PROCEEDINGS OF 27th CONFERENCE ON REMOTE SYSTEMS TECHNOLOGY, 1979

DEEP OCEAN APPLICATIONS OF MANIPULATORS AND WORK SYSTEMS

ROBERT L. WERNLI *Naval Ocean Systems Center*
Code 5214, San Diego, California 92152

KEYWORDS: *underseas, remote vehicle, remote handling*

ABSTRACT

The Naval Ocean Systems Center (NOSC) has been in the forefront of undersea vehicle and manipulator development since the early 1960s. Through extensive at-sea and laboratory test programs, methods have been developed to optimize these remote systems. The NOSC technological background is presented here with particular emphasis on the optimization of undersea manipulator and work systems. The methods of increasing system efficiency while keeping complexity to a minimum are also presented.

INTRODUCTION

The advancement of today's technology often results in the exposure of man to hazardous environments. In his quest for protection, he has made great strides in the field of remote systems technology. This is especially evident in the nuclear industry, where, for a generation, new manipulators and work systems have been developed to assist in the handling of hazardous materials. Today, with the conquest of new frontiers, remote systems technology is playing a greater and greater role. Sophisticated manipulator systems are being built for space exploration and development. The well-defined, mathematically structured realm of space is an ideal location for the application of this technology. An environment not so ideal, however, is that of the deep ocean. Mother Nature has not made man's conquest of the oceans an easy task. Corrosion, extreme pressures, unpredictable sea states, and severe ocean currents combine to provide an unstructured and hostile environment. Because of this, remote system technology is playing a greater role in ocean exploration and development.

The debate of whether man is required at the work site in a submersible is still on-going. But, in fact, almost all aspects of man's capabilities, except his ego, can be duplicated sufficiently to perform adequate underwater manipulation and work.[1] The increase in the off-shore oil industry has resulted in remotely controlled vehicles and work systems replacing divers and manned submersibles in performing many underwater tasks. In the future, as more equipment is designed to be maintained or inspected by remote systems, their use and efficiency will increase. Although the diver will not be totally replaced, his time in the water can be greatly reduced by the proper integration and use of remote systems technology.

BACKGROUND

One of the pioneers in the application of remote systems technology to the ocean has been the U.S. Navy. Since the early 1960s, the Naval Ocean Systems Center (NOSC) has been in the forefront of undersea vehicle and manipulator development. The basic approach has been to keep the system simple and reliable and to keep the operator topside in a safe, comfortable, controlled environment. Through the application of this design approach, a range of vehicles and work systems has been developed.[1-3] These systems, which are discussed in the following paragraphs, have been operational proof of these design philosophies.

Snoopy

The Snoopy vehicles are small, lightweight, portable submersibles primarily intended to provide a remotely controlled underwater observation platform. As the first in the series, Hydraulic Snoopy is basically a small flying television camera capable of operation to 61 m (200 ft). It carries a small grabber for simple recovery tasks. A more advanced vehicle, the Electric Snoopy, was developed with the capability to operate to 457 m (1500 ft). It is 1.07 m (42 in.) long, 0.76 m (30 in.) wide, weighs ~68 kg (200 lb) in air, and carries a line reel and grabber for recovery tasks. More recently, the NAVFAC Snoopy (Fig. 1) has been developed for use by the Naval Facilities Engineering Command during ocean construction work. It is similar to Electric Snoopy with the addition of a small scanning sonar system. During the past year, it has assisted in the recovery of three other tethered vehicles that were either lost or entangled on the ocean floor.

SCAT

The Submersible Cable-Actuated Teleoperator (SCAT) was initially designed to evaluate underwater head-coupled stereo television. A three-dimensional television display was installed in a helmet to which the motions of the television cameras on the bow of the vehicle were slaved. In this way, the vehicle operator was given the sensation of actually being in the SCAT. In addition, a simple, two-function claw was incorporated to provide a recovery capability. The SCAT is currently being reconfigured as a light-duty inspectional work vehicle capable of operating to 610-m (2000-ft) depths (Fig. 2).

CURV

The Cable Controlled Underwater Recovery Vehicle (CURV) was originally developed for recovery of ordnance items in 1965. The CURV I was outfitted with a simple claw built to recover MK-46 test torpedoes at depths below 457 m (1500 ft). The CURV I is well known for its assistance in recovering the hydrogen bomb, which was lost off Palomares, Spain in 1966 as a result of the collision of two U.S. Strategic Air Command aircraft. The CURV I vehicle has been replaced with the CURV II, with a depth capability of

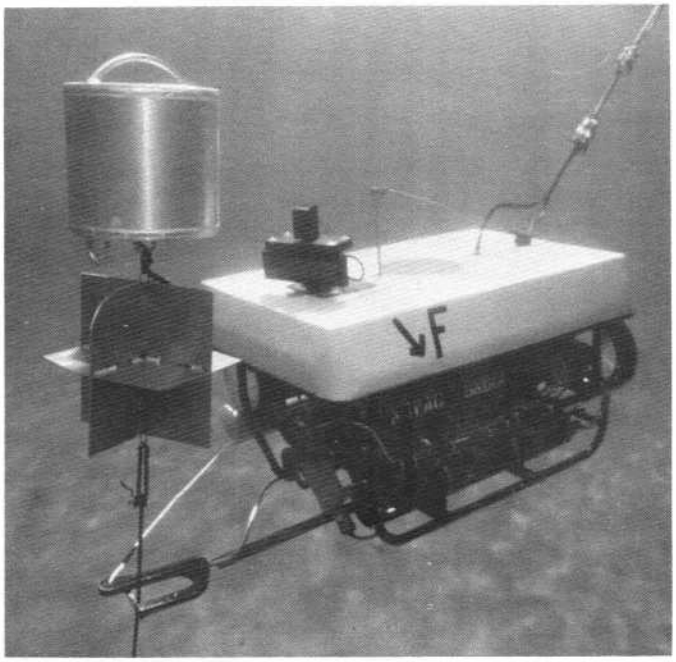


Fig. 1. The NAVFAC Snoopy attaches recovery line to target.

762 m (2500 ft), and the CURV III (Fig. 3), with a depth capability of 3050 m (10 000 ft). The manipulators on these systems have a replaceable hand that easily allows replacement by cable cutter, snare, toggle bar, hook, or other hands of various sizes and shapes. This adaptability more than proved itself when the CURV III was flown to Cork, Ireland in 1973, where it assisted in the rescue of the Pisces III, the manned submersible that was stuck at a depth of 457 m (1500 ft). A makeshift toggle was used to attach the lift line and ultimately raised the submersible safely recovering the two men below. The simple design of the CURV claw has provided over a decade of reliable, low-maintenance operation.

MNV

The Mine Neutralization Vehicle (MNV) was developed to classify and neutralize sea mines while being deployed from a minesweeper (Fig. 4). Location and classification is performed through the use of a high-resolution scanning sonar and an underwater television system.

NP

The Nozzle Plug (NP) vehicle was developed for the National Aeronautics and Space Administration (NASA) to assist in recovery of the solid rocket boosters (SRB) of the

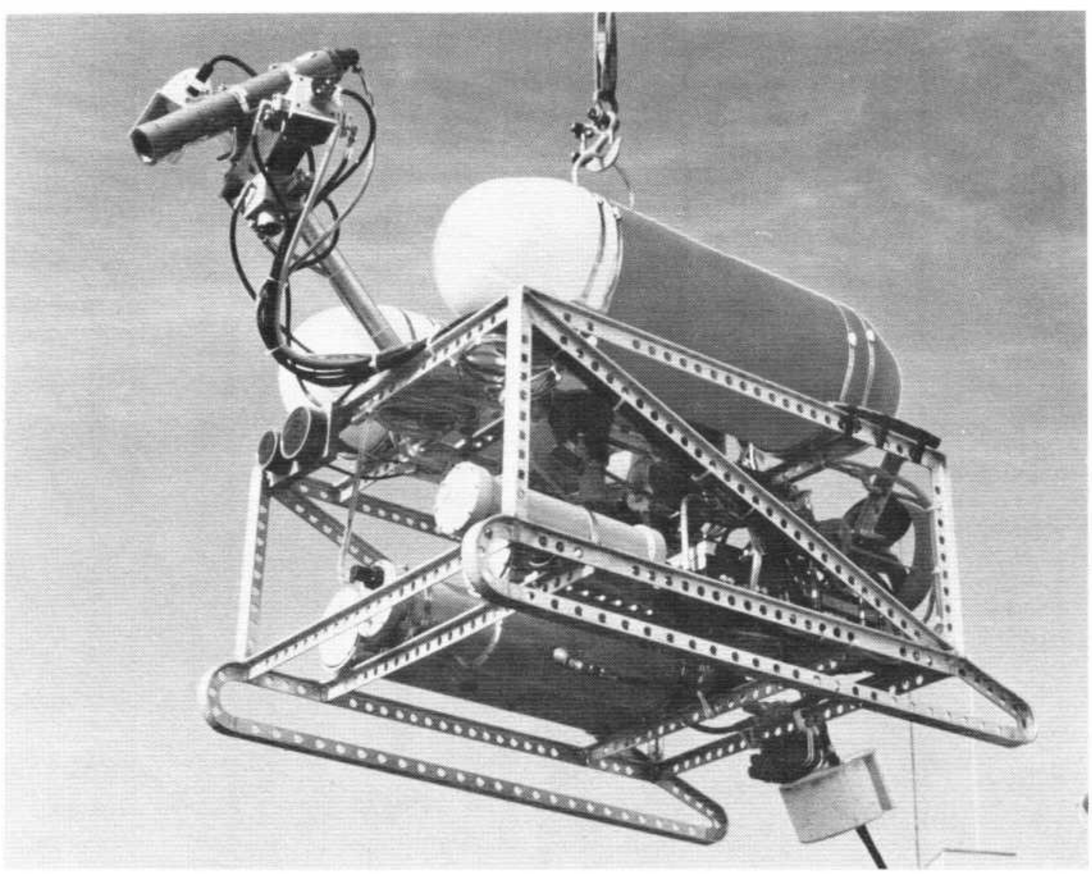


Fig. 2. The SCAT being launched prior to underwater television inspections.

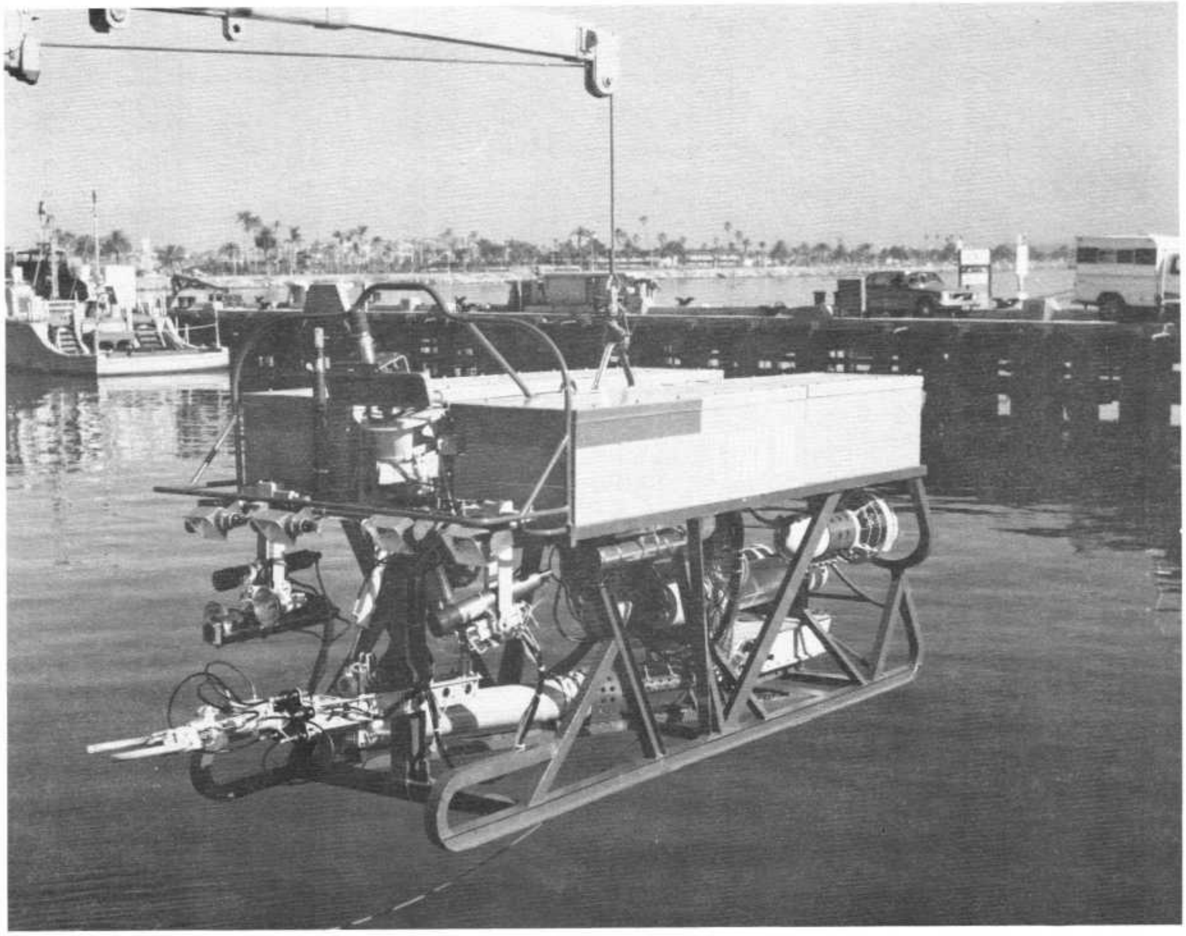


Fig. 3. The CURV III with ordnance recovery claw installed.

space shuttle program. This 4.27-m (14-ft)-high system, shown in Fig. 5, has a capability to fly into, seal, and dewater the partially submerged SRB, thus raising it to a position that will allow towing to a recovery site.

RUWS

The Remote Unmanned Work System (RUWS) is a 6100-m (20 000-ft) tethered vehicle system (Fig. 6). The RUWS work suit includes two manipulative devices (Fig. 7). A simple, heavy-duty, four-function arm (called the RUWS grabber) is used primarily for position keeping or object recovery, while a seven-function bilateral master-slave manipulator provides a dexterous working arm. To control the manipulator, the operator holds a pistol-grip controller and moves it to the position and orientation in space corresponding to that which he wishes the manipulator hand to assume. The RUWS vehicle carries several tools that can be acquired by the manipulator to do simple tasks, such as underwater cable cutting.

WSP

The Work Systems Package (WSP) is a work system comprised of three manipulators, 2 television cameras, and 15 interchangeable tools along with the required support equipment (Fig. 8). It is adaptable to six different undersea vehicles. The system is capable of underwater tool exchange and can complete complex work operations without returning to the surface. For example, the simulated flight recorder recovery (Fig. 9) used seven different tools and was completed in $<2\frac{1}{2}$ h. The WSP, which is designed to operate to 6100 m (20 000 ft), is one of the most successful remote work systems ever developed for research and development. Considerable advances in remote work systems technology has been acquired due to the extensive amount of research performed with the WSP. Therefore, it is discussed in more detail.

Manipulators

A simple, highly reliable, switch-controlled manipulator known as the linkage arm also has been developed by NOSC (Fig. 10). It is constructed through the use of a double parallelogram tubular linkage. This provides an arm with a high strength-to-weight ratio, capable of lifting 23 kg (50 lb), while weighing only 34 kg (75 lb).

An improved linkage manipulator, the nuclear emergency vehicle (NEV), was built for the former Nuclear Rocket Test

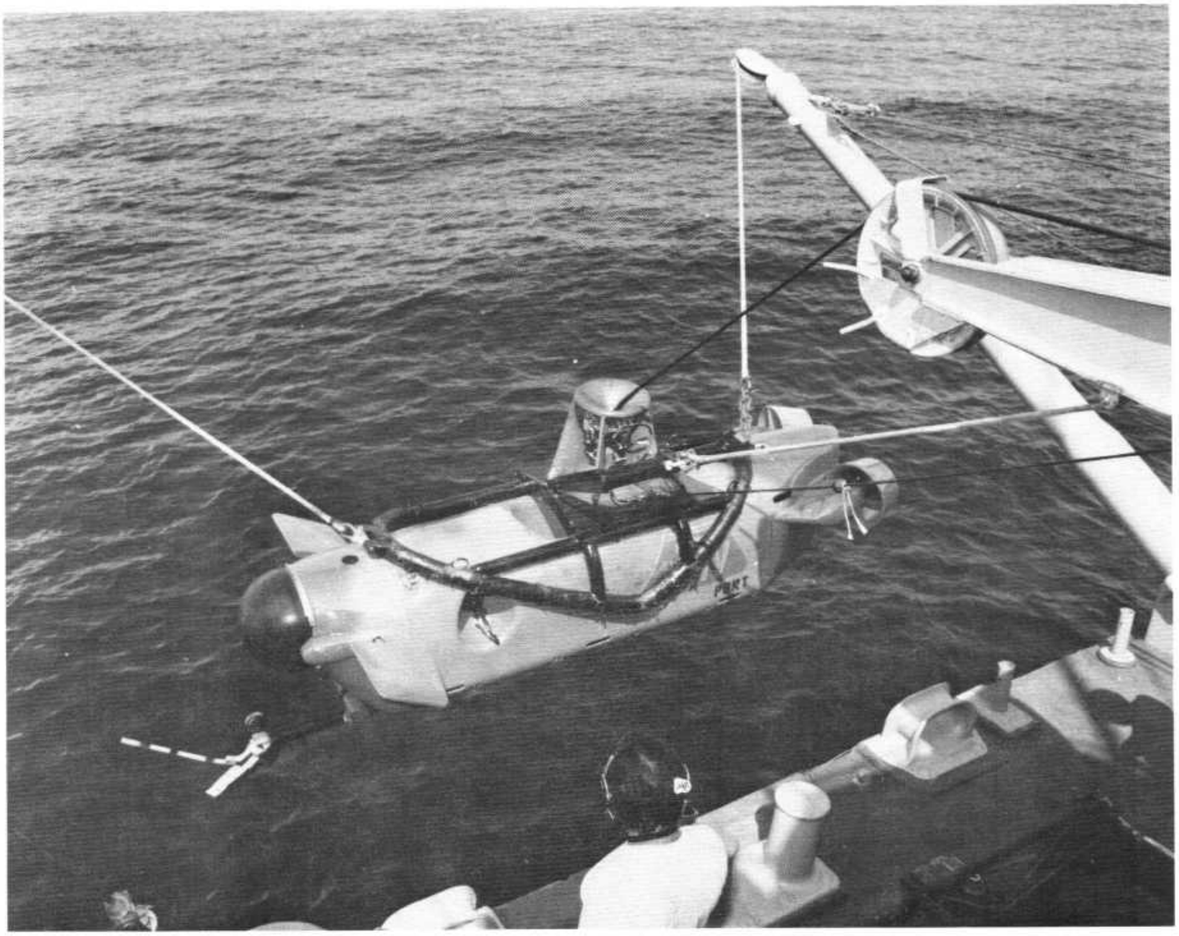


Fig. 4. The MNV being launched during at-sea mine neutralization tests.

TABLE I

Design Characteristics of NOSC Manipulators

Manipulators	Number of Functions	Weight in Air, kg (lb)	Lift Capacity, kg (lb)	Maximum Reach, cm (in.)	Operating Depth, m (ft)
SCAT claw	2	9 (20)	23 (50)	91 (36)	610 (2 000)
CURV I claw	3	45 (100)	182 (400)	127 (50)	610 (2 000)
CURV II claw	4	45 (100)	182 (400)	127 (50)	762 (2 500)
CURV III claw	4	45 (100)	182 (400)	127 (50)	3050 (10 000)
Linkage manipulator	7	34 (75)	23 (50)	140 (55)	2135 (7 000)
NEV manipulator	7	45 (100)	23 (50)	140 (55)	0
RUWS manipulator	7	27 (60)	20 (45)	127 (50)	6100 (20 000)
RUWS grabber	4	33 (73)	91 (200)	61 (24)	6100 (20 000)
WSP manipulator[a]	7	227 (500)	45 (100)	183 (72)	6100 (20 000)
WSP grabbers	6	113 (250)	113 (250)	274 (108)	6100 (20 000)

[a]Manufactured by PaR System Corporation.

Station, a joint U.S. Atomic Energy Commission–NASA facility near Las Vegas, Nevada. The NEV manipulator was designed for service on the nuclear emergency vehicle, for use in air only.

A summary of the manipulators developed by NOSC, and their capabilities, is presented in Table I.

WORK SYSTEM DESIGN PHILOSOPHY

Many areas of design must be taken into account when developing systems for remote work in the ocean. Since most of these are common to remote systems, i.e., structure, propulsion, electronics, etc., they are not addressed at this

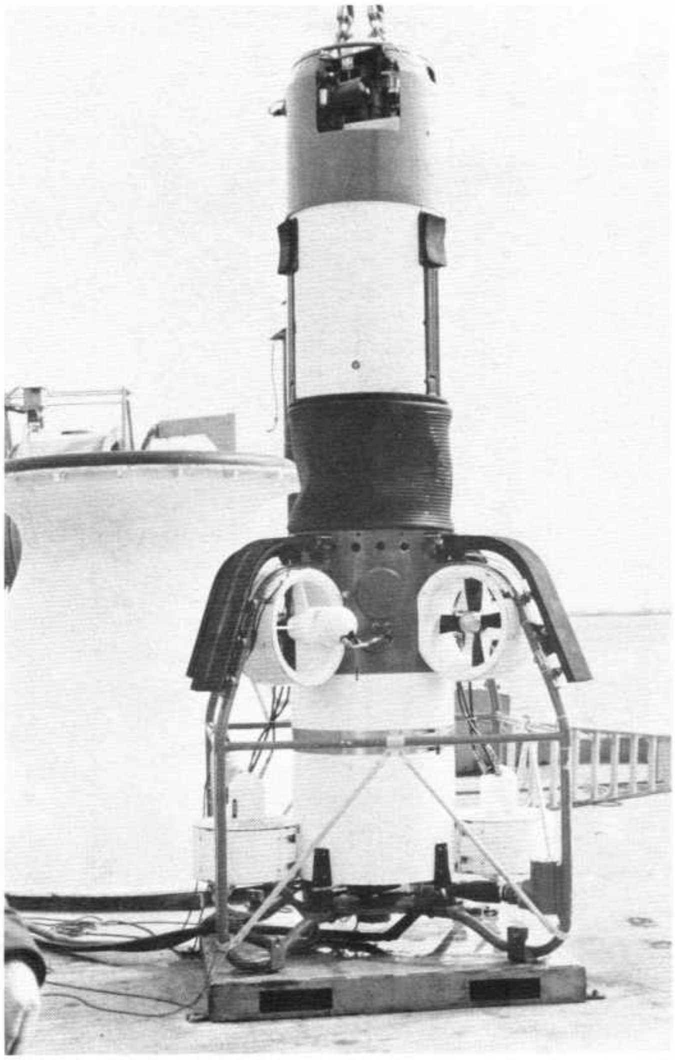


Fig. 5. The NP to be used by NASA in recovery of space shuttle rocket boosters.

time. More importantly, however, the design of the system that will actually perform the remote handling of work operations is discussed. This work system must be capable of the following:

1. attach to and maintain work system orientation at the work site
2. provide the manipulation required to operate tools to perform the remote tasks
3. provide an adequate viewing system to allow efficient and safe completion of the operations.

The system must have these capabilities not only on the bottom, but also during midwater operations.

Previous submersibles usually had no more than two manipulator arms; one to hold the vehicle in position, and the other to perform work operations. This configuration caused the system to be pushed away due to the reaction forces of the work manipulator, usually resulting in tool breakage or intolerable completion times of required tasks. To alleviate this problem, the WSP was designed using three manipulators: two manipulators to act as grabbers or restraining arms, while the third and more dexterous manipulator was used for performing tool exchanges and work tasks.

Grabbers

The design of the grabbers can be held relatively simple. Their primary function is to hold the work system in place, so they do not need additional elements such as elbows or extensive angular movements in each joint. The main problem with designing grabbers to act as restraining arms for a system is that not enough attention is paid to what is really being restrained. The grabbers must be designed for enough strength to hold the entire vehicle in place in the maximum expected cross current. The drag forces imposed on the vehicle by the cross current can be quite substantial and can easily damage the grabbers. When the work task is completed, it is also desirable to have a control which will open and retract both grabbers at the same time, thus eliminating the possibility of one grabber being damaged or caught when bearing the entire vehicle load while the other grabber is being retracted.

When designing grabbers, the type of objects to be worked on must be taken into consideration. Not all objects lend themselves to easy attachment of the work system. When working on the bottom or around objects with several appendages, grabbers with conventional-type claws can be used easily. However, if the object to be worked on is large with a smooth exterior, other techniques must be used. One such technique that is being developed is the use of suction pads for attachment to smooth surfaces. These devices lend themselves quite well to deep ocean applications, where extreme ambient pressures combined with a simple suction pad can provide adequate attachment forces.

Manipulators

The dexterous work manipulator is the heart of the system. It must be capable of exchanging and operating tools and performing the required work operations with accuracy and in the time allotted. Although manipulators come in various forms and levels of complexity, from very lightweight, open-framed, rate-controlled manipulators to more complex, master-slave-type manipulators with proportional control and force feedback, the complexity of the manipulator must be tailored to the types of tasks to be performed. Most tasks involving the use of tools can be adequately performed with a simple, rate-controlled manipulator. For example, the manipulator on the WSP is a seven-function, rate-controlled, hydraulically actuated manipulator. Other tasks requiring large excursions of the manipulator and random motions such as rigging or valve turning may be more efficiently performed through the use of master-slave-type manipulators. However, the following should be kept in mind:

1. a master-slave-type system occupies much more space in the control room and can impose considerable restraints if operated in the pressure sphere of a manned submersible

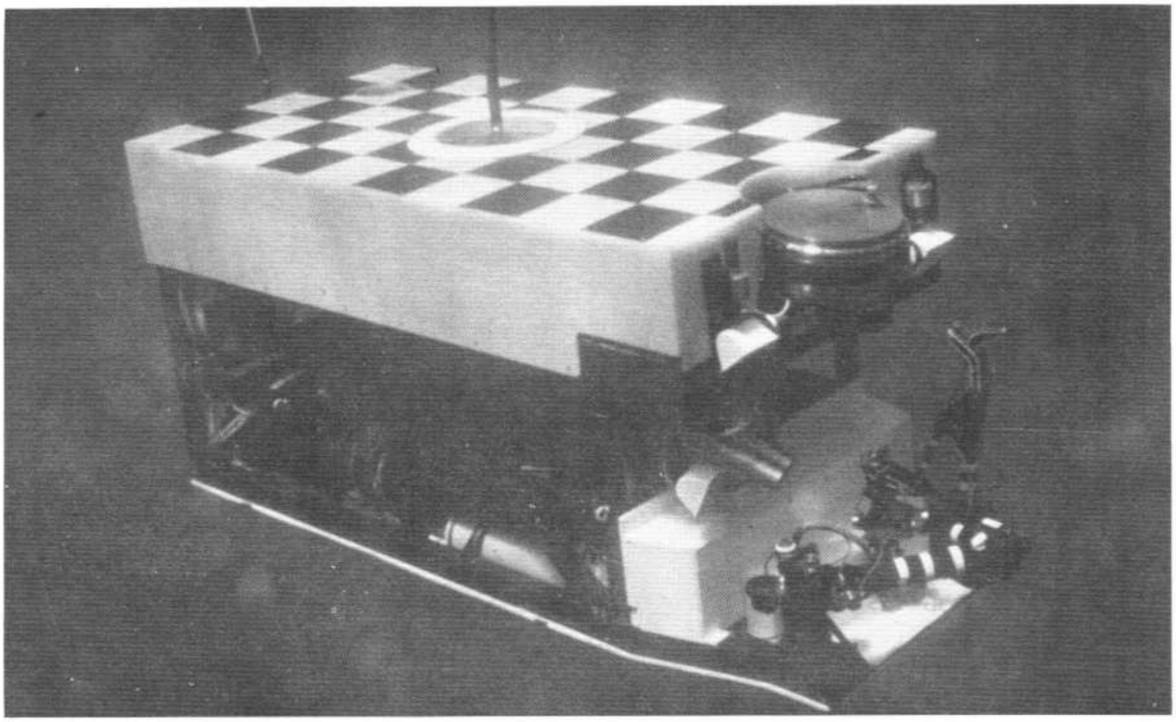


Fig. 6. The RUWS, which is capable of operating to 6100 m (20 000 ft).

2. when performing tool operations such as drilling or tapping, which require holding the manipulator in a predesignated position for an extended period of time, the master-slave harness can become very fatiguing

3. a more dexterous or master-slave-type manipulator generally results in a more expensive, complicated, less reliable system, although it may do the job faster and more accurately.

Because of its importance to the work tasks, the manipulator is usually the first item considered for modification. In fact, this may not be the place to start designing a more efficient system. Recent studies have shown that when performing work at sea with tools, the manipulator is used only 30% of the time, while the operator spends 37% of his time in decision making, 11% of the time in operating television cameras, and the remaining 22% of the time operating tools (Table II) (Ref. 4). Therefore, other areas, such as reducing operator decision time, eliminating the need for repositioning cameras, or increasing tool efficiency, can have a large effect on the efficiency of the entire system. Although a more dexterous, faster operating manipulator may aid in reducing operator decisions, the primary effect will be across only 30% of the total task time; i.e., that time which is spent actually operating the manipulator. Thus, a manipulator system that is twice as fast will not necessarily cut the total operational scenario time in half.

However, almost any method of increasing the efficiency of the overall system and thus reducing time and power consumption required by the work system is of great significance, especially when working with manned submersibles. For example, the WSP runs on 60-V dc batteries, either its own or those of a manned submersible. Since

Fig. 7. The RUWS manipulator suit during laboratory testing.

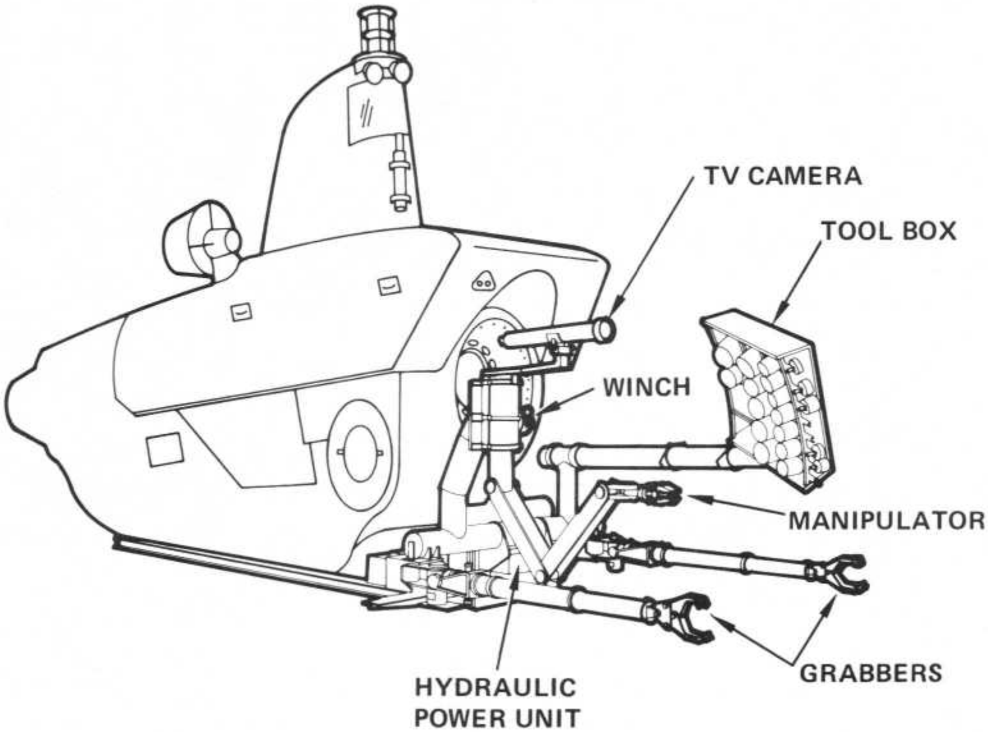


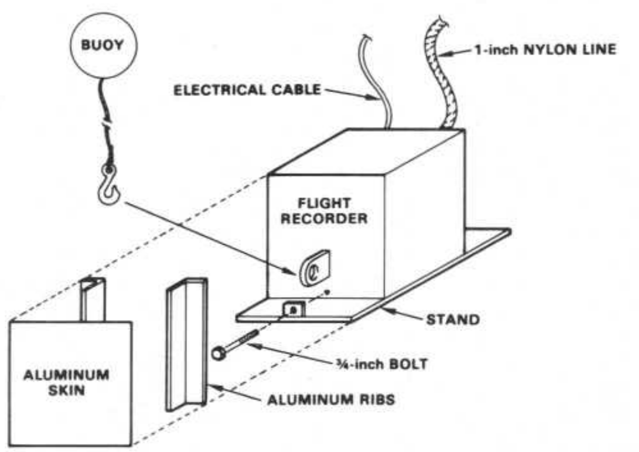
Fig. 8. The WSP as it would appear mounted to the Alvin manned submersible.

TABLE II

WSP Operational Time Distribution (%)

OPERATION WITHOUT TOOLS (%)	OPERATOR DECISION	MANIPULATOR OPERATION	CAMERA PAN-AND-TILT OPERATION	TOOL OPERATION	LIGHT OPERATION (1)
AVERAGE OPERATION TIME	50	33	17		100
LOW SPEED PUMP IDLE TIME (2)	50				
LOW SPEED PUMP DUTY TIME (3)		33	17		
TOTAL POWER CONSUMPTION	32	27	14		27
OPERATION WITH TOOLS (%)					
AVERAGE OPERATION TIME	37	30	11	22	100
LOW SPEED PUMP IDLE TIME	37			(22)[a]	
LOW SPEED PUMP DUTY TIME		30	11		
HIGH SPEED PUMP DUTY TIME (4)				22	
TOTAL POWER CONSUMPTION	17	18	6	(10) 26	23

(1) LIGHTING = 0.75 kW
(2) LOW SPEED PUMP IDLE = 1.55 kW
(3) LOW SPEED PUMP DUTY = 2.00 kW
(4) HIGH SPEED PUMP DUTY = 3.97 kW (ON-OFF ONLY)
[a] IT IS ASSUMED THE MANIPULATOR IS NOT BEING MOVED DURING TOOL ACTIVATION.



SEQUENCE OF OPERATION

1. EXTRACT THE DRILL MOTOR AND A 1-INCH DRILL BIT
2. DRILL ACCESS HOLES IN THE ALUMINUM COVER TO ALLOW SPREADER INSERTION
3. EXTRACT THE SPREADER, INSERT INTO THE ALUMINUM SKIN AND OPEN THE SKIN TO ALLOW INSERTION OF THE JACK
4. REPOSITION THE VEHICLE TO ALLOW USE OF THE JACK
5. EXTRACT THE JACK, INSERT, AND SPREAD APART THE ALUMINUM RIBS ALLOWING REMOVAL OF THE "FLIGHT RECORDER"
6. EXTRACT THE IMPACT WRENCH AND SOCKET AND REMOVE THE ¾-INCH BOLT FROM THE "FLIGHT RECORDER"
7. ATTACH A BUOY-LINE TO THE "FLIGHT RECORDER" AND REMOVE IT FROM THE TEST FIXTURE USING THE MANIPULATOR
8. EXTRACT THE CABLE-CUTTER AND CUT THE ELECTRICAL CABLE ATTACHED TO THE "FLIGHT RECORDER"
9. EXTRACT THE SYNTHETIC LINE-CUTTER AND CUT THE 1-INCH NYLON LINE ATTACHED TO THE "FLIGHT RECORDER" RELEASING IT TO FLOAT TO THE SURFACE

Fig. 9. Simulated flight recorder recovery scenario.

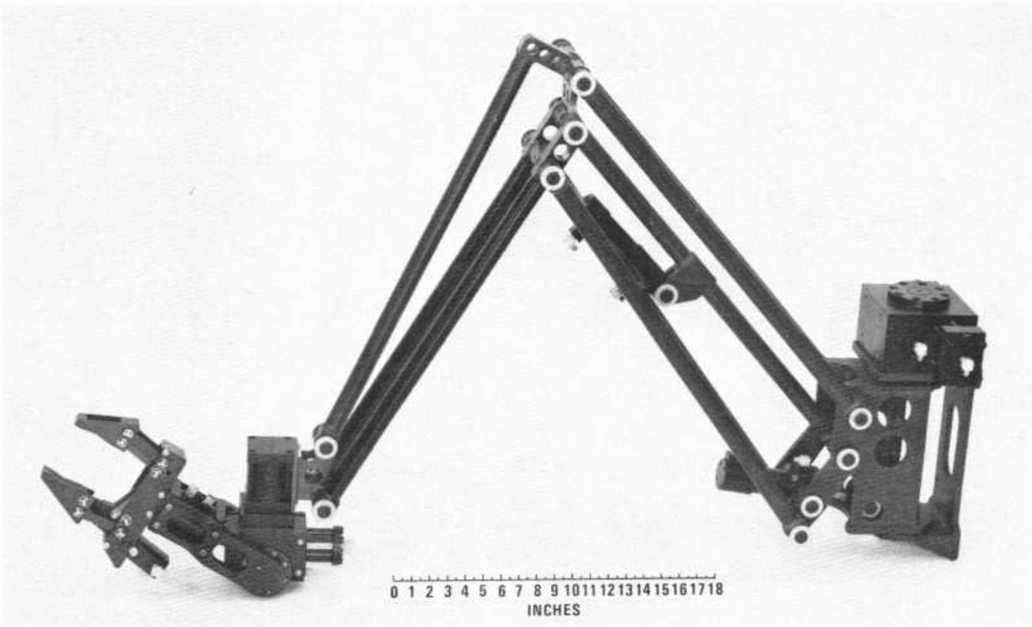


Fig. 10. The seven-function linkage manipulator.

manned submersibles have limited dive times, the impact of the task or mission to be performed on the battery supply of the vehicle is quite important, especially when considering the amount of time and power required to dive to 6100-m (20 000-ft) depths.

New technologies also are lending themselves to the performance of remote manipulation tasks. For example, through the use of minicomputers programmed to control manipulators, the amount of time to perform repetitive tasks can be considerably reduced. This can be of great benefit when undertaking such repeated tasks as tool exchanges performed by the manipulator. Results of the tests performed on the WSP using microprocessor control are presented in Table III. The benefit to the operator can be seen easily. Routines are also being developed in which the operator can push a button and a microprocessor can store the entire movement of the manipulator for future use. This can be of great benefit in complex path following or in performing tasks not known prior to the dive. Such a routine thus allows efficient integration of subroutine storage with actual operations. When considering programmed assistance, the designer must assure that the required programming time does not exceed the time in which the operator could manually perform the task, especially with tasks that are not too repetitive.

TABLE III

Comparison of WSP Task Times (min) Under Direct Operator Control and Computer Control

TASK	OPERATORS INEXP.	OPERATORS EXP.	PRO-GRAMMER	REDUCTION INEXP.	REDUCTION EXP.
ACQUIRE TOOL	5.18	2.12	0.90	82%	57%
REPLACE TOOL	3.24	1.42	1.31	59%	8%
ACQUIRE BIT	3.02	1.23	1.00	33%	17%
REPLACE BIT	3.56	1.30	0.74	79%	43%

With the addition of position sensors to the manipulator, the minicomputer can then be expanded to include control of the viewing systems. It would be a simple task to instruct the camera pan-and-tilt units to automatically follow the manipulator hand position. Table II indicates that savings of up to 17% can be achieved by eliminating the manual control of the camera systems. This would have the additional benefit of allowing the operator to concentrate on the task at hand without having to stop operations to move or adjust the television cameras.

CONCLUSION

Design of a more efficient manipulator or work system does not necessarily mean a more complex or expensive system. Through the use of simple, reliable systems with highly trained operators, great strides can be taken toward system efficiency. And, with the addition of today's computer technology, the system can approach automation requiring only a supervisory operator. The ocean is one of the few frontiers remaining to man, and its conquest will be through the use of remote systems; systems that are as simple and rugged as the ocean itself.

REFERENCES

1. Howard Talkington, "Manned and Remotely Operated Submersible Systems: A Comparison," Technical Paper 511, Naval Undersea Center (1976).

2. Richard W. Uhrich, "Manipulator Development at the Naval Undersea Center," Technical Paper 553, Naval Undersea Center (1977).

3. "Ocean Technology–A Digest," Technical Document 149, Naval Ocean Systems Center, San Diego, California (1978).

4. Robert Wernli, "Development of a Design Baseline for Remotely Controlled Underwater Work Systems," *IEEE Oceans '78*, Naval Ocean Systems Center, San Diego, California (1978).