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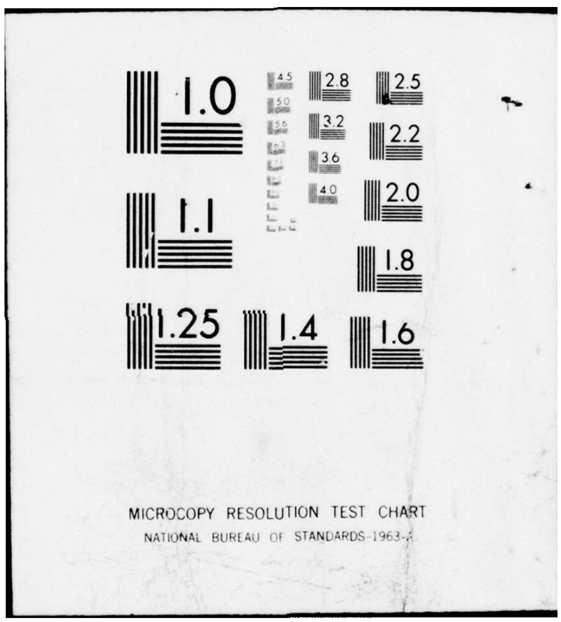
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MANIPULATOR DEVELOPMENT AT THE NAVAL UNDERSEA CENTER

by

Richard W. Uhrich
OCEAN TECHNOLOGY DEPARTMENT

January 1977

NAVAL UNDERSEA CENTER
SAN DIEGO, CALIFORNIA

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NAVAL UNDERSEA CENTER, SAN DIEGO, CA. 92132

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Technical Director

ADMINISTRATIVE INFORMATION

The undersea manipulators described in this paper were developed from 1965 through 1976 with the support of various sponsors. Their capabilities were reviewed from January through October of 1976. Writing of this paper was funded internally through the Naval Undersea Center's Independent Exploratory Development (IED) program.

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An overview of the remote manipulators developed by the Naval Undersea Center since 1965 is presented. Some of the factors affecting the design of manipulators for use at sea are defined, and specific recommendations are made for a manipulator system that would significantly improve the Navy's ability to perform underwater work.

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SUMMARY

PROBLEM

Review the undersea manipulators developed by the Naval Undersea Center. Additionally, identify those design features that have proven most valuable and should be incorporated into future manipulator designs.

RESULTS

An overview of the remote manipulators developed by the Naval Undersea Center since 1965 is presented. Some of the factors affecting the design of manipulators for use at sea are defined, and specific recommendations are made for a manipulator system that would significantly improve the Navy's ability to perform underwater work.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Over a generation ago an urgent need arose to handle radioactive materials safely by remote control. The result has been the evolution of many sophisticated manipulator systems for dry laboratory work. The market for underwater manipulators, however, has remained extremely limited. Additionally, the high-pressure, corrosive environment of the sea causes costly complications. As a result, expertise in the design of underwater manipulators has been limited mainly to a few large corporations or their subsidiaries and to certain U.S. Navy laboratories, primarily the Naval Undersea Center (NUC).

In the early 1960's it became necessary to perform tests on very expensive ordnance items at depths beyond diver capability. Occasionally, one of these items would sink, carrying with it valuable information, such as the cause of the failure. Since the first successful recovery of ordnance items by *CURV I* (for "Cable-Controlled Underwater Recovery Vehicle") in 1965, the Center has designed, fabricated, tested, and used a series of specialized manipulative devices and general-purpose manipulator systems.

This paper presents an overview of the manipulators developed by NUC, and a discussion of the progress that has been made since 1965. Some of the factors affecting the design of manipulators for use at sea are defined, and specific recommendations are made for a manipulator system that would significantly improve the Navy's ability to perform underwater work tasks.

MANIPULATOR HISTORY

CURV

The manipulator device for the first *CURV* was originally designed and built to recover MK-46 test torpedoes at depths below 1,500 feet (458 meters). Subsequently, it was adapted for other uses, such as attaching grappling hooks and lift lines to the parachute of the H-bomb that was lost in 2,900 feet (885 meters) of water off Palomares, Spain. Figure 1 shows the manipulator with a grappling hook in place. Since the device did not incorporate seven independent functions (three for positioning the hand, three for orienting the hand, and one for opening and closing the hand), it was commonly called a "claw" rather than a manipulator. This terminology has also been applied to the arms of *CURV II*, which replaced *CURV I*, and *CURV III*, which operates to a nominal depth of 10,000 feet (3,050 meters). The claws of *CURV II* and *III* are essentially identical, and incorporate arm elevation, arm roll, wrist yaw (lacking in *CURV I*), and grasp. The hand can also be jettisoned to trail a lift line to the surface when the recovery object is too heavy for direct lift. This feature also simplifies tool interchange, making the hand replaceable by a cable cutter, snare, toggle bar, hook, or other hands of various sizes and shapes. Figure 2 shows *CURV II* with an ordnance recovery device in place, while Figure 3 shows *CURV III*'s manipulator with a smaller hand attached. Still another type of tool is shown attached to *CURV III* in Figure 4. The adaptability that this design provides contributed to the success of *CURV III* in

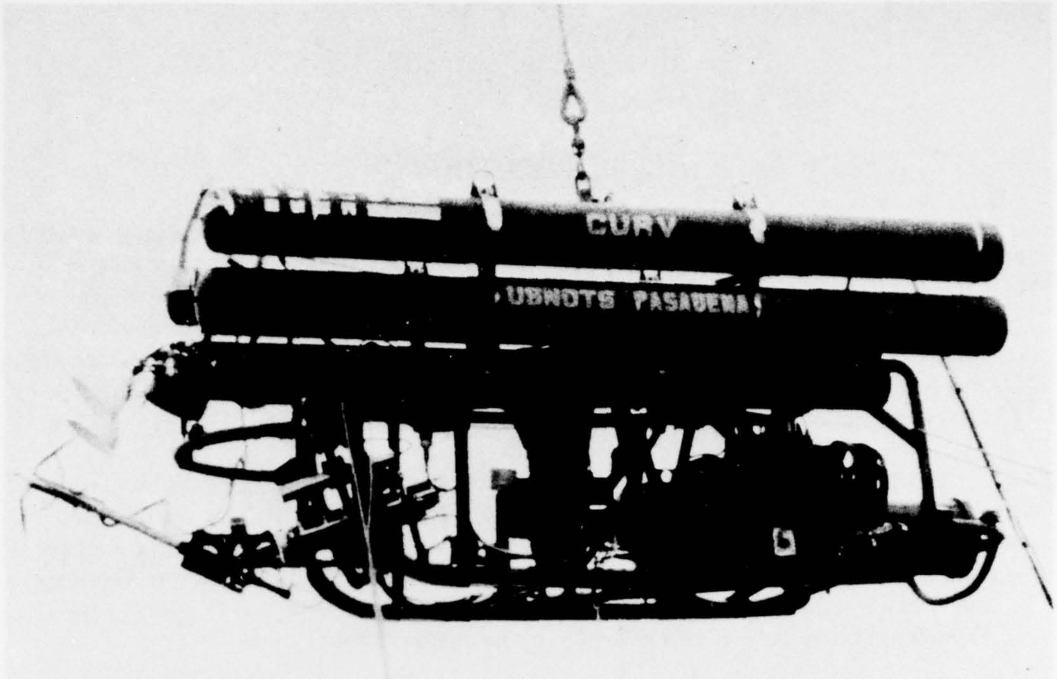


Figure 1. CURV I attached grappling hooks and lift lines to parachute of H-bomb recovered at sea off Palomares, Spain, in 1966. *268-1-77*

performing inspection and maintenance on the AFAR (for "Azores Fixed Acoustic Range") tower, and in rescuing the submersible *Pisces III*, with two men aboard, off Ireland. Figure 5 shows *CURV III*'s cable cutter in use on AFAR; electrical cables ranging from 1.5 to 3.5 inches (38 to 89 millimeters) in diameter were cut. During the *Pisces* rescue, *CURV III* found the downed submersible at a depth of 1,500 feet (458 meters) and attached a line by which it was raised.

The *CURV* claws incorporate off-the-shelf hydraulic actuators with a minimum of modification, and standard hydraulic valves in a one-atmosphere housing. The reliability of these devices has been proven by nearly a decade of low-maintenance operation.

LINKAGE ARM

In 1970 a more versatile, seven-function manipulator was designed and built to supplement the claws. Pictured in Figure 6, this device incorporated several unique features which make it unusually easy to operate for a switch-controlled manipulator. Its main feature is the linkage that constitutes the arm. The linkage contains a double parallelogram that maintains wrist orientation during arm motions, and a four-bar linkage that translates elbow actuation into linear extension of the hand without any sliding or telescoping members. The linkage also provides the arm with a high section modulus yielding a high strength-to-weight ratio. Though it weighs only 75 pounds (34 kilograms), the linkage mainpulator can lift 50 pounds (23 kilograms) at a reach of 55 inches (1.4 meters).

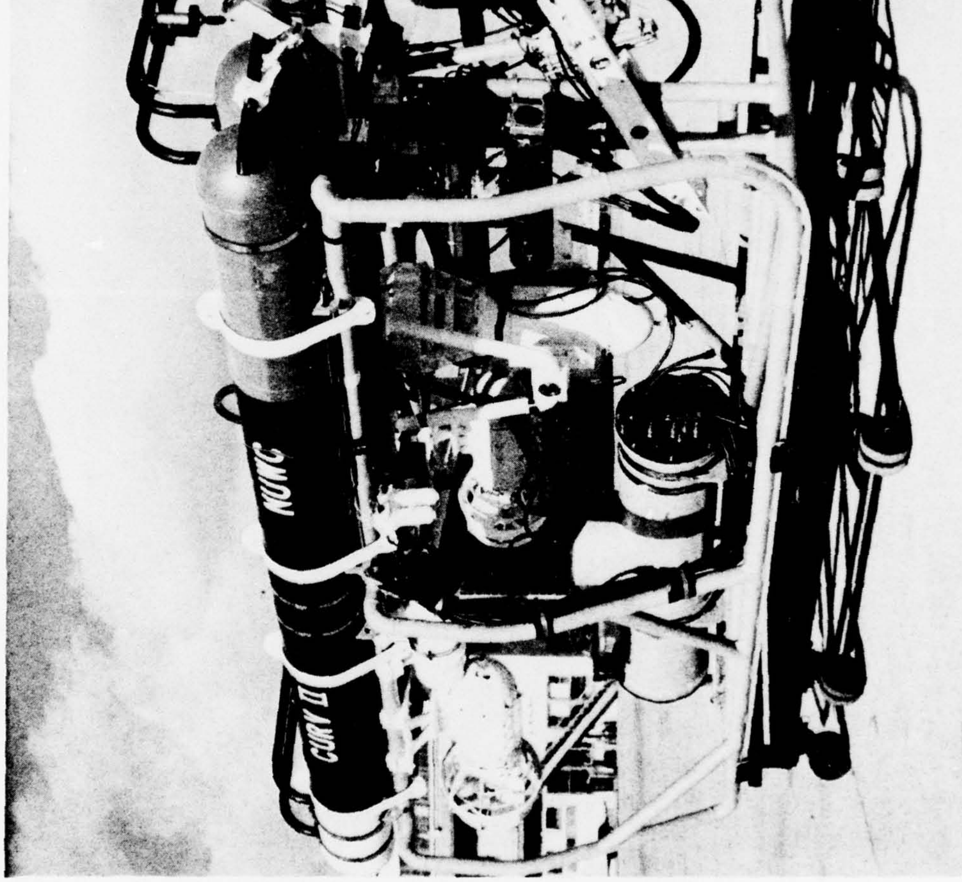


Figure 2. *CURV II* with an ordnance recovery device in place. *1577-3-74*

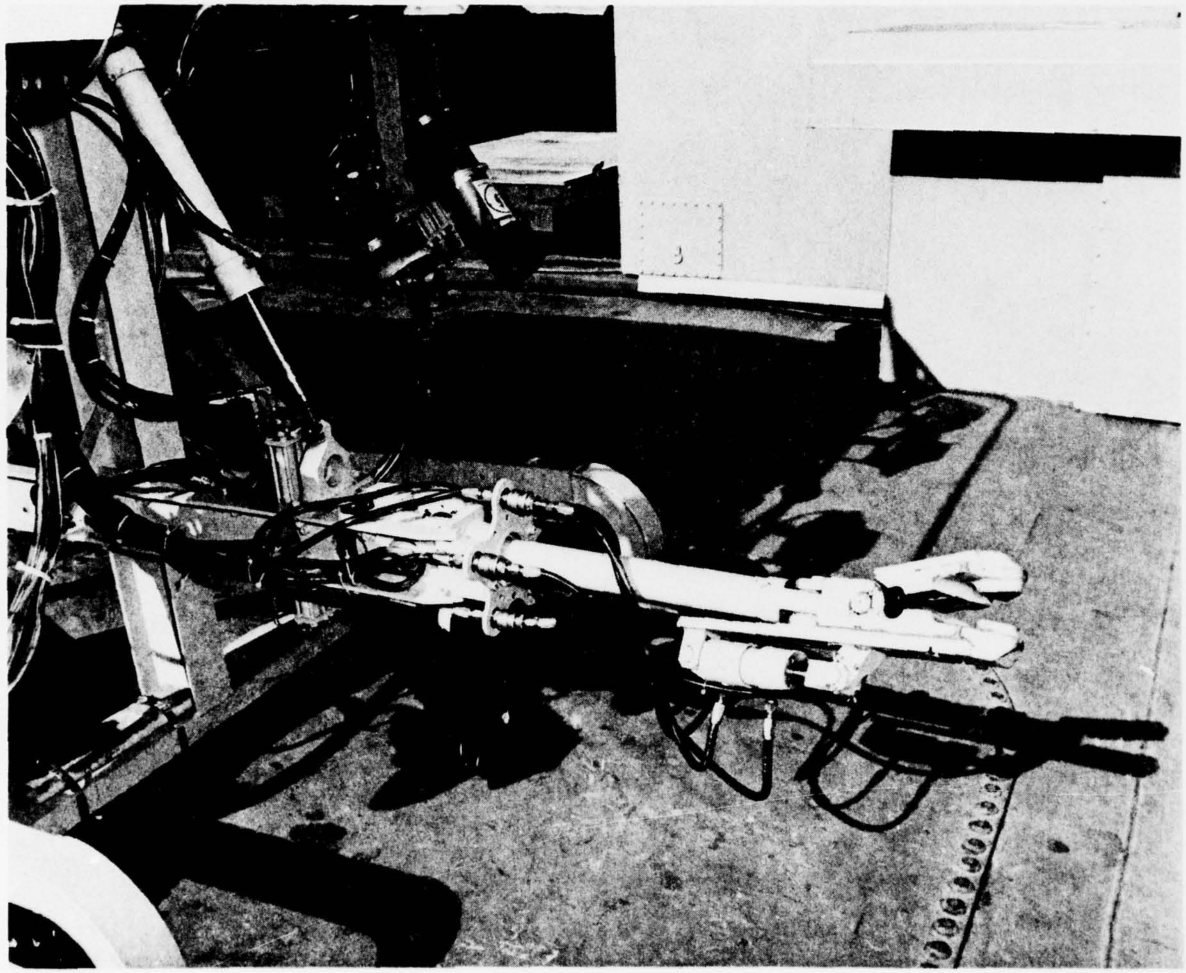


Figure 3. *CURV III*'s manipulator with a small hand in place. *6185-11-71*

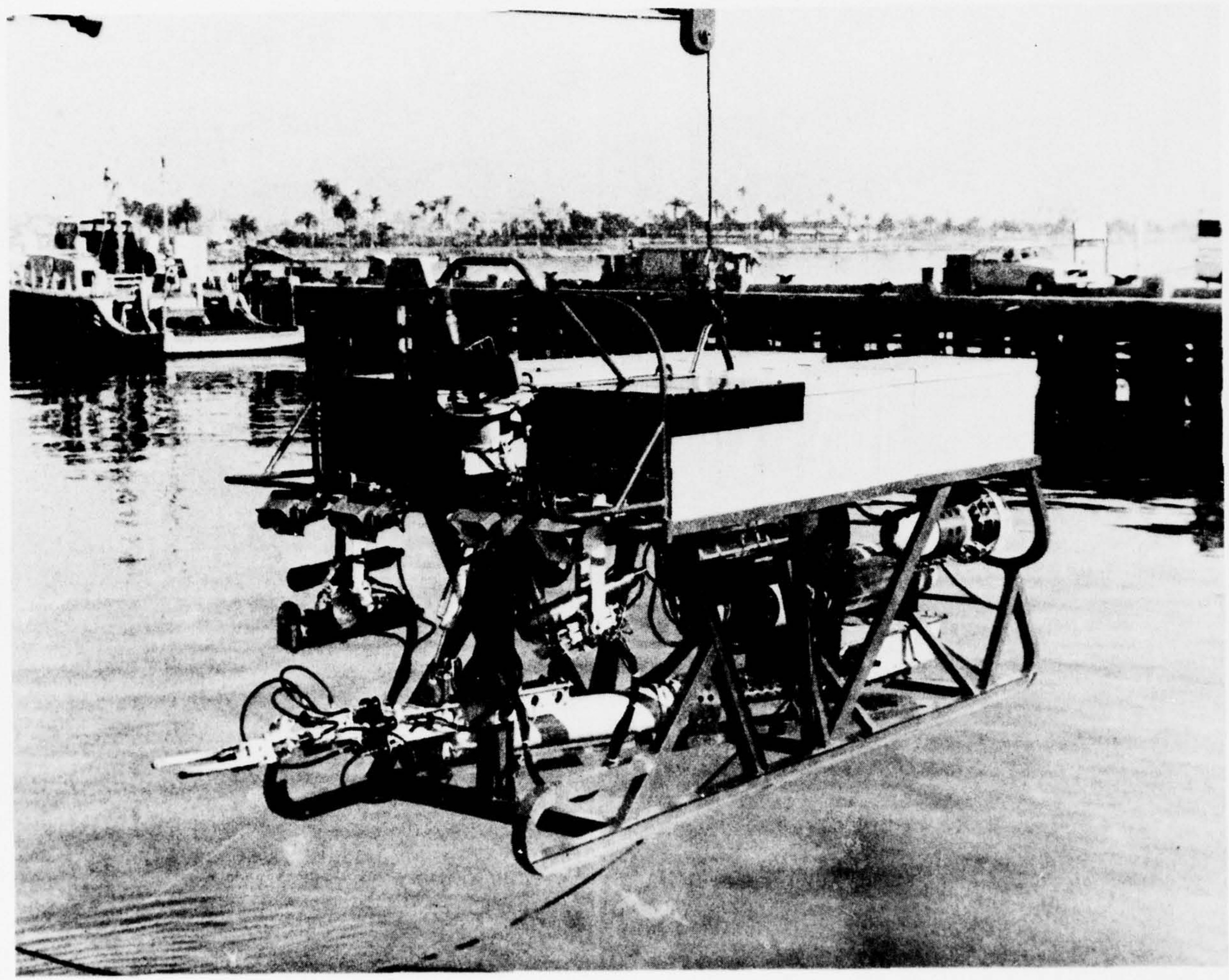


Figure 4. *CURV III* with scissors fitted to the manipulator. *986-4-73*

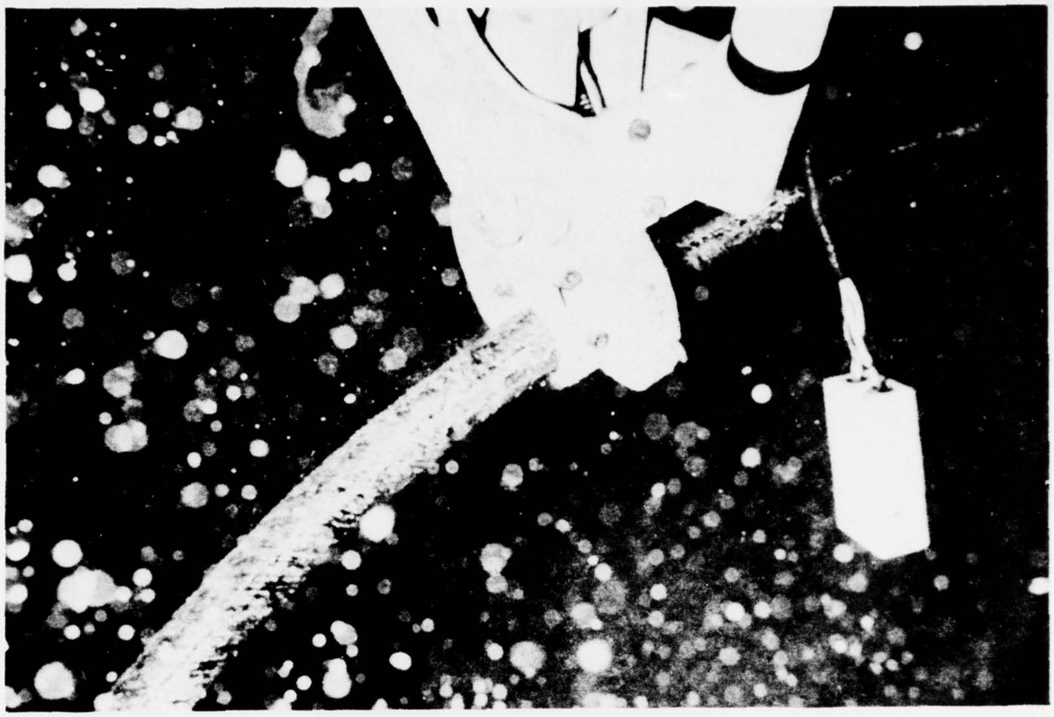


Figure 5. Cable cutter used with *CURV III*'s manipulator during maintenance of AFAR tower. *269-1-77*

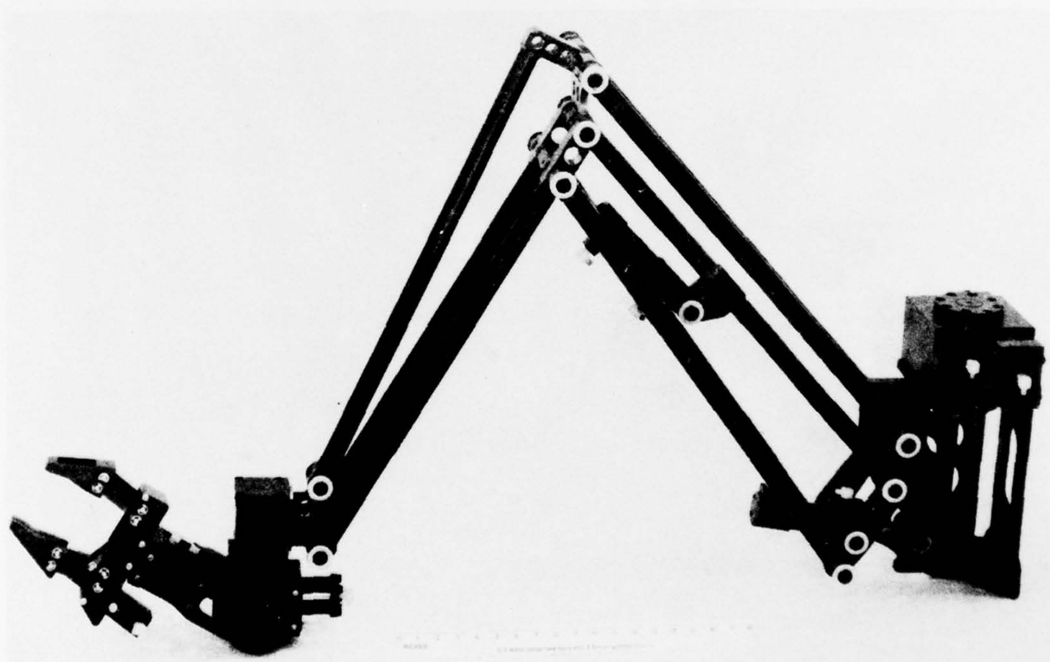


Figure 6. Seven-function manipulator built in 1970 to extend the capabilities of the *CURV* vehicles. *1718-6-71*

The seven functions of the linkage manipulator are azimuth, elevation, extension, yaw, pitch, roll, and grasp. The sequential arrangement of wrist actuators, combined with the linkage, causes the yaw axis to remain vertical and the pitch axis horizontal. Furthermore, all three wrist axes intersect at a single point, resulting in operational simplicity as well as mechanical compactness.

The hand itself is a unique linkage that provides synchronous parallel jaw action, with no sliding parts or gears. This linkage, like that of the arm, is well suited to saltwater immersion. The hand actuator is a single hydraulic piston.

NEV

A second linkage manipulator was built by NUC for the former Nuclear Rocket Test Station, a joint AEC-NASA facility near Las Vegas, Nevada. The NEV manipulator was designed for service on a nuclear emergency vehicle (hence "NEV") for use in air only. Figure 7 shows the device in laboratory testing at NUC. It incorporated several improvements over the *CURV* manipulator that increased the arm's range of motion; and its construction was heavier and simpler, since weight and corrosion were not critical problems. After the closing of the Nevada facility, the NEV vehicle and manipulator were transferred to the Jet Propulsion Laboratory in Pasadena, California, where the manipulator has been used for artificial intelligence research.

SCAT

SCAT (for "Submersible Cable Actuated Teleoperator") was designed to evaluate underwater head-coupled stereo television. A three-dimensional television display was incorporated into a helmet and the motions of the television cameras on the bow of the vehicle were slaved to the helmet. In this way the vehicle operator was given the visual sensation of actually being in the *SCAT*. Figure 8 shows the control unit. Behind the unit is the *SCAT* vehicle with the remote TV camera, which has turned to the left in response to the operator's head movement.

A very simple two-function claw was incorporated to assist in evaluating the head-coupled display and to provide a recovery capability to *SCAT*. Figure 9 shows that the claw consists of two fixed fingers and an opposing thumb rotated by a drive shaft from an actuator at the shoulder, or the point where the arm attaches to the vehicle. In this way all hydraulic lines are eliminated from the shoulder down, and the size and weight of the hand and wrist are kept to a minimum. Grip force may be adjusted by a pressure-control hydraulic servovalve. The arm also pivots about a horizontal axis at the shoulder, causing the hand to move up and down. The jaws or fingers are easily removed and interchanged to conform to objects of various sizes and shapes.

RUWS

RUWS (for "Remote Unmanned Work System") is an experimental teleoperator designed to perform work at depths to 20,000 feet (6,100 meters). The *RUWS* work suite includes two manipulative devices. The simpler of the two is a heavy-duty, four-function unit called the *RUWS* grabber, which is shown in Figure 10. The grabber has elevation, roll, pitch, and grasp functions, and serves to anchor the vehicle to the work or perform heavy

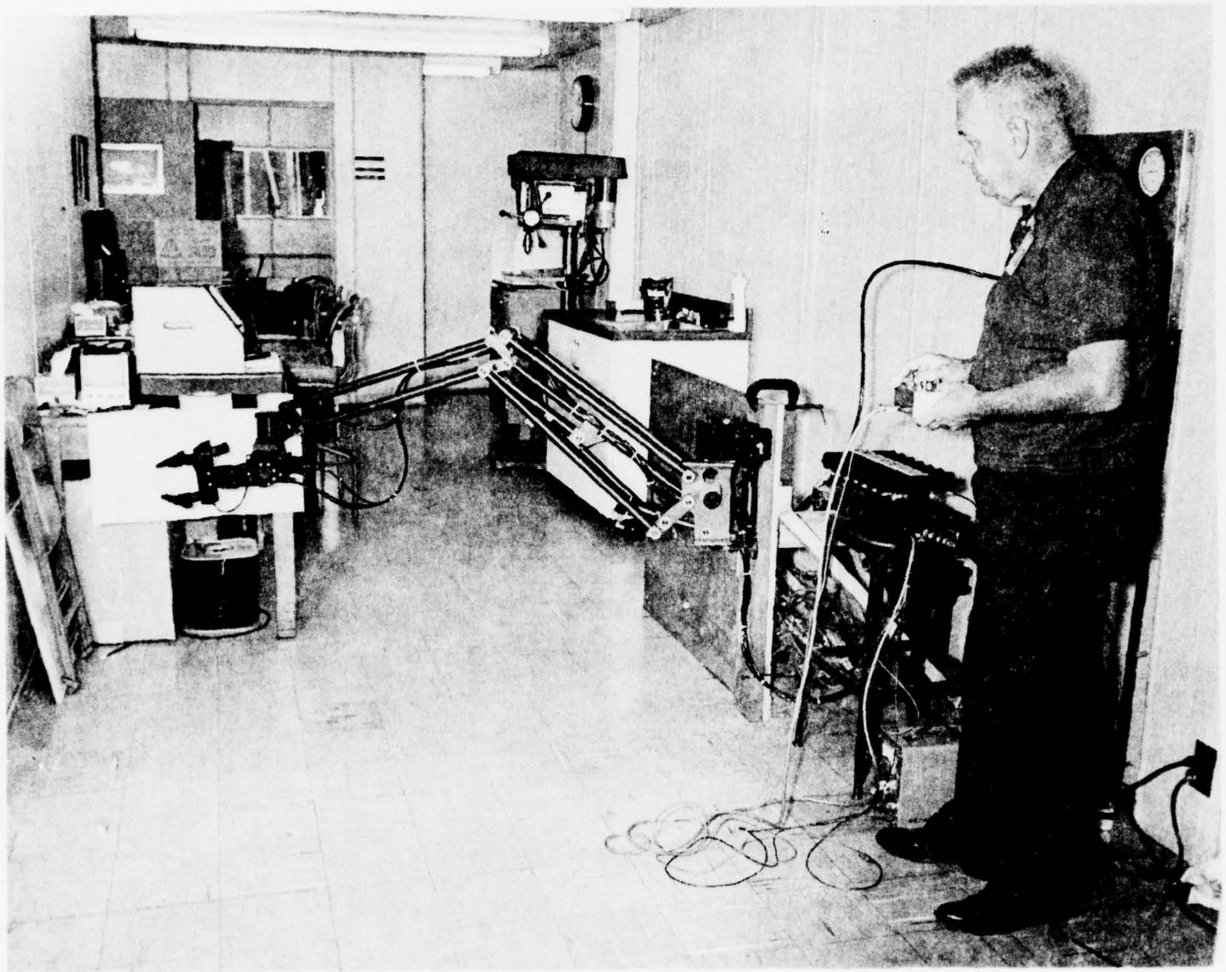


Figure 7. Linkage manipulator built by NUC for use in air on a nuclear emergency vehicle. *3874-7-72*

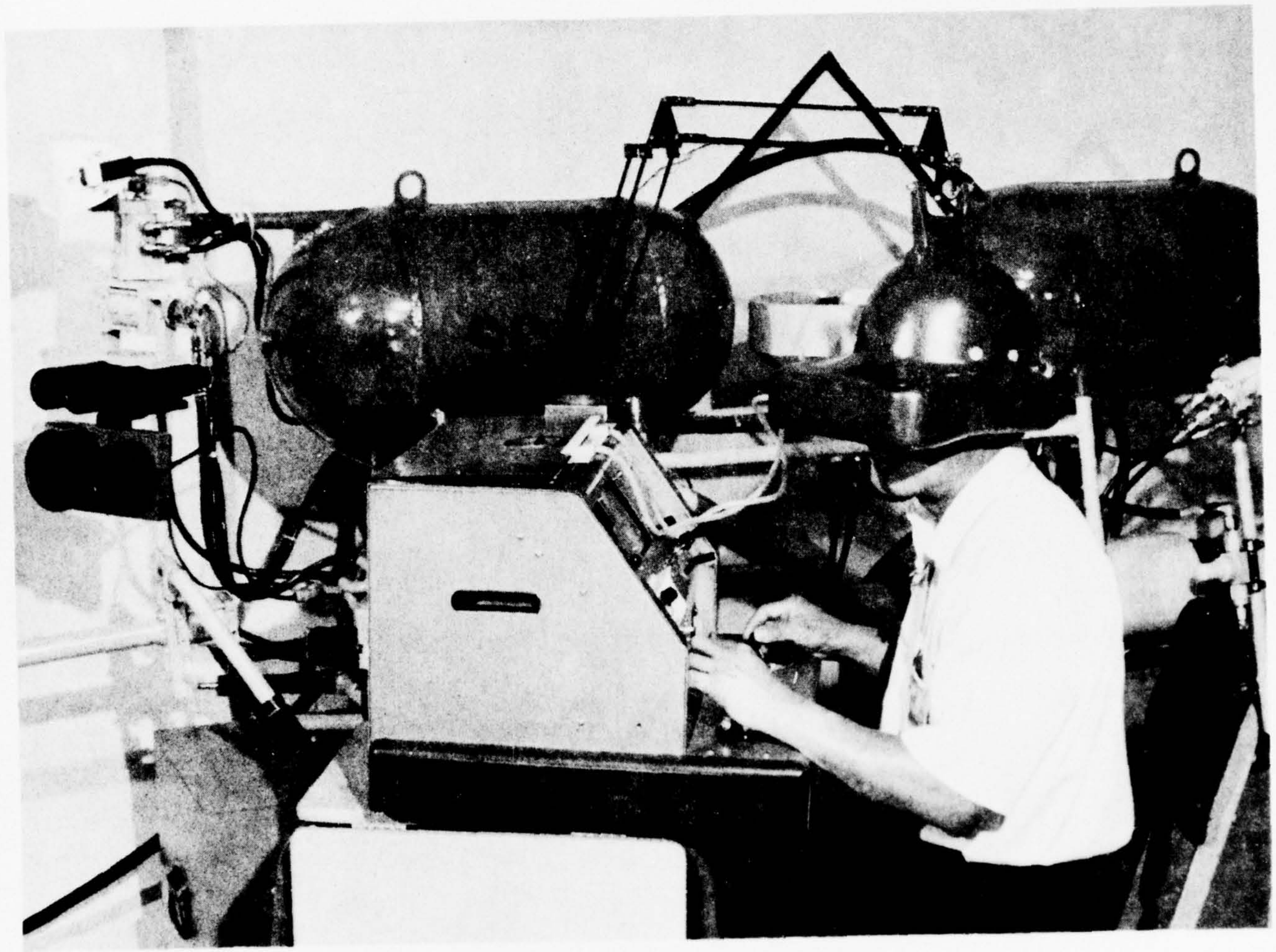


Figure 8. Head-coupled stereo TV was tested extensively on *SCAT*. Though cumbersome, the system showed conclusively that head-following camera orientation should be incorporated into undersea work systems. *244-1-73*

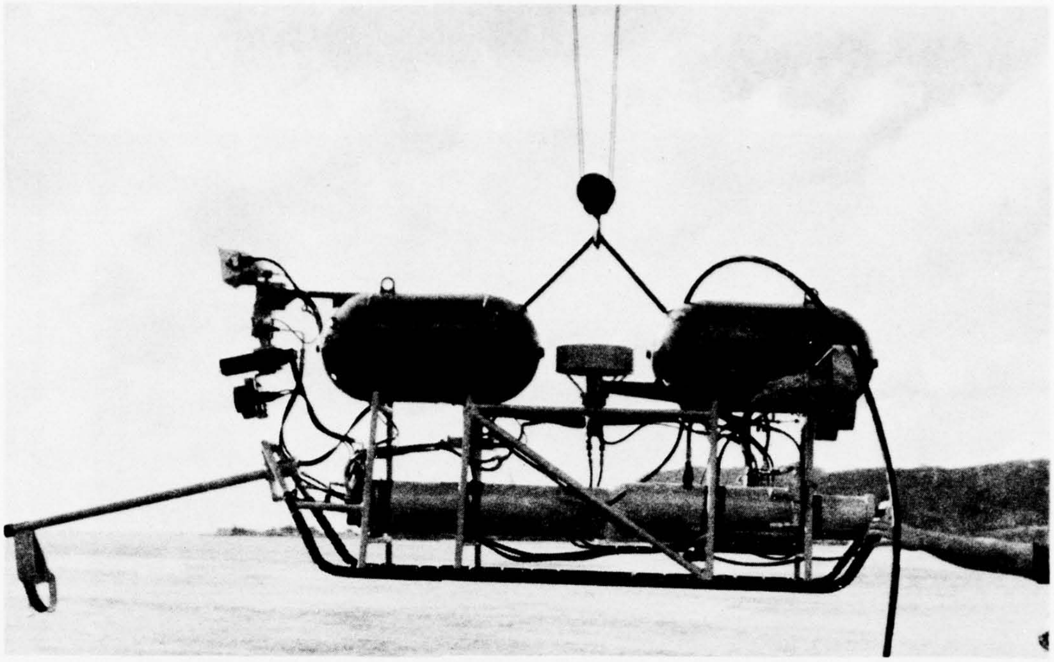


Figure 9. A two-function claw was used with *SCAT* to evaluate head-coupled TV. *1225-3-73*

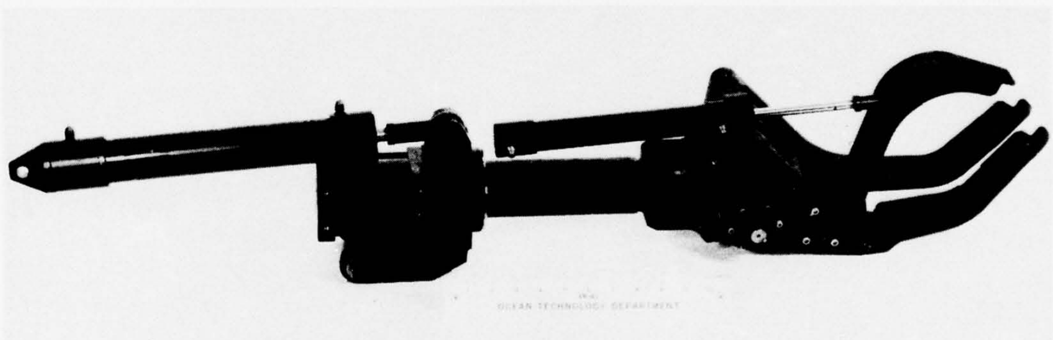


Figure 10. Heavy-duty grabber used with *RUWS* to secure the vehicle while work is performed using the main manipulator. *2492-4-72*

lift, in the same manner as the *CURV* claws. The grabber has interlocking thumb and fingers, like the *SCAT* claw, and a drive shaft that transmits roll torque from a shoulder actuator.

The main *RUWS* manipulator is a seven-function bilateral master/slave. Shown in Figure 11, it is probably the most advanced undersea manipulator presently in use. Position-sensing potentiometers are mounted on the joints of the analog controller (master) and of the manipulator (slave). A signal proportional to any position error is sent to pressure-control servovalves that tend to drive the manipulator actuators to eliminate the

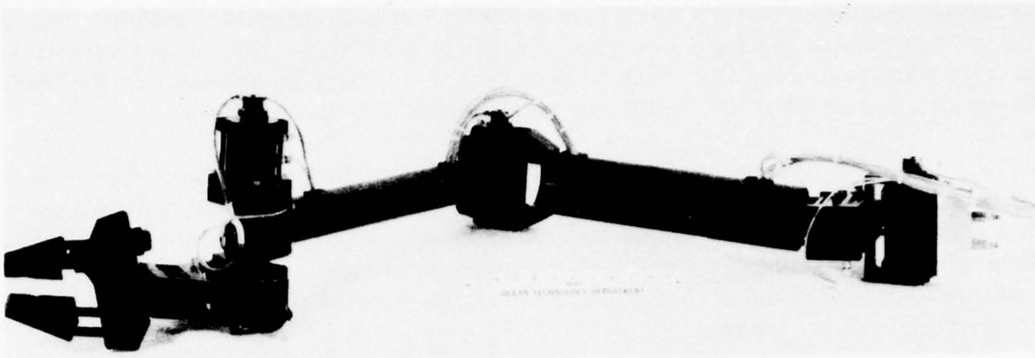


Figure 11. Main *RUWS* manipulator. *2493-4-72*

error. A similar hydraulic system on the controller also drives it toward the manipulator position, thus creating a feeling of force feedback. Three functions, shoulder azimuth, shoulder elevation, and elbow azimuth, are bilaterally controlled in this fashion. The wrist functions are unilaterally controlled, with no force feedback. Grip force is proportional to the distance the spring-loaded controller trigger is pulled.

The hand and wrist of the *RUWS* manipulator (see Figure 12) are mechanically similar to those of the linkage manipulator, but all hydraulic lines are internally ported to eliminate potential entanglement and damage. The controller is of the terminus type; it is

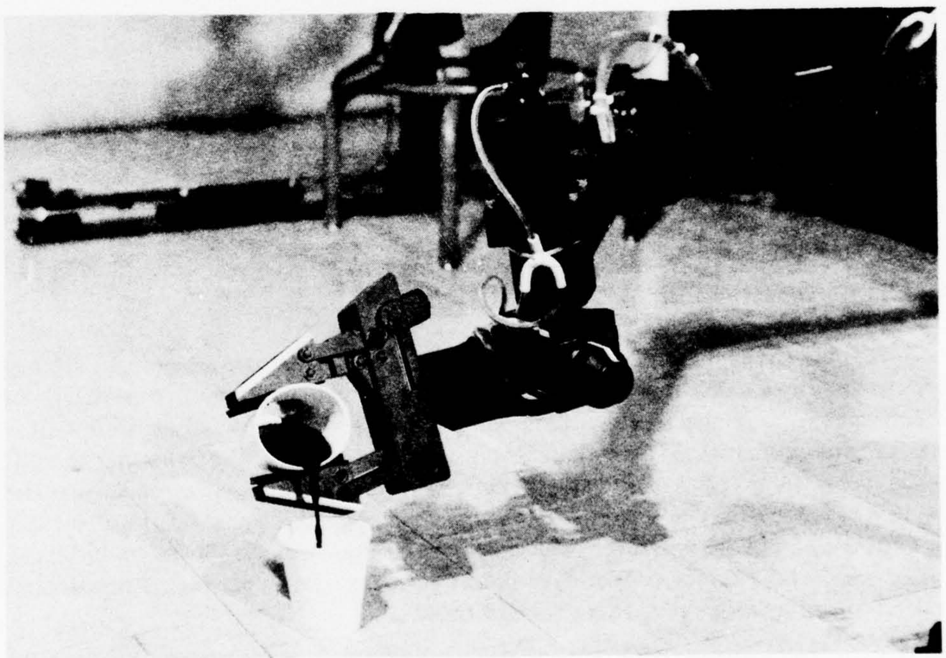


Figure 12. Hand and wrist of the main *RUWS* manipulator. Position control and force feedback enable the operator to handle delicate objects with considerable precision. *2589-4-72*

not attached to the operator's arm as is an exoskeletal or strap-on analog controller. Instead, the operator holds a pistol grip (see Figure 13) and moves it to the position and orientation in space corresponding to that which he wishes the manipulator hand to assume. Feedback forces are experienced as forces of the pistol grip against the operator's hand.

The use of terminus control not only gives the operator more freedom than a strap-on controller, it also permits a greater range of wrist motion. Furthermore, terminus control does not require that the controllers or manipulators be anthropomorphic in design and function. With this control system even an inexperienced operator can perform delicate tasks with both speed and dexterity. Figure 14 shows both the controller and the manipulator during laboratory testing.

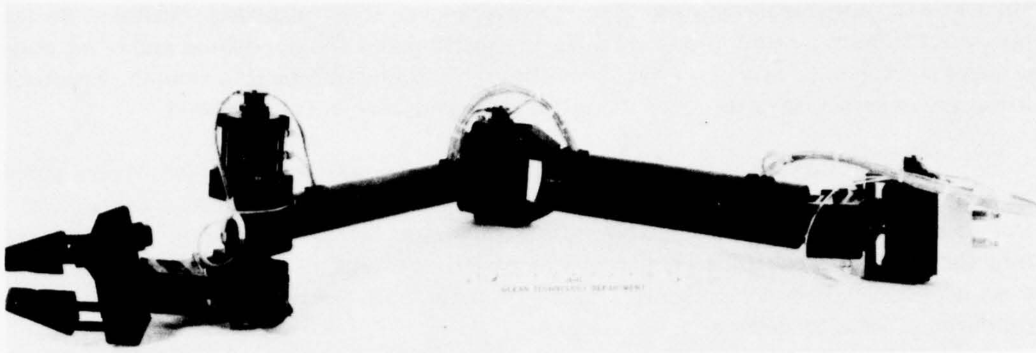
WSP

The Work System Package (WSP) is a complete work module that can be readily attached to a variety of manned and remotely operated underwater vehicles to enhance their work capability. It can operate to depths of 20,000 feet (6,100 meters). The WSP consists of three manipulators, a variety of tools, and two TV cameras, all configured as a single unit that can be mounted on various submersibles or remotely controlled underwater vehicles. Figure 15 shows the complete package. Two of the manipulators function in the same manner as the *RUWS* grabber; they hold the vehicle to the work site and perform heavy lift tasks. However, these grabbers have six functions: azimuth, elevation, telescoping extension, roll, pitch, and grasp.

The primary WSP manipulator is a modified version of a Programmed and Remote Systems (PAR) undersea hydraulic manipulator. It has seven functions: shoulder azimuth, elevation, elbow bend, wrist pitch, yaw, roll, and grasp. In addition, it is internally ported to provide hydraulic power to tools through special leakproof connections in the synchronous parallel jaws of the hand. A chain-drive mechanism within the oil-filled arm serves to maintain wrist pitch orientation during arm motions, and synchronous motors in the elbow and shoulder ensure that arm extension is linear. Figure 16 shows the WSP's primary manipulator fitted with a drill, while Figures 17 and 18 show the WSP mounted on *CURV III* and *RUWS*, respectively.

COMPUTER-CONTROLLED MANIPULATOR

NUC has experimented with preprogrammed manipulator control in an attempt to reduce the time and tedium of repetitive tasks. The linkage manipulator was fitted with position sensors and connected to a minicomputer. Figure 19 shows the system that was tested. The manipulator was used to perform simple tasks, while the computer recorded the sequence of positions required to perform each task. The task could be repeated under computer control any number of times at a rate many times greater than was possible for a human operator and with whatever position accuracies the operator chose to define. The sequence could also be reversed, for example, to return a tool to its storage position, or to return to a specific work site with a different tool.



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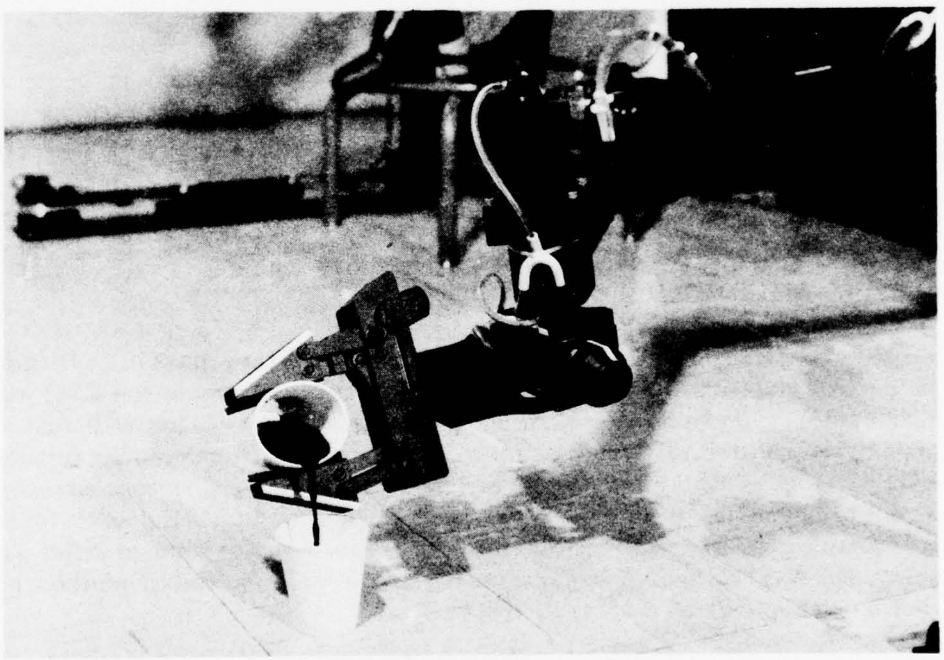

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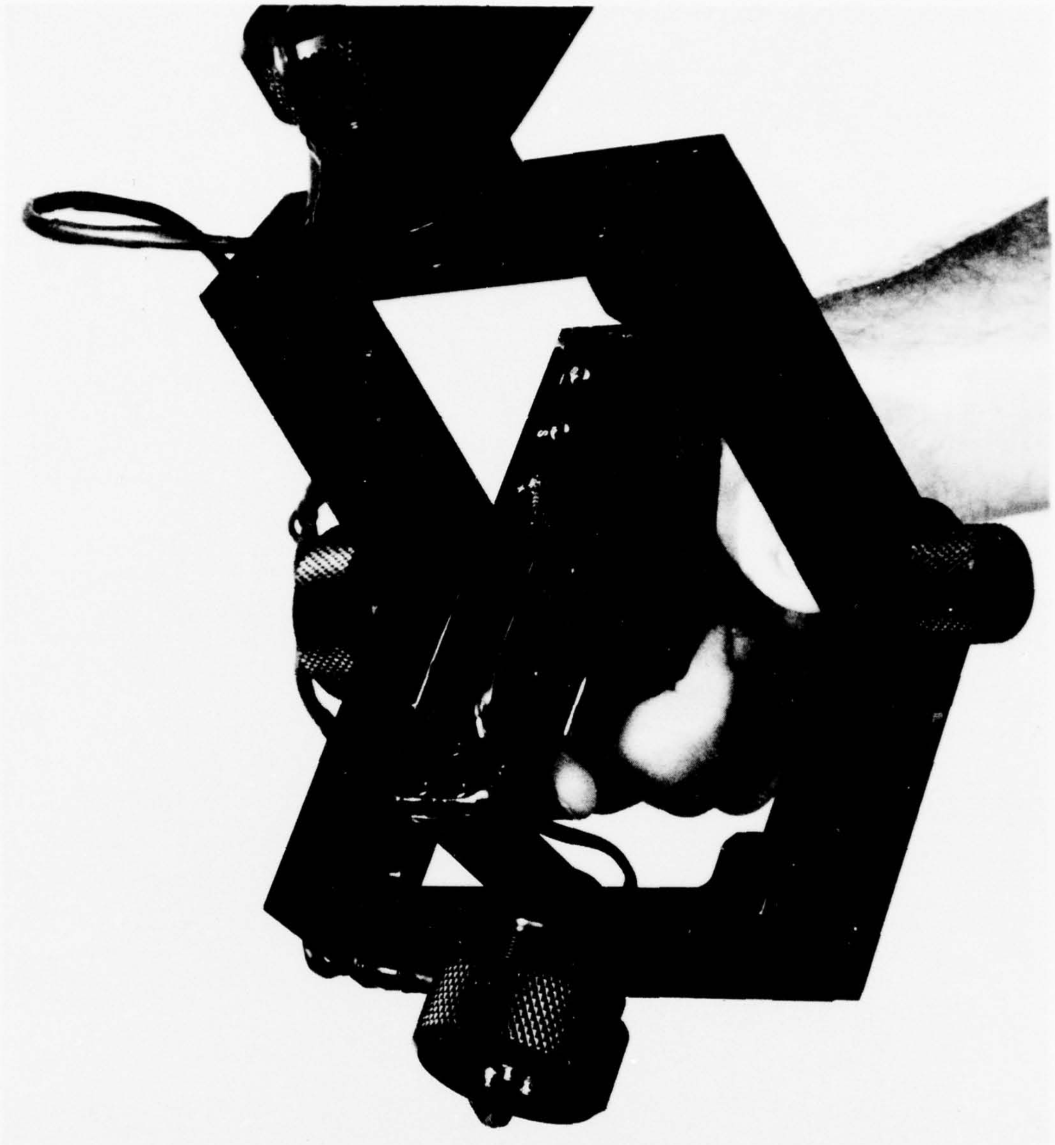


Figure 13. Pistol-grip terminus control for main *RUWS* manipulator. *2494-4-72*

This exploration of supervisory computer control showed definite possibilities for undersea use. The most promising include the performance of repetitive tasks, and the return of tools to their storage positions. Additionally, it might be possible to produce a library of task sequences and positions that could be initiated by keyboard commands. These capabilities would be valuable additions to a general-purpose underwater manipulator.

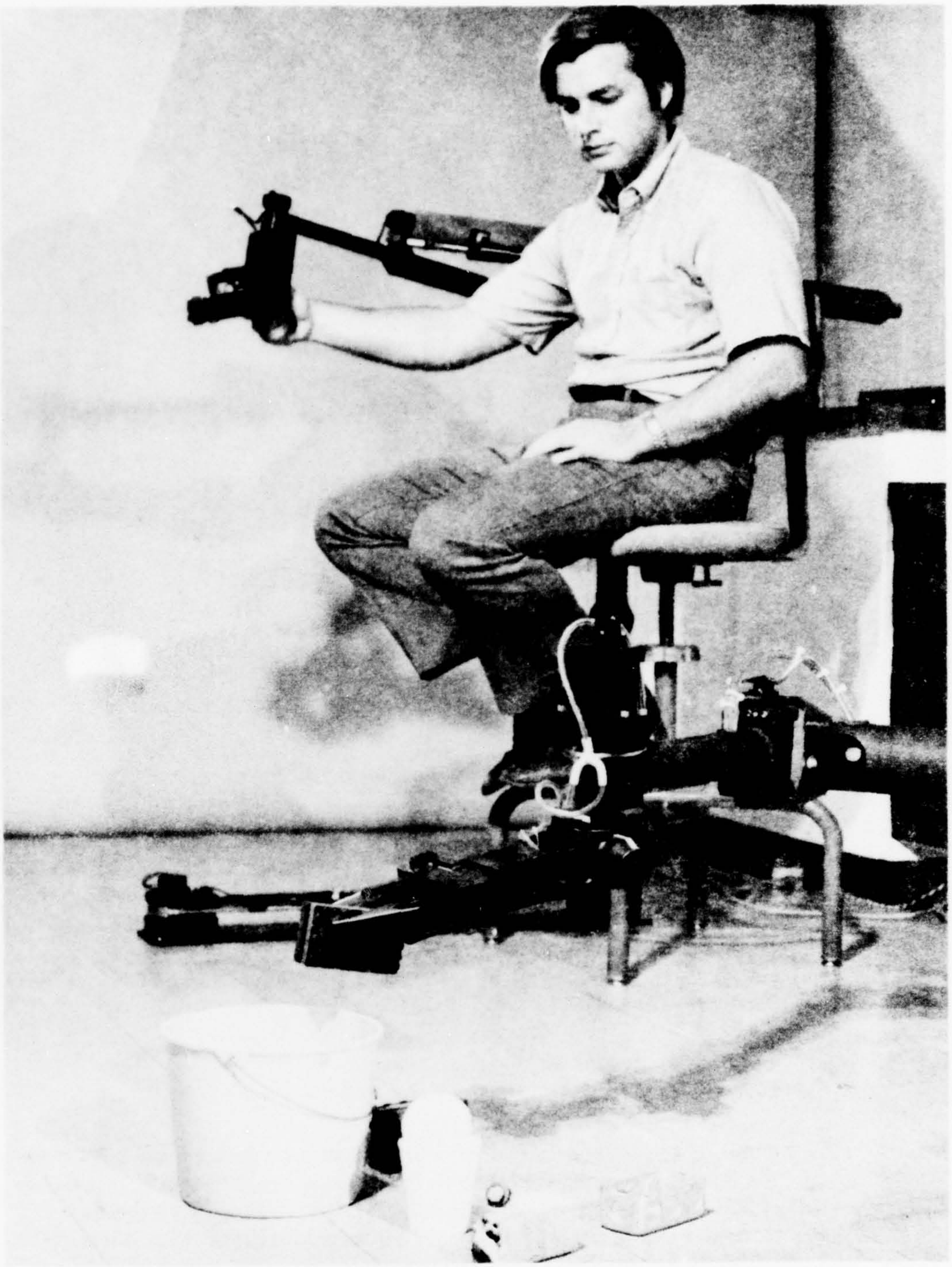
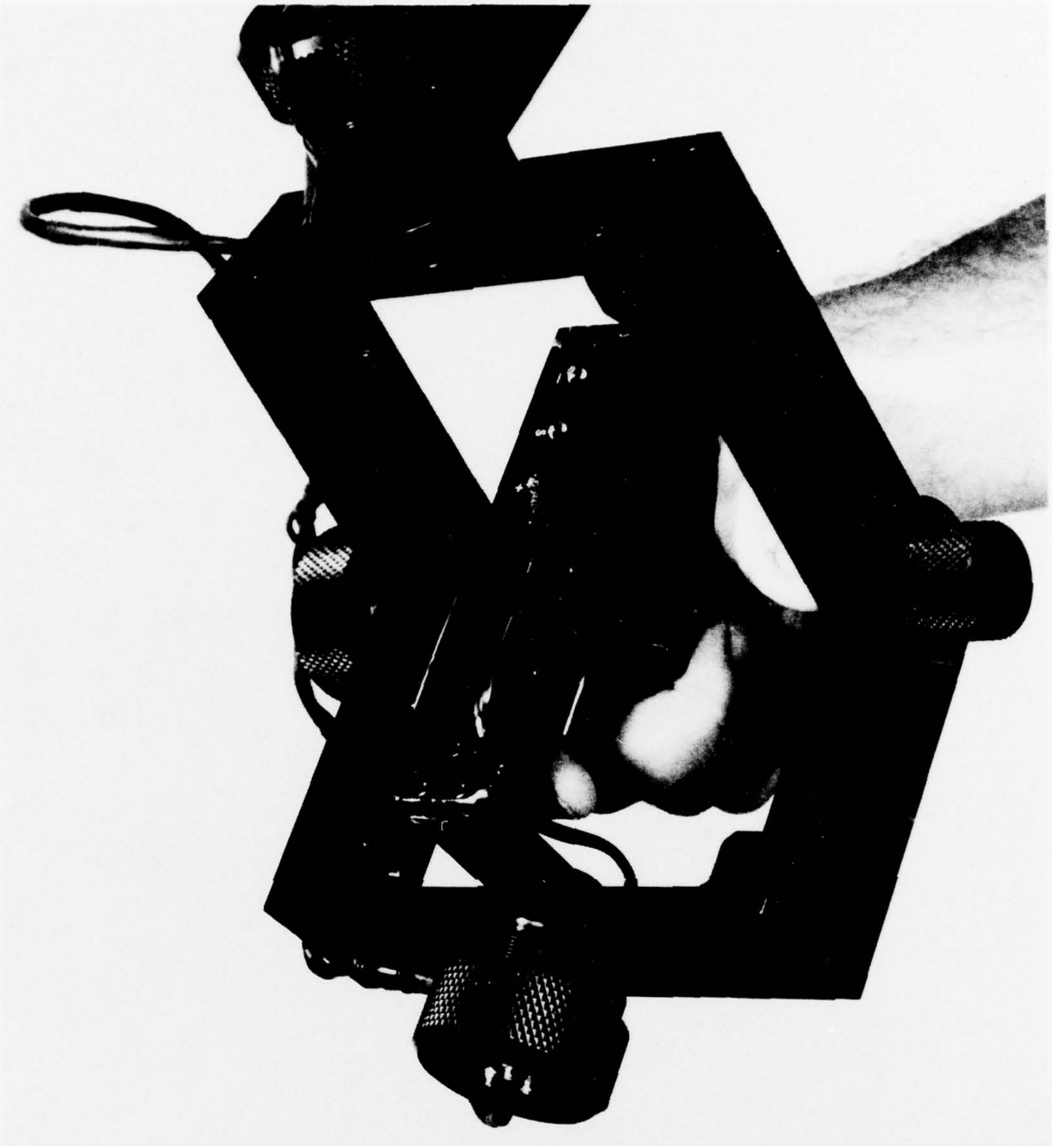


Figure 14. Controller and main *RUWS* manipulator during laboratory testing. *2588-3-72*



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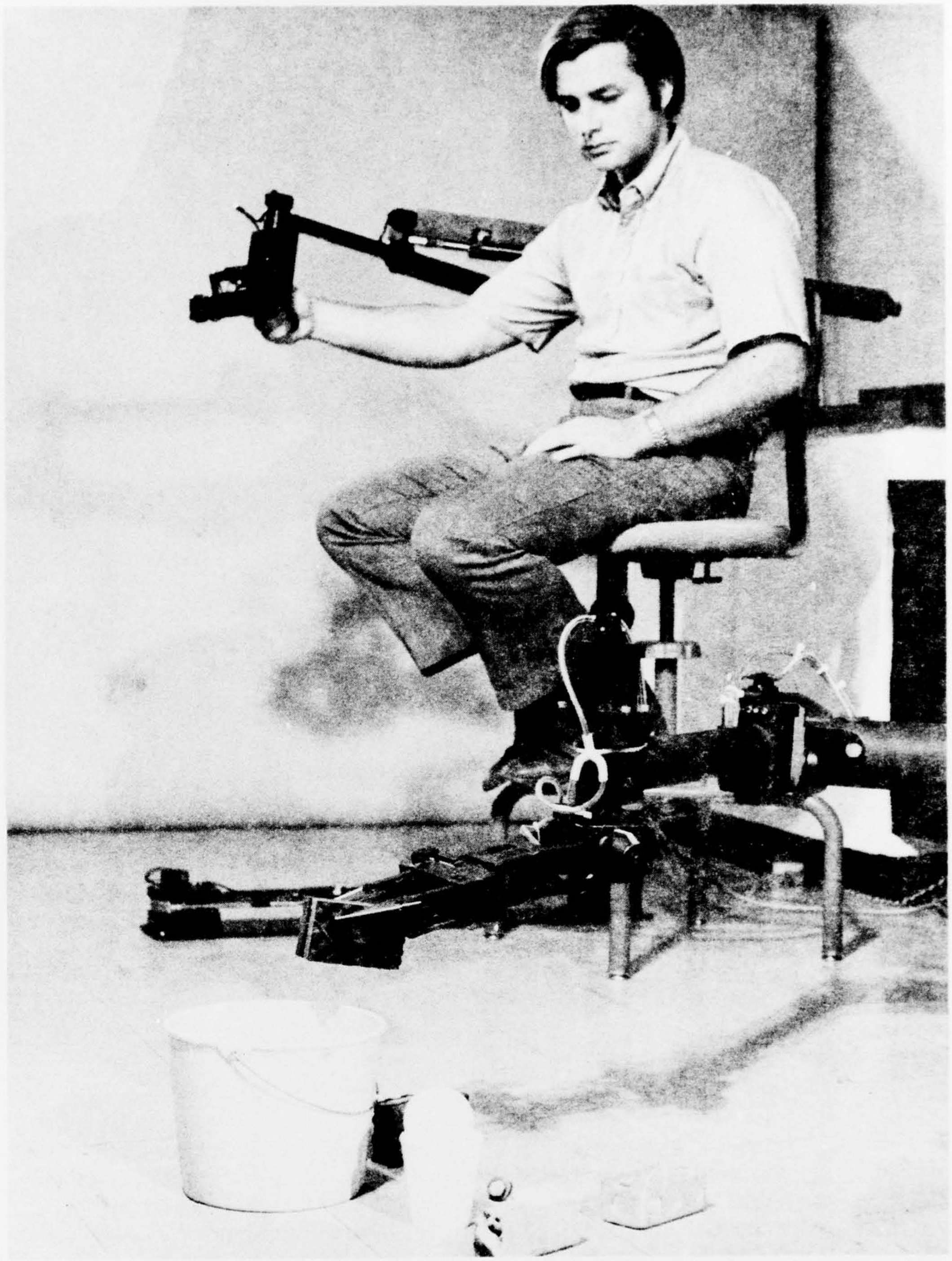

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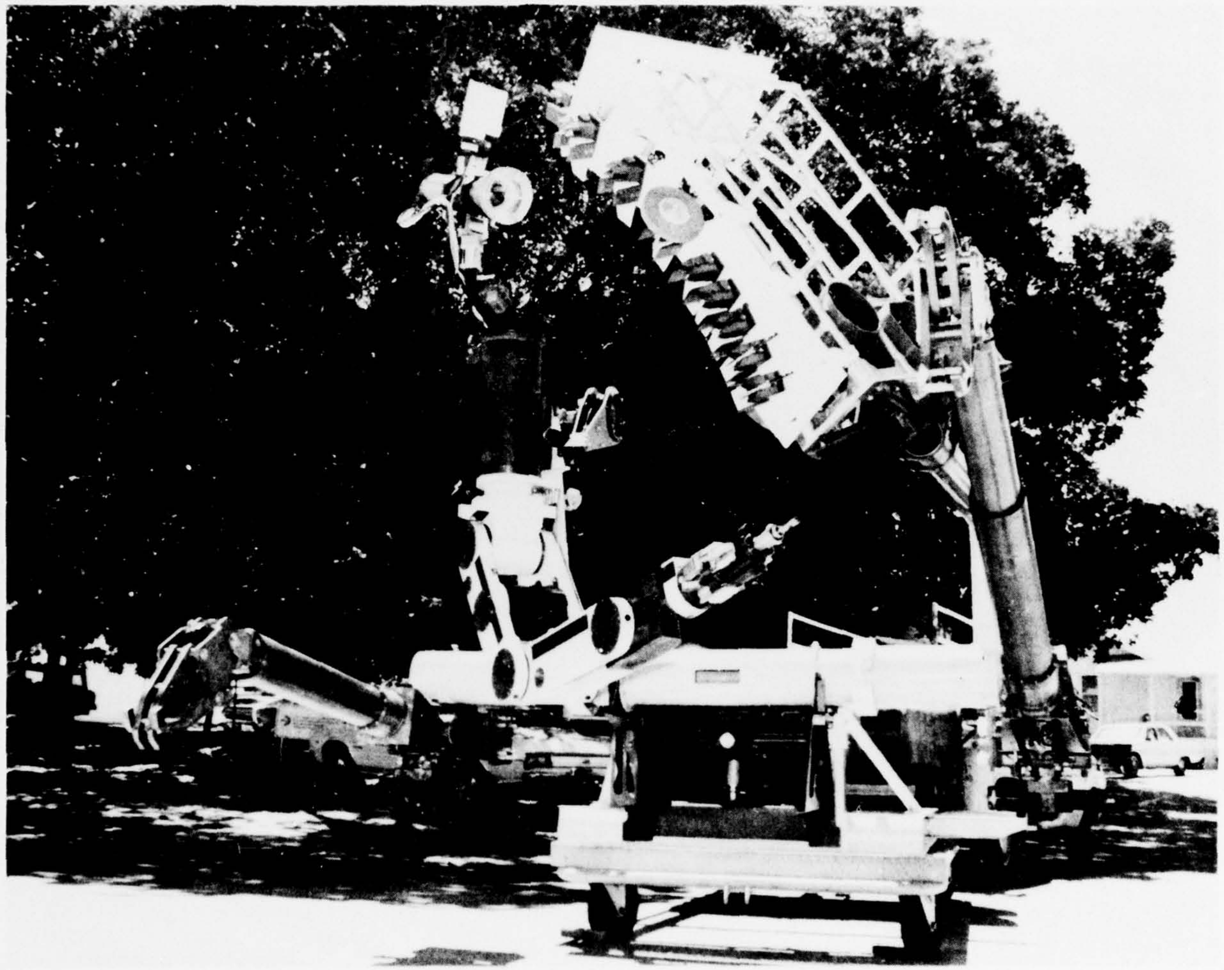

Figure 15. Work System Package (WSP). Grabbers at shoulders secure the system during work; the grabber at the right of the photograph has been elevated to show range of motion. *270-1-77*

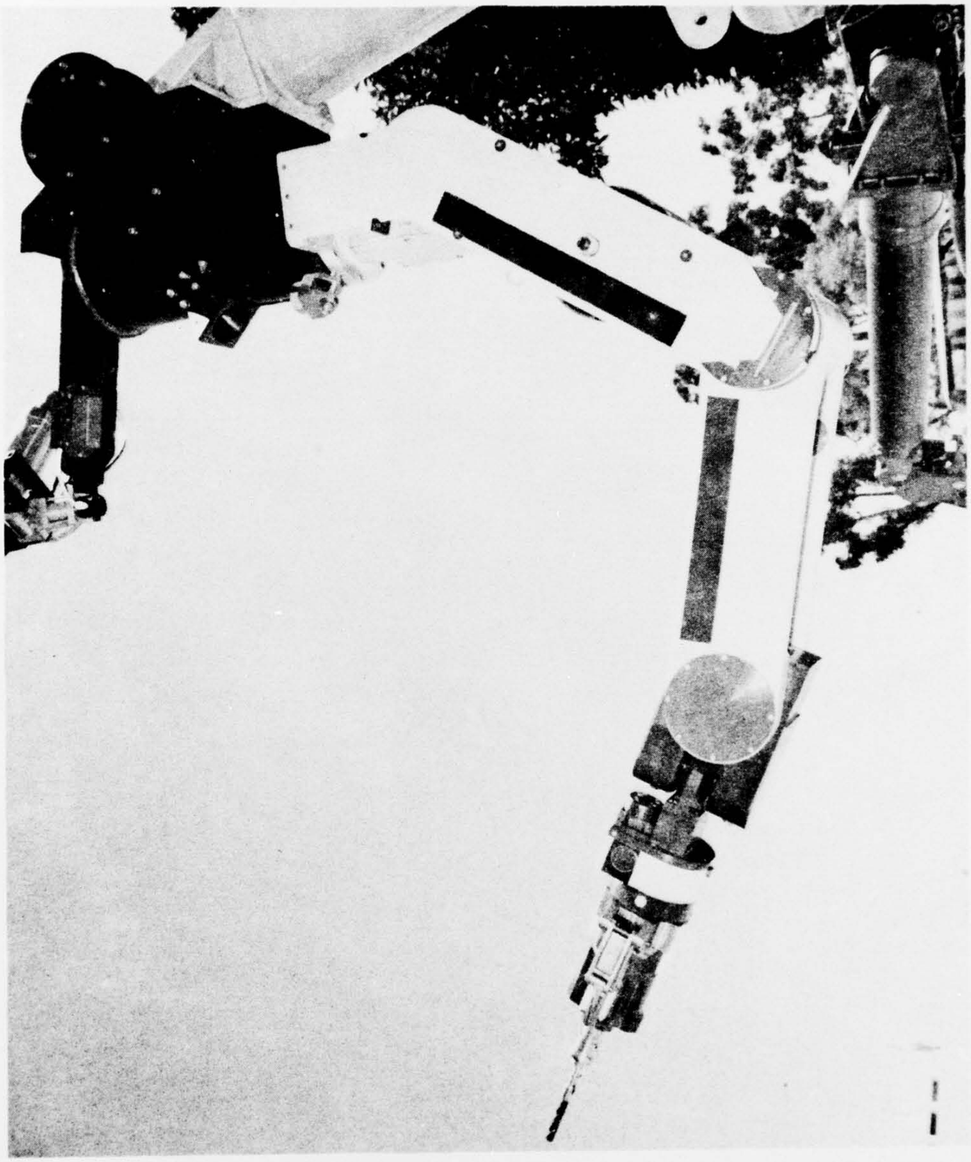

Figure 16. Primary WSP manipulator with drill attached. *4751-8-74*

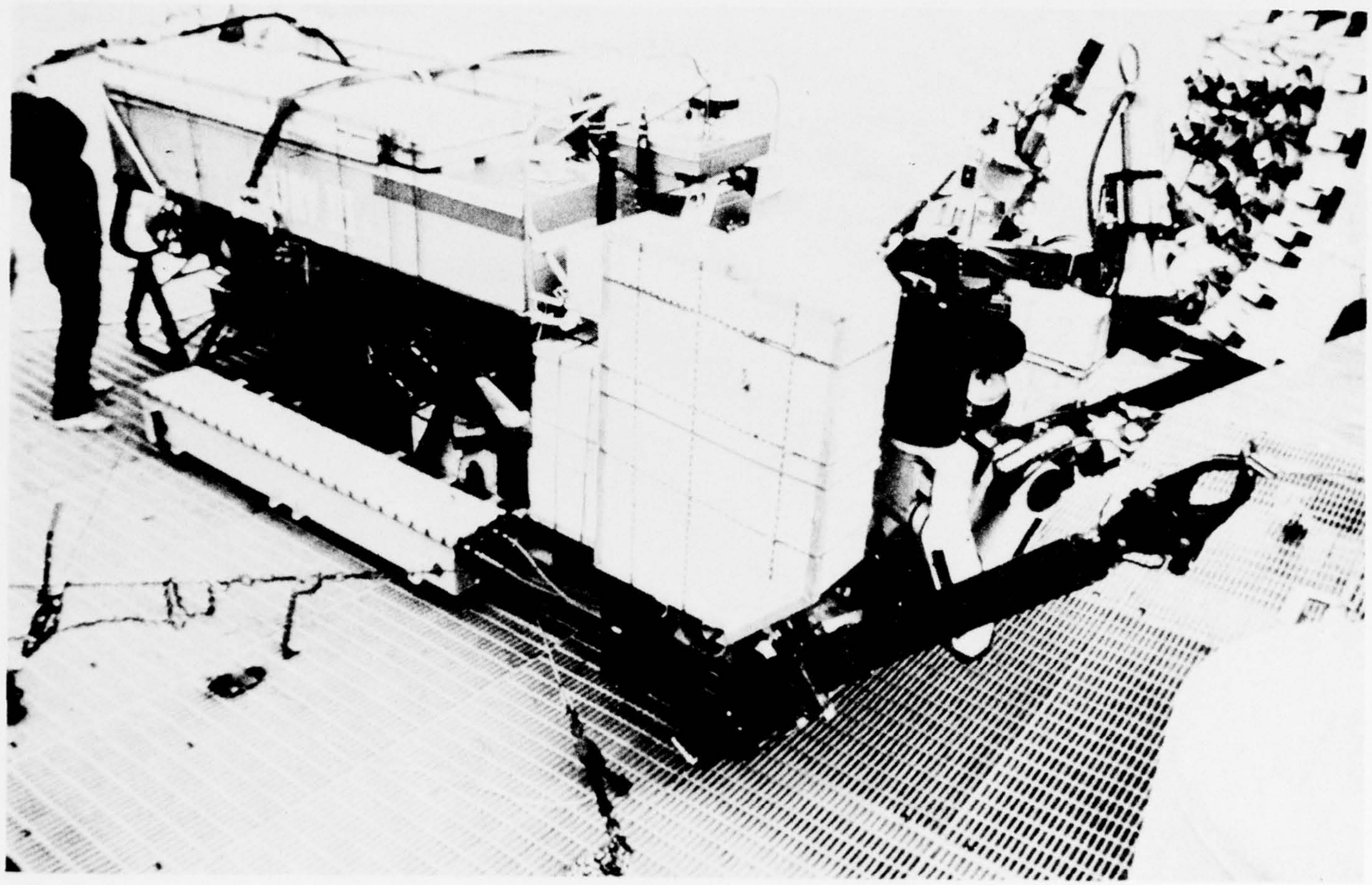

Figure 17. WSP mounted on *CURV III*. 1280-3-75

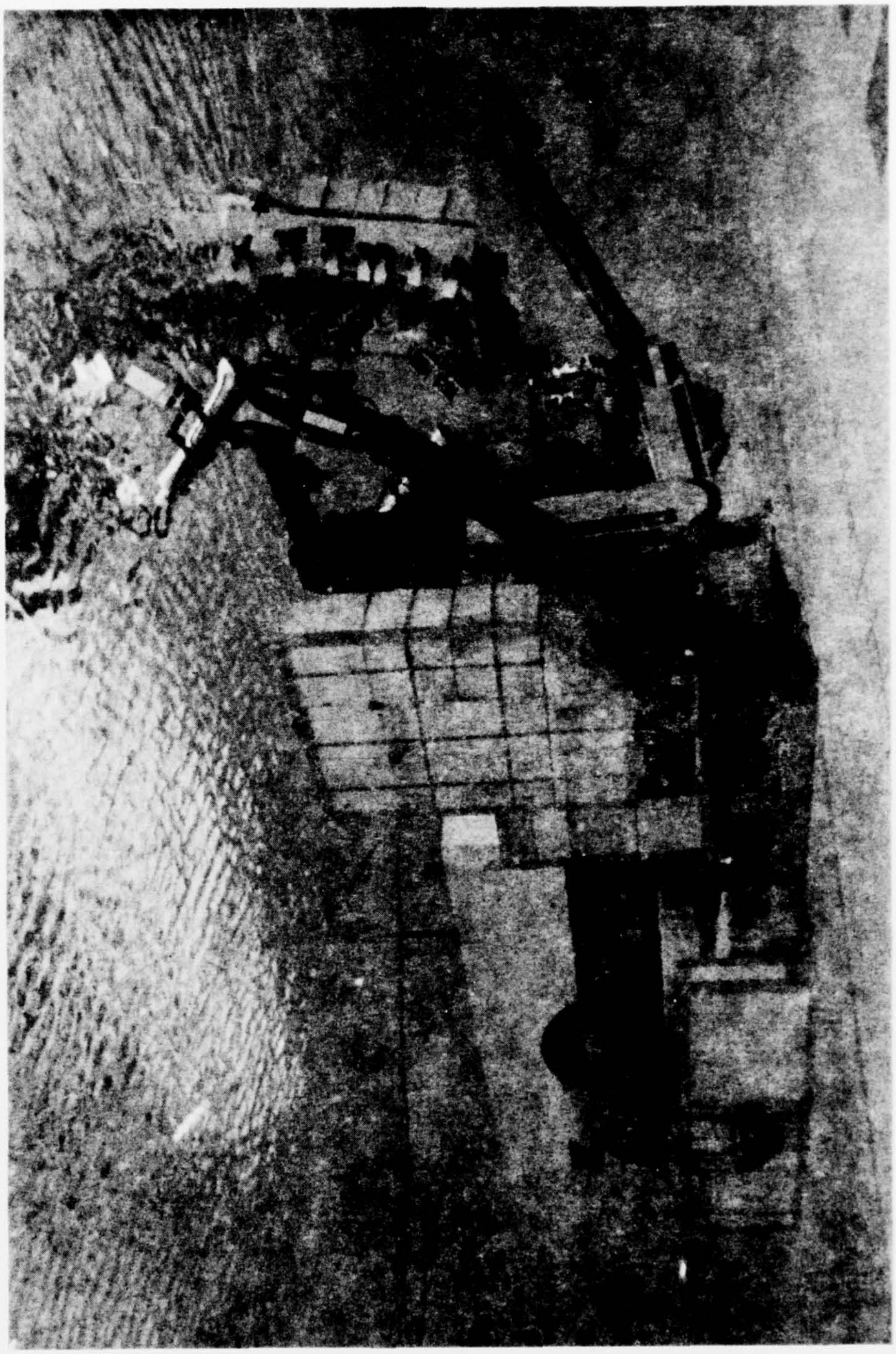

Figure 18. WSP mounted on *RUWS*. 24357-3-76

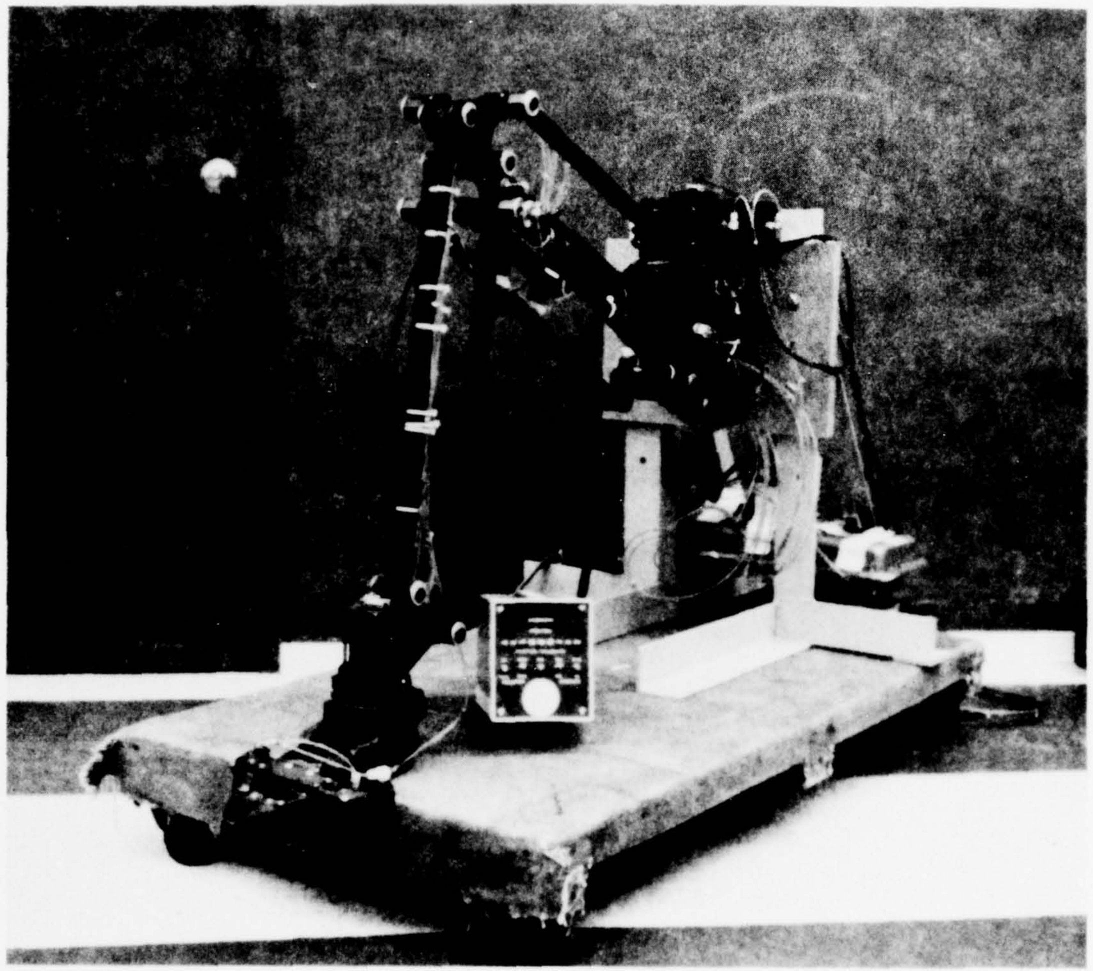

Figure 19. System tested to evaluate preprogrammed manipulator control. *7077-11-74*

SUMMARY

The manipulator systems developed by NUC offer various capabilities appropriate for the tasks they are intended to perform. Table 1 summarizes their characteristics. The next section will formulate a general design philosophy based upon experience gained using these manipulators at sea.

Table 1. Design characteristics of NUC manipulators.

Manipulators	No. of Functions	Weight in Air (lb.)[a]	Lift Capacity (lb.)	Maximum Reach (in.)[b]	Operating Depth (ft.)[c]
CURV I Claw	3	100	400	50	2,000
CURV II Claw	4	100	400	50	2,500
CURV III Claw	4	100	400	50	10,000
Linkage Manipulator	7	75	50	55	7,000
NEV Manipulator	7	100	50	55	0
SCAT Claw	2	20	50	36	1,500
RUWS Manipulator	7	60	45	50	20,000
RUWS Grabber	4	73	200	24	20,000
WSP Manipulator	7	500	100	72	20,000
WSP Grabbers	6	250	250	108	20,000

[a]pound = 0.454 kilogram
[b]inch = 2.54 centimeters
[c]foot = 0.305 meter

DESIGN CONSIDERATIONS

A manipulator must be well designed mechanically for performing the required tasks in the marine environment, and it must be integrated with the controls and displays that enable the operator to perform coordinated, accurate motions. Anyone with experience in remote work systems develops opinions on how to design a manipulator to optimize the capabilities of the operator through the man-machine interface, but these opinions must be reconciled with the experience of others: the human factors researchers and the operators who have routinely performed remote work in the deep ocean. In the past the operator has been forced to adapt his skills to the system rather than having a system designed to be compatible with his natural mental and physical capabilities, senses, and reflexes. Not enough effort has been expended studying these aspects of underwater manipulators. As a result, there has been no orderly evolution in underwater manipulator development as there has been in development of equipment for handling radioactive materials.

A major problem is that the optimum manipulator and control system for specific tasks varies considerably with the task. The capabilities of operators also vary, and often their preferences are a function of their experiences with particular types of manipulators, controls, displays, and tasks. However, experience has led to a general awareness of certain tradeoffs. For tasks requiring precise positioning, for example, rate-control devices are more accurate, whereas for general reaching and grasping, where coordination is more important than precision, master/slave manipulators are much faster. In rate-control manipulators, position feedback is purely visual; whereas master/slave manipulators, even with computer-generated displays, add a natural feeling of position. Two types of master/slave controls have been used: harness and terminus control. A harness control straps onto, or in some way attaches to, the arm of the operator, whereas the terminus control is held only at the hand or terminus. They operate in the same way; the manipulator (slave) is driven to conform to the configuration and position of the control (master). The harness control may be most valuable for use with anthropomorphic manipulators, especially those with a redundant function for elbow position. Terminus control, much more common in hot cell nuclear work, generally allows more operator freedom and a greater range of motion, and does not require an anthropomorphic manipulator.

A lesson to be learned from *RUWS* is that an anthropomorphic arm is not necessarily the ideal. Friction in the shoulder and elbow series of actuators (both of which are low-friction vane actuators) often makes smooth, coordinated motions difficult. A manipulator based on a spherical coordinate system, for example, would not have these joints in series. Furthermore, although the wrist is similar to that of the linkage manipulators, the motions of the anthropomorphic arm continually disorient the hand unless the wrist functions are moved to compensate. Additionally, movement may be limited. When the tool or work lies along the shoulder elevation axis, vertical motion is impossible. Yet another problem is the extreme vulnerability of the wrist position-sensors to damage, which has led to their removal and attempts to control roll and pitch by switches.

Force feedback, another of *RUWS*'s capabilities, is generally not incorporated into undersea manipulator systems because of the complexities involved and because operators have historically managed to get along without it. In certain tasks such as collecting biological specimens, where grip force is important, it is generally easier to accurately control grip force (for example, by pressure-control servovalves) without requiring force feedback, or to provide simple visual feedback (for example, by a differential pressure gauge on the grip actuator, or by a compliant hand whose distortion indicates grip force).

For general-purpose manipulators such as *RUWS* and WSP, however, it is anticipated that tasks requiring force feedback will occur. Examples are drilling and tapping, operations where too much force or misdirected force might result in a broken tool. Of course, wherever possible, tool drive, feed, and alignment should be automatic functions of the tool itself, not the manipulator. Unfortunately, this is not always possible. Another situation in which force sensing could be important occurs when the manipulator unexpectedly comes in contact with the work or the vehicle itself, whether through poor vision, bad system design, or operator inattentiveness.

For the master/slave manipulator, force feedback is most naturally provided by making the system bilaterial, i.e., incorporating within the controller actuators that drive it in the direction of forces encountered by the manipulator, the actuating force being proportional to the encountered force. This form of force feedback is imprecise but much more easily assimilated by the operator than, say, a computer-generated graphic display of force vectors.

Direct sensing of forces on an underwater manipulator is extremely difficult. Strain gauges have not proven reliable in a high-pressure, corrosive medium. Forces must therefore be sensed indirectly by measuring the pressure in the hydraulic actuators, or, as in RUWS, by measuring the voltage to the pressure servovalves that control the arm actuators. In either method, other forces are also sensed: arm weight, arm inertia and momentum, actuator static and dynamic friction, hydrodynamic drag on the arm, and pressure-drop due to hydraulic flow between the sensor and the actuator. Arm weight and inertia can be compensated for by small computers, as can hydrodynamic and viscous forces. These can also be minimized by proper design, deliberate slow movement of the arm, and operator familiarization with the spurious forces. Static friction must be minimized by proper actuator selection, but cannot be eliminated.

The manipulator must also be designed to avoid degenerative positions where forces on the manipulator are transferred purely mechanically to the vehicle and therefore are not sensed. This occurs when actuators are driven against stops or when a load is completely longitudinal to a series of rotational actuators, as is possible if the RUWS manipulator is completely extended.

Another important aspect of manipulator systems is visual capability. Operators of manned vehicles find that viewports generally have a narrow field of view, are subject to distortion, and are uncomfortably located. Yet they prefer to use these windows rather than looking at a comfortably located television monitor, even though the monitor may show a low-distortion picture from a camera than can be adjusted with pan-and-tilt and zoomed to change the field of view. The factors making the viewport more realistic than television are color, resolution, depth, sense of orientation, and fixed station points.

Color and resolution can be improved on underwater television cameras, but unless broad-spectrum lighting and clear water are available these may not really help. Moreover, experience with *RUWS* strongly demonstrates the need for stereo TV. During laboratory tests with *RUWS* the operator was only a few feet from the manipulator and had the benefit of good lighting and vision, enabling him to perform feats of great dexterity. Figure 20 shows *RUWS* in night pool tests. Use at sea, however, has been disappointing. The operator must contend with cloudy water, a flat visual field, and unfamiliar size and spatial relationships, and he is often forced to make quick trial-and-error tests. On *RUWS* a traversing mechanism allows the single TV camera to be moved to different station points across the front of the vehicle, thereby giving different perspective and parallax judgments of depth. However, this mechanism may further confuse the spatial relationships; if the operator's single "eye" is at an unfamiliar location with respect to his shoulder, he cannot judge which way to move his hand, for example, to cause the manipulator hand to move directly away from the camera. Stereo TV would solve this problem. Many stereo systems have been shown to give good depth resolution, and some such capability is needed to make undersea manipulators truly effective.

Another difficulty that the operator encounters is in maintaining a sense of orientation. Orientation and station-point feedback can be given by two methods; fixed camera

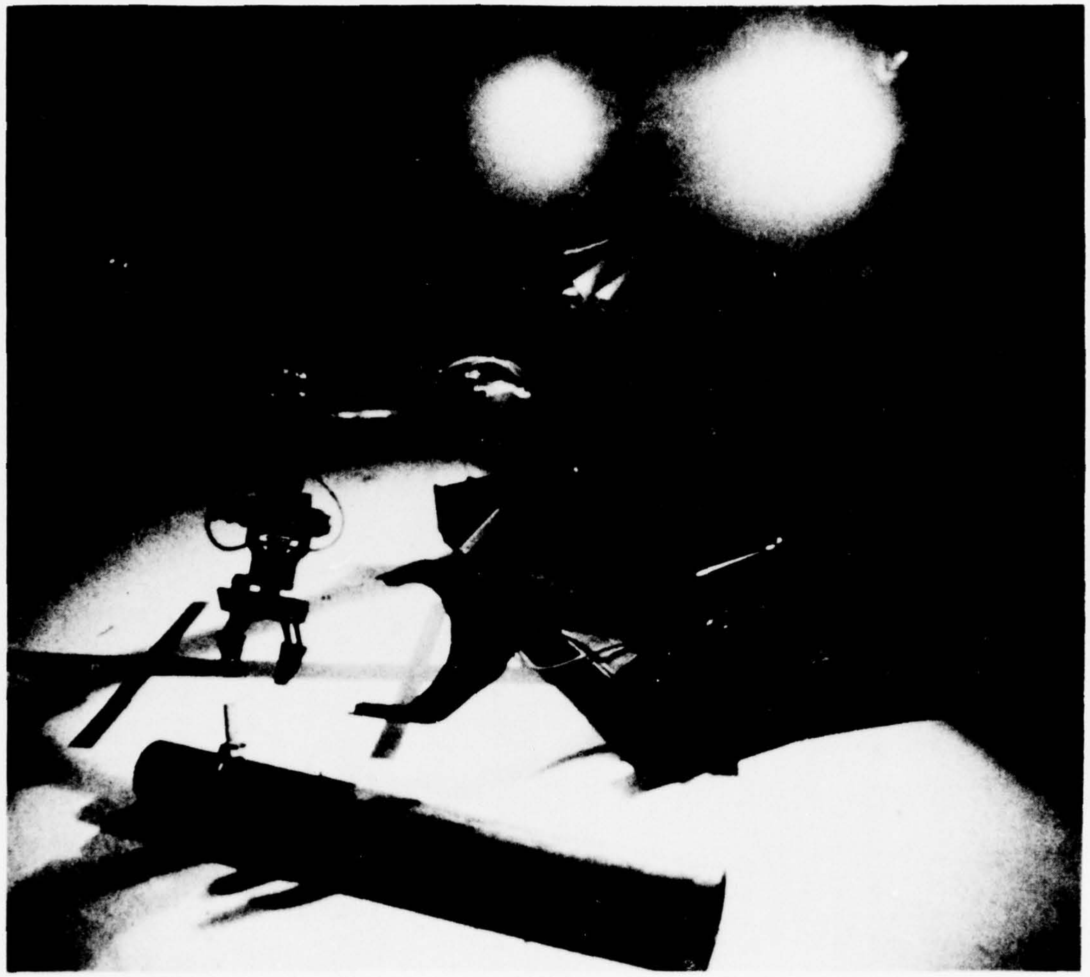

Figure 20. *RUWS* during night pool tests. *20286-4-74*

and monitor, or head-coupled television, especially incorporating head-following camera translation. Head-coupled TV also alleviates the problem of limited field of view, since a sweep of the head allows the operator to visually encompass as much of the remote environment as he wishes, and he instinctively retains the spatial relationship of objects not simultaneously visible in the camera's field of view.

Although *SCAT* has been reconfigured and no longer carries head-coupled stereo television, its demonstration was impressive. The sense of actually being present on the vehicle has never been equalled on a remotely controlled undersea vehicle. However, the viewing helmet and sensing linkage were never quite perfected. They were both found to be uncomfortable, heavy, and clumsy in use. Perfection of head-coupled stereo television and its use with a bilateral master/slave manipulator will be a major step forward in developing a system for remote work tasks that require a high degree of "eye-hand" coordination.

Even the development of a practical head-coupled television will not eliminate occasional blockage of the work by the tool or by the manipulator. For this reason one or more auxiliary television cameras, possibly including a wide-angle lens and zoom, would be advisable. Additionally, the manipulator's wrist size and mass should be minimized to avoid blocking the operator's view of the work. This will also minimize structural requirements and hydraulic porting of the upper arm joints. Therefore, when a specific task requires tool drive, feed, alignment, compliance, overload protection, or similar functions, they should be incorporated into specific tools, not the general-purpose manipulator.

It must be cautioned that the best general-purpose manipulator for underwater work is not necessarily the most sophisticated or complex. Cost, reliability, maintainability and the ability of the trained operator to work within limitations must also be weighed in deciding whether or not to incorporate seemingly desirable features.

SPECIFIC PROPOSALS

The optimum manipulative device for recovering MK 46 torpedoes would be very different from a manipulator designed for replacing a specific component of an undersea oil wellhead. But general conclusions can be drawn, based on NUC's experience, about how best to design a manipulator system which will further enhance the Navy's ability to perform general underwater work tasks in which dexterity and versatility are important.

The work system or vehicle should be able to anchor firmly to the bottom or to the work. This might require two or more heavy-duty grabbers like those on the WSP. Preferably, two manipulators would be incorporated, corresponding to the operator's right and left hands. The grabbers and manipulators should be hydraulically powered. The manipulators should have seven independent functions. The arm structure should be a linear linkage; the wrist should be of the *RUWS* type, internally ported with all rotary axes intersecting at one point. Parallel, synchronous jaws should be used on the hand for mating to a variety of specially designed tools.

Position sensors should be mounted on the azimuth, elevation, extension, and wrist yaw functions. These functions should be controlled by flow servovalves. Roll and pitch can use simple four-way valves. Grip should be controlled by a pressure servovalve.

Pressure transducers should be used to sense forces on the three position actuators, all of which should be low-friction piston or vane rotary types.

Such a manipulator would be operable in a simple rate-controlled (switch-controlled) mode or, alternatively, bilaterally position-controlled in three functions and unilaterally slaved in a fourth. Another possibility would be to preprogram the manipulator in four functions, azimuth, elevation, extension, and yaw. Those orientation functions with no position feedback (roll and pitch) are not disoriented by arm motions and should seldom need adjustment. Thus, no wires or potentiometers are required on the wrist, eliminating the "Achilles heel" of the *RUWS* manipulator. The use of flow-control servovalves permits precise positioning for computer or position control: any detectable position error will be countered by full system pressure, if necessary. The control characteristics for the proposed seven-function manipulator are summarized in Table 2.

Head-coupled stereo television should be incorporated. This will require development of a good display unit, which deserves highest priority. The camera(s) for this unit should be placed with respect to the manipulator shoulders as the operator's head is located with respect to the controllers. Auxiliary cameras should provide a wide-angle overview of the work area, and a close-up zoom capability from one side.

The work area and tool storage should be compatible with the manipulator's range of motions and reach volume. Redundant functions (tool advance, continuous rotation, impact, oscillation, etc.) should be incorporated into the specific tools, not the manipulators.

Table 2. Control characteristics for the proposed seven-function manipulator.

Mode Function	Switch Control	Position Control	Force Control	Force Feedback	Computer Control
Azimuth	✓	✓	✓	✓	✓
Elevation	✓	✓	✓	✓	✓
Extension	✓	✓	✓	✓	✓
Yaw	✓	✓			✓
Pitch	✓				
Roll	✓				
Grip	✓		✓		

BIBLIOGRAPHY

Estabrook, N., H. Wheeler, D. Uhler, and D. Hackman. Development of Deep-Ocean Work System. *Ocean '75: Engineering in the Ocean Environment and the 11th Annual Meeting of the Marine Technology Society*, Conference Report for the Joint IEEE/MTS meeting, September 1975.

Fugitt, R.B., and R.W. Uhrich. Underwater Stereoscopic Television and Display Realism. Naval Undersea Center, San Diego, Calif. NUC TN 358, July 1973.

Marrone, R.A., J. Held, and R.W. Uhrich. Naval Undersea Center, San Diego, Calif. NUC TN 818, Manipulator, Grabbers, and Tools for the RUWS Work Subsystem. November 1972.

Pesch, A.J., G.R. Simoneau, and R.G. Hill. Operator Performance in Undersea Manipulator Systems. General Dynamics, San Diego, Calif. Technical Report 4440-73-020, February 1973.

Pritzlaff, J., D. DeBell, R.W. Uhrich, and G. Conrad. The Un-Man in the Sea. *Astronautics and Aeronautics*, July 1972.

Rockwell, P.K. Underwater Manipulative Construction Systems. Naval Electronics Laboratory Center, San Diego, Calif. NELC TN N-1158, May 1971.

Uhrich, R.W. Proposed Manipulator System for CURV Vehicles. Naval Undersea Warfare Center, San Diego, Calif. NUWC TN 15, September 1967.

___________ Natural Response Underwater Manipulator System, *A Critical Look at Marine Technology*, Marine Technology Society, Washington, D.C., 1968, pp. 559–599.

___________ NUC Manipulators. *Engineering in the Ocean Environment*, Record of IEEE Conference on Engineering in the 1971 IEEE Conference held at San Diego, Calif., 21–24 September 1971. Institute of Electrical and Electronic Engineers, New York, N.Y., 1971.

___________ CURV Linkage Manipulator. Naval Undersea Center, San Diego, Calif. NUC TP 271, November 1971.

___________ Terminus Controlled Deep Ocean Manipulator, IEEE International Conference on Engineering in the Ocean Environment, September 1973.

Uhrich, R.W., and A.E. Munson. Position and Force Feedback Give Manipulator Precise Control, Ease of Operation. *Hydraulics and Pneumatics*, September 1973.

Watts, R.L. Guide to the CURV for Deep Operation. Naval Undersea Center, San Diego, Calif. NUC TP 338, April 1973.

Wernli, R.L. WSP/CURV III Operational Testing at San Clemente Island – 1975 Work Systems Package (WSP) Program. Naval Undersea Center, San Diego, Calif. NUC TN 1699, July 1976.

Wernli, R.L., and H.C. Wheeler. NUC Informal Progress Report FY 75 Work Systems Package Program. Naval Undersea Center, San Diego, Calif. NUC TN 1582, September 1975.