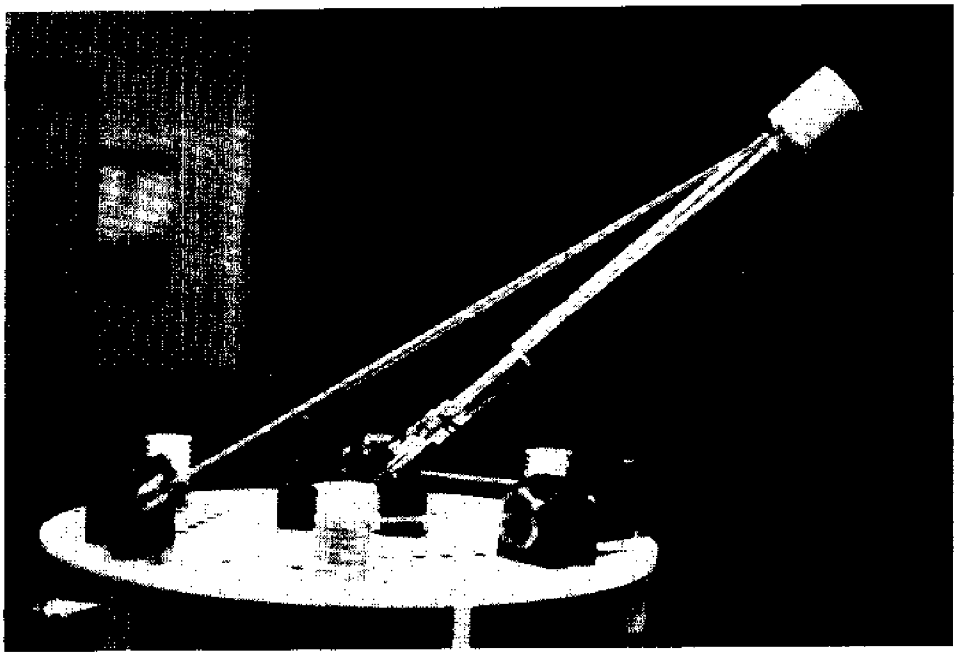


FIGURE 3.3: SENSOR IN CONTACT WITH OBJECT

The newly designed arm shown in Figure 3.4 will be very versatile. Landsberger designed it to be strong enough to retrieve loads weighing up to 200 or 300 lbs, and agile enough to perform underwater welding, cleaning or inspection tasks. Its anticipated weight is about 110 lbs in air, mostly accrued from the six slow speed, high torque hydraulic motors. Largely built of lightweight plastic with neutral buoyancy, its weight in water will be far less. Before spending money to build the arm, Landsberger and Homayoon Kazerooni simulated the design to prove its feasibility.



Parallel link manipulators have many advantages over serial link arms. For example, all the motors in Landsberger's design are placed at the base of the manipulator, where they stand less chance of being damaged. Additionally, clustering the motors at one point on the bottom eliminates the hydrodynamic drag of heavy motors on each joint which is characteristic of some conventional arms. A small error in the length of one cable is not multiplied by the length of the arm, as with a serial arrangement. Programming a serial arm to move from one point to another involves substantial computation to tell each joint where to move, but with a parallel arm the computation involves only simple geometry in a straightforward, fast computation.

Very high strength/stiffness-to-weight ratios can be achieved because actuating links bear no moment loads. Because the actuators act in parallel to position the end effector, the force and moment capacity of the manipulator is much higher than that of the individual servomotors. Manipulator inertia is minimal because only the end effector, not the bulky links and motors, wave around in space. The direct connection between the actuators and end effector eliminates the need for complex drive-trains and minimizes friction and backlash.

Even in early stages of development, the arm has proven the novel actuating principle on which the system is based, and has demonstrated the power, speed and smooth action realized by the floating linkage in which no rigid member exists between base and end effector. Its cost will be relatively low, the design is simple and rugged, and the computer support lies within the capacity of a microprocessor or personal computer.

Landsberger hopes to test the arm shortly. Eventually it will be attached to the <u>SEAGRANT 1</u> for experiments in welding, cleaning and inspection techniques. The arm will also be suitable for diverse non-marine applications including high-speed precision assembly, automated welding and painting, and large payload tasks such as loading and manipulating engine blocks or castings.

4.0 THE EFFECT OF TETHERS ON UNDERWATER VEHICLES

The development of unmanned heavy duty vehicles, though, is still at an early stage. Most of the existing unmanned vehicles are small, light vehicles designed for inspection purposes. Such small vehicles are not suitable for deep industrial applications, because they would be required to provide large thrust in order to carry heavy equipment, for installation, repair, and maintanence of subsea structures.

There is now a trend toward developing heavy payload vehicles suitable for deepwater pipeline inspection and construction. This development presents difficulties, caused primarily by the lack of information on the dynamics of such vehicles attached to a long umbilical cable.

In 1981, Professor Michael Triantafyllou of the MIT Ocean Engineering Department received a Doherty Professorship to study the design of a tethered heavy-payload underwater vehicle. He has studied cable dynamics as applied to tension leg platforms, marine cables and towing cables. He is also supported by the MIT Sea Grant Program to develop techniques to study cable statics and dynamics for offshore operations. Finally, Triantafyllou has applied recent advances in the analysis of marine cables to tethers on underwater vehicles.

Tethers serve several functions on underwater vehicles. They provide a mechanism for recovering the vehicle, they provide a path for transmitting control signals to the vehicle and for receiving information from the vehicle and they generally carry power down to the vehicle. Tethers also cause major problems in the operation of the underwater vehicles. Drag forces on the cable are transmitted to the vehicle and these forces will become more important as depth increases. The dynamic behavior cables may also become an important problem.

When a tethered vehicle is underway, static forces on the tether are induced by the thrust of the vehicle, by current flowing past the tether, and/or by the tether itself. Part of the thrust of a vehicle goes to offset static forces on the cable, while the remaining part is for the vehicle itself.

The heavier the vehicle, the more power it will need to move around. Tether size (diameter) increases with the amount of power needed, since larger electric currents are implied. Therefore, a heavy payload vehicle will require a larger than usual tether, resulting in even higher power requirements.

Control of a heavy payload vehicle will be complex. To minimize the effect of drag forces acting on the tether during maneuvering, the tether must be tensioned, since larger tension implies smaller sag, smaller projected area and smaller drag.

Cable entanglement is another problem when a vehicle goes around a marine structure. The cable needs enough slack so that the vehicle can avoid unexpected obstacles. Yet the tether must be taut enough to prevent it from getting caught on something.

A possible solution to this problem is to devise a way to control the cable tension both from the upper end and from the vehicle. For example, the cable winch would keep tension by winding up some of the cable while the vehicle would use its thrusters to maintain tension. The idea is to have some level of resistance on the cable winch and at the thrusters at all times as vehicle and winch work together to keep the cable tight. Controlling and synchronizing the two will be necessary to maintain an optimal pre-programmed tension.

5.0 AN UNDERWATER WELDING SYSTEM FOR REMOTELY OPERATED VEHICLES

In 1962 there were only 62 offshore oil drilling rigs in the world, but the number increased to 470 in 1978. According to the September 1983 Ocean Industry directory of marine drilling rigs, there are now 770 drilling rigs either in operation or under construction. As the number of ocean structures increases and as existing structures get older, there is an increased demand for underwater inspection and repair. Replacement of anodes for corrosion protection is particularly important. Underwater welding could be a more effective and a safer way of attaching replacement anodes than the present procedure of using explosively propelled studs.

In response to industry's demand for better underwater welding technologies, Professor Koichi Masubuchi of the MIT Ocean Engineering Department has spent many years developing and testing new concepts to improve existing technology and create new ones. Valuable information has been generated, and many theses, technical papers, and reports have been prepared. Professor Masubuchi developed the concept of fully automated, dedicated welding systems for marine applications. These systems were designed to be operated by people with little or no welding skills. Two U.S. patents, one on underwater stud welding and the other on underwater submerged arc welding, have been granted. A second patent on underwater stud welding is about to be issued.

5.1 Design, Construction and Testing of Underwater Stud Welding Systems

Current research work being directed by Professor Masubuchi and carried out by Chris Von Alt, a Masters Degree candidate in the MIT Ocean Engineering Department, is aimed at developing underwater welding and cutting systems which may be operated by remote manipulation techniques. A welding gun, envisioned for use from a remote control vehicle, has been designed, manufactured, and successfully tested in the laboratory. When the control system is completed, the entire package should be capable of producing a quality weld consistently and reliably without human intervention. Additional work on the stud welding system is aimed at the design of an overall control system capable of predicting weld quality remotely, without human intervention. The overall goal of the control system is to prevent a defective weld from being placed in service.

5.2 The Stud Welding System

The major components of the arc stud welding system are: the power supply which provides the required energy to form the weld; the control system which interfaces the power supply with the stud welding gun and coordinates the sequence of events which take place during the welding cycle; and the stud welding gun, an electro-mechanical device which causes steps shown in Figure 5.1 to occur.

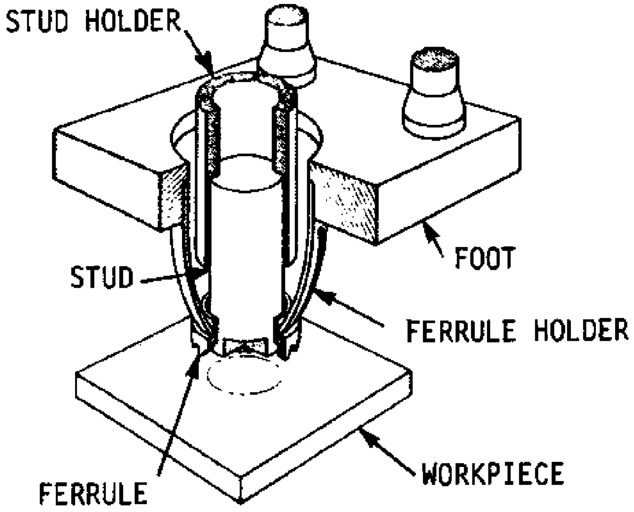
The primary advantage of the stud welding process is the speed of installation and the preservation of the watertight integrity of the joint, i.e., the stud weld is not a through hull penetrator. The arc stud welding process is a fairly simple welding process in comparison to other welding methods. Beyond making minor necessary adjustments to the stud welding gun, control box, and power supply (which are necessary only if the stud material and/or the stud diameter is changed), the operator simply inserts a stud and ferrule into the gun, places the gun perpendicular to the work piece in the desired location, and pulls the trigger to initiate the weld cycle.

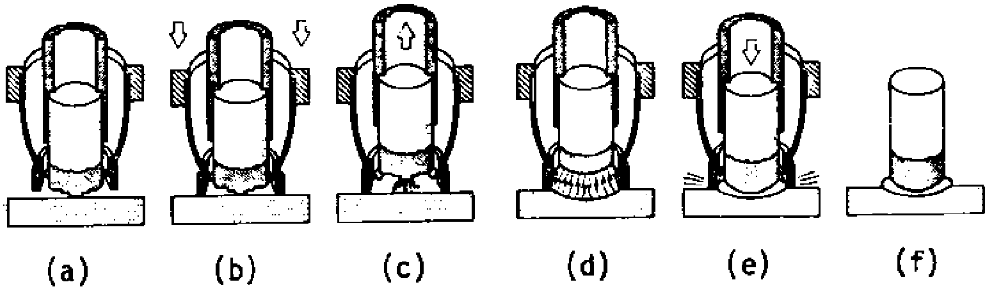
5.3 The Stud Welding Gun

Adapting the stud welding process for use underwater does not alter the sequence of steps, shown in Figure 5.2. A stud welding gun designed for use underwater retains all of the capabilities of normal in-air stud welding guns commercially available.

Initially an air stud welding gun was used in the research. Through the generosity of the Nelson Stud Welding Division of TRW, Inc., a Nelson NS-20A stud welding gun was made available to MIT for this purpose. Although the completed gun retained all of the operational characteristics of the NS-20A gun, substantial changes in the working mechanism of the gun were necessary in order to adapt it for underwater use.

In September 1982, an MIT Sloan School of Management market research team met with local marine contractors and equipment manufacturers to discuss the features they felt the underwater stud welding system should have. As a result of that meeting, Morse Diving Equipment Manufacturing Company of Rockland, Massachusetts, donated and built a prototype second generation stud gun. Thanks to this generous contribution, this prototype is now ready for laboratory demonstrations and will soon be ready for water tests.





(a) First, the stud is located on the workpiece.
(b) Force is applied so that the spring within the gun is compressed until the ferrule is seated firmly on the workpiece.
(c) When the welding current is turned on, the solenoid in the welding gun is energized, the stud is automatically lifted, and an arc between the face of the stud and the workpiece is initiated.
(d) With the stud in the lifted position, arcing spreads across the face of the stud and the heat of the arc melts an area on the workpiece and produces a weld puddle under the stud, and also melts a small portion of the face of the stud.
(e) When the welding current is stopped, the solenoid is de-energized and the face of the stud is plunged, by spring pressure, into the weld puddle.
(f) Finished weld; note shape of fillet formed by the ferrule.

Figure 5.1: Sequence of steps in arc stud welding

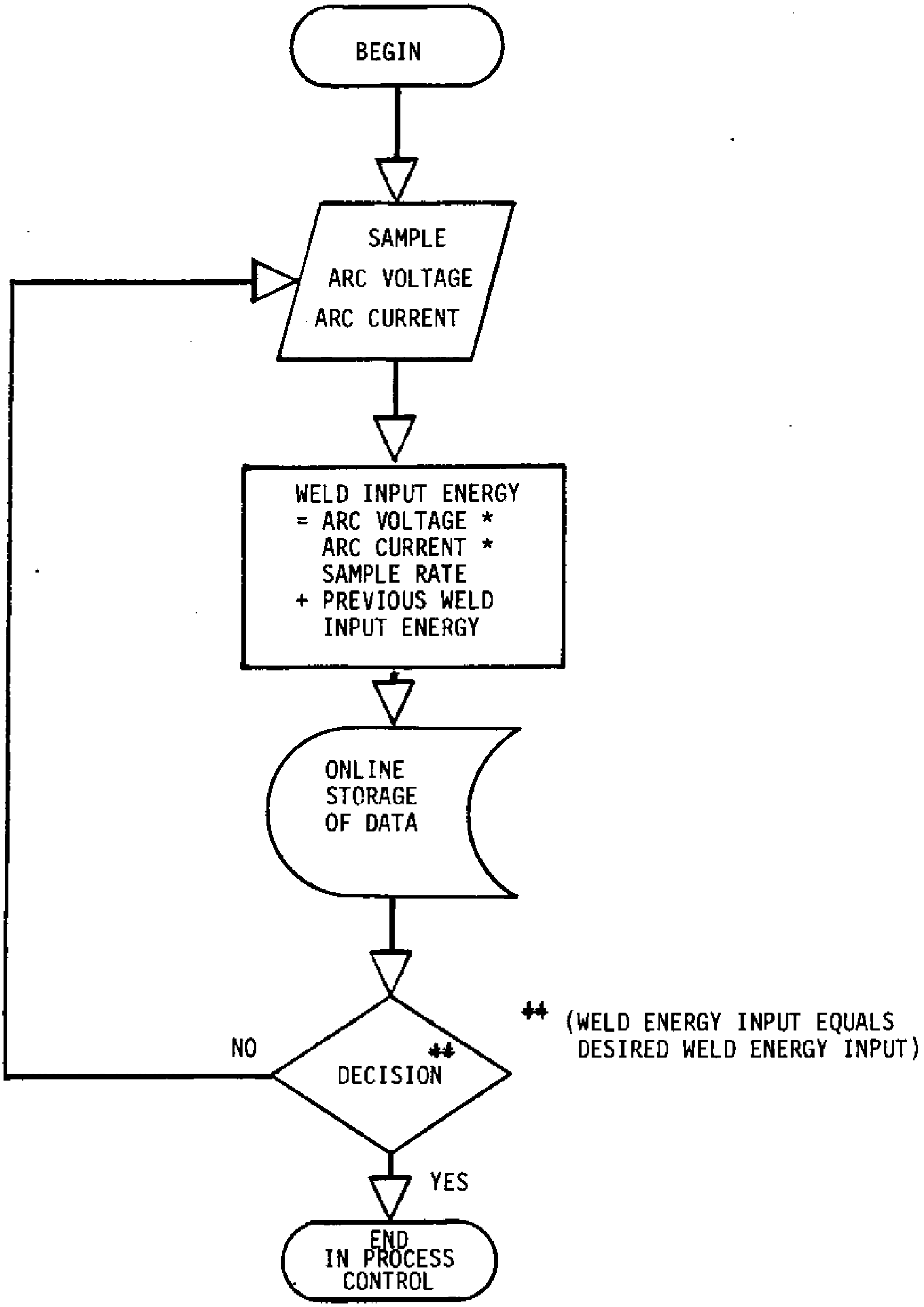


Figure 5.2: In-process control system for arc stud welding system

Examination of the essential operating mechanisms of the Nelson NS-20A gun indicated that the corrosive effects of the salt water environment would have detrimental effects on the gun's operation within a short period of time. It was therefore decided to isolate the inner mechanisms of the gun from the sea water in a waterproof housing. Because the stud welding gun requires a spring which returns the stud to the workpiece with a prescribed force and speed, the waterproof housing must be pressure compensated so that the prescribed speed and force are not affected by changes in depth. An oil bath was used in combination with a flexible diaphragm to communicate changes in ambient pressure of the sea water to the internal mechanisms of the gun. The oil provides continual lubrication to ensure the smooth operation of the gun. In addition, an oil-filled chamber will act as an insulator in the event of an internal fault of the solenoid, an additional safety feature.

In addition, the underwater stud welding gun incorporates a means of adjusting the return rate and force of the stud. Empirical studies performed by the stud welding industry have shown that this feature is essential when stud welding is performed in different positions, i.e., overhead, horizontally or flat. To achieve the desired end, a piston with a variable discharge rate has been incorporated into the gun. The design of the variable return piston is unique and is very different from the solution utilized in commercial units.

Besides the above mechanical aspects, certain features have been incorporated into the gun to help monitor the welding process and increase quality control. The gun has been specifically designed for use in either a remote mode, from a remote control vehicle, or by a diver. The gun may be used in either manner simply by changing the handle.

5.4 Control Systems for Stud Welding

Figure 5.3 is a block diagram of a control process for the fully integrated welding system. The basic concept is applicable to any welding process, although the emphasis of the discussion presented here is placed on arc stud welding.

The heavy horizontal lines show the progression of welding tasks which take place during the overall welding cycle. The lighter lines depict the flow of information input to the system from the weldment design tasks as well as information sensed during different tasks in the overall control process. At the heart of the overall control system is the in-process control system.

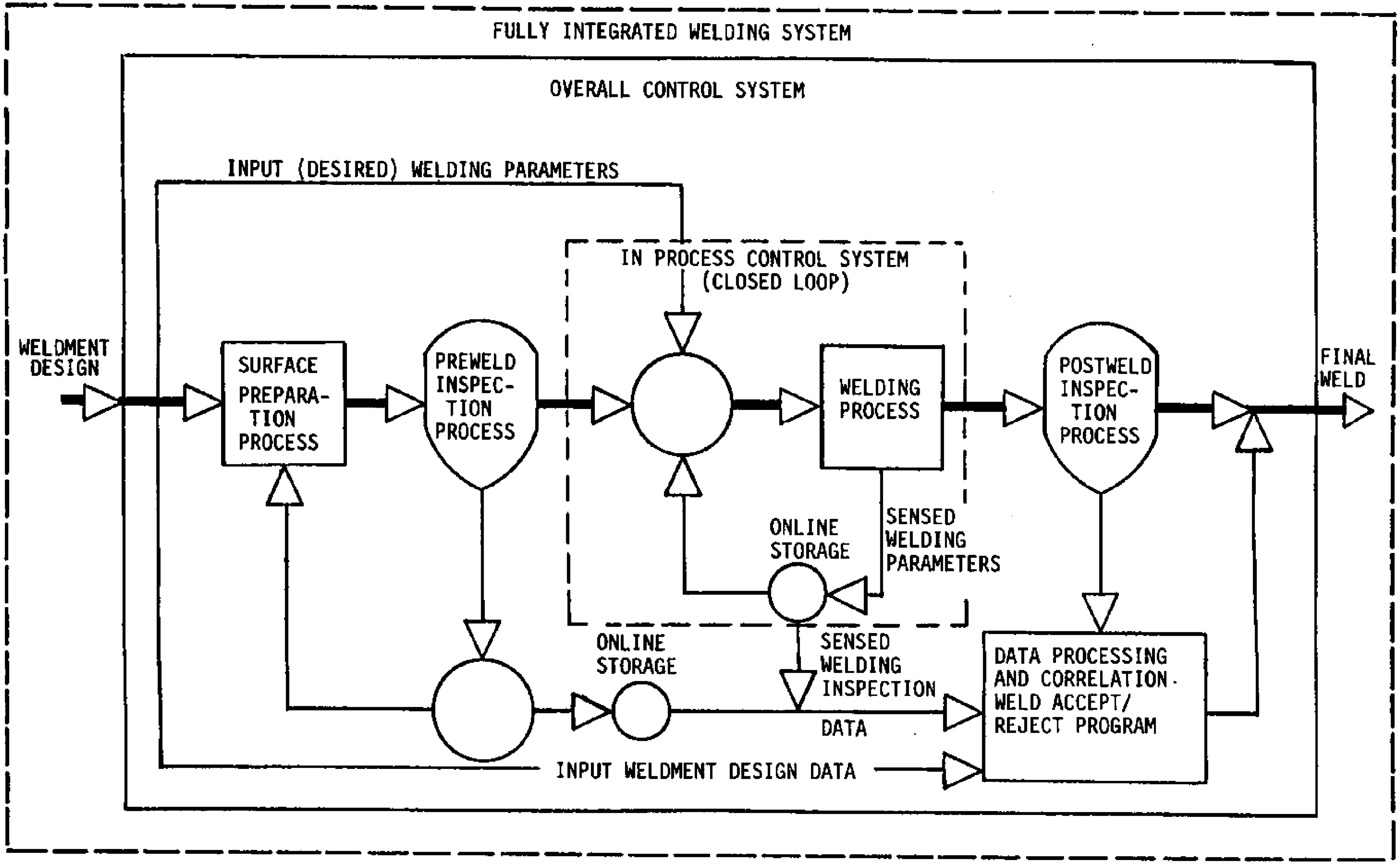


Figure 5.3: Control system for a fully integrated welding system

The development of a fully integrated automatic underwater stud welding system, which may be utilized by either a diver or from a remote control vehicle, meets the needs of the industry. Research work in this area has also been performed at the Industrial Research Institute in Shikoku, Japan, at Delft Institute in Holland, and at Comex Industries in France. Widespread interest has resulted as people recognize both the potential of and the need for an underwater stud welding system, and because the stud welding process is readily adapted to the underwater environment.

The actual market potential will not be fully realized until a proven system is available to industry. The researchers believe that emphasizing quality control and quality assurance in the welding systems represents a unique approach to underwater stud welding.

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7.0 APPENDIX

MIT Marine Industry Collegium Workshop #36
MIT Underwater Vehicle Research: Recent Advances & Future Programs
December 5, 1983
MIT Student Center - Room W20-491

8:30	Registration & Coffee
8:45	Welcome Norman Doelling, Manager - MIT Marine Industry Collegium
9:00	Overview of Supervisory Control for Underwater Telemanipulators at MIT Professor Thomas B. Sheridan, MIT Mechanical Engineering Department
9:30	Applications of Supervisory Control for Underwater Vehicles Dr. Dana Yoerger, MIT Department of Mechanical Engineering and Woods Hole Oceanographic Institution
10:30	Break
10:45	Underwater Vehicle Control Systems Homayoon Kazerooni, Graduate Student, MIT Department of Mechanical Engineering
11:15	Touch Sensing for Underwater Manipulators John Schneiter - Graduate Student, MIT Department of Mechanical Engineering
11:45	Lunch Student Center, Mezzanine
1:00	Underwater Welding Technology at MIT Professor Koichi Masubuchi - MIT Department of Ocean Engineering
1:30	Design, Construction and Testing of an Underwater Stud Welding System Christopher Von Alt - Graduate Student, MIT Department of Ocean Engineering
2:15	The Effect of Tethers on Underwater Vehicles Professor Michael Triantafyllou, MIT Department of Ocean Engineering
2:45	Preview of Lab Tours Dana Yoerger

3:00 Depart for Lab Tours

5:00 Wine, Beer, hors d'oeuvres - Hart Nautical Museum, Bldg. 5-329

Lab Tours by MIT Mechanical Engineering Department Graduate Students & Research Assistants

1. Man Machine Systems Laboratory - 30 minutes - Mark Noyes
2. SEAGRANT 1 - 30 minutes - Kleber Gallardo
3. Stud Welding - 30 minutes - Chris Von Alt
4. A Novel Manipulator - 30 minutes - Sam Landsberger