MIT SEA GRANT
Summer 1985

Quarterly Report

Update: MIT Underwater Robotics Research

Trying to make an underwater manipulator imitate a human diver is a formidable goal. Thomas B. Sheridan of the MIT Man-Machine Systems Laboratory thinks that, in the short run at least, the basic tasks most suitable to an underwater manipulator will be assembly - grasping and putting objects in place - which is useful in underseas oil exploration and extraction. In the future, when fine movements are possible, manipulators can grab hold of a specimen without damaging it and place it in a collection basket for fisheries or geological research. They could also disassemble machinery and examine it internally for maintenance or repair.

"Robotics is all about how to combine motoring and sensing" says Sheridan, who heads MIT Sea Grant's research in underwater telemanipulators. The manipulator must first reach a site, then maneuver objects. Sensing and muscle function have to be closely coordinated. Part of the unfriendliness of the underseas environment is the unpredictability of the orientation and shape of objects at each new site. While a factory assembly line is predictable, an object underwater might be encrusted with barnacles or buried under silt. Unexpected ocean currents could buffet the manipulator and disturb its working position.

Three MIT research projects described in this ***Quarterly Report*** *are aimed at improved sensing and motoring in the difficult ocean environment. A story on this page describes research on a parallel link manipulator which shows potential for speed, strength, and agility at relatively low cost. Built of lightweight plastic, the manipulator is expected to weigh only 90 pounds in water, including six precision, high torque hydraulic motors clustered at the base rather than on the joints.*

Another mechanical engineer is developing a technique for enabling robots to function effectively in uncontrollable environments such as the ocean (story on page 2). By considering hardware as well as software in manipulator control, this researcher uses actuators to modulate a manipulator's flexibility.

Control concepts and hardware developed at MIT can be field tested on MIT Sea Grant's unmanned, underwater vehicle, recently launched from Sea Grant's research vessel into Boston Harbor for the first time (story on page 3). Cooperation from several industries and a team of MIT students got the vehicle into operation. Especially valuable was International Submarine Engineering's contribution for five months of one of its engineers to oversee the project.

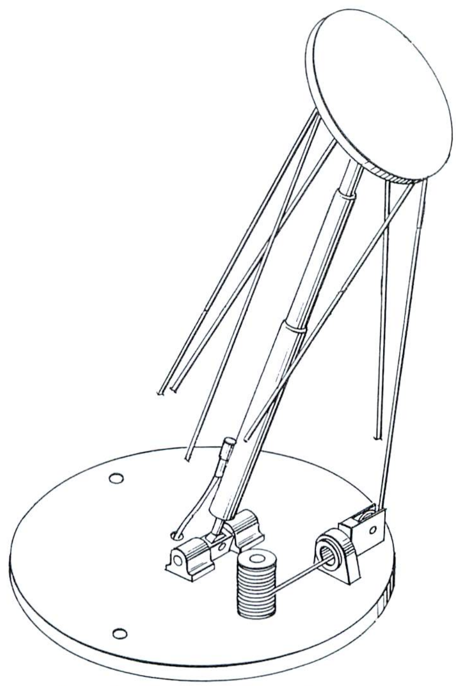

Figure 1. Parallel link manipulator

Parallel Linkage is Basis of New Manipulator

Most underwater manipulators have a serial link design, meaning that each moving joint is attached to the preceding part as in a human arm. In a parallel link manipulator, each actuator is directly connected to the working end of the arm. Sam Landsberger's Masters and PhD theses in the Department of Mechanical Engineering concern the design, construction and control of a parallel link manipulator with six degrees of freedom. This cable-controlled parallel linkage manipulator is unique, according to Professor Thomas Sheridan of the MIT Man-Machine Systems Laboratory, who adds, "It looks like we can achieve much better speed, stability, and mobility with this manipulator relatively inexpensively."

The arm is designed to be very versatile: strong enough to retrieve loads weighing up to 500 or 600 lbs, and agile enough to perform underwater welding, cleaning or inspection tasks. Largely built of lightweight plastic, its anticipated weight of 90 lbs in water is mostly accrued from its six precision, high torque hydraulic motors.

Parallel link manipulators have many advantages over serial link arms. By being placed at the base of the manipulator, all the motors in Landsberger's design 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. Only the end effector waves around in space, not the bulky links and motors, thereby minimizing the manipulator inertia. The direct connection between the actuators and end effector eliminates the need for complex drive-trains and lessens friction and backlash.

Programming a serial arm to move from one point to another requires substantial computation to tell each joint where to move, but with a parallel arm the computation involves only simple geometries and straightforward, fast calculations. Unlike most serial arrangements, a small error in the length of one cable is not multiplied by the length of the parallel arm.

Landsberger is almost finished expanding the system from three to six degrees of freedom. The increase meant that he had to manufacture new components, solve clearance problems,

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and rearrange and modify pulleys to prevent them from bumping into each other. He also had to learn to avoid commands which would twist up the cables or slam them against the motor. "If I tell the manipulator to turn 180 degrees when it can physically go only 90, it will still attempt to follow my command and something will probably break," he says. "I will incorporate a certain amount of smarts into the control so that even if the master gives it an unrealistic command, it will have enough sense to say, 'Sorry, I can't' instead of hurting itself."

A recent modification will incorporate a variable force in the spine, the central member which keeps the cables in tension. Landsberger can now control the pressure on line, so that for very light, delicate work, he can prescribe a very small preload to limit the load capacity of the manipulator. To lift something heavy such as a 600-lb rock, the operator would pump up the preload to 1000 or 1500 lbs force to make the arm very rigid and powerful.

"This arm seeks to answer the need for a powerful, fast, durable underwater manipulator," declares Landsberger. "The durable arms on the market are not usually fast and not necessarily strong, while the strong ones are usually slow." Typically an arm cannot pick up anything approaching its own weight, and Landsberger mentions arms on the market that weigh close to 1000 lbs with only 20-lb load capacities. "Hopefully mine will be able to lift six to seven times its own weight. It also doesn't carry its weight around with it wherever it goes; only the business end moves because of the cable parallel linkage. In industry both under and above water, there's a big problem with the accuracy and speed of robots being so compromised by any kind of load capacity or stiffness rigidity. My design addresses that problem directly."

Because the arm has a high load capacity and is rigid and fast, it could actually hold a submarine in place and fine tune the sub's position while another little arm might carry out work alongside it. Underwater currents and disturbances are very hard to counter with propellers alone on a sub. Landsberger says, "For any kind of work apart from just cleaning or visually inspecting, the submarine must be anchored firmly to the structure it's working with. I think having a grabber arm is probably essential."

From tests with the earlier three-degree-of-freedom subsystem, Landsberger found that the arm could move back and forth in air from one position to another a few inches away up to 30 times a second. Even though water would increase the damping, the manipulator is powerful enough that it can almost ignore the environment. "By varying the preload, we could set the cables all pulling with 200 lbs force. If we need to lift a 20-lb weight, that weight is such a tiny fraction of the 200-lb cable load that the arm almost doesn't realize that there's anything in the way," says Landsberger.

From its early stages of development, the arm has proven the novel actuating principle on which the system is based. It has demonstrated the power, speed and smooth action realized by the floating linkage which has no rigid member 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.

Eventually the arm will be attached to the SEAGRANT 1 vehicle (see page 3) 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.■

Modulated Flexibility Simplifies Manipulator Control

If all you had to do to drive from one place to another was follow a map, you could preprogram your car with the directions and sit back. What would happen, though, when your car unexpectedly encountered a snarled intersection?

Similarly, engineers can program a robot arm to move along a prearranged path to a desired point, or command the arm to push forward with a certain force until it arrives at the correct position. But problems arise when unexpected obstacles or forces get in the way. In a factory, engineers can adapt the environment, the production process, to accommodate the robot's limited ability to cope with interference. Underseas, however, controlling the environment is impossible. Things unpredictably get in the way.

Neville Hogan in MIT's Department of Mechanical Engineering is working out a technique he has for making robots capable of adapting to a chance environment, thus working more successfully within it. His concept is called "impedance control"; the idea is to determine the relationship between the

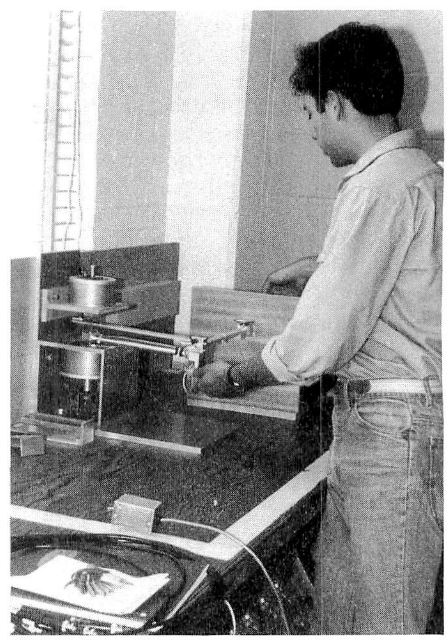

Figure 2. Student demonstrates use of impedance control to avoid collision

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movement of the robot arm and forces in the environment which react against that movement.

If an arm has infinite impedance, it is totally inflexible. It pushes on, regardless of interference. Like groping in the dark for a light switch with a perfectly rigid arm, this approach invites injury. However, if the arm has zero impedance, it will be pushed around too easily. In between these two extremes is finite impedance, where Hogan proposes to operate. He wants to modulate the degree of flexibility or stiffness of the arm as required by the environment or the manipulator's task.

Hogan envisions a system where the arm can say, "Tell me where to be, but if I must deviate, tell me what force to apply." His goal is a unified framework for considering the action of both hardware and software in manipulator control. The software will specify the preferred location of the manipulator, but the hardware will be sensitive to outside forces in its path.

In prior work with artificial arms for amputees, Hogan learned that the musculo-skeletal system can perform certain functions independently of the brain. The purpose of the initial brain command is to set a reference equilibrium position by specifying contraction force, stiffness, and viscosity of the muscles about a joint. After that, the brain apparently takes advantage of dynamic properties of the muscles and skeleton in the arm itself to adapt to forces in the environment. In a robot manipulator, Hogan would translate such adaptive behavior into impedance control, and would build this control into the manipulator hardware either through electronic feedback control or by using actuators that act like shock absorbers.

Besides helping a manipulator move around in its environment, impedance control also can help the manipulator in its dynamic interactions with objects while performing tasks. This is a major deficiency in today's robots. In operations such as drilling, chipping, or bending, both the workpiece and the tool exert complex forces and motions on the robot arm. If there is no adaptation to these added forces, control of the arm can become unstable. "Exploiting the intrinsic properties of mechanical hardware can...provide a simple, effective, and reliable way of dealing with mechanical interaction," Hogan says, adding, "If the environment is regarded as a source of 'disturbances' to the manipulator, then modulating the 'disturbance response' of the manipulator will permit control of dynamic interaction."

In some cases the manipulator may need to be stiff in one direction, but compliant in another. Tracking an edge, for example, the arm should be rigid in the direction it is travelling, but loose perpendicularly in case of bumps. Some operations may require a loose "wrist", while others require the wrist to be stiff. Impedance control allows the kind of versatility needed for different jobs.

Hogan's students are implementing impedance control in several projects. One student has devised a simple system which avoids colliding with an unpredictably moving object by adjusting its effective impedance. In another experiment, researchers got a robot to turn a crank without preprogramming its path. In a third project, a robot hand employs impedance control to use an object in the environment for support while assembling bolts. Hami Kazerooni, a Sea Grant researcher, has developed a computer simulation of impedance control applied to an underwater vehicle.

Since massive amounts of computation are involved in conventional manipulator control, Hogan currently is sorting out what is important to compute and what is not. Inverse kinematics, for example, is widely considered as one of the "fundamental problems" in robot control. It involves taking the desired position of the manipulator endpoint and back-computing to figure out what the joint angles should be to achieve that position. "It's hard to solve, it has no unique solution for a general manipulator, and the solution, if it exists, can't be gotten by direct algebra, but requires iterative procedures," Hogan says. However, he claims, the problem of inverse kinematics can be "completely eliminated" using impedance control. Put simply, the controller would "ask" each joint what contribution it could make toward pushing the endpoint to a specified point. Then each joint would push towards the goal in proportion to its predetermined contribution. In that way, it is irrelevant what configuration the joints are in when the endpoint reaches its goal, as long as it gets there.

Hogan suspects there may be other computational dilemmas that can be simplified or eliminated using impedance control. "One of the major difficulties in dealing with manipulators is identifying and eliminating preconceived notions," he says. ■

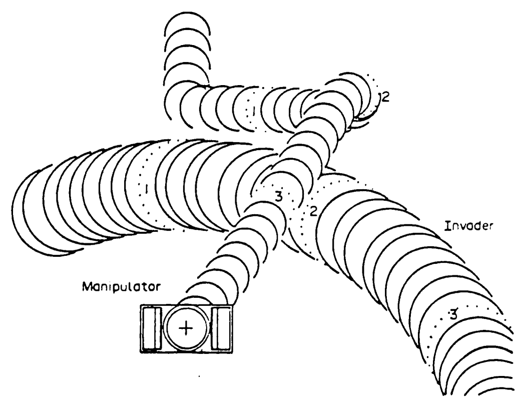

Figure 3. Behavior of a manipulator, under a single impedance command, as it avoids an unpredictably moving "invader"

MIT Sea Grant's Underwater Vehicle is Christened

On June 19, 1985, dripping with champagne, MIT Sea Grant's underwater robot vehicle, SEAGRANT 1, dropped into Boston Harbor, swam, and dove in view of supporters gathered to celebrate its premiere performance. Putting the six-foot, black and yellow vehicle into operation was the culmination of months of dedicated effort by a crew of MIT students led by Eric Jackson, an employee of International Submarine Engineering, LTD (ISE) in Canada. ISE sent Jackson to MIT for five months to manage the project which came to be known as "getting the vehicle into the water."

SEAGRANT 1, an unmanned, tethered vehicle, was donated to Sea Grant by two owners of the Perry Oceanographic Company to be used for testing underwater robotic control concepts. The vehicle came with power and propulsion systems, but no sensors or control system. In addition to Jackson's time, ISE contributed computers, connectors, and miscellaneous equipment. Chevron Corporation gave a generous grant to support the crew. A local manufacturer of oceanographic equipment, ENDECO, Inc., loaned a compass and sensors. Benthos, Inc. provided technical advice and several sophisticated high resolution cameras. Subsea Systems in California overhauled and repaired a video system. Flotation materials came from Emerson and Cuming, a subsidiary of W.R. Grace.

When Jackson took over the project, three students were actively involved in it. The group immediately began interviewing other students, eventually expanding the crew to 15. These talented and enthusiastic engineers revamped the hydraulic plumbing and wiring; designed and installed the onboard electrical power distribution

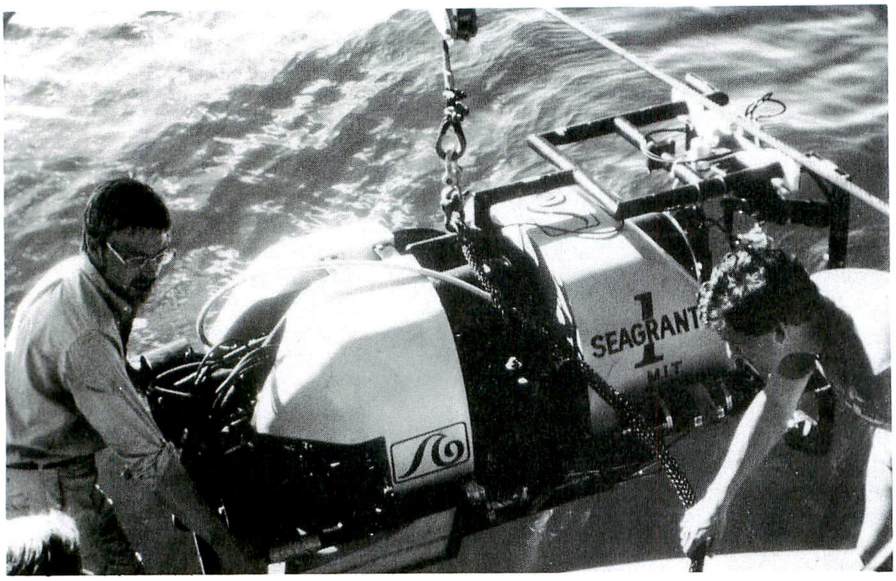

Figure 4. The maiden voyage of SEAGRANT 1

The SEAGRANT 1 Crew

Eric Jackson	Project Manager
Francis O'Neill	Assistant Project Manager, Mechanical Engineering
Andy Bennet	Ocean Engineering
Mark Brown	Aeronautics and Astronautics
Hanson Cheah	Freshman
Tom Darci	Mechanical Engineering
Dave DiPietro	Mechanical Engineering
Tom Esselmen	Electrical Engineering
Kleber Gallardo	Mechanical Engineering
Rohan Khaleel	Electrical Engineering
Tom Liu	Freshman
Alberto Moel	Electrical Engineering
Phillip Paolella	Mechanical Engineering
Andy Schiller	Mechanical Engineering
Jon Singer	Mechanical Engineering
Mark Traudt	Electrical Engineering
Omar Valerio	Electrical Engineering
Bill Walter	Mechanical Engineering
Dana Yoerger	Mechanical Engineering

system, complete with documentation; designed and built a camera mounting with pan and tilt feedback; designed and installed the communication system between the vehicle's computer and one on the mother ship; developed telemetry/control software; implemented the operator's computer display; balanced the vehicle; installed a generator; and completed all electronic interfaces.

Jackson's extensive knowledge of robotics theory and experience in underwater vehicle design guided the students as they created SEAGRANT 1. During sea trials, Jackson's experience with salt water, the problems it presents because of its penchant for conducting electricity, proved especially valuable in identifying and fixing leaky connectors and grounding problems. When the electrical system and the camera were debugged, the crew watched via TV monitor as SEAGRANT 1 chased lobsters around the harbor.

Besides catching lobsters, among the tasks being considered for the vehicle is a search for a seven-ton propellor which is believed to lie in Boston Harbor. The vehicle may also be helpful to the Coast Guard in locating oil leaks, and because it can dive in cold, unhealthy waters hazardous to divers, SEAGRANT 1 could get valuable visual records of the environment near sewage outfalls. A manipulator from Robotics Systems, Inc. will be installed on the vehicle to expand its capabilities.

SEAGRANT 1 represents an exciting example of government, industry, and university cooperation to provide hands-on educational experience for students while promoting important marine research. The vehicle's succesful launching is a milestone in MIT Sea Grant's long-term research effort in underwater telemanipulators.

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