The MIT Marine Industry Collegium
Opportunity Brief #14

Teleoperators Under the Sea

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PREFACE

This Opportunity Brief and the accompanying Workshop (held on October 24, 1978) were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 90 corporations and government agencies who are members of the Collegium. The underlying studies at MIT were carried out under the leadership of Professor T. B. Sheridan, but the author remains responsible for the assertions and conclusions presented herein.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

Norman Doelling

1 July, 1979

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1.0 A Business Perspective

The rapid development of new vehicles for "seeing" and "working" beneath the sea is closely related to both market need and technology evolution. The market need derives from the increasing search for and production of offshore petroleum, and the necessity of limiting the associated risks to lives, property, and the environment. The technology evolutions are primarily related to the continued decrease in cost, size, and power consumption of computer hardware, and to advances in digital control of complex systems, in man-machine systems design, and in the areas associated with artificial intelligence or robotics. Commercial systems incorporating some of these advances have reached a level of sophistication at which they are beginning to create their own demand by demonstrating an ability to carry out a wide range of useful, and often novel, underwater tasks.

At MIT several research projects are being carried out to design, develop, test, and extend the capabilities of undersea vehicles. These activities serve a dual purpose. They provide students with insights into and experience in the research and development process within a context of real-world problems. In addition, these activities may bring forth advanced designs that may serve either as the basis for tomorrow's commercial systems or as modifications and refinements to systems already in use. The work described relates primarily to untethered, unmanned vehicles, in part because such vehicles offer the greatest challenge and in part because solutions to the difficult problems associated with such systems will have useful applications in tethered and/or manned systems now being developed, built, and used.

This Brief is intended to give an overview of the work in progress at MIT. The subsequent Collegium workshop, held on October 24, 1978, provided an opportunity for designers, builders, and users of undersea vehicles to meet with the Principal Investigators and students engaged in research related to such vehicles. The meeting gave Collegium members a new perspective on the commercial potential and applications of this research, and enabled MIT and Sea Grant staff to learn about industry needs and suggestions for research directions.

A few years ago, there were no commercial systems capable of seeing or working in our undersea environment. Today, there are somewhere between 20 and 100 commercial units in the field, carrying out a variety of tasks such as inspecting underwater structures, monitoring construction, and assisting human divers. The average cost of these units is over a half-million dollars ($500,000) each. As these figures indicate, the market has grown from zero to several million dollars per year in a short time. With offshore drilling going into deeper waters, with pipelines and offshore support facilities becoming more numerous, and with regulations protecting the coastline becoming more stringent, we can expect an escalation in the demand for remotely operable undersea systems. Not only can we anticipate the need for many more units in the field, but also for more sophisticated units that combine the ability to work as well as to see in the ocean environment.

2.0 A Taxonomy of Undersea Vehicles

To describe the problems being addressed in current research at MIT, it is essential to use a common taxonomy (classification system) and to have an understanding of the problems being addressed and the kinds of vehicles to which they are relevant. We use the term "teleoperators" to refer to vehicles that allow us to sense (see, hear, feel, etc.) and/or to manipulate things at a distance. More formally, a teleoperator may be defined as "a vehicle having sensors and actuators for mobility and/or manipulation, remotely controlled by a human operator, thus enabling the extension of the sensory-motor function to remote or hazardous environments."

2.1 A Three-way Classification System

One useful way of classifying teleoperators is on the basis of whether they are manned or unmanned, tethered or untethered, and whether they can only "see" (Search and Survey Vehicles) or whether they can also "do" (Work Vehicles). As Figure 1 (taken from Figure 2.2 of Reference 1) indicates, no <u>unmanned</u>, <u>untethered</u> <u>work</u> vehicle exists yet. But one can find several existing examples of each of the other seven categories. Much of the research work at MIT is related to the unmanned, untethered work vehicle, because most of the interesting technical problems of guidance, command and control associated with it are present, to some extent, in each of the seven other categories illustrated.

The problems of controlling manipulators or tools in the unmanned, untethered work vehicle are large and obvious. However, even in the manned, tethered work vehicle, the operator is "remote" from the manipulators being controlled. Thus the research on the more complex unmanned

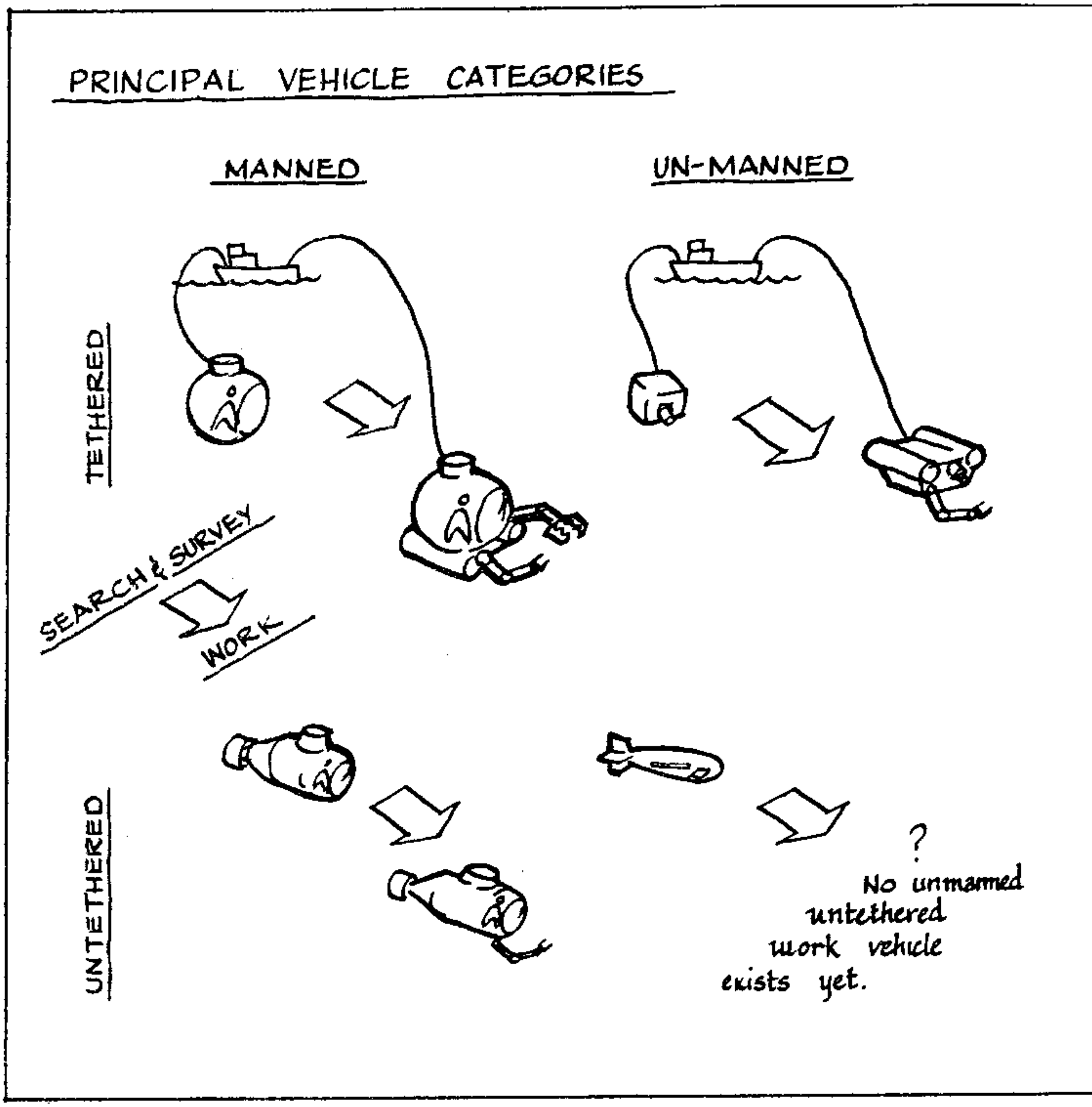

FIGURE 1 VEHICLE CATEGORIES for general purpose submersibles can be used for describing needed future developments.

As operations approach greater depth the increased cost and safety requirements suggest UNMANNED vehicles. Problems of reduced mobility due to tether drag, tangle and snare suggest UNTETHERED vehicles. Most undersea operations are incomplete without some kind of manipulation or WORK, for example search and recover, select and sample, inspect and repair.

The few untethered unmanned vehicles in existence are only search and survey vehicles. Significant problems of limited communication must be solved to provide either better control from the surface (teleoperation) or automatic control (robotics) or a combination (supervisory control).

system can contribute to the improved utilization of the simpler, manned work vehicle.

The three way classification system is not complete. Some tethered systems are towed, rather than being self-propelled. Furthermore, tethered self-propelled vehicles may also be classified as vehicles receiving power from a support ship and vehicles using an on-board power source. However, from a control, or man/machine viewpoint, this classification system is sufficient.

2.2 Direct Control versus Supervisory Control

As Figure 2 implies, classification may also be made on the basis of communication modes for command and control. Of particular concern to the research on undersea teleoperators at MIT is the concept of supervisory control versus direct control.

Most machines, vehicles or manipulators are controlled in some sense directly by a human operator. Even though the vehicle may be remote from the human operator, the system moves only in direct response to the human commands. Direct controls are useful when the human operator is in very close communication with the system being controlled.

However, when long time delays in communication occur, as was the case in remotely controlling a vehicle on the moon, some new control problems arise. To avoid accidents like falling into an unseen hole, the vehicle had to have some local autonomy (and intelligence). But since it wasn't smart enough to run around by itself for very long, it still had to be supervised.

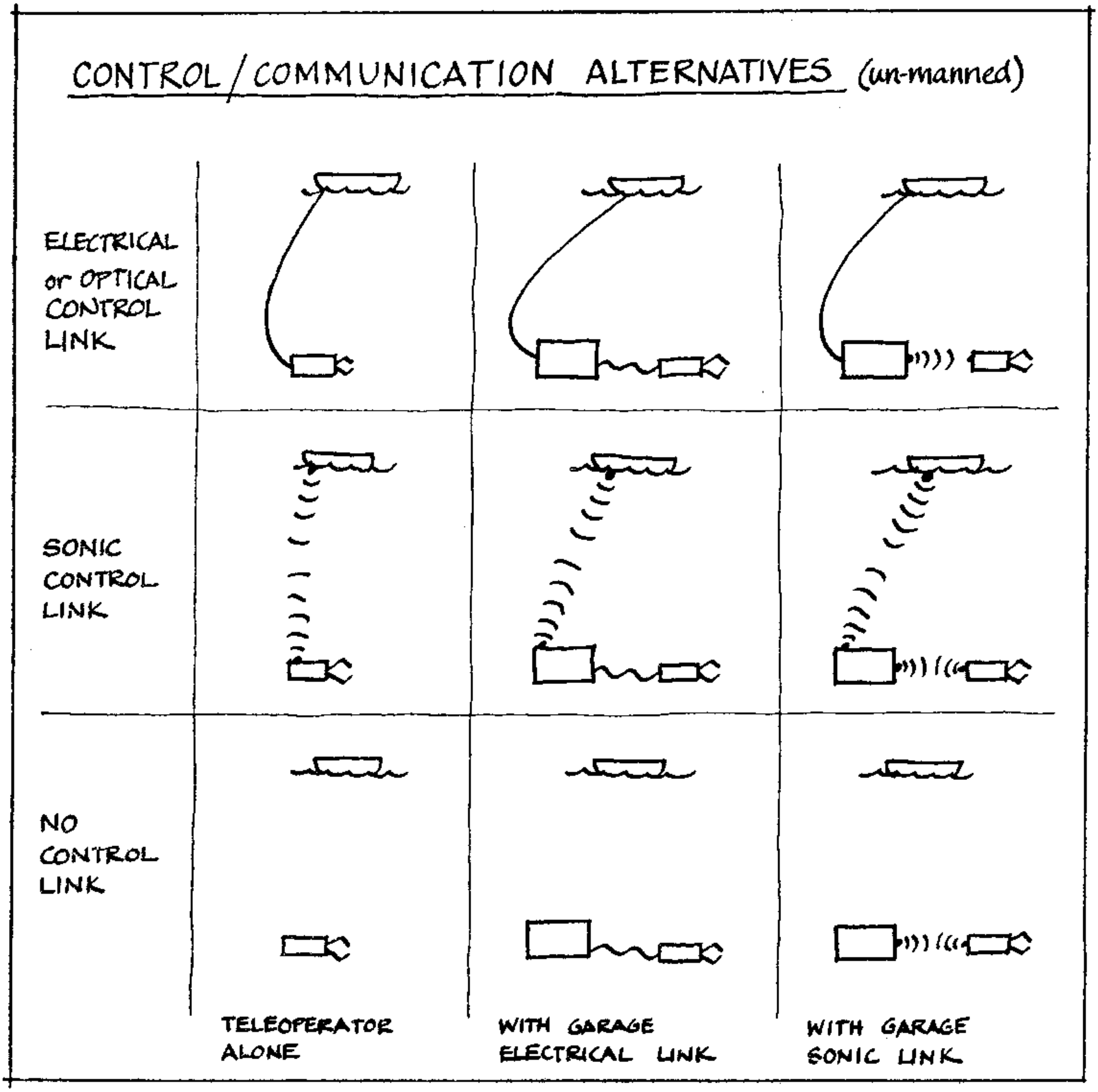

FIGURE 2 COMMUNICATION ALTERNATIVES for unmanned vehicles will be important in determining the trade-off between human and computer control. The particular configuration will, of course, depend on task to be accomplished, operating depth, size, speed, power source, duration, etc. The above matrix classifies alternative forms of communication: 1) with the surface ship (if any); 2) with an intermediary "garage" (if any).

This led to the notion of supervisory control, which can be thought of as a bridge between direct control and completely preprogrammed or robotic control.* More formally, supervisory control is "A hierarchical control scheme whereby a (teleoperator or other) device having sensors, actuators and a computer, and capable of autonomous decision making and control over short periods and restricted conditions, is remotely monitored and intermittently operated directly or reprogrammed by a person." (Reference 1)

The distinctions between direct and supervisory control are illustrated in Figure 3.

The notion of supervisory control is key to the current research on undersea vehicles both at MIT and elsewhere. Any persons seriously interested in remotely controlled vehicles must be comfortable with the concept. An excellent, readable and insightful exposition is contained in "Human and Computer Control of Undersea Teleoperators" (Reference 1).

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* We explicitly eliminate from consideration classes of work vehicles that might be described as varieties of robots, that is, vehicles that are completely pre-programmed to carry out a specific task and are sent off to do it under complete pre-programmed control. Basic advances are needed in pattern recognition, programming methods, and other areas of artificial intelligence before <u>useful</u> work applications can be undertaken.

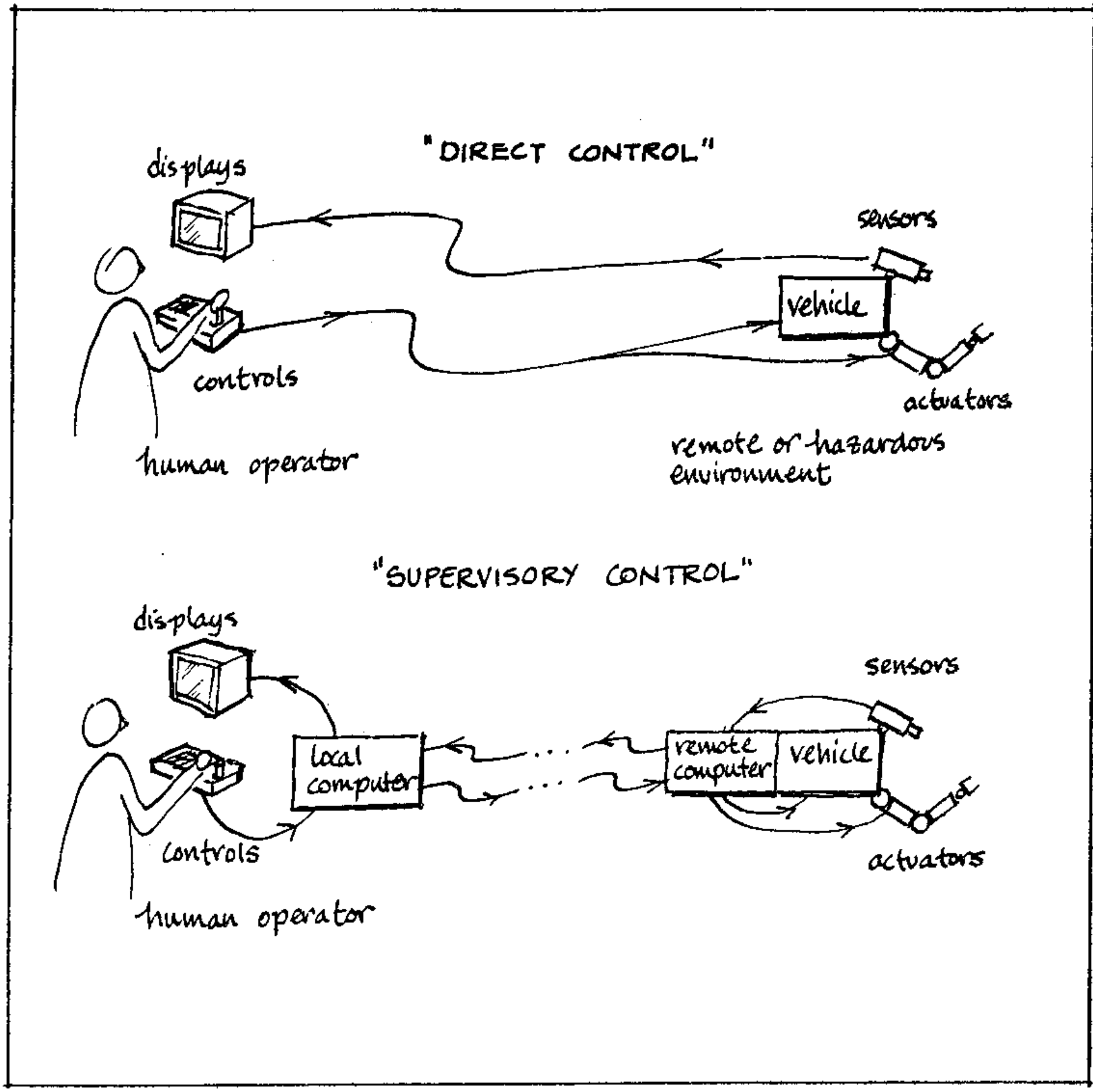

FIGURE 3 DIRECT AND SUPERVISORY CONTROL OF A TELEOPERATOR

3.0 Research in Progress

3.1 Context

Engineering research in a university environment must provide a relevant challenge to the students and faculty performing the research. Thus the problems selected for study are chosen for their intellectual content as well as other factors and not necessarily for the same reasons of "need" that might be perceived by industry or government researchers. In general there is a strong overlapping of areas of problem identification, but there will be differences concerning which problems should be addressed first. In particular, there is a tendency for university researchers to address tomorrow's key problems rather than today's key problems. We hope our research efforts indicate this bias.

With respect to teleoperation, there is a rich variety of problems to be worked on. We are emphasizing study in three problem areas, related to untethered, unmanned vehicles. The first area of study involves actual design and construction of search and survey vehicles, i.e., ones that see. We are not yet considering a work vehicle of the untethered, unmanned type.

The second area in which we are working is communication to and from a remote untethered vehicle. We are studying how best to communicate, command and control information with remote vehicles in the ocean using a combination of sonar and modem (MOdulation-DEModulator) technology adapted to the ocean environment.

Third, we are addressing the man/computer interface problems that are common to all supervisory control systems. We are emphasizing those aspects that especially relate to the underwater work vehicle, and particularly to the remote control of manipulators.

3.2 Untethered, Unmanned Search and Survey Vehicle Design

Several years ago a group of MIT students took as their undergraduate work project the construction of a robot submarine. The object of the exercise was to gain experience in the process of design and development rather than to fulfill a specific product need. The current research on robot submersibles is also driven by educational needs, but to a greater extent than before, the project is oriented toward a specific search and survey mission.

The important differences between Robot I and Robot II (as they are referred to) are:

1) A completely different approach to the autopilot design (digital instead of analog) and introduction of a supervisory computer, whose programs can be changed during a mission. Robot II allows communication between the surface and the vehicle, making use of the basic elements of supervisory control as defined in the previous section.

2) Robot II is being designed to include a variety of transducers or sensors to allow the robot to control itself, to sense some aspects of its environment, and, to a degree, to tell the operator about the environment in which it is operating, and where it is. The supervisory computer will be programmed to direct the operation of the vehicle on the basis of the information obtained from its sensors.

For example, ballasting and trim would be under automatic control. Sonar systems for collision avoidance, bottom following, side scan and navigation will be studied. In addition, sonars for handling com-

DEVELOPMENT PROGRAM

1. MECHANICAL

A. HULL

B. PROPULSION

C. ENERGY SOURCE

D. CONTROL SURFACES

E. BALLASTING AND TRIM

2. CONTROL SYSTEM

A. SUPERVISORY COMPUTER

B. DIGITAL AUTOPILOT

1. ATTITUDE SENSORS
2. COMPASS
3. SERVO MOTORS
4. MICROPROCESSOR

3. SONAR

A. SIDE SCAN

B. TRANSPONDER NAVIGATION

C. COMMAND

D. BOTTOM FOLLOWING

E. COLLISION AVOIDANCE

DEVELOPMENT PROGRAM FOR ROBOT II

FIGURE 4

mand and control information will be accommodated (see Section 3.3 below). The development plan for the untethered, unmanned search and survey vehicle is outlined in Figure 4.

3.3 Development of Underwater Communication Systems

While cables have obvious advantages in terms of communication and power supply, they have equally obvious disadvantages: they cause drag, snag on things, leak, break, and require enormous winches which in turn require larger ships to handle them. Thus elimination of cables has considerable appeal.

The object of this development program is to apply modern communication techniques to the ocean sonar signaling system, i.e., to synthesize systems that are optimum with respect to some set of constraints. Modems or telemetry systems designed specifically for the ocean environment will have to be investigated. Based on the physics of the ocean and known hardware (transducers, etc.), preliminary indications are that the performance of systems can reasonably be expected to look like those depicted in Figure 5.

During the Collegium workshop on October 24, 1978, Professor Baggeroer discussed two possible approaches, which are illustrated in Figure 6. One represents a purely untethered, cable-less system. The other would be useful on platforms in which high resolution communications might be needed, but when the need to avoid entanglement of the vehicle is important.

3.4 Research on Supervisory Control of Undersea Teleoperators

Whether one is inside a manned submersible controlling manipulators or on a surface ship controlling a manipulator on a vehicle 1000 feet below, one is <u>remote</u> from the manipulators being controlled. Thus

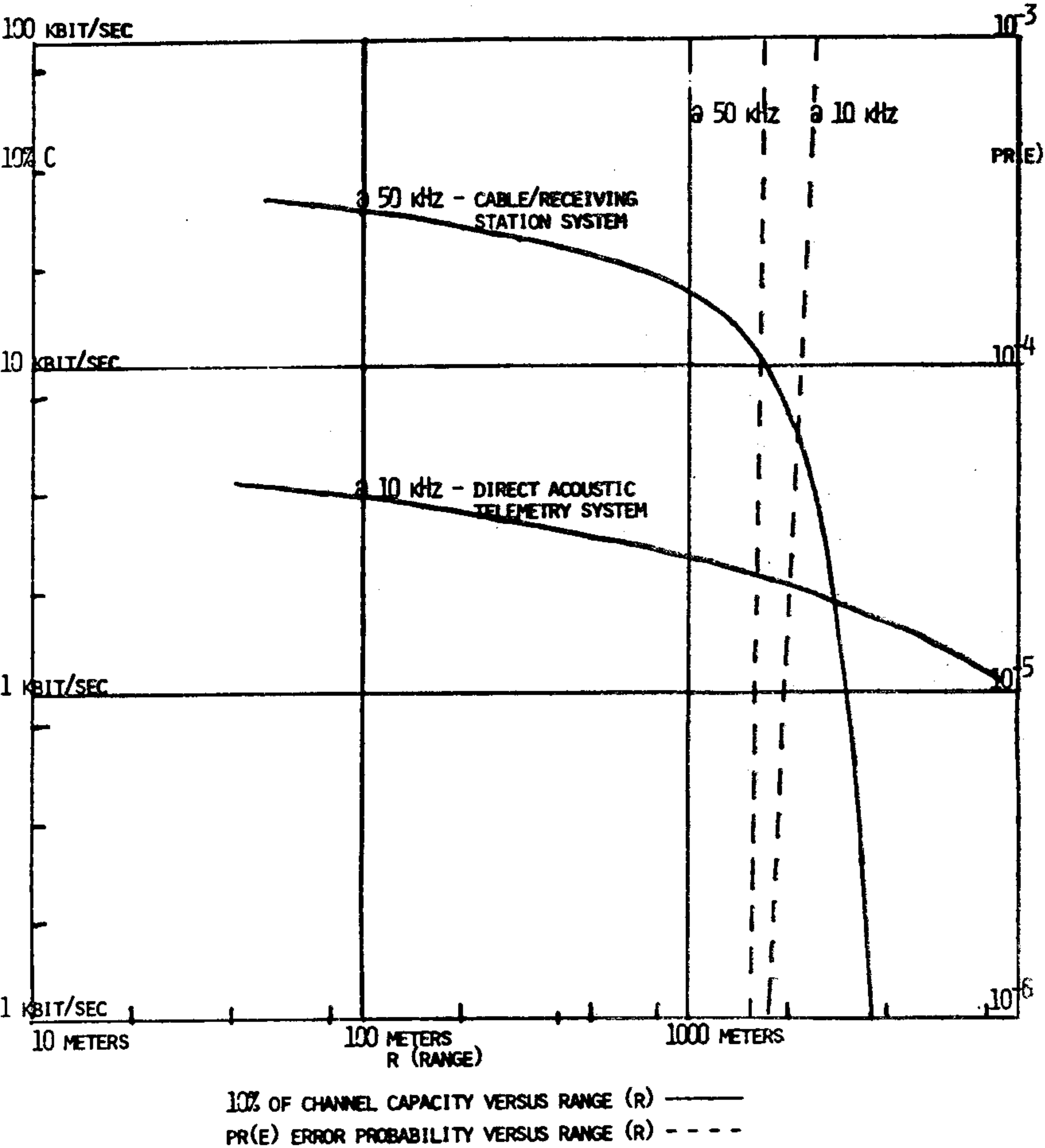

FIGURE 5

PERFORMANCE PARAMETERS FOR REPRESENTATIVE UNDERWATER COMMUNICATIONS SYSTEMS

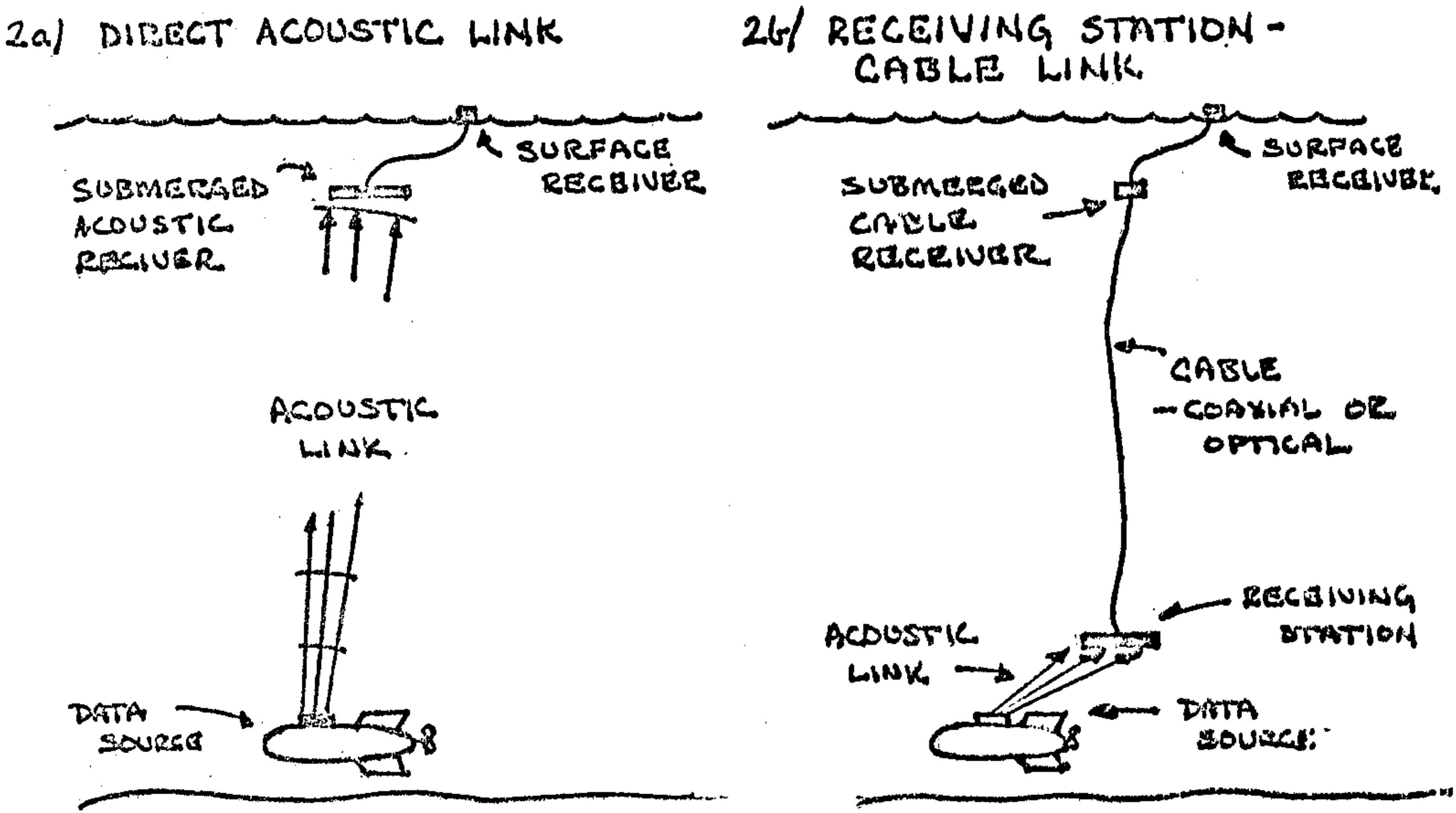

FIGURE 6 COMMUNICATION SYSTEMS PROPOSED

the notion of supervisory control appears relevant to almost any operations of manipulators or tools in ocean environments.

3.4.1 Research on Task Analysis for Undersea Teleoperators

A completely general purpose teleoperator would be prohibitively expensive (and unrealizable), and yet, very special purpose teleoperators are undesirable because they have to be redesigned and rebuilt (or junked) if a new or different task must be done. Thus it's essential to understand the kinds of work done in the ocean in order to achieve a useful balance between a very special purpose, low cost system and a very general purpose system.

As a starting Masters Degree student, Mark Schneider reviewed the literature and interviewed people who work beneath the sea. While this thesis (Reference 2) provided needed insights for initial research, it also identified specific additional information requirements and research which is needed to design reasonably general purpose teleoperators for doing useful work beneath the sea. The essence is distilled as follows:

"In view of the close relationship between task analysis and performance measurements of teleoperators, the research needs in these two areas are combined. Moreover, because tasks and the tools to do them must be matched, research is necessary to further clarify the teleoperator matching relationship.

"Continuing efforts are needed to define and classify undersea tasks of the kinds which might be amenable to teleoperation (although it is clear that such taxonomies will evolve as missions evolve and as teleoperator technology changes what is achievable by teleoperation). Data on both sequential contingencies and distributional frequencies should be compiled. Since much of what now passes for task analysis is compilation of anecdotal data, there is a clear need to observe, measure and record more objectively and precisely what is now done or attempted by divers or teleoperators." (Reference 1)

3.4.2 Computer-Assisted Control of Teleoperator Systems

Computers are an inherent element in supervisory control and two central issues are 1) how to make the computer easier to use and more helpful to the operator and 2) how much of the work load should be carried out by the operator and how much by the computer; how should each share in the work or how should they trade the work.

One area of active research is in language and hardware design for making programming a manipulator control simpler. One such system and language, modestly entitled SUPERMAN, shows promise as a useful supervisory manipulator control system. It accommodates multiple input mechanisms (keyboard, dedicated symbolic keys, and analogic inputs) to make it easy for a human to "talk" to the computer. The computer in turn talks to the operator via displays, pushbuttons, audiowarning signals and the like. This work by T. L. Brooks in the Man-Machine Laboratory at MIT was demonstrated via video-tape at the workshop.

3.4.3 Predictor Displays as Control Aids for Human Operators

We have used the term "remote" to connote a distance between the operator and the system being controlled. In some circumstances the operator may also be remote in time from the system being controlled. Time delays between the time an operator initiates an action and the time the action is confirmed present well known, very difficult control problems.

Time delays in some control systems arise from two sources. One source is the slow speed of sound in water. This problem is amplified by the requirement for a "round-trip-time" of a command signal to the untethered vehicle and the return of an acknowledgment signal from the vehicle. The other source of time delay arises because of the long time which may be required to send a large body of data through the limited sonar band width of the sea.

Video pictures provide an explicit example of time delay associated [redacted]

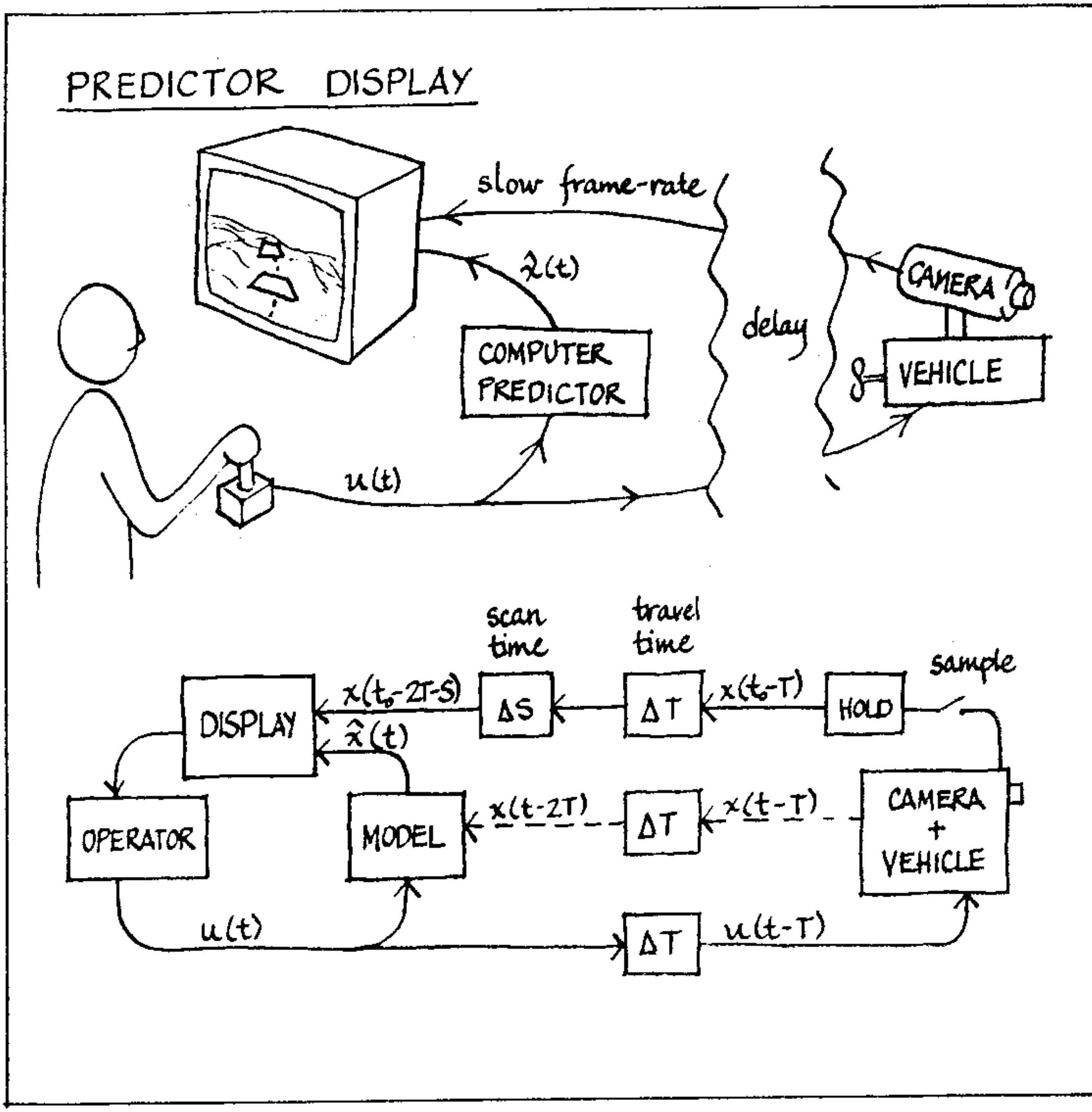

FIGURE 7 PREDICTOR DISPLAYS present the operator with dynamic information important for good control which he would otherwise have difficulty estimating. For example, a sonic link might give delayed (time T) and slow-frame-rate pictures (5 seconds/frame) at least 2T + S seconds "old". A local computer model of the vehicle's response is used to calculate and display the "current" estimated position of the vehicle, $\hat{x}(t)$ on the basis of the operator's commands u(t) and possible auxiliary position data (x(t - 2T), dotted line). The predictor symbol could be displayed in perspective superposed on the delayed picture. (Verplank, 1978).

4.0 Overview and an Invitation

The research being carried out within this theme area has been only briefly outlined, but its relevance to the requirements for vehicles to be in service five years hence should be clear. The NOAA Office of Sea Grant, the Office of Naval Research and the Naval Explosive Ordnance Disposal Facility as sponsors, and the Principal Investigators and students all value and welcome interactions, critiques, suggestions, and discussion with manufacturers and users of undersea vehicles concerning the course of the research, other research needs, operational problems, and the like.

While fostering this form of industry/government/academia cooperation, we hope to create a partnership in research, development, and education which will lead to better vehicles, sooner. Please contact the author if you have comments and suggestions.

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