Robotics Undersea

Key concerns include position feedback, preprogrammed tool exchange and work operations, automatic television tracking, object and plane definition, and manipulator controls

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During the past two decades, the U.S. Navy has been a leader in the field of developing unmanned undersea vehicles and work systems. This technology base, developed under such programs as CURV III (Cable-Controlled Underwater Recovery Vehicle), RUWS (Remote Unmanned Work System) and WSP (Work Systems Package), has been transferred to industry. As a result, the use of similar remotely operated vehicles (ROVs) has been increasing in areas such as the North Sea where they are aiding divers in their work and completely replacing them in others. ROVs are being used by NASA to recover the solid rocket boosters of the space shuttle, and by the nuclear industry for the inspection of internal systems, a hazardous job previously performed by divers. However, the industrial acceptance of these systems is in its infancy. There is always a lag between development of a system

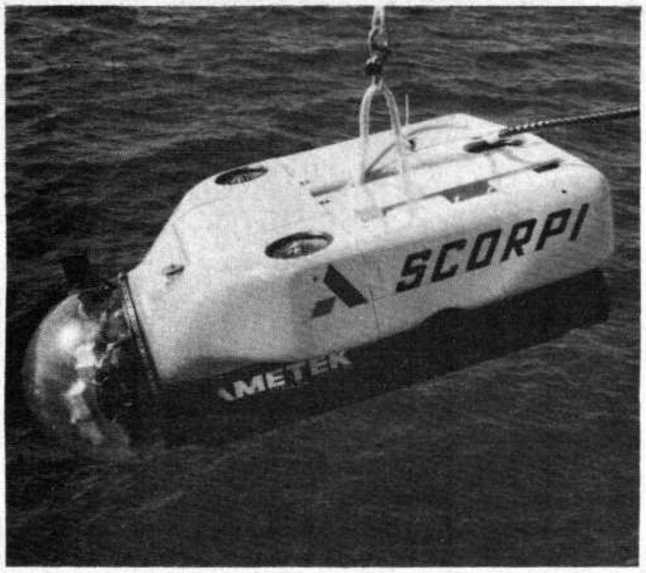

Fig. 1 SCORPI inspection vehicle.

and the confidence required by the user before becoming comfortable with it. Therefore, technological advances must be incorporated into systems at the earliest possible time to reduce the lag time of technology transfer and acceptance. In accordance with this philosophy, the Navy is continuing its quest to advance the state of the art in the area of ROVs and work systems.

One of the primary technological areas being addressed is the application of robotics to these systems. Robotics can have different meanings to many. However, it can generally be described as integrating the computer into a system, turning some or all control functions over to it, having it make key decisions, and reporting the results to the supervisory operator. The integration of the work system, the computer, and the supervisory operator is a critical area. Which one will control the operation? How much will it control it? How is control systematically passed from one to the other?

Classification of Systems

As in the use of the term robotics, the definition of a work vehicle or system may also be interpreted differently depending on the user. Therefore, the following classification of ROV capabilities is provided.

Inspection—All ROVs are capable of outside inspection of an object. However, this definition applies to vehicles capabale of inspection only, e.g., the Scorpi manufactured by Ametek, Straza Div. (Fig. 1). A vehicle with a capability of inside inspection, e.g., inside the cockpit of an aircraft lost at sea, would require a manipulator or arm that could hold a TV camera to be extended into the object, such as the RCV 150 by Hydro Products (Fig. 2).

Recovery—This definition covers any type of recovery operation, from simple grasping of a small object on the ocean floor, to recovery of a large object by means of a claw-type mechanism. When a recovery task becomes more complicated and involves, for example, placing slings around an object or rigging it with lines or snap hooks, it approaches but is not included in the category of work. If a system is not dedicated to making mechanical modifications to the object, it is classified as a recovery system.

Work—This category is defined as the performance of mechanical modifications to an object. Although these modifications may be for the purpose of recovery, they are still considered work operations, and a system with this capability woulld be considered a work system rather than a recovery system. An example is the Work Systems Package developed by the Naval Ocean Systems Center (NOSC) (Fig. 3).

By combining the manipulators required to perform the previous tasks, a means is then available to classify systems through the number of manipulators integral in the system (Fig. 4). For example, with an inspection system, no manipulators are required to actually see the object of interest, although it would be nice to have a single manipulator to retrieve a small object or perform some other minor task. For recovery tasks, at least a single manipulator is necessary, and a more desirable configuration would be one with two working arms. In other words, a system such as CURV III, with a single simple manipulator, could recover a torpedo, but it would be very hard for it to perform complete rigging operations. This would require a second arm for assistance, such as holding on to the point to be rigged with one arm while the other does the rigging. Unless the object is large (i.e., stable), and the vehicle is sitting on the ocean floor, no work can be done unless you have hold of the object to be worked on. This is dictated by tool positioning accuracies required to perform "real world" work. Holding on to the object is necessary to stabilize the work system with respect to the

Fig. 2 RCV-150 with manipulator.

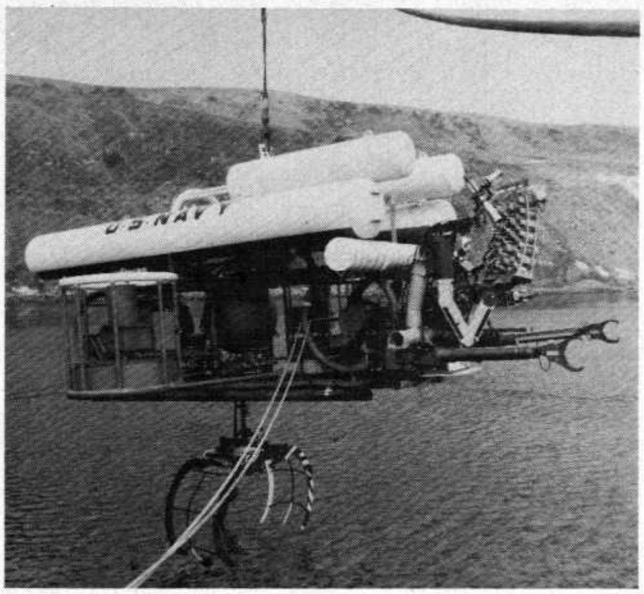

Fig. 3 Work systems package mounted on the Pontoon implacement vehicle.

object. The argument for stabilizing the work system is quite evident in the industrial world, where robots are being used extensively for manufacturing or work processes. In industry, all systems are programmed around a defined set of locations, a "work cell." Within the work cell the location and orientation of all items—tools, machines, manipulators, parts, etc.—are known. This allows the manipulator or robot to efficiently perform its function with minimal assistance from the human supervisor. Ascertaining component positions is usually costly in the form of time, money, or both. Once this information is lost, some price must be paid to reacquire it. Often, the price is the intervention of the human operator into a task that could have been performed autonomously. Therefore, if given the choice of a system design to which computerized control methods are to be applied, a system that can retain the position information—i.e., establish a work cell—would be preferred. Unlike industry, undersea vehicles face a harsh, dynamic environment, and therefore require a multiarmed system that can create a work cell, i.e., a *work system.*

The controls required for a system to operate efficiently depend entirely on the type of tasks to be performed. Therefore, the system configuration, i.e., the number of manipulators, can be associated with a series of specific tasks. This association is provided in Fig. 5, in which the three generic types of systems (inspection, recovery, and work), the number of manipulators, and potential tasks are correlated. The "minimum manipulator requirement" is considered that which is definitely required to perform a given task, although through the use of brute force and ignorance some of the tasks can be completed with a simpler system. The "optimum manipulator requirement" indicates the number of manipulators that would be desired to efficiently perform the task. In general, a one-manipulator system would be considered an inspection system; two manipulators would classify it as a recovery system, while a three-manipulator system would be considered a work system. Therefore, to increase the work or task capability of a vehicle it is necessary for the manipulator suite to go through a metamorphosis as it changes from an inspection to a work system. With the definition of a work system provided, the application of the computer to it, and some potential benefits can be discussed.

Design Philosophy

As previously described, the heart of any work system is the manipulator suite. The question is which type of manipulator is required to perform underwater work tasks, especially if computer controls are being considered. The answer has two parts.

The first part concerns the sophistication of the system required to do the task. Most manipulators can fit into three classes based on their design and control system: Simple rate control (without position feedback); position controlled (with position feedback, e.g., terminus controlled or master-slave); and position-controlled with force-feedback. Studies have been performed by several researchers that relate the performance of these types of manipulators to task complexity. In general, as the manipulator becomes more anthropomorphic, the time to perform a task decreases and the complexity of the tasks that can be completed increases. Eventually, each type of manipulator reaches a practical threshold beyond which it can't realistically perform tasks (Fig. 6).

The second part of the answer addresses the usual tradeoff problems involving manipulator complexity, reliability, cost, efficiency, and capability. Figure 6 also shows the general relationships between these factors. Obviously, an efficient system capable of doing most tasks will increase in cost and complexity while decreasing in overall reliability.

Since the ultimate goal is to incorporate computer control, the selection process is narrowed. In order to use the computer, the position of all joints to be controlled must be known; therefore the manipulators without feedback are immediately eliminated. This constrains the designer to at least a medium level of complexity in manipulator design. Although the addition of position sensors on the manipulator may be a trivial task for most industrial applications, their addition on undersea manipulators becomes quite complex when they must be isolated from the water, pressure, and the usual hazards of working in unknown environments.

The requirement for force-feedback is, therefore, the only decision remaining. Although force-feedback manipulators have outstanding benefits, they also impose

System Type	Manipulators Required	
	Minimum	Optimum
Inspection	0	1
Recovery	1	2
Work	2	3

Fig. 4 System manipulator requirements.

Specific task classification	Optimum manipulator requirements	Generic task classification	Minimum manipulator requirement
Outside inspection	1	Inspection	0
Inside inspection	1		1
Small object recovery by grasping	1		1
Ordnance recovery	1	Recovery	1
Jetting	2		1
Small object recovery by line attachment	2		1
Large object recovery by claw attachment	2		1
Cable clearance	2		1
Explosive pad-eye attachment for recovery	2		1
Object preparation and rigging for recovery	3		2
Undersea structure inspection (with tools)	3		2
Special purpose tooling use	3		2
Offshore emergencies	3		2
Component extraction from object	3	Work	3
Object installation and maintenance	3		3
Large object recovery by multiple attachment	3		3

Fig. 5 System configuration versus task capability.

fatigue on the operator, which is not desirable during long operations. In addition, this type of system will force a quantum leap in the levels of cost and complexity. Therefore three other factors should be considered. First, most tasks can be completed with a position-controlled manipulator without force-feedback, although at a subsequent cost in efficiency. Second, where force-feedback is absolutely necessary, it has been shown that it can be presented visually, allowing completion of these tasks, although with a time penalty. In this case, the master controller is not increased in complexity. Third, through the use of the computer, the manipulator design can be kept relatively simple while still providing force vector data. Thus, the typical force-feedback manipulator system is not

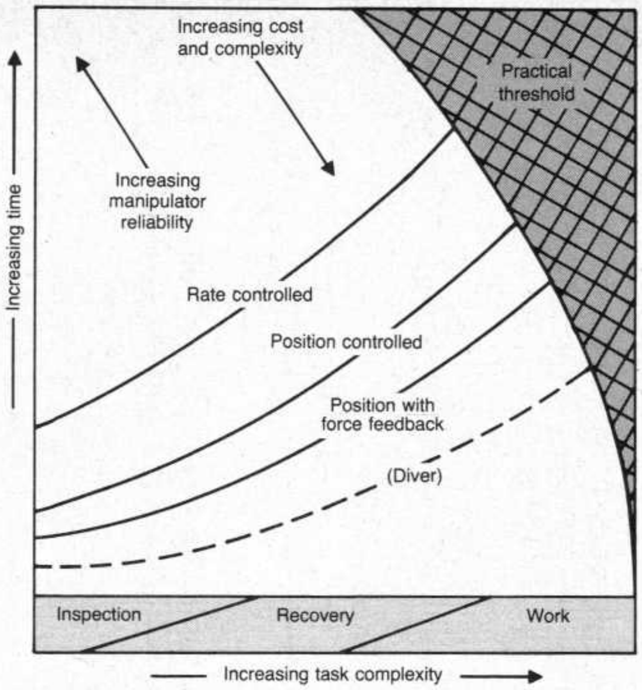

Fig. 6 Parametric manipulator relationships.

a basic requirement since most of its benefits can be acquired in other, more simplified ways.

Computer-Augmented Control System

After the design engineer addresses all the previous tradeoffs, he may often wonder how he is going to design a state-of-the-art system, or advance technology, when to do so will obviously condemn the system due to its high complexity, cost, etc. Fortunately, the addition of the computer to the system design reduces many of the previous problems while advancing systems technology and increasing system efficiency. For example, previous master-slave manipulators have used replica type controllers. These controllers have the same number of joints and degrees of freedom as the slaved manipulator, although they are of a smaller scale, and cannot be easily simplified. Through computer integration, mechanical complexity of the controller can now be placed into the software with the resulting simplification of the mechanical system. Through the use of algorithms for transforming coordinates, the controller can be reduced to a simple terminus type position-controller, as shown on the control console in Fig. 7. The computer controller may also allow simplification of the mechanical design of the slave arm. Often, mechanical complexity is increased to allow the manipulator to follow linear paths, or its dexterity is reduced to allow it to be more easily interfaced with the controller. Much of this can also be done with the computer by turning this requirement over to the control software itself, thus simplifying the manipulator.

With the computer-controlled work system justified, the engineer is left with a final decision: Which type of controller to use to best perform the high number of tasks required by the work system. Some systems, such as the Work Systems Package, were designed to perform many tasks completely without coming back to the surface to change tools. Design of such a system requires an in-depth look at the tool suite, being sure that you have the

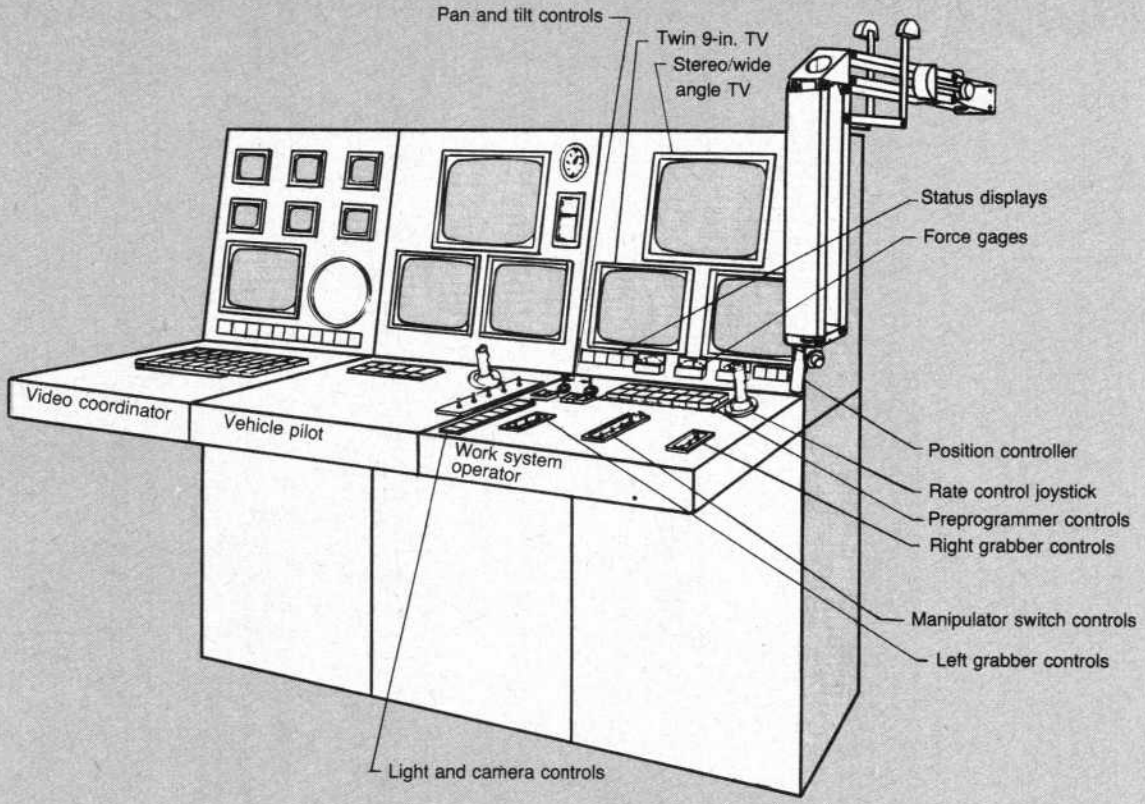

Fig. 7 Control console concept.

best tool for each job, and in some cases a few of the tools will back up others in the performance of a similar task. Based on the task at hand, the manipulator operator, much like the mechanic working on a car, will reach into his toolbox and obtain the tool *he* feels is best for the job in that situation. Since this choice is operator-dependent, it is often given a fair amount of design attention. This is the point where I feel that the design process often comes to a halt. The manipulator and tools have been chosen and are usually followed by a tradeoff to choose *the* best controller. What is overlooked is that the choice of the controller is more task- and operator-dependent than the tools themselves. The operator needs to be given a choice of which combination of input and output devices he desires to use for the task at hand. This becomes even more evident when the mission will be a long one, using more than one operator, since each may have a preference for which controller is the best. For example, with the choice of the computer as one of the controllers, the operator will obviously use it in any situation where it is considered beneficial. This will greatly reduce operator fatigue. Sitting at a control console for six hours operating a work system has a high fatigue level to begin with. Combine that with several hours of the operator using "body English" to move the manipulator on the TV monitor a "little bit closer" to the object, and you have one tired operator with an awfully stiff neck. The more a control system can reduce this fatigue level and provide the supervisory operator with an occasional break, the more efficient the overall operation will become.

Manipulator Control Modes. As discussed, the choice of the controller is dependent on the task at hand, the tool to be used, and the operator's preference. Therefore a multimode control console is desired that provides this versatility.

Switch Control (*open loop*). This control choice is included as a "fallback" option in the event of a position sensor or computer failure. Although a primitive method, this type of rate control has its advantages for the operator using certain types of tools in work situations. Often a slight movement by a single joint is all that is required, such as in drilling or cutting operations, and the operation would be hampered if other joints were moved. Therefore a position controller may not be desired in this situation, since a slight movement could cause other joints to become misaligned. It is also a less fatiguing form of control for the operator during long tasks. This type of rate control has been used successfully on the WSP.

Switch Control (*closed loop*). Through the addition of the computer to the control system (with position feedback), the capability exists to greatly improve the function of rate commands. By adding closed-loop rate control the computer can actually generate a sequence of position commands extending in the desired direction. The manipulator will be controlled through the calculated sequence of positions as if they were a preprogrammed sequence or one generated by a position controller.

A variation of this type of control is the capability of automatic tool advance. A sequence of positions can be generated to cause the hand (or tool) to advance in a desired direction. Advantages of operating in the closed-loop manner are:

- the switches, or joystick, can control true linear orthogonal motions, with no cross-coupling of functions.
- there will be no creep in vane-actuated functions

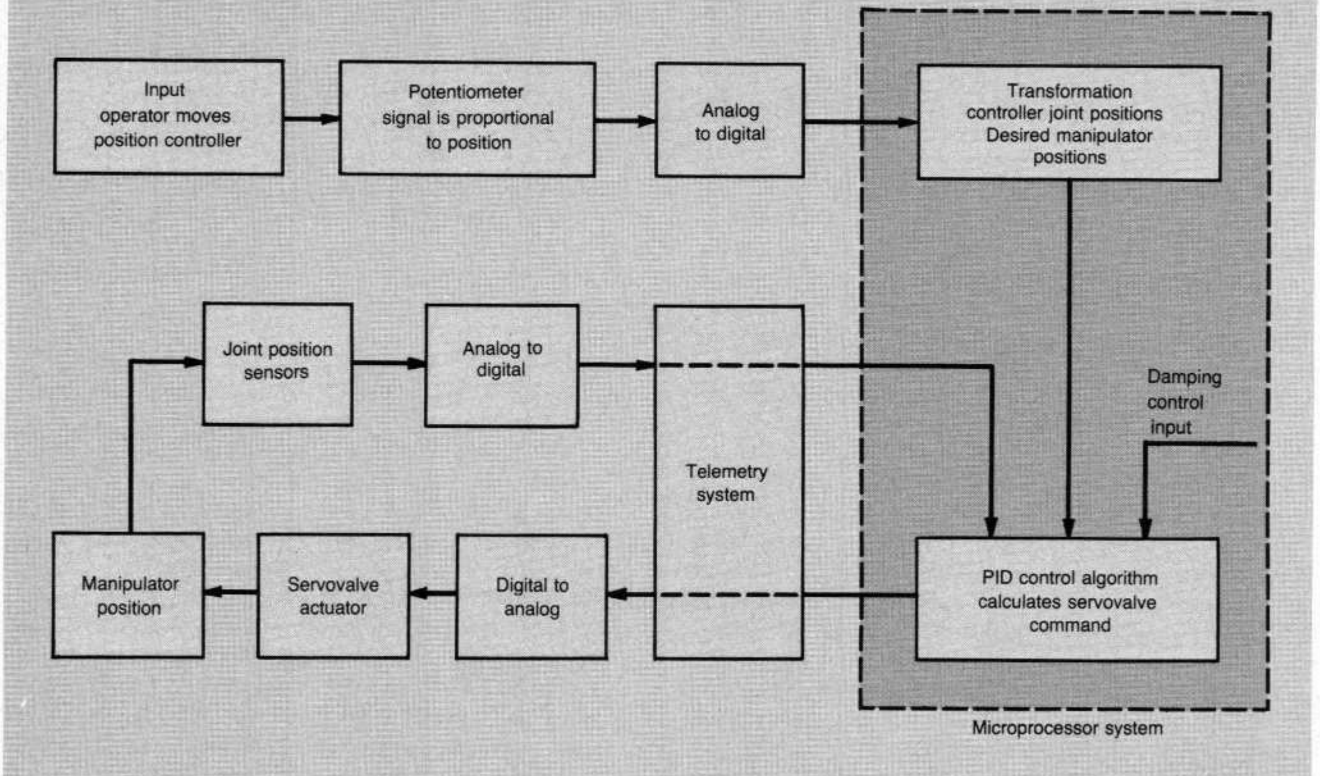

Fig. 8 Position-controlled manipulator flow chart.

- position and position commands can be monitored for sudden increases in error, as a simple collision warning.

Joystick Control. It would be desirable to have a joystick-type controller on the console to allow control similar to that with switches, but with the capability of controlling several functions at one time at a rate proportional to the displacement of the joystick. This would be beneficial in certain types of work where it is desired that the hand or tool follow a path in a straight line along a surface. This controller could operate the manipulator with respect to a set of coordinates located at the shoulder or wrist, depending on the task at hand. Once again, an excellent example of operator preference based on task requirements.

Position Control. This system has two key aspects: the method with which the computer controls the manipulator, and the method with which the operator controls the computer. It should be noted that the computer control of the manipulator actually applies to all closed-loop control methods.

The movement of the manipulator is caused by the computer's activation of servovalves on the arm, based on feedback from the position sensors. The servovalves will be driven at a rate proportional to the spacing of the commanded points to which it is to move and to the error between actual position and commanded position. This theoretically results in all functions arriving simultaneously at each desired position. However, the points to be transited will never actually be reached: the commanded points will continuously leap ahead as they are approached within some acceptable error (also a function of point spacing), like the electric rabbit at a dog race. Depending on the spacing of stored position commands, motions can be swift and smooth, or slow and precise. For this reason, the technique is called a "dog race."

Industrial robots typically use dc-torquemotors as actuators, so the signal is proportional to the actuator torque. In that case, as in using hydraulic *pressure* control servovalves, the signal should not be merely a function of the position error. The rate at which position error is changing, the error *derivative*, can be added to improve the dynamic response of the system. Thus, for example, if the error derivative is negative, implying the error is diminishing, the signal to the valve should be less than if the derivative is positive, indicating a growing error. A mechanical analogy to this control technique is a dashpot coupling the position controller and the manipulator arm. A correcting force proportional to the rate of change of error is transmitted to the manipulator via the dashpot.

Some compensation should also be made for steady-state position error caused by gravity, or "droop." Without such compensation, there would always have to be some error to create the actuator forces to resist weight. This error is often eliminated by adding a signal component proportional to the time integral of error, so that eventually even a small error creates a large enough restoring force to eliminate that error. When all three components—position error, integral, and derivative—are used, the system is called a PID controller.

A simpler control system can be developed if *flow* control servovalves are used. These produce essentially full system pressure at even very low signals; the *rate* of motion is controlled directly, not the torque. Therefore there should be no steady-state error, and integral compensation will not be necessary. Mathematically speaking, the integration occurs in the transfer function of the arm. Furthermore, since rate of motion is directly proportional to serovovalve signal, a simple error-proportional system should result in no overshoot. However, a differential term in the control algorithm would improve the response time of the manipulator. Tests or computer simulation would be required to determine the proper system gain, update rate, the effects of point spacing, and the potential advantage of differential compensation. An example is shown in Fig. 8.

In addition, during operation in any of the closed-loop modes, a collision by the manipulator can be sensed as a sudden increase in position error. The actual position of the manipulator will always be known and the computer could use this information to prevent collisions. However, this would require significant computer capability.

The method with which the operator controls the manipulator is also simplified through the integration of the computer. As previously discussed, earlier position controllers were more complex, usually a scaled-down version of the manipulator. They are often a strap-on or "harness" exoskeletal type controller, constraining to the operator and usually fatiguing. If force-reflecting, they are usually overly complex mechanically and also fatiguing. In addition, they do not lend themselves to the cramped quarters of a control van. Therefore a nonreplica type controller would be beneficial, since it would fit nicely over the control console, using the computer to perform the required coordinate transformations.

The manipulator geometry can't be changed, so that portion of the calculations is fixed; but by simplifying the controller, the other half of the calculations can be reduced. Designing the controller arm with a double parallelogram linkage causes the platform on which the pistol grip is attached to always remain horizontal. Therefore the axis of the potentiometer sensing yaw of the pistol grip is always vertical, and the pitch axis is always horizontal. This geometry simplifies the controller calculations to a few simple equations. Other minor changes to such a system could make it slightly more simple mechanically, or desirable from the human factors standpoint, but would cause the coordinate transformations to become much more complex. Thus, the controller shown in Fig. 7 is not optimized for mechanical simplicity, for computer design, nor for human factors; it is the result of a tradeoff among these three considerations.

As mentioned, the nonreplica controller can reduce the large swept volume required by other geometrically similar controllers. Since the motions of the nonreplica controller are converted to cartesian coordinates, its positions can simply be incremented by an arbitrary x, y, and z distance. If, in the course of a task, the controller handle reaches an awkward or uncomfortable position, the operator can electronically decouple it from the manipulator and reposition it to his liking. He merely holds down a button while he adjusts the controller, and all subsequent motion commands will be calculated relative to the position of the handle when the button is released. This process will be referred to as "ratcheting" because of the analogy to a socket drive tool. As a result of this ratcheting capability, the operator can remain comfortably seated, with elbow resting on the console, while controlling the manipulator hand near the ocean bottom, reaching to maximum elevation, or even working aft.

Programmed Control. Among the closed-loop options shown to be highly desirable is programmed control, in which the computer would be used to completely automate repetitious operations, such as tool exchange or other simple functions. This will not only reduce the amount of time to perform such operations by 50 percent or more, but will greatly reduce operation fatigue, once again giving the operator a break while the computer performs the more mundane operations. In addition, programs have been developed that will allow the operator to program the system at the work site, allowing the recall of subroutines to be repeated only a few times, such as following a path back to the work site and realigning itself.

System Controls. Once the computer is integrated into the system, other options now become available to the operator.

Automatic Pan and Tilt. The television cameras are mounted on actuator systems which drive them in the "pan and tilt" (P&T) motions. By automating the P&T system, the operating time can be reduced by up to 17 percent.

For automatic pan and tilt, the computer is required to perform a function that is entirely different from that for preprogrammed control. Instead of remembering a series of commands, it must perform a rapid and relatively sophisticated set of trigonometric calculations in order to generate those commands. Specifically, given the manipulator geometry and the P & T geometry, it must take the manipulator's measured joint angles and geometrically transform them into P & T joint commands.

There are high-level robotics languages designed for versatility in performing transformations from one arbitrarily defined device to another. The solution to this general problem requires very complex and time-consuming matrix algebra. However, for specific devices with fixed kinematic properties (e.g., the manipulator and P&T assemblies), the generalized transformations can be reduced to a simpler set of computations, so the specific kinematic equations for the system can be derived. By starting with the shoulder of the manipulator as the origin, and working outward segment by segment and joint by joint, it is relatively simple to find the cartesian coordinates of the hand. Then, as a sort of inverse problem, since the P&T location is known, the pan angle and the tilt angle necessary to aim the camera at the hand can be found.

Although Fortran would probably not be chosen as the final programming language, it was used to test the complexity and validity of such a solution. The program required about a dozen Fortran lines. It involved 10 trigonometric sines and cosines, and a couple of arc tangents. Both sine and cosine functions can be performed extremely rapidly and relatively accurately by using a single "look up" table in which the computer would have stored the values of these functions. This eliminates the slow process of calculating them using an approximating expansion. The arc tangent can be handled similarly, but requires several times as much computer memory for achieving the same accuracy.

Since the solution to this transformation is a collection of sums and products of trigonometric functions, the accuracy of the results will degrade with each such operation through built-up computational errors. Therefore, a microprocessor using a 16-bit word size—such as an Intel 8086—might better fit such needs rather than a standard 8-bit one. The program language most compatible with the Intel is PL/M. The location of the computer would optimally be in the topside van, rather than on the vehicle.

This places no special burden on telemetry bandwidth, since high-resolution position signals will be sent up the cable, rather than commands sent down. Low-resolution valve commands will also be sent down the cable, but this is a tiny fraction of total bandwidth. Locating the computer topside is in keeping with a general philosophy of having as much hardware as possible on the surface, rather than on the vehicle. It also provides the ultimate backup: In the unlikely event of a computer failure, a new card can be easily inserted. In the more likely event of a position sensor failure, operation can continue in the open-loop mode.

Object Definition and Visual Displays

A major problem with operating undersea vehicles is that they must often work in turbid water conditions, often caused by the vehicle itself as its thrusters disturb the bottom sediment. In a low current environment, this could be a potential disaster, since the water may not clear for some time. However, the computer can once again come to the rescue. Through the use of computer algorithms, the tip of the manipulator hand can be located, and this position data used to "paint a picture" of the object in the computer. As the manipulator touches its way through the scene, the contact points can be stored to produce a graphical representation of the object. Should the object be unfamiliar, but the task simple, the mission may be completed. However, should the object of interest be known in advance, the possibility of storing it graphically in the computer exists. Then, by defining some key points, the computer memory of the object can be fitted to the data on the screen, providing a complete "picture" of the object. At this point, the operator can work on the object or turn the work over to the computer through preprogrammed subroutines.

Control Console. Figure 7 illustrates the concept of a control console with three stations: video coordinator, vehicle pilot, and work system operator. The first two stations are drawn schematically, just to show their relationship to one another and to the work system controls. The video coordinator would be responsible for general monitoring, sonar operation, navigation, and selecting the video allocations needed by the pilot and operator. The pilot must fly the vehicle, guided by the coordinator, and position it with respect to the work in close cooperation with the work system operator. Only the right station, the work system controls, are addressed herein.

The primary controls for the manipulator and grabbers (stronger, less dextrous manipulators designed to aid in position keeping) are labeled in the lower right of Fig. 7. The various controls have been previously described. The position controller is a fully counterbalanced mechanical device which bears no resemblance to the manipulator, but from its joint position the computer will generate manipulator joint commands that cause the manipulator hand to follow the operator's hand. The rate control joystick will operate like an aircraft control stick; it will be spring-loaded to neutral, and displacement fore-aft, left-right, up-down will cause the computer to generate hand motions in the corresponding directions at rates proportional to stick displacement. The programmer controls will be used to store and command positions, position sequences, hand motions (such as tool advance), or whole tasks (such as tool replacement). The manipulator switch controls will be used, like the joystick, to control true orthogonal motions in a closed-loop, computer-generated position sequence or, in the event of computer or position sensor failure, the switch will command specific functions in an open-loop manner. The grabber controls would always operate in an open-loop manner. Manipulator and grabber switches are recessed to prevent inadvertent actuation.

The pan-and-tilt controls consist of two position-control joysticks. These are located on the upper left lap panel for ease of reach by the operator's left hand. Below these are switches for selection and control of cameras and lights, a function that can also be handled by verbal request of the video coordinator.

The primary displays are dual 9-in. (22.9 cm) TV monitors and a 15-in. (38 cm) monitor on which can be displayed the views from the various TV cameras or computer-generated graphic displays. Below the monitors are the usual system status displays and the manipulator analog force gages. The force feedback data and other system status information could also be displayed graphically on the video monitors.

Although there are multiple controllers on the console, it should not be considered to be complex with reduced reliability. Quite the contrary, since the computer controls all manipulator motion, the multiple controllers represent only redundant methods of directing the computer. The desired type of controller to be used is up to the operator, and should one fail, it results in only the loss of that input device with its resultant impact on operation efficiency. The control console is very versatile with built-in redundancy, an asset to any work system.

The Future

The control system discussed does not yet exist, although all aspects of it are within the state of the art and most have been developed or tested by various research organizations. Therefore the quest is to effectively integrate these subsystems into a work system designed to itself be integrated into an operational environment. Integration of such a system will not come easily, since the developers and the users must be aware of and design around the others' needs. This will result in the omnipresent lag time in transferring state-of-the-art technology to solving operational problems in the field. Yet there are more advances on the horizon. The control system of the future will turn more over to the computer. The operator will be able to verbally control certain functions while the computer provides the most critical display for that operation, be it visual, position, force, etc. The work load will be reduced to one where the fatigue factor has been eliminated, and the operator becomes a true "supervisory operator," with the computer handling the remainder. Eventually, with advanced vision systems, the work system may approach autonomy; however, it will hopefully fall just short of the capabilities of HAL, the rebel system of the movie *2001—A Space Odyssey*.

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