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Design for Remote Work in the Deep Ocean

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For man to operate in the deep ocean, certain adaptive techniques are required for use of conventional mechanical and electrical components or systems. Extensive involvement by the Navy in development of undersea vehicles and work systems has made them leaders in this field. Using the Work Systems Package (WSP), a 20,000-ft manipulative work system, as an example, this paper will discuss such design areas. Methods of defining and solving problems on the WSP and other systems will be addressed along with general problems facing the design engineer. It is hoped that this paper will present the reader with a better understanding of the problems to be encountered in designing for remote work in the deep ocean.

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ABSTRACT

For man to operate in the deep ocean, certain adaptive techniques are required for use of conventional mechanical and electrical components or systems. Extensive involvement by the Navy in development of undersea vehicles and work systems has made them leaders in this field. Using the Work Systems Package (WSP), a 20,000 ft. manipulative work system, as an example, this paper will discuss such design areas. Methods of defining and solving problems on the WSP and other systems will be addressed along with general problems facing the design engineer. It is hoped that this paper will present the reader with a better understanding of the problems to be encountered in designing for remote work in the deep ocean.

INTRODUCTION

One of the greatest challenges facing man today is the conquest of the deep ocean. Man has conquered the moon and he has the planets in his sights. Given today's technology and the fact that the constraints imposed on designs in space applications are rather well defined, these goals are all within his grasp. Unfortunately, this is not the case in attempting to design for ocean applications. Mother nature does not want to release her hold on this planet's oceans. Through the effects of corrosion, extreme pressures, unpredictable and high currents, and overwhelming sea states, she has posed a real challenge to man and today's technology. But, the oceans are being conquered. Man is maneuvering on the surface and to extreme depths in manned submersibles and with remotely operated or unmanned vehicles.

Although man has been able to maneuver in the oceans and make his presence felt either in person or via television link, the real conquest has yet to be performed. This conquest is projection of man's capabilities to any point in the deep ocean; in other words, use of a system in the ocean which can perform total work operations for the operator whether he be in a manned submersible or at a topside control console using a tethered control link. Up to now, most submersibles or tethered vehicles have had very limited work capabilities or were retrofitted with some type of work capability after the original design had been completed. With the increase in undersea work operations related to the salvage industry, recovery requirements, and the growing offshore oil industry, the need for efficient undersea work systems is defined. These work systems must have more capabilities than their limited predecessors; they must have the capability of arriving at the location, analyzing the situation, and performing a repetitive operational scenario with a variety of tools to complete the job without having to resurface every time a new tool is required. Although these work systems could be used by divers or on manned submersibles, the real challenge is to design them for totally remote use on a tethered vehicle, thereby leaving the operator in an air-conditioned, topside environment, where he can control the operations below the surface in safety and comfort.

In answer to this challenge, the Navy has recently completed development and testing of the Work Systems Package (WSP) (Figure 1) (1). This work system, an outgrowth of the Navy's Deep Ocean Technology Program, was designed to perform recovery, implantment, salvage, repair, and other operations at depths to 20,000 feet. It is a multi-function work system comprised of manipulators, tools, TV cameras, and required support equipment (see Table 1) which can be adapted to the manned submersibles ALVIN, SEACLIFF, and TURTLE or to the tethered unmanned vehicles CURV III (Cable-controlled Underwater Recovery Vehicle) and RUWS (Remote Unmanned

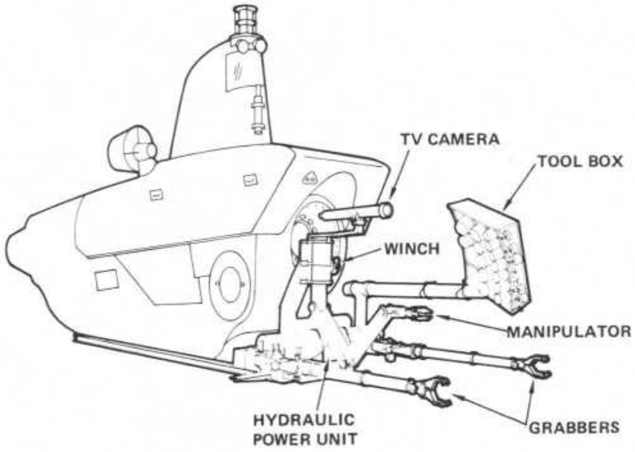
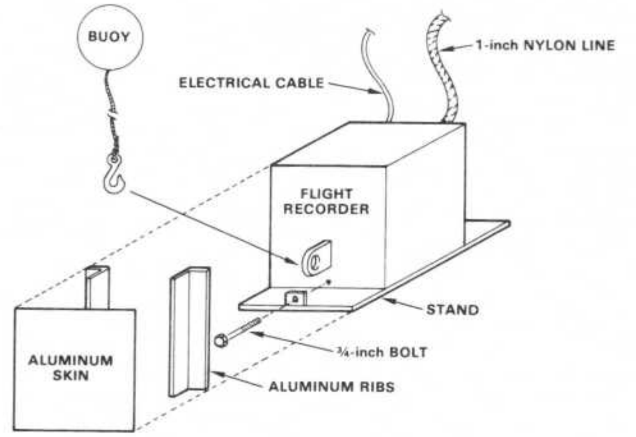


Fig. 1 The WSP as it would appear mounted to the manned submersible ALVIN.



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. 2 Simulated "flight recorder" recovery scenario.

DESIGN DEPTH	20,000 feet
SIZE	WIDTH — 9½ feet HEIGHT — 8½ feet
WEIGHT	AIR — HARDWARE = 5938 lbs FOAM = 4001 lbs WATER — NEUTRALLY BUOYANT
MANIPULATOR	ONE WORK MANIPULATOR — 100 lb LIFT TWO GRABBERS — 250 lb LIFT
TOOLS	WINCH — 1000 lb PULL 16 HYDRAULIC & VELOCITY POWERED TOOLS
HYDRAULIC SUPPLY	SYSTEM — 1.0 GPM, 2000 psi TOOLS — 2.5 GPM, 3000 psi
SENSORS	TWO LOW-LIGHT LEVEL TV's 4 QUARTZ IODIDE LIGHTS (500 watt) 2 QUARTZ IODIDE LIGHTS (250 watt)
ELECTRONICS	REDUNDANT, PRESSURE TOLERANT, TIME-DIVISION MULTIPLEX
POWER	LEAD ACID BATTERIES, 60 VDC, 18 kWh

Table 1. WSP Equipment Specifications

Work System). The development of this work system has provided man with the capability of performing real work in the ocean environment. Operational scenarios such as the example of Figure 2 have been performed at sea and in the laboratory successfully. As a result of extensive at-sea and laboratory testing of the WSP, a quantitative description of the system and its capabilities now exists which can be used to aid the designer of future work systems.

Using the WSP as an example, this report will describe the elements comprising a work system. Subsystem design problems, techniques and recommendations for future work systems based on new technologies, and experience gained while successfully operating the WSP on the CURV III and RUWS tethered vehicles will be discussed.

SYSTEM CONFIGURATION

One of the hardest portions of the design problem is that of coming up with the proper concept or system configuration. This usually arises from the lack of a proper definition of the system's mission. For example, the range of missions in undersea work covers such areas as inspection of offshore drilling platforms with small remotely controlled vehicles, recovery of downed aircraft or ordnance, up to recovery of entire submarines. The method used to delineate the mission for the WSP was to define a matrix of all possible classes of objects to be recovered or worked on (e.g., aircraft, submarines, space capsule, etc.) and all types of work that would be expected to be performed on these types of objects (e.g., survey, destroy, repair, raise, disassemble, etc.) (2). With this matrix defined, the engineers then had a tool available for identifying the mission and assuring that it was covered entirely with a practical conceptual design. Following definition of the mission, the identification of the operating criteria is also essential. Changes in operational sea states, current velocities, depth requirements, maneuverability, and work capability all have considerable impact on the initial design concept and should therefore be accurately identified in the early stages. Therefore, as in all design situations, after proper definition of the problem, the preliminary design of components or subsystems can be initiated.

STRUCTURE

Since the spatial configuration of the manipulators, tools, TVs, etc., is defined in the conceptual phase, the primary structure becomes nothing more than a means of orienting these components in space. The WSP main structure is composed of 5086 tubular aluminum, primarily due to the torsional rigidity of this shape. The structure, along with several other components, is allowed to free flood with seawater during operations, thus eliminating the need for pressure compensation. For components which cannot operate in seawater--the electronics, for example--oil-filled housings are used to provide pressure compensation. This is performed by placing the components in a lightweight aluminum enclosure and adding a flexible bladder or diaphram, or a flexible metallic bellows which provides pressure equalization across the enclosure walls. Pressure compensation has the advantage of eliminating costly, complicated, and heavy pressure bottles to house the components. Sealing problems and the high cost of electrical penetrators are also eliminated.

Even with these benefits, there are some disadvantages to pressure compensation. The main disadvantage is that several types of oils are required in a complex work system. Attention must be paid to oil viscosity, dielectric properties, component compatibilities, etc. This results in a minimum of three types of oil being required: hydraulic oil; mineral oil for battery containers, if required; and a third oil compatible with electronic and electrical hardware. However, when properly designed for oil filling and preventive maintenance on interior components, the pressure-compensated systems appear the most advantageous in deep-ocean applications.

After definition of the concept and structural configuration and before subsystem development, the buoyancy and handling problems of the system must be addressed. Ideally, the work system to be developed will adapt to only a single vehicle or will be part of the vehicle itself. In the case of the WSP, more than one method of handling and buoyancy material integration had to be explored due to the number of vehicles with which the system was to be interfaced. However, system modifications were kept to a minimum by adapting to the various vehicles by means of a skid frame and interface plate, which allowed the work system to stay in a static configuration. The buoyancy of a system is often considered late in the design; but in fact, it can have substantial impact on the system design and should be integrated at the initial stages. For example, the WSP buoyancy material, needed to provide neutral buoyancy while submerged, accounts for one-third of its in-air weight. This means that for every additional pound of buoyancy required, 2 pounds of in-air weight is added to the system. The integration of the buoyancy material, and thus the trim characteristics of the system, must take into account viewing requirements, manipulator movement requirements, along with the structural integrity required to withstand the ocean environment.

Handling of the system should also be dealt with very early. Quite often the system being designed will operate off ships-of-opportunity, which may impose severe problems during launch and recovery in heavy seas. Since the designer cannot always be assured of the type of crane or system to be used to launch the vehicle, he must insure that the method of rigging the vehicle for lift is fail-safe. For example, lifting hardware should be kept clear of critical system components, or during handling in rough seas damage to those systems is almost certain. Also, the lift points must be attached to a portion of the system which in no way can fail or come off either through jettisoning or component or weldment failure. Expensive systems have often been damaged due to failure to properly integrate the handling system. These failures can not only cost an entire vehicle or program, but can easily result in personal injury.

One last area concerning structural characteristics which should be mentioned is corrosion. In the case of work systems or undersea vehicles, general corrosion of the system is not usually a problem. Methods of passivating, hard anodizing, and painting with epoxy-based paints tend to take care of the general corrosion problem as long as adequate freshwater wash-downs, preventive maintenance and repair procedures are maintained. The problems arise in the area of crevices or recessed locations, which are hard to reach and usually entrap some saltwater. As is usually the case, these are the areas where stainless steel hardware or components are used in conjunction with the aluminum structure or housing. Such a condition can be made manageable through two procedures. The first is the application of a nickel-filled compound to all mounting hardware and the application of zinc ointment on all metal interfaces. It is important that all metal interfaces are covered and not just dissimilar metal interfaces, since entrapped seawater along with areas of reduced oxygen due to tight interfaces can set up galvanic corrosion cycles. And, of course, the second method is extensive use of preventive maintenance and reapplication of anodic coatings at proper intervals. Proper system design in the early stages to help eliminate areas conducive to corrosion and designing for easy preventive maintenance can help in solving the problem of corrosion.

MANIPULATOR SUITE

In order to perform any type of work operations in the ocean, the work system must be capable of two things: (1) attach to and maintain the work system orientation at the work site, and (2) to provide the manipulation required to operate tools to perform remote tasks. The system must have this capability not only on the bottom, but also during mid-water operations.

Previous submersibles usually had no more than two manipulator arms; one to hold the vehicle in position, 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 breaking of tools 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 exchange and the work tasks.

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 the additional elements such as elbows or extensive angular movements in each joint. Therefore, they lend themselves easily to a free-flooded type of design. The main problem with designing grabbers to act as restraining arms for a system is that not enough attention is paid to what they are really restraining. 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 will 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 easily used. But, if the object to be worked on is large with a smooth exterior, other techniques must be used. One such technique which 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.

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, three things 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 may 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 TV cameras, and the remaining 22 percent of the time operating tools (Table 2). (3). Therefore, other areas such as reducing operator decision time, eliminating the need for repositioning of 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 only be across 30 percent of the total task time, i.e., that time which is spent actually operating the manipulator; thus, a manipulator system which is twice as fast will not necessarily cut the total operational scenario time in half.

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)*	
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)

*IT IS ASSUMED THE MANIPULATOR IS NOT BEING MOVED DURING TOOL ACTIVATION.

Table 2. Operational Time Distribution (percent)

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 20,000 foot depths.

New technologies are also 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 have 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.

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%

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

The benefit to the operator can be easily seen. 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 which are not too repetitive.

TOOL SUITE

The determination of an appropriate tool suite to comprise a work system is a critical element. The WSP tool suite evolved after iterations were performed on the matrix which defined the original mission requirements. The final iteration resulted in a series of materials to be operated upon and certain methods of operation such as drilling, tapping, grinding, jacking, etc., which would result in the completion of one of the original tasks requirements, such as Figure 2. Based on the nature of the materials (e.g., thick, thin, soft, hard, etc.), the force requirements could then be determined for the tools, thereby defining them and their operating characteristics. As an example, the WSP tools, the first designed specifically for deep-ocean application, are listed in Table 4.

With the definition of the tool and manipulator suites, the problem was encountered of combining these into a working system. Early methods of supplying power to tools limited the number of tools, since each required its own hydraulic hose and hose reel. The result was a large, bulky, cumbersome system. Holding these tools in place might have involved spring-loaded mechanical bins capable of compliance when the tool is grasped by the manipulator and possibly a mechanical latching mechanism to hold the tool in place. Given the number of tools needed for a complete work operation on a single dive, these methods were unsatisfactory. The two methods used to solve this problem by the WSP seem quite simple in retrospect, but were a major step forward in work systems integration. The first provided power to each tool through a series of hydraulic quick-disconnects which could be mated with the manipulator hand. Hydraulic power was provided through two hydraulic hoses run outside of the manipulator through a slip ring assembly in the manipulator hand and quick-disconnect to mate with the tools. Guides common to the tool and the manipulator hand allowed precise positioning upon tool exchanges, and small retractable clips insured that the tools would not come out of the hand once grasped. Testing performed with the mating connections while the system was under pressure in muddy environments showed almost negligible water intrusion into the hydraulic system. The second solution, simple but most effective, concerned the tool bins themselves. Each tool has its own bin mounted on an extendable tool box which can be positioned in the viewing area of the work system to allow tool exchanges. In each tool bin is a series of compliant nylon brushes designed to hold the tools in place with a 40 to 60 pound retention force. These nylon brushes prevent the tool from falling out of the holder during operations and also provide the compliance required to allow successful remote tool exchanges. The manipulator, with its 100 pounds of extraction force, can easily remove the tools from the simple, non-corroding holders. Required bits for the tools are held in spring clips around the outside edge of

OPERATING MODE	POWER HEAD	BITS	FUNCTION	CAPABILITY
ROTARY HYDRAULIC	HIGH SPEED	WIRE BRUSH, GRINDER, CUTOFF WHEEL	BRUSH, GRIND, CUT	125 in/lb
	LOW SPEED	DRILL, TAP, DIE	DRILL, THREAD	275 in/lb
	RECIPROCATING KNIFE	———	ROPE CUT	2-in ROPE
	CHIPPING HAMMER	CHISEL	CHIP	37 lb 21 STROKES PER sec
	IMPACT WRENCH	SOCKETS	BOLT-UNBOLT	1,320 in/lb
	WINCH	———	PULL	1,000 lb
LINEAR HYDRAULIC	JACK	———	JACKING	19,000 lb, 8 1/2 in
	SPREADER	———	SPREADING	2,876 lb, 13 in
	CABLE CUTTER	———	CUT CABLE	23,000 lb, 1-in WIRE ROPE
POWER VELOCITY	CABLE CUTTER	———	CUT CABLE	1 1/4-in WIRE ROPE
	STUD GUN	PADEYE	ATTACH PADEYE	1/8- TO 5/8-in THICK MILD STEEL

Fig. 4 WSP Tool Suite

the tool box and can be easily exchanged through the use of quick-connect chucks built into the rotary tools.

Although the tool exchange system developed for the WSP has worked very well, it is not optimum. The requirement of placing tools in a position that allows the manipulator to extend radially outward to obtain them is not necessary, depending on the system design. Laboratory testing has shown that with experienced operators, the ultimate in experience being preprogrammed control, tools can be acquired quickly and in less favorable orientations. This now provides the designer with the option of moving the tool bins back into the system or vehicle, where they can be more protected, offer less drag, but still be retrievable by the manipulator.

SENSOR SUITE

The viewing system has the biggest impact on the total operation. No matter how sophisticated the manipulator or tool suite, if you can't see the work area, you can't do the work. Although work is being performed in developing manipulators which have the capability to "feel their way" around the work area and draw a picture of what is encountered, their usefulness in practical underwater work is very limited. An adequate viewing system is critical to the work system operator. The primary elements of the sensor suite are the television cameras, lights, and a method of moving them through pan and tilt motions.

TV cameras available to the designer range from standard vidicon cameras to silicon-intensified target (SIT) type cameras. The SIT cameras are low-light-level cameras and are capable of working with low-power lights to decrease back-scatter susceptibility and increase far-field vision. These have been used with success on the WSP. A more recent development, the silicon diode vidicon camera, combines the best characteristics of both previous cameras and looks very promising for future use. (4).

In choosing the lights to be used on the system, the designer has another problem. The lights which have the best spectral match with seawater, such as thallium iodide or mercury vapor, require long warm-up times between operations and a heavy electrical ballast for each light. The quartz iodide lights, which do not have a good spectral match with seawater, provide instantaneous start-up and are very lightweight. If the lighting system being designed must operate off battery supplies, intermittent operation may be desired; therefore, the quartz iodide may provide an adequate solution. For example, the WSP has six quartz iodide lights, each placed to highlight a different viewing area. Thus, there is no need to have all of them on at once. If unlimited power is available and weight is not a critical consideration, then a lighting system providing a better spectral match will probably be the best candidate. However, a recent development has combined the instantaneous start-up of a quartz halogen light with the blue green spectral match of the mercury vapor available after a short warm-up time, thus providing the best characteristics of both lights. Although this new light must go through a typical warm-up cycle on subsequent turn-ons, its future looks very promising.

The ability to provide immediate and accurate camera positioning in both pan and tilt motions is required. Whether the pan and tilts consist of rotary or linear actuators and servo or solenoid valves, their integration must be precise to ensure a reliable system. Without quick and efficient movement of the TV cameras, the entire mission will suffer. As mentioned, the minicomputer can be adapted quite successfully for programming manipulator motions. If the manipulator has position sensors installed on it to allow such programming, then it is a simple task to program the TV pan and tilts to exactly follow the manipulator hand motions. (5). Testing (Table 2) has shown that when operating with tools, 8 percent of the operator's time can be saved through the use of programmed pan and tilt movement. An additional 9 percent can be saved in simple viewing operations without tools. Even without a sophisticated position-sensing system on the manipulator, automatic positioning can still be achieved. By using sensors on only the manipulator shoulder pitch and azimuth motions and with a relatively wide-angle field-of-view camera, adequate path following can be achieved.

Recent testing (3) has also shown that the following system capabilities are desirable: (a) a zoom lens on at least one camera is required to allow close-up viewing of the work area; (b) wide angle lens capability is also desired to increase the field-of-view and give the operator a better sense of overall manipulator and tool positioning; (c) multiple stationary cameras would be advantageous to the operator, allowing him to switch to them for reference purposes or to provide additional perspectives; (d) the provision of some type of audio feedback to the system operator would be advantageous when operating tools, providing him with instantaneous status of operations.

Other recent developments in technology will have future impact on sensor suite design. The first, development of a pressure-tolerant, oil-filled television camera will eliminate the need for large, heavy, expensive pressure housings on television cameras. Second, research in acoustic imaging technology has shown that it may be possible to perform basic work operations with a trained operator in zero visibility. Also, studies being conducted show that stereo TV systems may provide benefit to the operator, especially in turbid water. (5,6).

COMMAND CONTROL

The command and control of today's submersibles and undersea vehicles no longer requires pushing the state-of-the-art. Systems such as the time division multiplex system used by the WSP provide accurate control of the numerous functions required in the operation of a work system. Down-link and up-link signals can be transmitted easily over a single coaxial cable. Also, as experience grows with pressure-tolerant electronics, the list of components capable of being operated at ambient pressure is being enlarged.

The biggest challenge for the electronics is the transmission of enough television data to allow successful completion of work operations and to provide monitoring of other vehicle areas to avoid entanglements or other unanticipated problems. Since present cable designs are bandwidth limited, dependence is placed on electronic processing. Testing has shown that the operator can work easily with "quasi-real-time" television pictures, those being defined as providing a smaller number of TV lines at a slower rate. Although less data is being transmitted to the operator, for all practical purposes he sees no difference in the quality of the TV picture. With these types of processing of the television systems, up to four "quasi-real-time" television pictures can be sent over a single coaxial cable previously capable of transmitting only one real time TV picture.

HYDRAULIC AND ELECTRIC POWER

Hydraulic power is by far the most advantageous form of power that can be supplied to the work system. Hydraulic power allows precise control, high power density, insensitivity to depth pressures, and can be easily connected to all required subsystems. Through the use of pressure-compensated hydraulic reservoirs, the hydraulic system will always operate at ambient pressure plus the output of the hydraulic pump. However, without proper system design this could produce catastrophic results, since the operating pressure with respect to the surface is approximately 13,000 psi at the 20,000 foot depth. Therefore, all tools and high-operating-pressure areas are provided with a relief valve to the reservoir set at a few hundred psi above the operating pressure. This assures that no entrapped pressure will remain in the system during ascent. As an example, the power system for the WSP is operated from a 60-VDC lead-acid battery bank consisting of 6-volt, golf-cart-type batteries adapted for deep-ocean use. These battery banks supply power to a 1-GPM, 2000-psi motor pump unit for operating the primary system and a second high-flow 2.5-GPM, 3000-psi unit for powering the tools. As a safety precaution, a crossover valve is installed between the two systems to provide backup should one system fail.

On battery-operated vehicles, an efficient hydraulic power system is definitely required. Tests have shown (Table 2) that up to 32 percent of the power consumption of the work system can be spent while the operator is contemplating his next move. Therefore, it is important that not only the system be efficient during actual tool operations, but that the system be quite efficient during idling time when decisions are being made.

CONCLUSIONS

Design of an efficient work system is a complicated effort which must give first priority to total system integration. Modifications to any subsystem, no matter how important a role it plays, must be addressed to the system level. The state-of-the-art in undersea vehicle and work system design is progressing rapidly. New technologies are rapidly becoming available, but must be applied to remotely operated deep-ocean systems with care. Designing and working in the deep ocean is invigorating, challenging and often frustrating, but it is a field that can provide total fulfillment to the design engineer.

NOMENCLATURE

ft = feet; equals 30.48 cm

in. = inches; equals 2.54 cm

psi = pounds per square inch; equals 0.070 kg/cm^2

lb = pounds; equals .4536 kg

gpm = gallons per minute; equals 63.1 cm^3/sec

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