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Experience with an Unmanned Vehicle-Based Recovery System

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The Naval Ocean Systems Center (NOSC) has been in the forefront of undersea vehicle and manipulator development since the early 1960's. Through extensive at-sea and laboratory test programs, methods have been developed to optimize these remote systems. NOSC's technological background is presented here with particular emphasis on the optimization of undersea manipulator and work systems. 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. Today, with the conquest of new frontiers, remote systems technology is playing a greater and greater role. Sophisticated manipulator systems are being built to work in the nuclear environment and 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 worksite 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].[2] The increase in the offshore 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 in the near future, his time in the water can be greatly reduced by the proper integration and use of remote-systems technology. Ultimately, completely autonomous systems will begin doing tasks formerly requiring the "human touch."

Background

One of the pioneers in the application of remote systems technology to the ocean has been the U.S. Navy. Since the early 1960's, 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 the Navy's 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 recent years, it has assisted in the recovery of three other tethered vehicles that were either lost or entangled on the ocean floor.

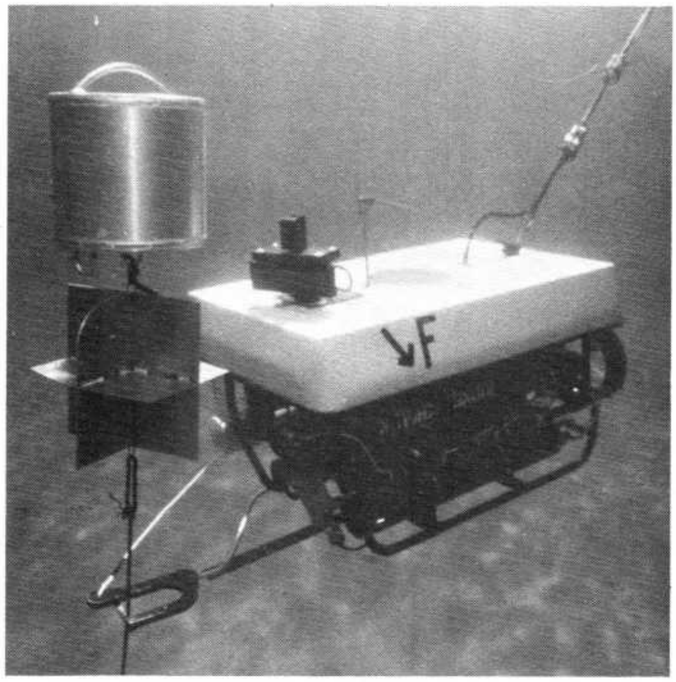

Fig. 1 The NAVFAC *Snoopy* attaches recovery line to target

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

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[2] Numbers in brackets designate References at end of paper.
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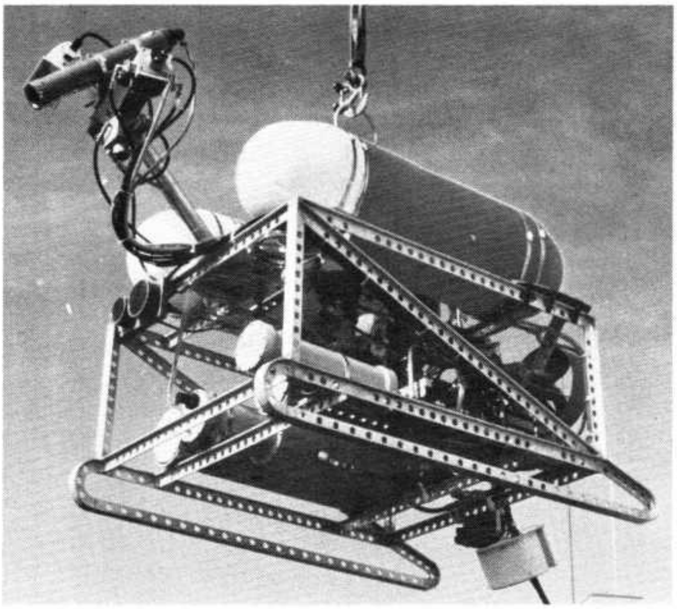


Fig. 2 The *SCAT* being launched prior to underwater television inspections

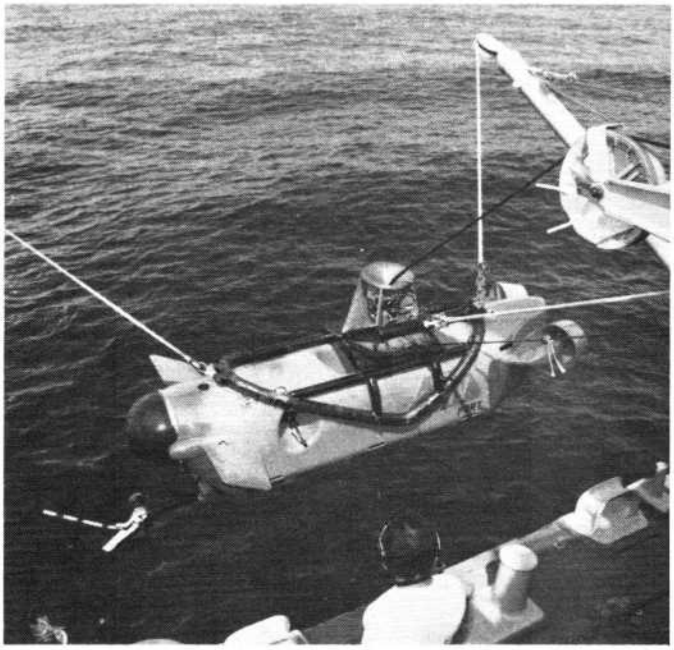


Fig. 4 The *MNV* being launched during at-sea mine neutralization tests

to provide a recovery capability. The *SCAT* is currently being reconfigured as a light-duty inspectional work vehicle capable of operating to 610-m (200 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 nuclear 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 by the *CURV II*, with a depth capability of 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.

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

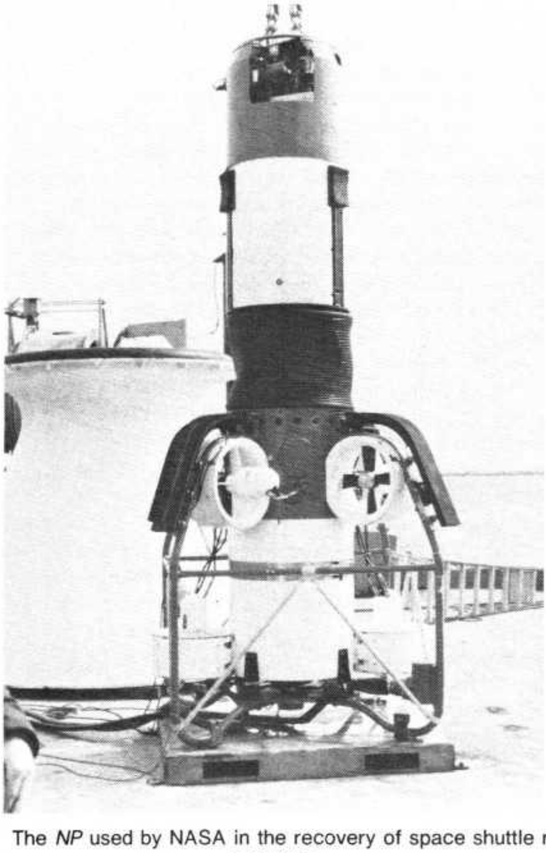


Fig. 5 The *NP* used by NASA in the recovery of space shuttle rocket boosters

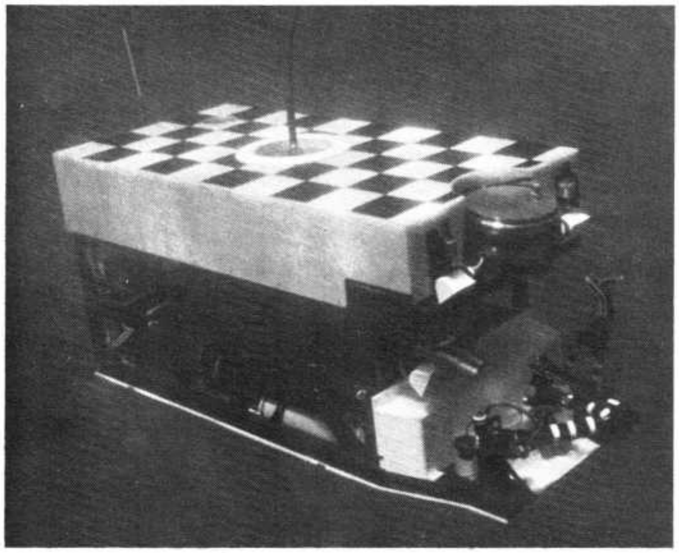


Fig. 6 The *RUWS*, which is capable of operating to 6100 m (20 000 ft)

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 space shuttle program. This 4.27-m-high (14 ft) 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.

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

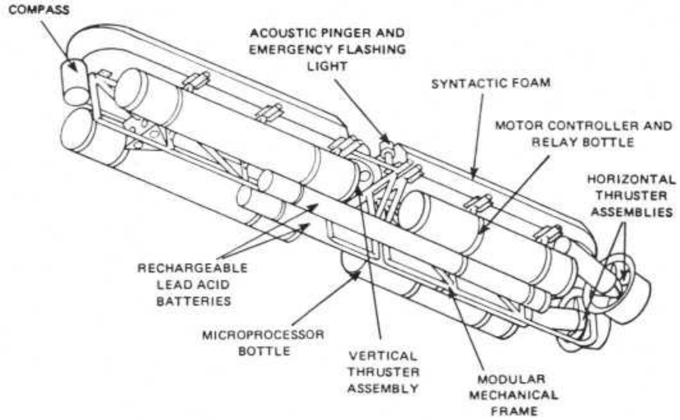


Fig. 8 *Freeswimmer* schematic

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.

Freeswimmer. The NOSC/USGS (U.S. Geological Survey) *Freeswimmer* (EAVE West) is an unmanned untethered underwater submersible designed as a testbed platform for advanced pipeline and structures inspection and Navy search and recovery technology. The vehicle is designed to operate in a two-computer supervisory controlled configuration to provide demonstrations of advanced technology in both teleoperator and autonomous modes of operation. The vehicle itself (Fig. 8) is 2.7 m (9 ft) long, T-shaped, with open-frame configuration mounted to a series of syntactic foam blocks for buoyancy. The T-shaped frame was used to minimize total weight of the frame and was made in three sections to allow lengthening of the vehicle to accommodate 25 lb (11.25 kg) of additional payload per foot of extension. The long narrow configuration was chosen to allow for minimum drag in the water. Propulsion is provided by three thrusters, giving the vehicle three degrees of freedom in the water (two canted horizontal thrusters and one vertical thruster). The operating console is an Intecolor 8051 color graphics display terminal and its associated minifloppy disk drive, keyboard, and 24K of user memory. The entire vehicle system is currently being used to demonstrate advances in the technological areas of controls and displays, fiber optics communication links, supervisory controlled manipulators, and automatic pipe-following techniques [4, 5].

WSP. The Work Systems Package (*WSP*) is a work system comprising three manipulators, two television cameras, and 15 interchangeable tools along with the required support equipment (Fig. 9). 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 performed while operating with the *CURV III* used seven different tools and was completed in less than $2^1/_2$ hr. (Fig. 10). 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 have been acquired due to the extensive amount of research performed with the *WSP*. Therefore, it is discussed later in more detail.

Manipulators. A simple, highly reliable, switch-controlled manipulator known as the linkage arm also has been developed by NOSC (Fig. 11). It is constructed through the use of a double parallelogram tubular linkage. This provides an arm with a high

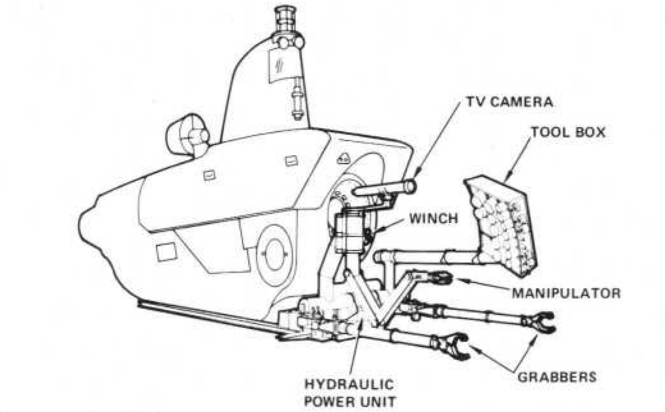


Fig. 9 The *WSP* as it would appear mounted to the *Alvin* manned submersible

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*) manipulator was built for the former Nuclear Rocket Test Station, a joint U.S. Atomic Energy Commission/National Aeronautics and Space Administration (NASA) facility near Las Vegas, Nev. 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 1.

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, that is, structure, propulsion, electronics, etc., they are not addressed at this 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.

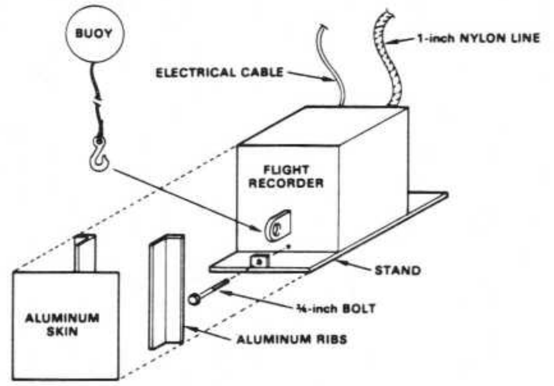
The system must have this capability not only on the bottom, but also during midwater operations.

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 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 extensive angular movements in every 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-



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. 10 Simulated "flight recorder" recovery scenario

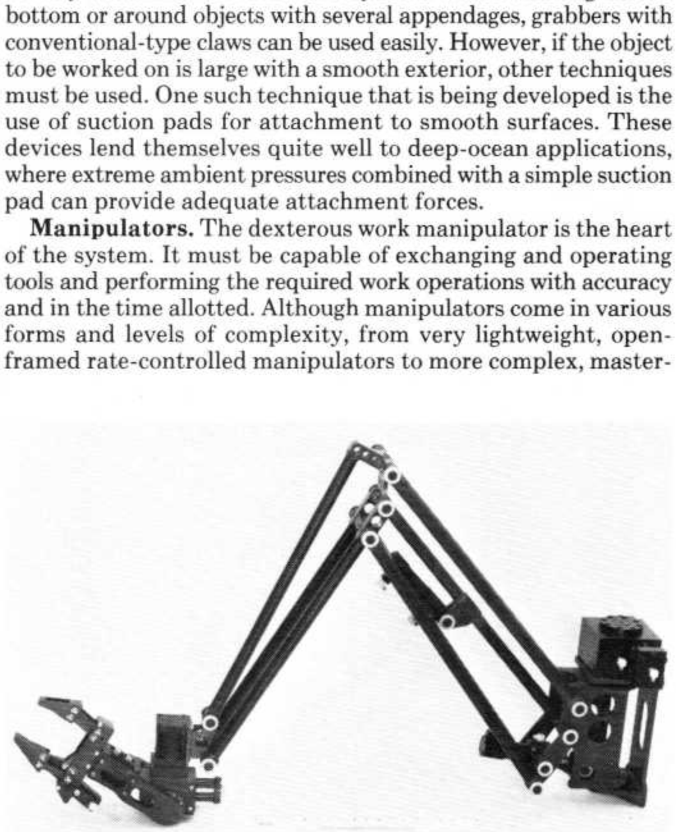


Fig. 11 The seven-function "linkage" manipulator

Table 1 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 Corp.

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,
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 percent of the time, while the operator spends 37 percent of his time in decision-making, 11 percent of the time in operating television cameras, and the remaining 22 percent of the time operating tools (Table 2) [6]. 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 percent of the total task time, that is, 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-Vdc batteries, either its own or those of a manned submersible. Since 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 3. The benefit to the operator can be seen easily. Routines have been 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

Table 2 WSP operational time distribution (percent)

Operation without tools (%)	Operator Decision	Manipulator Operation	Camera Pan-and-Tilt Operation	Tool Operation	Light Operation[a]
Average operation time	50	33	17	...	100
Low-speed pump idle time[b]	50	...	...	...	...
Low-speed pump duty time[c]	...	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)[e]	...
Low-speed pump duty time	...	30	11	...	...
High-speed pump duty time[d]	...	...	...	22 (10)	...
Total power consumption	17	18	6	26	23

[a] Lighting = 0.75 kW
[b] Low-speed pump idle = 1.55 kW
[c] Low-speed pump duty = 2.00 kW
[d] High-speed pump duty = 3.97 kW (on-off only)
[e] It is assumed the manipulator is not being moved during tool activation.

Table 3 Comparison of *WSP* task times (minutes) under direct operator control and computer control

Task	Operators Inexp.	Operators Exp.	Programmer	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

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.

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 2 indicates that savings of up to 17 percent 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. These are but a few of the areas that lend themselves to computer control. Eventually, it is conceivable that preprogrammed submersibles with object locating and recognition routines will be entering the field of undersea work.

Recent at-sea testing

During Fiscal Year 1979, techniques for remote work and recovery operations in the deep ocean were evaluated. As a result, an early concept of a recovery system was established. However, the answers to several tradeoff questions were required to complete the concept. Additional input from practical at-sea tests of the concept would be required. It was decided that two systems currently exist which, if mated together, would closely meet the requirements for work capability, size, and thrust capability of that concept: the Work Systems Package (*WSP*) previously described, and the Pontoon Implacement Vehicle (*PIV*) (Fig. 12).

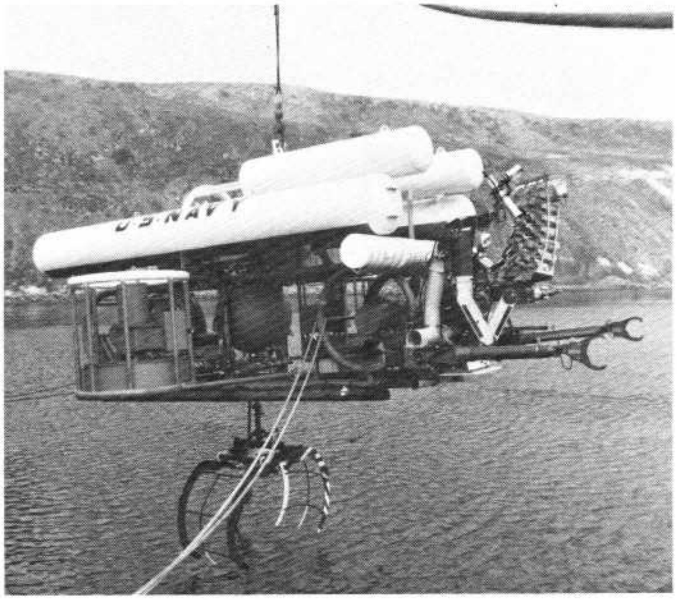


Fig. 12 Work System Package/Pontoon Implacement Vehicle

The Pontoon Implacement Vehicle was chosen as the mounting platform for the *WSP*. The *PIV* was developed as a part of the Large Object Salvage System (LOSS) at the Naval Coastal Systems Center, Panama City, Fla. The *PIV* is a cable-controlled, highly maneuverable vehicle with a high thrust capability and a 900-kg (2000 lb) variable ballast system.

The *WSP* and *PIV* were mated together and transferred to San Clemente Island (SCI) for testing. The purpose of the test was to investigate or develop applicable recovery techniques to be used in conjunction with a remotely controlled vehicle/work system. Results from the testing will be used in the formulation of a technology base which will provide the Navy with the capability to develop future systems to perform deep-ocean recovery operations [7].

An operational depth of 65 to 95 ft (20 to 29 m) was chosen to maximize documentation by divers. Tradeoff studies were conducted during FY-79 to determine the most appropriate method of rigging and lifting objects from the ocean bottom for the *WSP/PIV*. For testing purposes, objects were chosen to reflect the general characteristics of classes of objects which might require recovery. Studies were conducted to determine the most effective scenarios for attachment, rigging, and recovery of these objects using an unmanned tethered vehicle. It was assumed that the object had been located, marked, and photographed and that the recovery team knew, as accurately as possible, the condition of the object to aid in the choice of attachments. Several different techniques were utilized for the recovery exercises, depending upon the generic class of the target.

During the 30 days of testing at SCI, 14 dives were made with the vehicle which accumulated a total of 58 hr of in-water time. The operating experience gained with the vehicle/work system and the substantial amount of photographic documentation acquired have greatly enhanced the success of this series.

The basic approach to these tests was from an engineering standpoint. Given a recovery task, an engineering approach could be made to the task which would result in the development of simple and reliable techniques to ensure a successful recovery through the use of remote systems. Based on this approach, the following objects were successfully rigged for recovery and lifted to the ocean surface using those recovery techniques:

a. Slinging and lift of an F4 aircraft.

b. Claw attachment to and recovery of a jet engine.

c. Rigging and recovery of a large steel object.

In addition, techniques were developed which successfully demonstrated the system's capability to perform the following:

a. Rigging of objects (installation of lift lines, snaphooks, etc.).

b. Performance of midwater maneuvering, docking, rigging, and recovery operations.

c. Successful installation of lift slings on an intact aircraft.

d. Object recovery using the vehicle variable ballast and thrust as the lift force.

e. Remote implacement and deployment of a lift module which can be controlled by the work system or a microprocessor to generate a 4500-kg (10 000 lb) lift force.

f. Object recovery using the lift module while under diver control.

g. Installation of "toggle bolt" lift points through heavy steel plate.

The knowledge gained from these operations will enhance man's quest in extending his presence throughout the oceans via remote systems and is already being incorporated into the conceptual design of an advanced tethered vehicle/work system.

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 and eventually only a programmer. Application of this technology to system design, combined with a "real world" engineering approach to the problem, can result in a system highly advanced in its capability. 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.

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