The MIT/Marine Industry Collegium

Opportunity Brief

TELEMANIPULATORS FOR UNDERWATER TASKS

A Project of the

MIT Sea Grant Program

The MIT/Marine Industry Collegium

TELEMANIPULATORS FOR UNDERWATER TASKS

Opportunity Brief No. 3

Revised Edition

August 15, 1976

Marine Industry Advisory Service

MIT Sea Grant Program

Cambridge, Massachusetts 02139

Report No. MITSG 76-7

Index No. 76-707-Zvo

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Sea Grant Program

ADMINISTRATIVE STATEMENT

In 1975 the MIT Sea Grant Program formed the MIT/Marine Industry Collegium, a working partnership between MIT Sea Grant and U.S. Industry to promote the commercial development and application of new marine technologies. In seeking to meet this objective, the Collegium acts as an information resource for industrial members, conducts meetings, workshops, and special programs, and publishes information on new ocean-related business opportunities.

The principal publications of the Collegium are Opportunity Briefs. These 15-25 page papers deal with specific business opportunities growing out of Sea Grant or other MIT sponsored marine research. Opportunity Briefs describe a new technology or process, outline economic and marketing implications, review technical requirements, and consider environmental, regulatory, and political factors. Briefs are a joint effort of subject experts, the MIT Sea Grant Marine Industry Advisory Service and Collegium members. The briefs remain anonymous to give greater freedom in the expression of opinions and in speculation about particular future opportunities.

The five Opportunity Briefs prepared during the Collegium's 1975-1976 year were:

Chitin and Chitin Derivatives

Offshore Mining of Sand and Gravel

Telemanipulators for Underwater Tasks

Advances in Underwater Welding

Untethered Robot Submersible Instrumentation Systems

Each of these Briefs was first issued to Collegium members in draft form. Following this, we held meetings to explore the topic in more depth and to discuss further directions with representatives of interested companies. The Brief in its edited form incorporates many of the comments and suggestions that we received from members through correspondence, phone conversations, and Collegium meetings.

If you would like to receive any of our other Opportunity Briefs, or wish to pursue further any of the topics covered, please contact the Marine Industry Advisory Service, MIT Sea Grant Program, Room 1-215, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139.

Dean A. Horn
Director

August 15, 1976

Room 1-211 77 Massachusetts Avenue Cambridge, Massachusetts 02139 617/253-7041

CONTENTS

1.0 A BUSINESS PERSPECTIVE 1

2.0 HISTORICAL BACKGROUND 3

3.0 TELEMANIPULATORS AND DIVERS: A COMPARISON 6

4.0 ADVANCES IN TELEMANIPULATOR TECHNOLOGY 10

5.0 RESEARCH NEEDS 16

6.0 MARKETS AND MARKETING 19

7.0 COLLATERAL REFERENCES AND READING 21

8.0 ADDENDUM 24

1.0 A BUSINESS PERSPECTIVE

Although exploitation of mineral resources from beneath the sea began only twenty years ago, substantial amounts of our petroleum, sulphur, phosphate, manganese, and other associated resources will be obtained from the oceans in the near future. Exploration, production, and transportation of these resources beneath and on the sea require an increasing number of complex mechanical tasks that must be carried out in the hostile environment beneath the ocean surface. As these tasks take place in deeper and deeper water, the capabilities of divers to carry out the tasks decrease, the cost of using divers and support systems rises, and problems of diver safety increase.

In short, the hazards and cost of using divers are escalating as the need to have hands and eyes beneath the sea is rapidly expanding.

To accomplish safely the increasing number of underwater mechanical tasks, we need both men and machines, working together. The types of man/machine combinations required include free divers with hand tools; work packages controlled and operated by free divers; manipulators controlled by operators in untethered, self propelled submersibles or in tethered, unmanned submersibles; and surface controlled manipulator systems with television eyes. As working depths increase, humans will be forced to become less directly involved in actually carrying out the underwater tasks, and remotely controlled manipulators will become required to augment human capabilities.

The simple ingenious manipulators developed to date have been sorely wanting in capability and dexterity compared with divers. The potential of computers appropriately coupled to men and manipulators has been grossly neglected in the undersea market. There exists a sizeable body of technology and art related to telemanipulators used in the space, nuclear, and industrial markets. This technology can and must be applied to the undersea market. In addition, the last three years have seen astounding decreases in size, power consumption, and cost of computers, together with their increased reliability. These advances, coupled with parallel advances in control techniques and software, now permit the design and application of sophisticated telemanipulators to undersea tasks.

Development and marketing of telemanipulators and work systems offer an interesting product and profit potential over the next decade. The companies best able to contribute to and benefit from new business in telemanipulators include firms with skills in human factors technology, electronics, computer applications, as well as the mechanical skills needed to provide the rugged, reliable, sophisticated equipment needed in a deep sea environment.

2.0 HISTORICAL BACKGROUND

The expressions "teleoperator" and "telemanipulator" have been used to connote dexterous machines controlled by man but located remotely from the human operator. Thus they describe a class of man-machine systems designed to project man's innate dexterity across distance and/or into environments which are hazardous and perhaps lethal to humans.

The development of teleoperators began in the late 1940s with the need for nuclear laboratory technicians to manipulate experimental apparatus inside of "hot" cells. At first technicians used simple mechanical linkage systems while viewing the experimental apparatus through leaded glass windows. Later, bilateral (force-reflecting) master-slave servomanipulators were developed along with closed circuit television viewing systems to give the remote operator "feel" and close-up vision.

In the late 1950s the requirement for performing operations on the moon added a new dimension to remote manipulation problems. The time delays in propagation of control signals from earth to the moon (or beyond) led to the need for some form of local, semiautonomous control to prevent oscillation and to provide instantaneous response to local hazards in the environment. Thus came the concept of supervisory control, in which a human supervisor and a local computer cooperate to achieve an efficient control system with capabilities exceeding that of either alone.

In the mid to late 1960s, the Man-Machine Systems Laboratory of the MIT Department of Mechanical Engineering did a variety of experiments in teleoperation to simulate earth-to-moon manipulator control through a time delay, the first "supervisory control manipulator."* An improved similar device was later developed at Stanford Research Institute.

Recent development of manipulator arms for the space shuttle has renewed interest in computer-plus-manual control. Of particular relevance are coordinate transformation techniques, or "resolved motion rate control" and "active force accommodation" algorithms, developed by Whitney originally in the MIT Man-Machine System Lab and subsequently at the Charles Stark Draper Laboratory.

Recent attention to industrial production by mechanical arms has concentrated on developing more rapid, precise manipulators and upon pattern recognition schemes (including Whitney's) for coupling sensed force patterns and visual patterns to control laws.

This body of technology and know-how which was developed for aerospace and nuclear needs is applicable to problems of control for undersea manipulators.

Development of undersea manipulators has paralleled the development of aerospace, nuclear and industrial systems, but undersea manipulator emphasis has centered on the mechanical aspects of the design, and the control technology available has not been fully exploited. A few research submersibles of the late '50s and '60s used manipulators, which were operated by switches that actuated separate hydraulic valves for each degree of freedom for the arm-hand (Alvin, Beaver). Most of the work on improved systems is based on improving mechanisms, tools, and vehicle control. Advances and contributions

*A topically-arranged bibliography is included in Collateral Readings and References (Section 7), p. 21.

by the Naval Undersea Center, Woods Hole, Westinghouse, General Electric, General Dynamics and others are reflected in the references cited in Section 7.

3.0 TELEMANIPULATORS AND DIVERS: A COMPARISON

In determining the costs of telemanipulators in comparison to divers, three factors must be considered:

1. the relative efficiency (or dexterity) of telemanipulators vs. divers;
2. the relative cost of telemanipulators and the submersible or work system associated with them vs. the cost of divers and their support systems; and
3. the hazards associated with each system.

The first two items are a measure of the costs of accomplishing a specific task by telemanipulators relative to divers. These factors are discussed in Sections 3.1 and 3.2 below.

Although the costs of hazard to life and limb are impossible to quantify, such costs express themselves partly in insurance rates for divers and partly in the price that divers will demand to assume the risks associated with deeper diving. A recent British report gives the annual diver fatality rate in the North Sea as 10/1000 per year, which is 33 times that for coal mining and 220 times that for factory work in the United Kingdom. These statistics alone are a compelling reason for considering the need for telemanipulators to replace divers in some environments.

3.1 Economic comparisons. The cost of using skilled divers to carry out underwater tasks can vary greatly depending on such factors as the work cycle, the duration of the job, the weather, the type and amount of support equipment required, the depths at which divers are working, and the local wage structure.

In appraising the potential costs of underwater welding, Moore made a detailed investigation of the costs of jobs of different duration for various depths based on costs that applied in the Gulf of Mexico circa 1974-1975. (His detailed assumptions and results are found in Section 8, p. 24). Representative data are given below for a job requiring two days and another requiring five days on the bottom. A four man saturation diving team is used for both tasks.

TWO DAY JOB

DEPTH	DAYS IN WATER	COST/BOTTOM HOUR*
200 ft.	4	$2400
500 ft.	7	3763

FIVE DAY JOB

DEPTH	DAYS IN WATER	COST/BOTTOM HOUR*
200 ft.	7	$1655
500 ft.	10	2200
800 ft.	13	2745

Moore also shows that, on an hourly basis, a manned submersible would cost roughly $1300/bottom hour and a remotely manned vehicle might cost about $550 to $600/bottom hour.

These data do not imply that a total job can be done more cheaply by manipulator systems, since nothing has been said about relative time to accomplish a task. The data do suggest that, for deeper operations and for

*A bottom hour is the time actually spent working, not including descent, decompression, etc.

Relatively short jobs, submersibles with manipulators may cost only 1/2 or 1/3 as much on an hourly basis which will tend to offset their lack of dexterity.

A further indication of the very high costs of using divers is given in a recent paper by Sletten concerning problems of underwater inspection of North Sea structures in depths from 25 to 30 meters. He estimates that a 1 man-hour job of inspection above water takes about 100 man-hours underwater and that the associated costs are even more than 100 times greater.

3.2 Dexterity comparisons. Studies comparing experienced divers to skilled operators with relatively crude manipulators have shown that manipulators take significantly longer than divers to accomplish various representative undersea tasks. The time ratio is highly task-specific, ranging from 1/1.3 (diver time/manipulator time) for tapping holes to 1/30 for close tolerance connect/disconnect tasks, with an "overall" ratio of about 1/4. Precise alignment is particularly time consuming, because touch feedback is lacking and vision may be impaired by the manipulator arm blocking the view. These studies included several control systems available at the time, none of which was found to be superior for all tasks studied.

These studies were carried out in a water tank that represented near surface conditions for the scuba diver. Increasing depth would not substantially impair the efficiency of the manipulator but might reduce the efficiency of the worker by 25 to 50%. Thus for the present, the overall ratio of 1 hour of diver time for 4 hours of manipulator time might be only 1/3 or 1/2. Additional work cited in Section 7 by Yastrebov suggests ratios in the range of 1/2 to 1/10.

Although these dexterity comparisons strongly favor the use of divers, the remote manipulators on which the comparison figures are based have been relatively crude devices from the standpoint of user control. These devices did not have the sophistication of current industrial and space manipulators, much less the advantages of new technology now being developed. Application of technological advances reviewed in the next section can be expected to produce significant improvements in controllability.

Additional improvements could be achieved by designing undersea equipment for handling by remote manipulators. Improvements could be made by arranging for simple guides or "docking cones" to aid in positioning of one object relative to another, or for "handles" by which a manipulator may secure itself, much as a diver might manipulate with one hand while holding on with the other hand. Sea floor equipment can be designed with modules that are more easily replaced, much as computers are made today.

Advances in controlling techniques through applications of new technology and redesign of equipment to be handled thus allow telemanipulators to become more cost competitive with divers.

4.0 ADVANCES IN TELEMANIPULATOR TECHNOLOGY

Technological advances applicable to improvement of underwater telemanipulators are related to significant advances in three areas. First, modern control theories have provided new insights into human behavior as applied to the control of machines. In some cases, limited forms of intelligent and reflexive behavior can now be programmed into a computer, thus enabling machines to carry out tasks that formerly required continuous human control. Second, computer technology has made enormous strides toward lowering costs, while improving versatility and reliability of computers. As a result, it is now both economically and technically feasible to build limited "intelligence" into certain machines. Finally, advances in sensing techniques have made it possible to provide better control feedback to human operators. Television cameras and touch sensors may now be used to simulate more nearly the eyes and hands of an underwater diver.

4.1 More flexible force-reflecting control schemes. Bilateral master/slave servomanipulators are designed so that when the operator displaces the master, the slave is displaced correspondingly, until the slave hand exerts a force on some external object, at which point the master exerts a corresponding force (in the opposite direction) on the human operator's hand. Even though master and slave communicate only through an electrical or electrohydraulic link, the apparent effect is one of direct mechanical contact between the human operator and the external object.

Such force reflection techniques have been available in nuclear and industrial manipulators for many years. However, these techniques have hardly been used for undersea operations, probably because master mechanisms were too large or awkward for use in the manned submersibles. Also the strict geometric isomorphism between master and slave may not be convenient for many underwater tasks.

Recent studies have shown that the master can be smaller, operate at a much lower force level, and be different geometrically without seriously impairing performance--provided that the directional correspondence is approximately the same. Scale models of the slave work environment in conjunction with the master have been shown to be a helpful control technique, especially in maintaining reference orientation. These techniques should adapt readily to telemanipulation from the surface through closed-circuit TV.

4.2 Resolved motion control. In underwater manipulation, a joystick or push buttons are often used to control a manipulator. In such situations, the operator typically has no way of knowing how the actuation of any particular articulation (for example, a motor controlling a given joint in the linkage) will drive the endpoint. The cascade of trigonometric transformations in the series linkage is too complex for such a determination. Recent developments in computer aids have solved this problem, so that the human operator can simply command the endpoint (rather than each joint articulation) to go up, down, left, right, twist, etc., relative to his own (or the platform's) reference system--and the end point will obey. This trigonometric unscrambling is entirely embodied in computer logic and is, therefore, potentially a very low cost feature.

4.3 Computer-programmed automatic subroutines. Many component movement patterns are the same every time they are executed and are quite time-consuming for the operator to execute with the manipulator. Examples are scrubbing and scraping, returning to a reference position after doing a task, and twisting a bolt. With the aid of a computer these actions can be preprogrammed, so that at a certain point in the task the operator can simply press a button and the computer will take over and perform the subroutine. Programming of such subroutines can be done easily by having the operator drive the manipulator through the motions one time, then having the manipulator replicate those actions. Also, when the manipulator is in a particular position to which the operator may wish to return, the operator can assign a "name" to that position and have the manipulator return there under its own program control from any other position at any time. Combinations of such computer-control subroutines can be built up as the operator gains experience. Laboratory experiments have demonstrated the efficacy of such "supervisory control" but there has been little actual application of it as yet. Further development is clearly needed for specific manipulator applications.

4.4 Mechanical "touch" sensing. Except for a very few experimental trials in laboratories, and almost none underseas, "sight" (in the form of miniature TV cameras using electronic image-enhancing techniques) is the only form of remote sensing that has accompanied remote manipulation. There are several other sensing techniques in which significant progress has been made in the last few years.

"Touch" is regarded by laymen as a single sense. In the human body, however, touch is mediated by several different kinds of force strain, by nerve endings in the skin, and by nerve endings in the muscles, tendons, and joints. Similarly, touch in a remote manipulator can be effected in a variety of ways, as has been shown in numerous experiments.

The most obvious form of touch sensing consists of arrays of miniature sensors mounted on the gripping surfaces of an artificial "hand" and, perhaps, on the ends or outsides of the "fingers" which come in contact with objects the hand manipulates. The important parameters of such devices are:

1. the physical principle by which the transducer works;
2. the intensity resolution of transducers;
3. the spatial resolution of sensor array;
4. how the data are processed and/or displayed to the computer or human operator.

Transducers for such sensor arrays are based on a variety of physical principles. Some are basically on-off devices, conventional spring depression microswitches or cat's whiskers, which when subjected to axial or lateral loads bend and make contact with the metal rings in which they are supported. Such transducers have been made as small as 1/8 inch on center, in arrays up to 6 X 24 individual transducers. Some of the touch sensor transducers made are capable of providing measures of continuous force magnitude: one type uses pieces of electrically conducting rubber that change their resistance when deformed; another consists of mechanical devices that release air or light beams (between LED and photo resistive elements) when depressed. However, experience has shown that on-off information about where the hand is in contact with external objects is most important, even with a crude array on the gripping surface and a few sensors on the ends.

Another type of touch sensor utilizes a deformable mirror on the back side of the gripping surface. An image is picked up and sent by TV to the human operator, who gets a good qualitative image of pressure patterns as they are formed by the deformation of the mirror. Such artificial touch devices are analogous to the skin sensors in the human body which resolve surface forces differentially in space with little concern for magnitude. There have also been sensors built which aggregate all forces and movements applied to the hand (six degrees of freedom) with relative precision in magnitude. These have usually taken the form of strain gage bridges.

4.5 Active accommodation. Accommodation refers to a particular technique, developed at the Charles Stark Draper Laboratories, which combines the use of a six-degree-of-freedom strain gage sensor located at the manipulator wrist together with the resolved motion computations described in 4.2 above. Accommodation has been shown to be potentially useful for performing such laboratory tasks as putting a peg in a hole. It is very easy for a computer-driven arm or a human-operated master-slave manipulator to get "stuck" trying to put a peg in a hole if less-than-perfect. An active accommodation routine alleviates this problem by "relaxing" the peg in certain degrees of freedom while maintaining force and motion in the axial direction of the hole. Passive accommodation of ordinary compliance also has a role to play here and current research is exploring the interaction of active and passive accommodation.

4.6 Supervisory control of automatic reflex control loops. Automatic routines can be programmed to make a manipulator respond to signals generated by a touch sensor. It can move until it touches something, then stop, or at that point branch into another subroutine, such as pulling back if it is not supposed to touch anything in that sector of space. Similarly, the manipulator can be programmed to slide along the surface, or to open its jaws to grasp an object. Programs can cause the manipulator to close on an object and adjust itself until both jaws show equalized pressure, at which point it attempts to pull on the object.

The human supervisor, now armed with the ability not only to program subroutines that are "open-loop" relative to the environment, can also program routines that are "closed-loop" through sensing of the environment. Potentially he can name reference positions, specify sensor conditions that initiate branch points, and link together subroutines that eliminate repetitive operations and adjust to minor position changes or force disturbances in the environment. He can also program emergency conditions; for example, if the grasped object begins to stop, the computer can order the manipulator to grasp tighter or to relax to ensure that grasp is not lost and the object dropped.

4.7 Proximity sensing and computer controlled inspection. For various inspection tasks, a TV camera or other sensor can be used to inspect a pipeline or ship hull, for example. In such cases, a miniature TV camera may be held by a manipulator attached to a vehicle that is fixed or moving at slow velocity. The proper distance may be maintained by a short range sonar, by a laser triangulation device, or even by a long "cat's whisker" sensor.

5.0 RESEARCH NEEDS

The potential users of underwater telemanipulator systems, and the potential designers and manufacturers of telemanipulator systems share very few common characteristics. The former group thinks and works with things mechanical; the latter thinks, works, and designs in computer terms. The potential users place a high value on simplicity and reliability; designers tend to enjoy complexity and are more tolerant of failure--as long as it can be repaired. Thus, industrial firms and government agencies engaged in undersea handling operations have chosen not to become engaged in some of the more esoteric aspects of remote and computer-controlled manipulation. Traditionally, divers have handled most contingencies that may occur and, where necessary, diver skills have been augmented with relatively crude manipulators capable of carrying out the required tasks. However, as the complexity and depths of required operations increase, this approach becomes less and less viable.

If telemanipulation remote inspection and associated control techniques are to be implemented in the form of reliable, cost-effective products, the developers and designers of such systems will have to collaborate closely with potential users of the systems. Only through such a collaboration can systems be designed to carry out appropriate tasks with the required dexterity and reliability. At least three major research and development efforts should take place:

1. The first is a detailed study of the various underwater tasks that must be performed and that are difficult, hazardous or inefficient for humans.

Those tasks can then be matched against new tools and control techniques that are becoming available. Tasks must be classified in terms of sensory requirements, forces to be applied and withstood, distances of remote operability, accuracy and speed required, repetitiveness, depth ranges, and types of terrain and water conditions, etc. Tools and control techniques would be classified in terms of sensing capability, force, speed and kinematic capabilities, precision, operator training required, reliability, safety, maintainability, and capital and operating costs. The study should employ both quantitative systems-analysis tools and an aggregation of expert opinion in assigning benefits and costs to various alternatives.

2. A second effort would involve laboratory simulation tests using master-slave manipulators and supervised computer-controlled manipulators to accomplish tasks outlined in Item 1. Experiments would include closed-circuit TV degraded to simulate deep, turbid water conditons and work objects mounted on a floating platform to simulate the effects of buoyancy and water currents.

The prime purpose of these experiments would be to acquire some understanding of the interaction of relevant variables, and demonstrate and anticipate the problems met under sea. The software development potentials would be defined for computer-aids in the planning, teaching, monitoring and emergency takeover aspects of human supervision of computer-controlled manipulation. "Failsafe" procedures should be developed so that failures would be recoverable, or at least not catastrophic. In conjunction with the task analysis of Item 1, laboratory experiments would bring empirical evidence to bear on various tactical trade-offs and strategies for the most rapid completion of typical tasks.

3. Finally, prototype systems should be built for trials in the ocean environment. Since many of the most important variables to be tested in improved telemanipulations will be computer controls and sensory feedback devices, it may be possible in some cases to use existing manipulators and/or submersibles to carry out field trials economically and effectively.

6.0 MARKETS AND MARKETING

According to a survey published in *Ocean Industry* in October, 1975, there are about 96 manned submersibles used for oceanographic research, inspection and repair. About 13 companies are currently manufacturing these submersibles and about 55 companies and institutions operate them. Over half of these submersibles are noted as having some form of manipulators. No data seem to be available on remotely manned underwater inspection systems. They probably add 10 to 20 vehicles which are potential users of limited telemanipulators.

New submersibles and remote work systems are being announced continuously by existing and new-to-the-market companies. We estimate the markets for new telemanipulator systems to be on the order of thirty (plus or minus 30%) systems per year and that the market should grow perhaps 20% per year, based on (1) cumulative need associated with on-going maintenance and inspection of existing platforms, pipelines and communication systems; (2) the needs associated with continued offshore exploration and new production and (3) on retrofit to existing submersibles. The systems should cost from $100,000 to $200,000 each, so an annual dollar volume of $2,000,000 to $10,000,000 is implied.

Marketing to the offshore industry is complex. The oil production and exploration companies are the ultimate users of such equipment, but they are seldom the purchasers. Most equipment is bought by service organizations that provide equipment (and personnel for operation and maintenance) on a contract basis to the oil companies or to other contractors, the latter of whom in turn provide services to the oil companies. Thus, many different companies are directly or indirectly involved in purchasing decisions.

Finally, it should be noted that the market (and the competition) is truly multinational; techniques and products proven successful in the North Sea, for example, are soon used worldwide--in the Gulf of Mexico, Alaska, and Indonesia. The implications for post-sale service and for spare parts inventories are profound.

7.0 COLLATERAL READINGS AND REFERENCES

In lieu of the usual listing of references, we present here a series of references keyed by topic to sections of the text which they support or supplant.

SECTION 2

About teleoperators in general

Johnsen, E. G., and W. R. Corliss. Teleoperators and Human Augmentation and Teleoperator Controls. Washington, D.C.: NASA Office of Technology Utilization, December, 1968.

About MIT work only

Ferrel, W. R. "Remote Manipulation with Transmission Delay." PhD Thesis, Department of Mechanical Engineering, MIT, September, 1964.

Whitney, D. E. "State Space Models of Remote Manipulation Tasks." PhD Thesis, Department of Mechanical Engineering, MIT, January, 1968.

Ferrell, W. R., and T. B. Sheridan. "Supervisory Control of Remote Manipulation." IEEE Spectrum, Vol. 4, No. 10, October, 1967, pp. 81-88.

Hardin, P. A. "'And Tree' Computer Data Structures for Supervisory Control of Manipulation." PhD Thesis, Department of Mechanical Engineering, MIT, October, 1970.

Sheridan, T. B. "The Several Roles of Man as a Supervisor of Robots." Proceedings of the 1974 International Conference--Systems, Man and Cybernetics. IEEE-74-CHO-908-4-SMC, pp. 453-457.

Sheridan, T. B. "Considerations in Modeling the Human Supervisory Controller." Proceedings of the International Federation of Automatic Control, 6th Triennial World Congress, Cambridge, Massachusetts, August, 1975.

Whitney, D. E. "Resolved Rate Control of Manipulators and Human Prostheses." IEEE Transaction, Man-Machine Systems, June, 1969.

About Stanford work only

Hill, J. W., and A. J. Sword. "Studies Design and Develop Improved Remote Manipulator Systems." Stanford Research Institute Report 1587, November, 1972.

Hill, J. W., McGovern, D. E., and A. J. Sword. "Study to Design and Develop Remote Manipulator System." Stanford Research Institute Report 2583, April, 1974.

Some interesting recent studies

"Remotely Manned Systems." Proceedings of the Second Conference on Remotely Manned Systems, June 9-11, 1975.

Undersea manipulators

Winget, C. L. Hand Tools and Mechanism Accessories for a Deep Submersible. Woods Hole Oceanographic Institution, Ref. 69-32, May, 1969.

Uhrich, R. W. "Terminus Controlled Deep Ocean Manipulator." Proceedings of the 1973 IEEE Conference on Engineering in the Ocean Environment, September, 1973.

Fugitt, R. B. "Small Remotely Manned Systems." Proceedings of the 1973 IEEE Conference on Engineering in the Ocean Environment, September, 1973.

Pesch, A. J., et. al. Capabilities of Operators as Divers: Submersible Manipulator Controllers in Undersea Tasks. Groton, CT: General Dynamics Corporation, June, 1970 (AD-716532).

Estabrook, N., et. al. "Development of Deep-Ocean Work System." Proceedings of the IEEE Ocean 75 Conference, September, 1975, pp. 573-577.

Fugitt, R. B. "Design and Operation of Two Remotely Manned Undersea Vehicles." Proceedings of the IEEE Ocean 75 Conference, September, 1975, pp. 870-876.

Uhrich, R. W. "NUC Manipulators." Proceedings of the IEEE 71 Conference on Engineering in the Ocean Environment, September, 1971, pp. 301-308.

Drenning, R. P. Manipulator/Deep Ocean Tool Work System. Annapolis, MD: Westinghouse Corporation.

SECTION 3

Concerning diver safety

British Medical Association. The Medical Implications of Oil Related Industry. Edinburgh, Scotland: British Medical Association. (BMA, Scottish House, 7 Drumsheugh Gardens, Edinburgh, EH3 7QP), as quoted in Ocean Engineering.

Concerning the relative efficiency of divers and manipulators

Moore, Alan P. "Metals Joining in the Deep Ocean." Master's Thesis, Department of Ocean Engineering, MIT, May, 1975.

Yastrebou, V. S. "Comparative Efficiency of a Diver and Underwater Divers." Proceedings of the Society for Underwater Technology Conference on Oceanology International 72, London, 1972. (as quoted in Moore)

Sletten, R., et. al. "Problems in Underwater Inspection of North Sea Structures." Proceedings of the IEEE Ocean 75 Conference, September, 1975, pp. 716-721.

SECTION 6

About current submersibles

Weeden, S. L. "Submersible Business is Booming." Ocean Industry, October, 1975.

8.0 ADDENDUM: "Appendix A--Calculation of Cost vs. Depth Relations for Diving Systems," taken from Arnold P. Moore, "Metals Joining in the Deep Ocean," Master's Thesis, Department of Ocean Engineering, MIT, May, 1975.

Welding Costs for Conventional Surface Diving

Daily Costs

depth	bottom hrs. / man day	salary [a]	depth bonus [b]	support [c]	DDC [d]	HeO_2 [e]	cost / bottom hr.
33 ft.	7 hr.	$ 2000	---	$1500	---	---	$ 125
50	4	2000	---	1500	$ 75	---	223
70	3.5	2000	$ 20	1500	75	---	261
100	2.43	2000	50	1500	75	---	388
140	1.9	2000	130	1500	150	---	549
170	1.2	2000	210	1500	150	---	935
210	0.33	2000	340	1500	150	$2090	5,340

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable.

Charges based on Gulf of Mexico rates.

(a) 500 $/day/welder

(b) Variable with depth

(c) Includes diving and welding support equipment (Diving barge additional if required)

(d) Decompression Chamber (DDC) required below 50 ft. depth

(e) HeO_2 breathing mixture required below 200 ft.

Welding Costs for Saturation Diving

Total Job Costs

job duration	depth	time under pressure[a]	salary[b]	sat syst and support[c]	mixed gas[d]	mobilization	cost / bottom hr.[e]
1 day	200 ft.	3 days	$ 14,400	$ 45,000	$ 12,000	$ 16,000	$ 3,642
1	500	6	28,800	90,000	18,000	16,000	6,367
2	200	4	19,200	60,000	20,000	16,000	2,400
2	500	7	33,600	105,000	26,000	16,000	3,763
5	200	7	33,600	105,000	44,000	16,000	1,655
5	500	10	48,000	150,000	50,000	16,000	2,200
5	800	13	62,400	195,000	56,000	16,000	2,745
10	200	12	57,600	180,000	84,000	16,000	1,407
10	500	15	72,000	225,000	90,000	16,000	1,679
10	800	18	86,400	270,000	96,000	16,000	1,964

See footnotes next page

Welding Costs for Saturation Diving (footnotes)

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable.

Charges based on Gulf of Mexico rates.

(a) One day decompression required for each 100 feet of depth regardless of job duration

(b) 1200 $/day under pressure/diver

(c) 15,000 $/day includes saturation diving system and diving and welding support equipment (Diving barge additional if required)

(d) Mixed gas cost assumed 8,000 $/day for work, 2,000 $/day in chamber (Gas cost actually increases with depth but cost data unavailable)

(e) 6 working hours/bottom day/diver

Manned Submersible Deployment Costs

depth	bottom hrs. / day	cost / bottom hr.
1 ft.	10 hr.	$ 1,280
500	10	1,299
1,000	10	1,318
5,000	8	1,765
10,000	6	2,450
15,000	4	3,635
20,000	2	6,821

All costs apply to a manned, untethered submersible with an operating endurance of 12 hours.

Coat data: (1) Surface support 12,000 $/day

(2) Salary and consumables 80 $/hour

(3) Capital recovery factor is 37.05×10^{-3} $/hour/ft.

(Reference 24 adjusted for 8% annual inflation)

Remotely Operated Work Vehicle Deployment Costs

depth	$\frac{\text{bottom hr.}}{\text{day}}$	$\frac{\text{cost}}{\text{bottom hr.}}$
1 ft.	24 hr	$ 535
500	24	554
1,000	24	573
5,000	24	728
10,000	24	921
15,000	24	1,114
20,000	24	1,307

All costs apply to an unmanned, tethered remotely operated work vehicle with an operating endurance of several days.

Cost data: (1) Surface support 12,000 $/day

(2) Salary and consumables 35 $/hr.

(3) Capital recovery factor is 38.61×10^{-3} $/hour/ft.

(Reference 24 adjusted for 8% annual inflation)