DEVELOPMENT OF A DESIGN BASELINE FOR REMOTELY CONTROLLED UNDERWATER WORK SYSTEMS

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Abstract

The Work Systems Package (WSP), following two years of at-sea testing and evaluation, has completed an extensive laboratory time-motion analysis. This analysis, designed to simulate remote operation, provided a controlled evaluation of the system.

Instrumentation was installed to provide time-motion and power consumption data on system components. The work tasks were divided into numerous subtasks and behavior motions which would be representative of the WSP's diverse capabilities. A computer analysis was performed on the data to provide a quantitative description of the WSP, its capabilities and the parameters effecting them. Thus, the effect of system modifications on mission time and power requirements can be easily simulated to assist the designer in system optimization.

The operational evaluation of the WSP has, for the first time, provided a quantitative data base on which to base future underwater work system designs.

1. Background

The Work Systems Package (WSP), under the direction of the Naval Sea Systems Command, was designed, fabricated and is undergoing operational testing at the Naval Ocean Systems Center (NOSC) in San Diego. As part of the Deep Ocean Technology (DOT) project, the WSP program was initiated in February of fiscal year 1972, by NOSC working in conjunction with Battelle Institute, Civil Engineering Laboratory and the David Taylor Naval Ship Research and Development Center/Annapolis. The Work Systems Package (WSP) is designed to provide a versatile work capability when mounted as a unit on the Navy's Cable Controlled Underwater Recovery Vehicle (CURV III) or the Remote Unmanned Work System (RUWS) unmanned cable controlled submersible vehicles, and the ALVIN, SEACLIFF, and TURTLE manned vehicles. In addition, it can be positioned and controlled by divers or operated independently from a surface support ship for operations at shallow depths without the need for a submersible.

The system was designed to accomplish a complete work task on the ocean floor without the necessity of resurfacing for tool interchange. Potential tasks include salvage, recovery, installation and repair operations. Basic components of the work package (Fig. 1) include two simple outer manipulator arms without elbow functions that act as "grabbers" or restraining/holding arms to steady the vehicle or hold small work pieces.

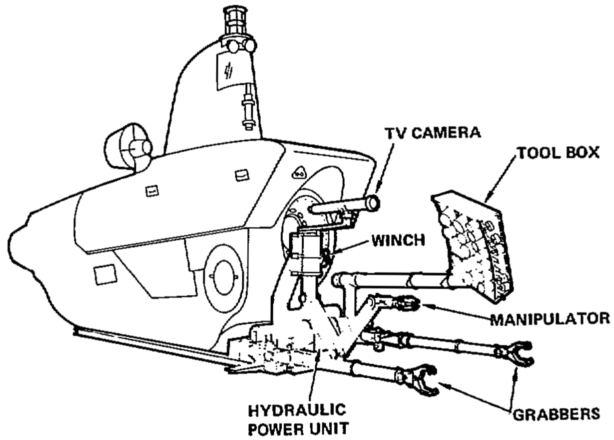


Figure 1. WSP as it would appear mounted to the manned submersible ALVIN.

A centrally located seven-function manipulator arm can select, interchange and operate a variety of hydraulically-powered, explosively-actuated or electrically-actuated tools. Included in the tool storage box are tools to perform cable cutting, synthetic line cutting, nut torquing, jacking, prying, wire brushing, sawing, grinding, drilling, tapping, chipping and stud driving. An electrically-driven hydraulic pump unit supplies the power to most tools. Electric power is supplied to the system from a self-contained battery package. Control of all operations and functions is provided through a multi-plexed telemetry circuit from the vehicle. Pressure tolerant electronic and hydraulic components operate at full ambient pressure in oil filled, pressure compensated enclosures.

Upon completion of assembly, checkout and preliminary tests, the WSP was mated to the CURV III for its first major in-water test. The WSP underwent six weeks of operational testing at the Navy's San Clemente Island test facility in fiscal year 1976. Such tests as underwater docking with a submerged test fixture, tool exchanges and operation, object identification and recovery, and a simulated flight recorder recovery were successfully completed.

The superior operability of the system, the short-time (2 to 2-1/2 minutes) required for remote tool exchanges underwater and the successful performance of a complicated recovery sequence requiring exchange and operation of nine different tools and bits in 2-1/2 hours, achieved, and in many cases, surpassed original design goals.

Following the successes at San Clemente Island, the WSP was flown to NOSC's Hawaii Laboratory for interface and testing with the Remote Unmanned Work System (RUWS). The WSP and RUWS were mated and operated in the RUWS test pool in preparation for support of the Large Object Salvage System (LOSS) operational demonstration at the Naval Coastal Systems Laboratory (NCSL) during the fiscal years 1976 and 1977. The WSP/RUWS was flown to Panama City, Florida, where it successfully completed support of the LOSS operations. The systems easily performed such tasks as midwater docking, cable cutting, stud driving, messenger line attachment, and air hose attachment using quick-disconnects.

The WSP was then returned to San Diego where it was prepared for an extensive laboratory evaluation of the operating characteristics of the system. This laboratory evaluation is the subject of this report.

2. Test Description

Test Setup

The WSP was set up in the laboratory at NOSC, San Diego. A frontal work plane test fixture, the primary work area for which the WSP was designed, was set up exactly as the test fixture used during the San Clemente Island tests with CURV III (reference (1)). This would allow comparison of lab tests results to those acquired at sea.

To simulate at-sea conditions, the operator was isolated from viewing the work area directly. Viewing was provided by the two low-light level TV cameras and the two monitors located on the WSP control console. The two cameras, one located approximately in the center of the system and the other on the upper right side above the manipulator, provided the dual perspective necessary for the performance of tool exchanges and work operations. Both cameras could be remotely moved in pan and tilt from the control console by means of position control joysticks.

The manipulator is a seven degrees-of-freedom, rate-controlled, hydraulic manipulator, which is controlled through the activation of discrete action joystick (toggle) switches. Through utilization of a special chain drive within the manipulator, the plane of the wrist joint remains constant in reference to the horizontal, irrespective of the operation of either the shoulder pivot or elbow joints. Simultaneous activation of both joints results in a linear motion of the wrist pivot axis along a line passing through the intersection of the shoulder rotate and pivot axes. The combination of the chain drive and linear extend features provides a linear feed capability for the operation and interchange of tools and bits.

Each tool of the WSP is stored in its assigned location in an extendable tool box. Stiff nylon brushes provide the restraint required for retention and the compliance necessary for tool exchanges. Hose reels are eliminated from the system by running hydraulic lines down the manipulator, through a hydraulic slip ring in the hand to two quick-disconnect fittings designed to mate underwater with each tool. Mechanical guides along both the tools and the manipulator hand ensure proper alignment, while interlocking notches on the tool secure it in the hand when gripped. Through the linear extend feature of the manipulator, tools can be gripped easily and extracted from the tool box for work operations.

Tools which require bits, such as drills, taps, sockets and saw blades, are equipped with a special quick-disconnect chuck assembly. Bits are obtained by deflecting this chuck against the bit holder on the tool box, moving the tool forward until the bit is fully inserted, and pulling the bit laterally out of its clip. This last action releases pressure on the tool chuck, thus locking the bit in the tool. Bits are replaced by following the reverse procedure. Figure 2 illustrates an acquired saw bit just after it has been pulled laterally out of its clip.

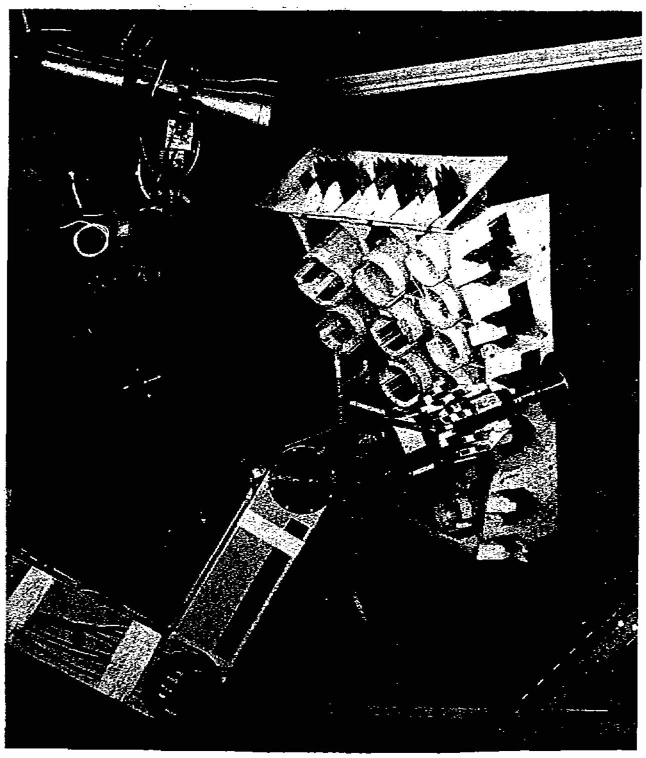


Figure 2. WSP manipulator extracting cutoff wheel from the tool box. Two TV cameras and winch are visible in the upper left of the photo.

The primary analysis of the tests was directed towards a description of the manipulator, tools, control functions and their interactions.

Task Requirements

The objective of the laboratory testing was to obtain sufficient data to permit accurate prediction of work completion time and power consumption for typical WSP salvage missions. Through applications of this data base, subsystems which would receive the greatest benefit through a design modification would be identified and more advanced work systems could be reliably designed.

To achieve this goal, the tasks performed in the laboratory had to be representative of those performed at sea during the San Clemente Island and LOSS operations. This would allow verification of the laboratory data in salvage mission projections. The tasks would also be representative of those performed at Electric Boat (References 2, 3 and 4) which would be used in future time-motion analysis.

The resultant Laboratory Test Plan consisted of 14 tasks that collectively utilized a representative sample of all tool types and their various precision requirements.

The 14 tasks selected for evaluation in the laboratory included the following:

1. Sample retrieval
2. Acquire tool
3. Replace tool
4. Acquire bit
5. Replace bit
6. Cut rope sample
7. Cut cable sample
8. Brushing
9. Hooking
10. Valve turning
11. Unbolting
12. Sawing
13. Drilling
14. Tapping

Data Requirements

To provide accurate projections of salvage missions, the data taken must be subdivided into subtasks small enough to be representative of all system operations. Therefore, each of the 14 tasks was subdivided into four subtasks, or Behavior Elements, which consisted of various combinations of the basic actions (travel, tool use and alignment) required to perform the task. All work and tool capabilities required on realistic WSP salvage missions can be represented by sequentially performing a series of these tasks and subtasks. Each of the categories of travel, alignment and tool use were subdivided by the requirement for force control, high or low precision and specific tool function.

In addition, data were taken on the amount of time the manipulator operated or was idle and the amount of time the TV pan and tilts were utilized. This would provide a more accurate time motion analysis of the operator's workload.

Data were taken also on the power consumption of the system during the performance of each of the subtasks. This was of primary importance since the WSP is designed for installation on battery operated manned boats with limited dive times. When the 30 VDC and 60 VDC power consumption of the WSP is known, it is possible to determine the impact on these vehicles and the dive time or number of dives required to perform a given salvage mission.

Test Subjects

The subject pool consisted of four operators one with 100 hours experience in operating the WSP during previous testing and major WSP sea trials, and the others with only limited experience (less than 10 hours each) in operating either laboratory or operational manipulator systems. Data obtained from the experienced subject were utilized to validate the laboratory test data as a representative performance of the WSP in underwater conditions. Data collected on the four operators were evaluated and their performance with the WSP was averaged to provide realistic estimates of time and power parameters. The operators performed each of the 14 tasks repeatedly for 10 trials to ensure the existence of an adequate data base free of significant learning effects. Data representative of learning were eliminated from the final data pool to represent performance by experienced operators as nearly as possible.

3. Test Results

Operator Workload Allocation

The first task of the data analysis was to identify and eliminate learning effects from the data base. During projection of slavage scenarios, elimination of the learning effects will provide more reliable results.

Figure 3 shows the learning curves resulting through 10 trials of tool acquisition. It can be seen that the naive subjects approached the proficiency of the experienced operator during the testing period. Since these data points were taken throughout the entire test period (as opposed to sequential operation of primary tasks), the effect of total system learning can be indicated.

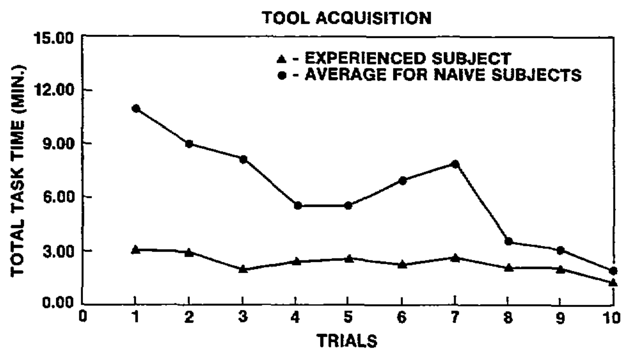


Figure 3. Subject learning curves for tool acquisition.

Since erratic behavior is expected when learning is occurring, a good measure of learning is the variability of variance associated with each task mean. If no learning occurs, the operator's performance would be relatively stable. Figure 4 is a comparison of the total variance occurring in trials four through 10 with the overall variance occurring in trials one through 10. A 40 percent reduction in variance is found for all subjects and all tasks for trials four through 10, thus substantiating the assumption that task learning occurs in trials one through three. The analysis, therefore, was focused on mean task time for trials four through 10.

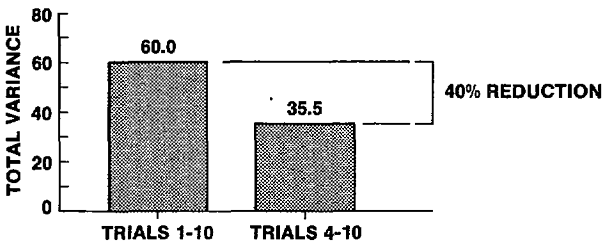


Figure 4. Comparison of total variance for all tasks - all subjects.

The resultant task performance times averaged across subjects appear in Table 1.

	TOTAL TIME (MIN.)	STD. DEVIATION (MIN.)	VEHICLE* 30 VDC POWER WATT-HR	VEHICLE** 60 VDC POWER WATT-HR
1. SAMPLE RETRIEVAL	1.58	.27	5.5	84
2. ACQUIRE TOOL	4.32	2.95	13.4	191
3. REPLACE TOOL	2.74	1.83	8.3	112
4. ACQUIRE BIT	2.58	1.43	12.1	117
5. REPLACE BIT	2.93	1.90	9.0	127
6. CUT ROPE	2.02	.30	6.6	125
7. CUT CABLE	1.30	.42	4.3	66
8. BRUSH	2.39	.59	8.2	155
9. WINCH HOOK	5.45	2.17	17.2	239
10. VALVE OPEN	1.03	.26	3.3	51
11. UNBOLT	1.66	.89	5.4	79
12. SAW ALUMINUM	7.61	3.12	26.0	542
13. DRILL HOLE	2.25	.63	7.6	118
14. TAP HOLE	2.50	1.15	8.2	119

* ASSUMES THE UTILIZATION OF ONLY ONE TV MONITOR

** ASSUMES THE UTILIZATION OF 750 WATTS FOR UNDERWATER LIGHTING: ONE 250 WATT LIGHT ON THE TV BRACKET AND ONE 500 WATT SIDE LIGHT

Table 1. Summary of WSP laboratory results for total task time and power consumption.

Table 2 gives a breakdown of the operator's time based on the data taken. Two of the most striking results indicated by Table 2 show the amount of time the operator spends contemplating the situation or problem and the amount of time spent operating the TV pan and tilts. Efforts to reduce these times would have considerable impact, possibly without complicated or expensive system modifications. In comparison, the first area usually addressed for modifications is the manipulator, which could result in a more expensive, complicated, less reliable system, although it may do the job faster and more accurately. But, according to the data, this decrease in time will apply primarily to manipulator operation, 33 percent of the time spent and not necessarily across the time of the entire mission by that same amount. Since several areas are interrelated, adjustments to the data, based upon subtask modifications, will allow a more accurate evaluation of potential system modifications and concentration on areas where maximum benefit will be realized.

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).

Power Allocation

The power analysis on the system was broken into two sections. The first was the 30 VDC power required by the Command/Control electronics; the second was the 60 VDC power required by the lights and hydraulics. The WSP runs on 60 VDC batteries, either its own or those of a manned submersible. Therefore, the impact of the task or mission to be performed on the battery supply of the vehicle is important. Also, in the case of a manned boat, the 30 VDC power is provided by the life support system power of the vehicle. Therefore, adequate data in this area are also required. Table 1 provides the power data required for the performance of any of the tasks. The power data have been derived to represent operation on a manned vehicle with one TV camera and a lighting load of 750 watts.

Table 2 shows the allocation of this power to the system. It was found that the overall power consumption was directly proportional to the task times and that the manipulator and tool operation used 75 percent of the power, while the lighting accounted for 25 percent of the power consumption. By utilizing the data of Table 2, areas of high power consumption can be identified and reduced. For example, the time spent by the hydraulic system idling accounts for 32 percent of the power consumption. The power loss in this area could be reduced by increasing the efficiency of the hydraulic system during idle or by reducing the operator decision time.

Data Validation

Utilization of the laboratory data to predict salvage scenarios for WSP in an ocean environment requires that proof be developed to show that the laboratory and at-sea performances are equivalent. Development of such proof is possible via comparison of the data base collected in the laboratory and the data collected during the San Clemente Island and LOSS support operations and sea trials. Since the experienced subject is common to all the test series, direct comparison of his data provides the required validation.

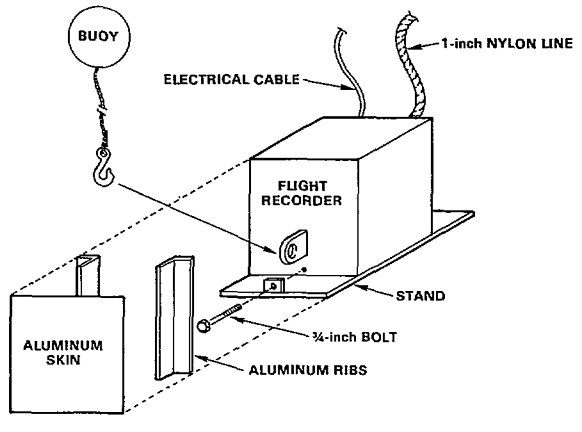
Comparison of the data bases may occur at two levels: (1) comparison of the performance of specific tasks and (2) comparison of the completion times for entire salvage scenarios.

Two specific tasks were replicated in the laboratory and the at-sea data bases. These are tool acquisition and tool replacement. Data indicate the average performance times and standard deviations recorded are statistically identical at a 99 percent level.

The completion of three major salvage scenarios during WSP sea trials allows comparison of the predicted completion time with that actually recorded at sea. Two scenarios were completed during the San Clemente Island sea trials: salvage of a simulated flight recorder (Figure 5) and recovery of a test box. One scenario was completed during the LOSS support operations: connection of an air hose and messenger line. Completion time for these three scenarios was predicted by sequentially adding appropriate task and subtask data recorded in the laboratory.

The data indicate that the actual scenario times are accurate to within the standard deviation calculated.

Therefore, the laboratory task and subtask data effectively represent the general performance capabilities of the WSP system at sea. Further, the prediction of large salvage scenarios (in excess of 30 minutes) with laboratory data provides an accurate prediction of work completion times for actual undersea missions.



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

Figure 5. Simulated "flight recorder" recovery scenario.

Predicted Salvage Missions

With the validation of the data base, it can now be used to predict salvage mission time and power requirements. With this in mind, ten different work scenarios were evaluated to demonstrate the WSP's salvage capability. A list of the scenarios and their respective time and power requirements are shown in Table 3.

SCENARIO DESCRIPTION	TOTAL WORK TIME (min)	STANDARD DEVIATION (min)	30 VDC VEHICLE POWER (KwHr/Watt-Hr)	60 VDC VEHICLE POWER (KwHr/Watt-Hr)
1. CUT OPENING, THIN METAL	216	17	0.70	12.3
2. CUT OPENING, THICK METAL	265	17	0.89	16.3
3. REMOVE ELECTRONICS	110	11	0.35	5.3
4. PADEYE DRILL/TAP FASTENERS	29	6	0.09	1.2
5. PADEYE CONVENTIONAL FASTENERS	122	12	0.40	5.6
6. RIG CABLES	65	6	0.21	3.2
7. OPERATE SEA VALVES	46	5	0.14	2.0
8. LOSS SUPPORT OPERATIONS	10	3	0.03	0.4
9. SCI FLIGHT RECORDER	79	10	0.25	3.6
10. SCI TEST BOX RECOVERY	38	7	0.12	1.7

Table 3. Estimated work time and power consumption for ten salvage scenarios.

A detailed description of the tasks and their analysis can be found in Reference 5. For simplicity, only one task is shown here. That task, the "simulated flight recorder recovery," which was performed at SCI, is shown in Figure 5. Performance time predicted for this scenario was 89 minutes (maximum) compared to 91 minutes recorded at-sea, which substantiates this technique.

System Modification Studies

Controller Evaluations

One of the applications of the WSP data base is the capability to evaluate modifications to critical subsystems. One such area is the manipulator controller.

Control options include pushbutton fixed rate (WSP current design), pushbutton variable rate, joystick fixed and variable rate, discrete position control, and harness (master-slave) position control. Experimental data collected at Electric Boat Division, (References 2, 3 and 4) were used in the projections.

The pushbutton fixed rate controller is taken as the baseline data since its operation was similar to the controller used on the WSP. The resultant increase or decrease in subtask completion time for other control options is indicated relative to the baseline data. Adjustments to the baseline for the ten salvage scenarios is presented in Table 4. Projection of the effectiveness of each of the control options listed in Table 4 is made by adjusting the subtasks of individual tasks by the Electric Boat Data.

	PRESENT WSP BASELINE	PUSH VARIABLE RATE	JOYSTICK FIXED RATE	JOYSTICK VARIABLE RATE	DISCRETE POSITION CONTROL	HARNESS POSITION CONTROL
1. CUT OPENING, THIN METAL	1	.93	1.34	1.18	1.53	.93
2. CUT OPENING, THICK METAL	1	.94	1.48	1.28	2.43	.99
3. REMOVE ELECTRONICS	1	1	1.29	1.13	1.88	.77
4. PADEYE DRILL/TAP FASTENERS	1	.97	1.24	1.07	1.69	.66
5. PADEYE CONVENTIONAL FASTENERS	1	.96	1.27	1.11	1.72	.70
6. RIG CABLES	1	.91	1.08	.97	1.37	.55
7. OPERATE SEA VALVES	1	1.02	1.26	1.11	1.98	.74
8. LOSS SUPPORT OPERATIONS	1	.90	1.10	1.00	1.40	.50
9. SCI FLIGHT RECORDER	1	.94	1.16	1.04	1.56	.61
10. SCI TEST BOX RECOVERY	1	.92	1.15	1.03	1.53	.58
	1.0	.95	1.24	1.09	1.71	.70

Table 4. Normalized scenario completion times utilizing various control types.

Depending on the type of work to be performed, the benefit of the different controllers can be easily seen. Results indicate a potential savings of 30 percent of salvage time through the use of the harness position controller. The savings in power may not be quite as high since, although the time required to complete the task is less, the power consumed per unit time will be higher. One must also consider the working environment of the operator when considering control devices. It is not an easy task to use a position controller when viewing through a manned vehicle viewport as opposed to a more spacious control room topside in a tethered vehicle configuration. The designer is now given an indication of the proper design path in achieving an efficient work system. This path could be easily verified through hands-on testing of the most probable modification candidate without the need of testing all of the other options.

Automatic Manipulator Control

The use of minicomputer programmed control of manipulators and robots in industry has increased rapidly. Such automation has increased accuracy and decreased work time in the performance of repetitive tasks. Therefore, it becomes a viable area for application to the WSP. In an effort to determine its benefit, a series of tests was performed using a microprocessor controller for the WSP manipulator. The controller was programmed to go through a series of tool and bit exchanges which it accomplished with excellent time reductions and near perfect alignment and target location. The time reductions, Table 5, are shown as compared to both experienced and inexperienced operators. Preliminary adjustments to the data base were performed using only the experienced operator times of Table 5 and resulted in an 18 percent time reduction. It can be concluded that the data acquired with the programmer tests will yield even more dramatic results.

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

Automatic Camera Control

With the inclusion of position feedback sensors on the manipulator, the possibility of automatic camera positioning exists. Microprocessor control could be easily applied to have the pans and tilts move the cameras so that they will follow the manipulator hand exactly. This would enable the operator to concentrate on the task and not have to stop work operations to move or adjust the cameras.

Calculating the reduction in salvage scenario completion times is straightforward. If it is assumed that all present camera control times will be eliminated by automatic positioning, completion times may be calculated by subtracting the predicted camera operation time from the predicted scenario completion time.

The resultant data indicate that an average 8 percent reduction is achieved across all the salvage scenarios.

4. Conclusions

It has been shown that the data base which has been generated for the WSP will be a valuable tool to those individuals working on advancing the state-of-the-art in undersea work systems. The system designer now has an indication of the areas where he should concentrate and the potential benefits achievable. The laboratory tests performed with the WSP have also yielded a great deal of practical data on performing remote work in the areas of viewing, sensors, tool and control requirements and much more. For a more detailed discussion of the actual work tasks and recommendations, the reader is referred to the laboratory test report, Reference 5. The testing also has shown areas where more research is required to answer the question of how man is to work remotely in the sea. Hopefully, these and other studies will continue the quest for that answer.

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