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OCEAN ENGINEERING SUMMER LABORATORY 1975

**Massachusetts Institute of Technology
and
Maine Maritime Academy**

**A. Douglas Carmichael
and
David B. Wyman**

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

**Report No. MITSG 76-3
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Administrative Statement

The Ocean Engineering Summer Laboratory provides students from the Massachusetts Institute of Technology and from the Maine Maritime Academy with the opportunity to apply classroom knowledge to the actual designing, building, and testing of equipment for use in the ocean environment. This report describes student work completed during the summer of 1975. The continued development of the computer-controlled robot submarine was a major focus of this year's summer laboratory. Other projects, including the construction of a pedal vehicle for SCUBA divers, of a windmill-powered generator attached to a buoy, and of a floating breakwater, and the testing of cable strumming during tidal cycles, also demonstrate the positive benefits of students' experiences in solving "real-world" ocean engineering problems.

Dean A. Horn
Acting Director

April 1976

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SUMMARY

The fifth Ocean Engineering Summer Laboratory has been conducted and is reported here. The descriptions of the projects undertaken by the students are presented as chapters in this report. Three projects are continuations of previous work, utilizing the data and the technology developed in earlier Summer Laboratories.

During June and part of July 1975 the wreck of the "Defence" was examined by members of the AINA (American Institute of Nautical Archeology) and the Maine State Museum. (This wreck was discovered near Castine by participants in the 1972 Summer Laboratory). Students assisted in the examination of the "Defence" as part of the AINA team. They operated the air lift and participated in the survey and mapping of the site. These students also contributed to the sonar and magnetometer surveys described in Chapter 10 of this report.

PROJECT SUMMARIES

No.	Title	Student Participants	Summary
1	The Undercycle	J. C. Newman	A pedal vehicle for SCUBA divers was designed and built.
2	The Submarine Robot		The background to the submarine development is described.

No.	Title	Student Participants	Summary
3	The Hull and Propulsion System	D. G. Abbott M. Klonowski P. Kramer S. D. Jessup	The design, fabrication and operation of the hull and mechanical systems in the vehicle are described.
4	The Robot Electronics	W. Burke M. R. Fidelman C. L. Finkelstein M. J. Saylor G. J. Keller J. M. Driear R. A. Longhorn	The design and development of the computer and autopilot are described. The computer software and operating programs are also discussed.
5	The Robot Emergency System	W. H. Haag P. Kramer W. F. Whitelaw	The recovery of the vehicle in the event of possible malfunctions is discussed.
6	The Robot Test Program	D. G. Abbott W. Burke C. L. Finkelstein M. Klonowski P. Kramer W. Whitelaw	The operational development of the vehicle leading to the measurement and recording of water temperatures is described.
7	A Windmill Powered Buoy	C. W. Fay	The design, construction and operation of a windmill powered generator attached to a buoy are presented.

No.	Title	Student Participant	Summary
8	The Cable Strumming Experiments	S. W. Carle R. Ethier I. Kan R. J. Yak C. H. Mazel	Cables were set up on a sandbank and measurements of amplitude and frequency were made during the tidal cycle.
9	A Portable Floating Breakwater	B. C. Amero R. Gehring J. Leonard	A 60 foot long, 6 foot diameter floating breakwater was constructed and installed.
10	Preliminary Sonar and Magnetometer Survey for Vessels Destroyed in the Penobscot Expedition of 1779	B. L. Collins T. Darlington H. K. Dunning K. Fitzpatrick J. Jacoby M. McGuckin J. Mallory T. Mangion P. Scanlon G. Williams D. Wyman	Detailed surveys in the region of the "Defence" were conducted. In addition, areas where historical evidence had indicated possible wrecks were lying on the Penobscot River were also surveyed.

PREFACE

The Ocean Engineering Laboratory provides the opportunity for undergraduate students to design and build equipment for use in the oceans, and then to test the devices produced. This is the main objective of the laboratory. The relative inexperience of the students in engineering design and the time and other constraints results in equipment which not always operates successfully despite the energy and ingenuity of the students. On the other hand, modest successes are achieved at times and the pleasure that such successes provide is encouraging to observe.

The ten chapters of this report do not adequately convey the whole experience. Meetings were held in the evenings to describe the various projects and to present technical movies of interest.

About half the students participated as divers and carried out diving projects. A group of students also built and tested diver propulsion units constructed using commercial plans. The safety officer for the diving program was Professor Edgar Biggie of the Maine Maritime Academy.

Many distinguished visitors came to see the summer program in operation, and Dr. Harold Edgerton and Martin Maylach brought survey instruments which were used in the search for archaelogical sites. These efforts are described in Chapter 10 of this report.

1. THE UNDERCYCLE

The scuba diver with his rubber fins is capable of modest performance and maneuverability under the oceans. It was felt that the divers range of operation and his speed could be improved by providing him with a lightweight pedal vehicle that he could use for underwater transportation. The design, development and early testing of such a vehicle is described here.

1.1 PRELIMINARY CONSIDERATIONS

The major question is whether the power developed by such a system would be sufficient to propel a man underwater at a useful speed. Previous research and experimentation has resulted in the following relationship for the drag of a diver:

$$\text{Drag} = 4\ v^2$$

Drag is measured in pounds and velocity in knots. While a well conditioned human can develop as much as one horsepower with his legs for a short time, a more conservative figure of one tenth of one horsepower is sufficient to propel a diver at a speed of one and a half knots. For a brief period of time, a diver might be expected to reach speeds as high as three knots.

While a cyclist has little difficulty in keeping up a cadence of sixty to seventy revolutions per minute, it was thought that this might be difficult underwater, as the movement of the legs would introduce additional drag. While much of this problem can be solved by choosing

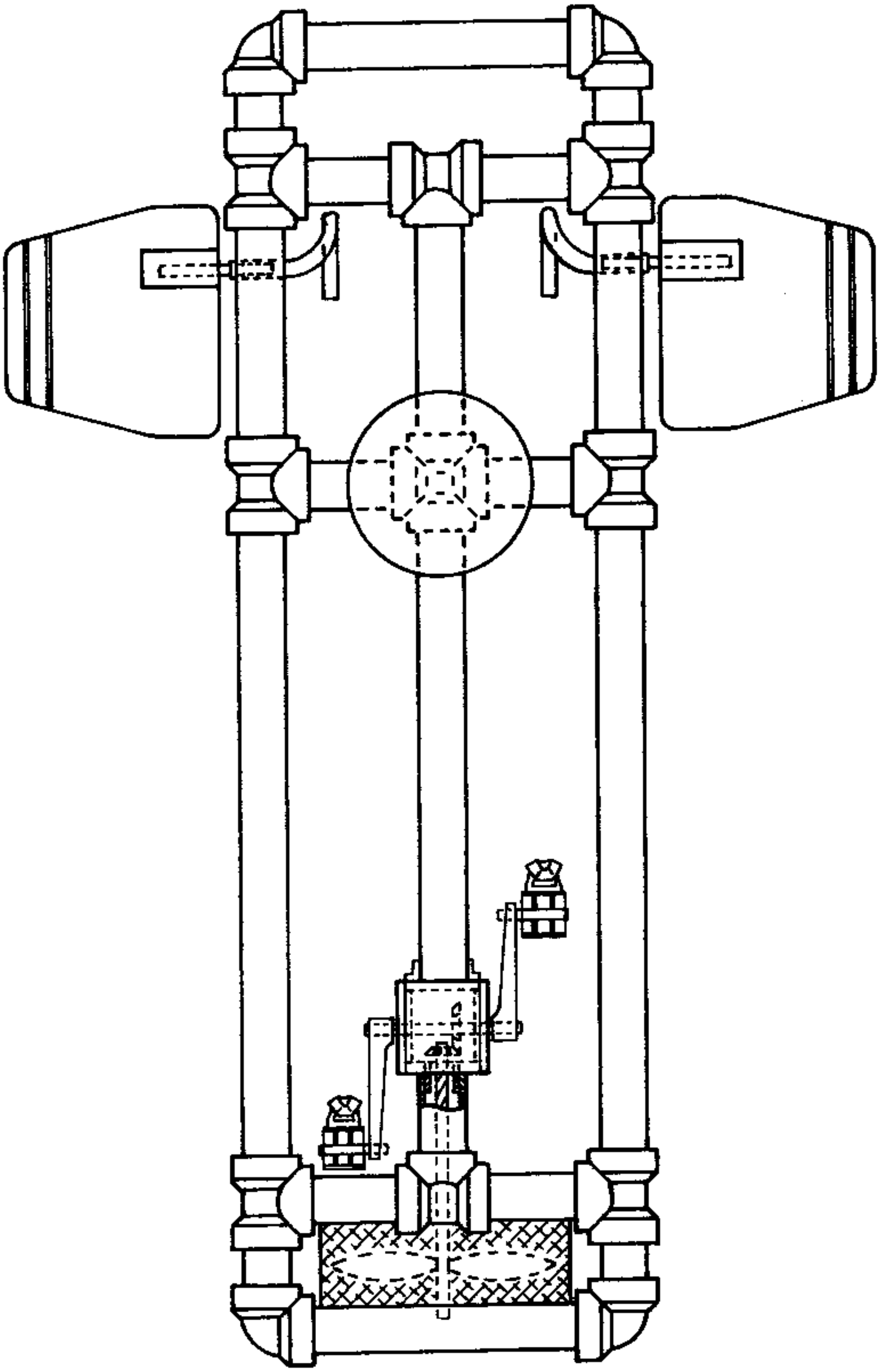


FIGURE 1.1 The Undercycle

the proper gear ratios and a slower cadence, it is clear that a relatively slow rpm of the propeller is an inherant part of an underwater man powered vehicle. It was very important, therefore, that as large a propeller as feasible be chosen, and that the rest of the craft be designed around its characteristics. The propeller chosen is a three bladed, fiberglass propeller, slightly over eighteen inches in diameter. The pitch to diameter ratio was measured to be roughly 1.1. From these characteristics the ideal revolution speed of the propeller was determined to be one hundred and fifty five rpm, yielding an excellent efficiency of 0.65.

1.2 DESIGN AND CONSTRUCTION

The major pieces of design work were the basic frame of the vehicle, the control surfaces, and the drive mechanism. The original design of the frame called for a tubular aluminum A frame structure. This design was changed to a rectangular shape in order to facilitate construction and mounting of the control surfaces, as shown in Figure 1.1. One and a half inch (inside diameter) PVC pipe and pipe fittings were used to construct the frame. The overall length of the craft is slightly under seven feet while it is about two feet wide. Mounted at waist level on the frame is a twelve inch plywood disc. The frame of the undercycle is free flooding, and since PVC has a specific gravity of about 1.2, the frame itself is negatively buoyant. At present, through the use of flotation material inside the frame the buoyancy of the overall craft is only slightly negative. The bow floats a bit higher than the stern, this having been found a convenient way to ride.

The control surfaces of the undercycle consist of two, individually operated front diving planes. Each of these planes has an aspect ratio of approximately one and a surface area of two square feet. Surrounding the propeller is an eight inch band of aluminum, which besides guarding the propeller serves effectively as a stabilizer. There is no rudder on the craft, steering is accomplished by raising (or lowering) the diving planes to different angles. The vehicle rolls into turns in much the same manner that an airplane does. Assuming a total mass of diver, equipment, and undercylce, of three hundred pounds, the vehicle has a calculated turning radius of twenty nine feet. At cruising speed the time needed to complete a ninety degree turn would be eighteen seconds.

The most difficult design problem is the drive mechanism, or more specifically, the gearbox. The pedals equipped with toe clips to keep one's feet from floating off, are attached to regular bicycle crank arms. These are attached to the brass axle shaft, which passes through the gearbox and carries a bevel gear. The propeller shaft protrudes from the gearbox in the rear, and runs to the stern inside the center pipe of the frame.

The gearbox is a four inch long section of six inch diameter PVC pipe. The axle shaft is centered in the endcaps of the gearbox. Designed with a watertight seal, the shaft is seated in noncorroding Teflon flange bearings, with dynamic "O"rings completing the seal. The drive shaft is similarly designed. The gears consist of a four inch diameter, cast iron bevel gear and a smaller hardened steel pinion. These gears, while well greased, should ideally have a protective coat to eliminate corrosion. The bevel gear has sixty four teeth while the pinion has sixteen, yielding a four-to-one ratio. Thus, in order to rotate the propeller at the optimal rate of one hundred and fifty five rpm the rider must pedal at a rate of under forty rpm.

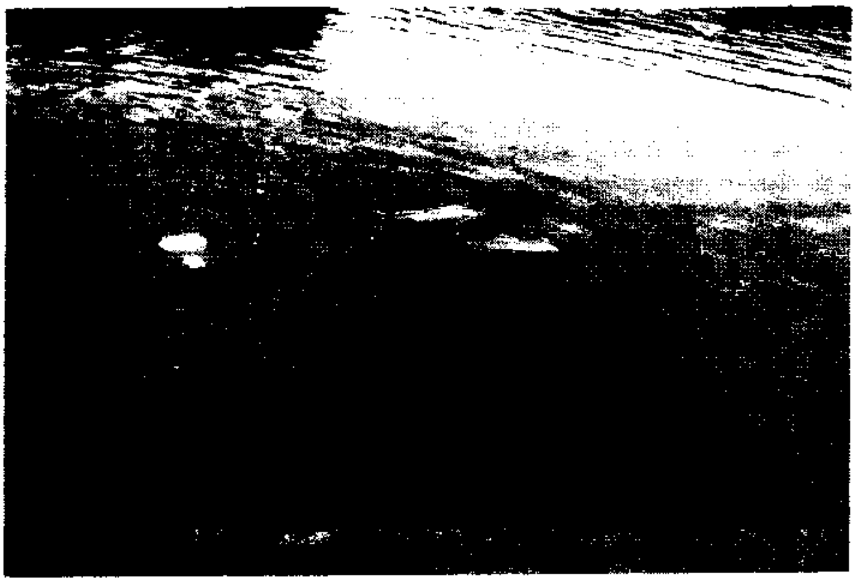
1.3 THE TESTING PROGRAM

The initial tests of the craft were to accomplish little more than determining the necessary ballasting and proper placement of the control surfaces. Eventually the buoyancy of the craft was adjusted to be slightly negative with the stern more so, to make riding near the surface possible without the propeller breaking the surface. The initial placement of the front planes was found to be satisfactory. Holes were drilled through the frame to allow for the handlebars.

The actual period of testing resulted in failures by several different parts of the craft. The original pedal crank arms, machined from PVC were not strong enough to resist the shearing force applied to them by pedaling. Several pins were also replaced with quarter inch diameter hardened steel cotter pins, as even easy pedaling developed very large forces and torque. The seal on the drive shaft at the rear of the gearbox proved defective which allowed the gearbox to flood. Besides greatly increasing the rate of corrosion of the gears this causes a great loss of buoyancy, nearly twenty pounds.

While all of the above failures were repaired or allowed for by modifications in the design, the craft still suffered from one problem. The transverse thrust of the propeller causes the entire craft to roll. This can be prevented by tipping up the opposite diving plane. However,

a. The Undercycle on the Beach



b. The Vehicle in Operation

FIGURE 1.2 The Undercycle

this results in many difficulties in maneuvering. The solution to this problem would be a weighted keel of perhaps twenty pounds placed below the rider.

1.4 CONCLUSIONS AND RECOMMENDATIONS

While the problem of the torque caused by the transverse thrust of the propeller unfortunately makes the undercycle somewhat difficult to learn to ride, the vehicle must be considered a partial success. It moves forward and backwards, and it turns and dives faster and easier than expected. Consideration could be given to sealing the frame as well as the gearbox. The tubes of the frame could be equipped with valves making the trim adjustable. While the vehicle is not easy to carry by oneself, it is not more difficult than a surfboard. The undercycle can carry much more gear than a diver can while swimming, and as the pedals turn almost effortlessly, it is a great deal more fun.

2. THE SUBMARINE ROBOT

2.1 SUMMARY

The design of the robot and its construction was completed for the 1974 Summer Laboratory. There were some shortcomings with the original design and it was not operated successfully under its own control in 1974. The method of operating the control surfaces (rudder and driving planes) was unreliable and changes in the computer and autopilot electronics were required. The development of the robot was continued during 1975 and it eventually operated under computer control with all systems working during the 1975 Summer Laboratory.

2.2 BACKGROUND

The design, construction and development of a computer controlled robot capable of making continuous measurements of temperature, salinity, and turbidity during controlled missions was considered to be a useful project for students of the summer laboratory. The specification for the vehicle was as follows:

Design Speed	3 knots
Maximum Range	20 miles (at 3 knots)
Maximum Depth	200 ft.
Maximum Weight	250 lb. in air
Instrument Payload	50 lb.

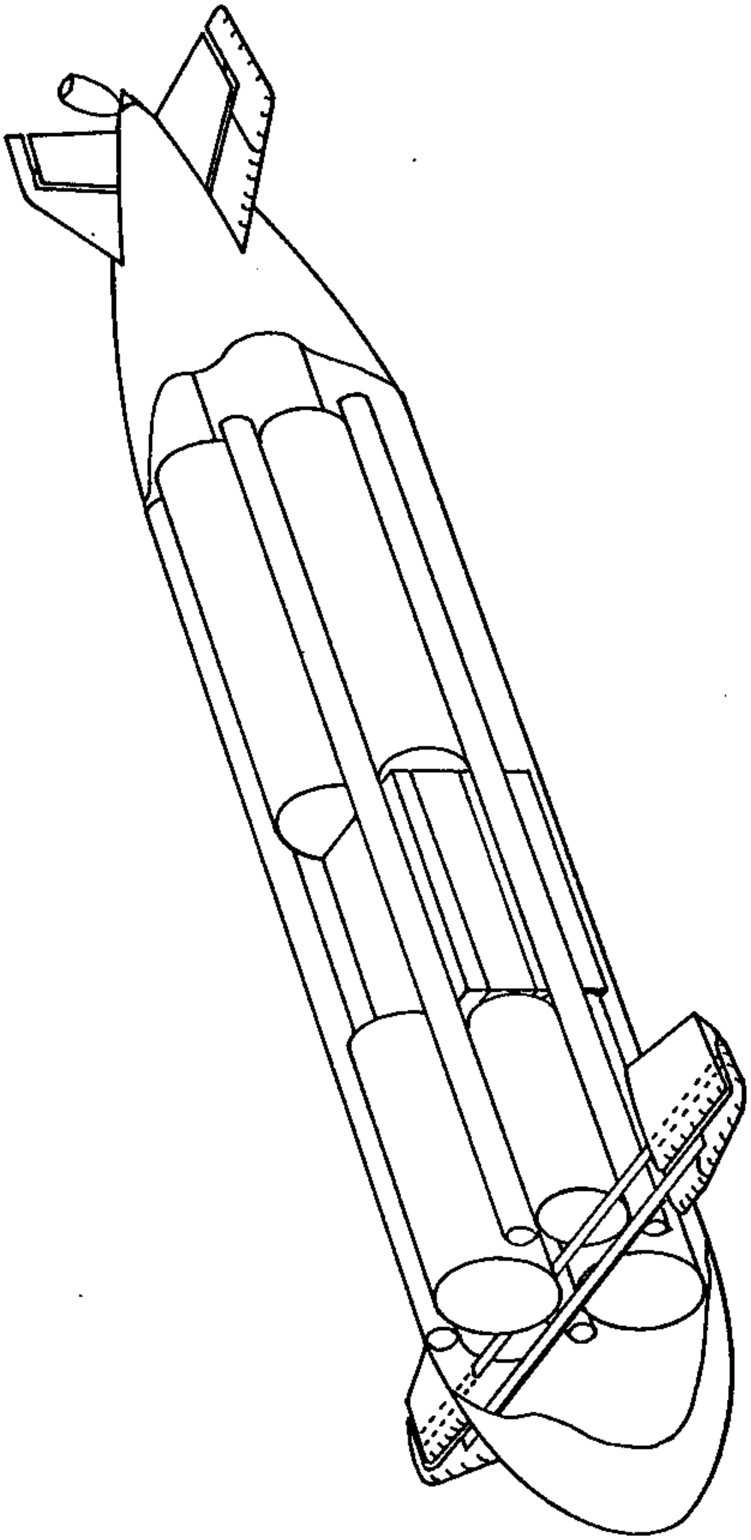


FIGURE 2.1 The Robot Submarine

Using this basic specification a design of vehicle was evolved which has proved to be satisfactory in every important aspect.

The robot is free flooding with all the critical components enclosed in watertight PVC tubes. The energy source is an automotive lead-acid battery and the propulsion is by means of a propeller driven by an electric motor through a reduction gearbox. A mini-computer provides the control commands which are executed by an autopilot. The computer memory can be used to store transducer and instrument outputs in addition to the control programs.

3. THE HULL AND PROPULSION SYSTEM

3.1 THE HULL

The outer skin of the robot is made up of a fiberglass nose, a fiberglass tail section, and cylindrical aluminum skin between the nose and tail sections split along the horizontal centerline, as shown in Figure 3.1.

Inside the aluminum skin there are three compartments separated by aluminum bulkheads. These bulkheads are located on four 2 inch diameter PVC tubes which are the main structural members of the submarine. In each of the front and rear compartments, in addition to the four 2 inch PVC tubes there are two 4 inch and two 6 inch PVC tubes. These tubes essentially fill the space in the front and rear compartments beneath the aluminum skin.

The lower 6 inch tube in the front compartment contains the autopilot while the similar tube in the rear compartment houses the mini-computer. The other six inch tubes could be used for scientific instruments although they have not yet been used for such purposes.

The bow diving planes are structurally supported by an aluminum beam which is bolted to the front bulkhead and passes across the submarine. The stern diving planes and rudders are supported by PVC fairings bolted to the fiberglass rear tail-section.

On the centerline of the tail section is the 6 inch PVC motor tube which houses the propulsion motor, reduction gear, and electrical

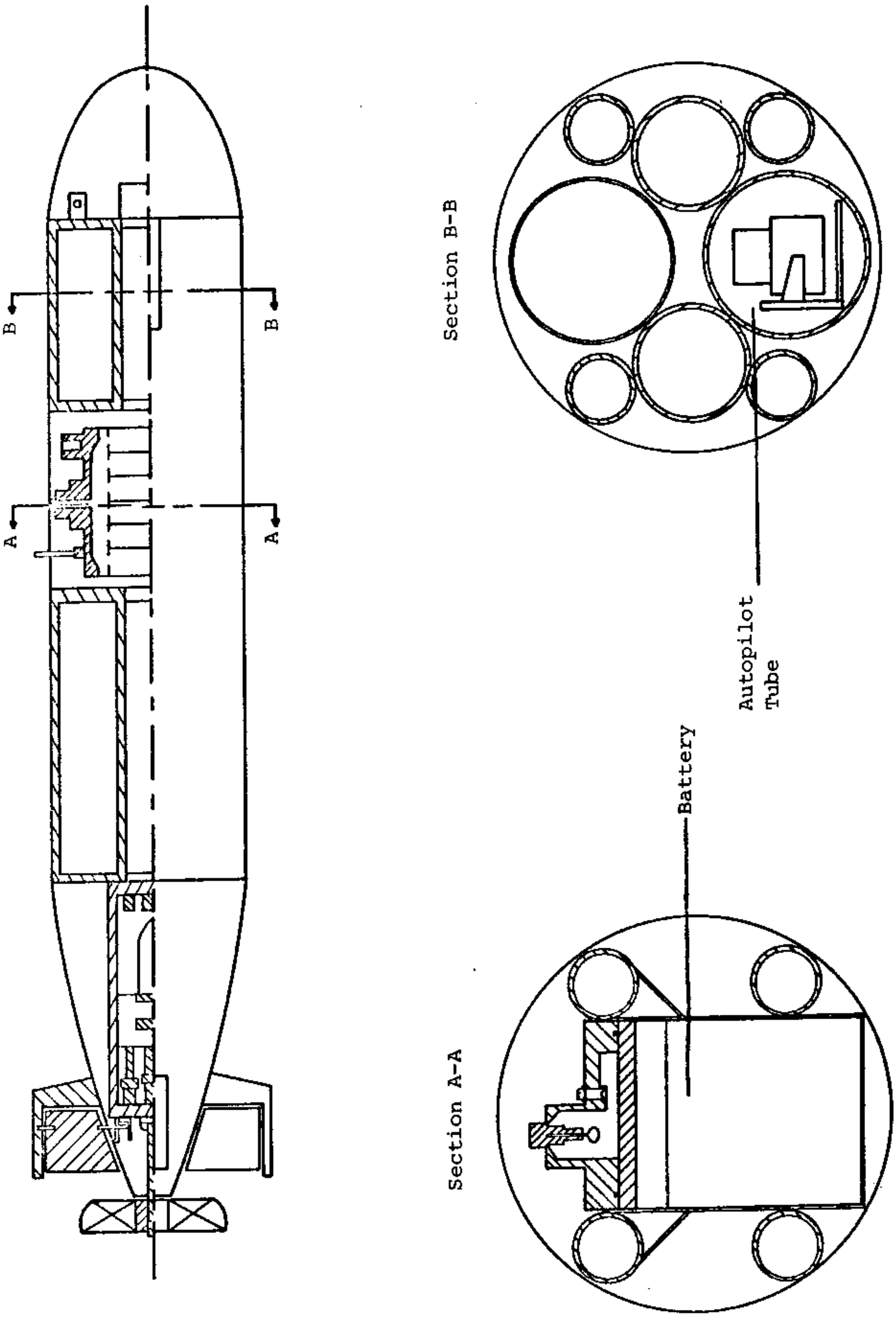


FIGURE 3.1 The Arrangement of the Robot Submarine

filter circuits and relays. In addition the servomotors for the rear diving planes and rudders are placed in the motor tube.

The space inside the nose fairing is largely available for instrument packages. The only components in the nose are a small sensor package, a short length of 2 inch PVC tubing housing the front servomotor, and a small container for lead shot, used to trim the submarine.

3.2 THE PROPULSION SYSTEM

The robot has a two bladed aluminum propeller 12 inches in diameter driven through a 10:1 reduction gearbox by a 12 volt dc motor. The energy is supplied by an automotive lead acid battery modified for immersion in seawater.

3.2.1 The Propulsion Train

The electric motor was obtained from an electric outboard motor system. The motor characteristics were determined by a brake test and matched to the measured propeller characteristics and predicted drag of robot by the reduction gearbox. It was predicted that a 10:1 reduction gear ratio would be appropriate as it would match the motor and propeller close to their respective maximum efficiency levels. The reduction gearbox was built from inexpensive stock gear-wheels and bearings.

The shaft to the propeller passes through "O" ring seals in the endcap of the motor tube as shown in Figure 3.1. The propeller is carried in bearings supported by an aluminum structure braced by the motor tube. The propeller shaft between the motor tube endcap and the propeller has a small coupling to allow for misalignment.

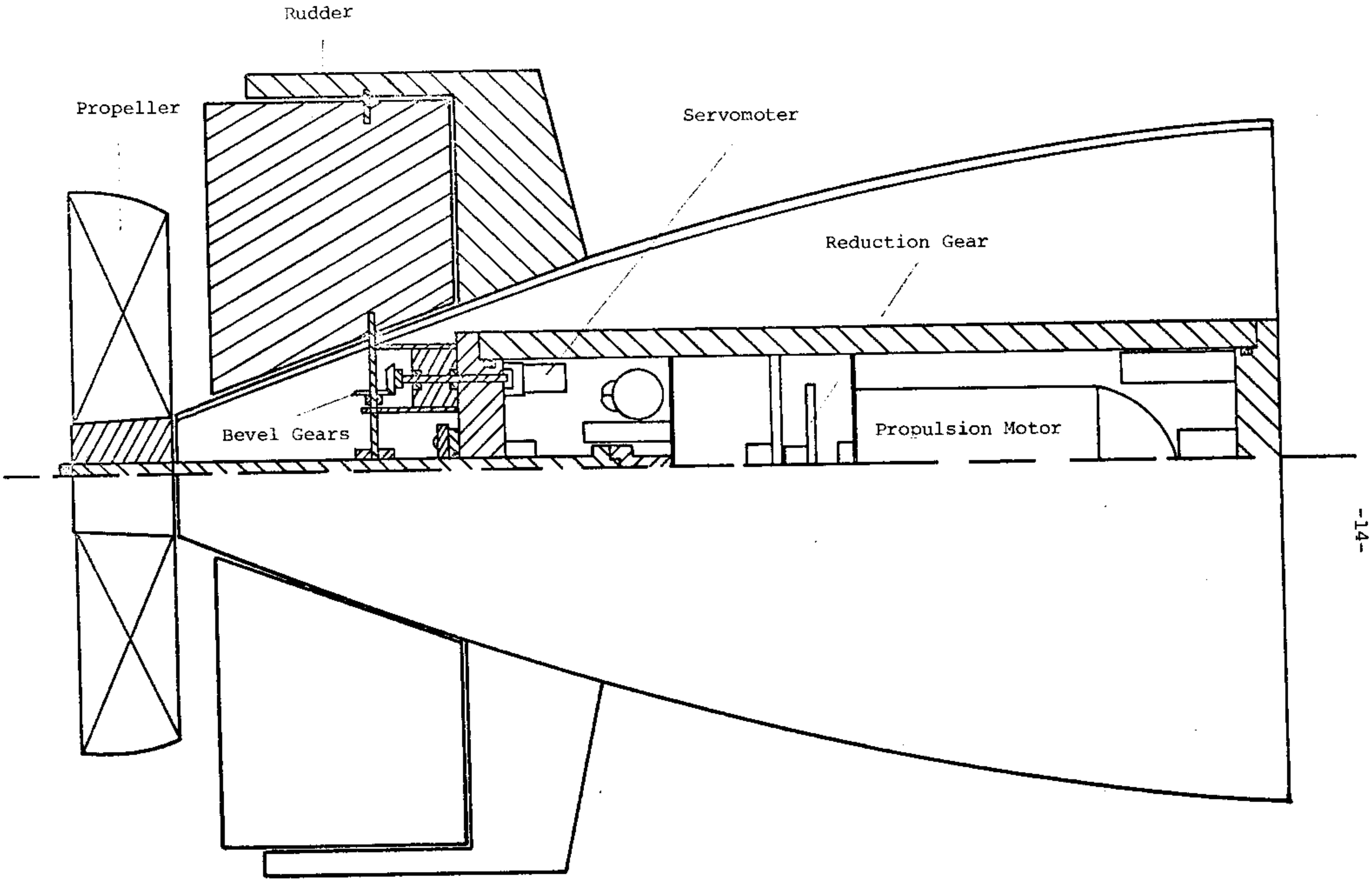


FIGURE 3.3 The Motor Tube and Stern Control Surfaces

3.3 THE CONTROL SURFACES

The bow and stern control surfaces are actuated by small servomotors which have intergral position feedback potentiometers. These servomotors have a total angular travel of about 270° while the control surfaces were designed to have a range of $\pm 30^{\circ}$. Small gear trains are used to obtain the reduction.

3.3.1 Bow Diving Planes

The servomotor for the bow diving planes is housed in a short length of 2 inch PVC tubing and attached to one endcap. The single stage gear system giving reduction is fabricated into the endcap to provide an axial output via a dynamic "O" seal. The endcap on the other end of the servometer housing has the sealed electrical plug to transmit the electrical signals to and from the the servometer.

The control surfaces are actuated by a shaft which is placed transversely on the centerline of the submarine. This shaft has small cranks and connecting rods driven by the output shaft of the servomotor tube, as shown on Figure 3.2.

The diving planes have fixed sections, fabricated in PVC, which protect and support the moving control surfaces. These fixed sections also provide the outer bearings to align and allow movement of the control surfaces. The inner bearings for each moving control surface are flanged plastic bearings attached to aluminum strips which are screwed to the aluminum skin. The use of slotted holes permits accurate alignment of the bearings to facilitate free movement of the control surfaces.

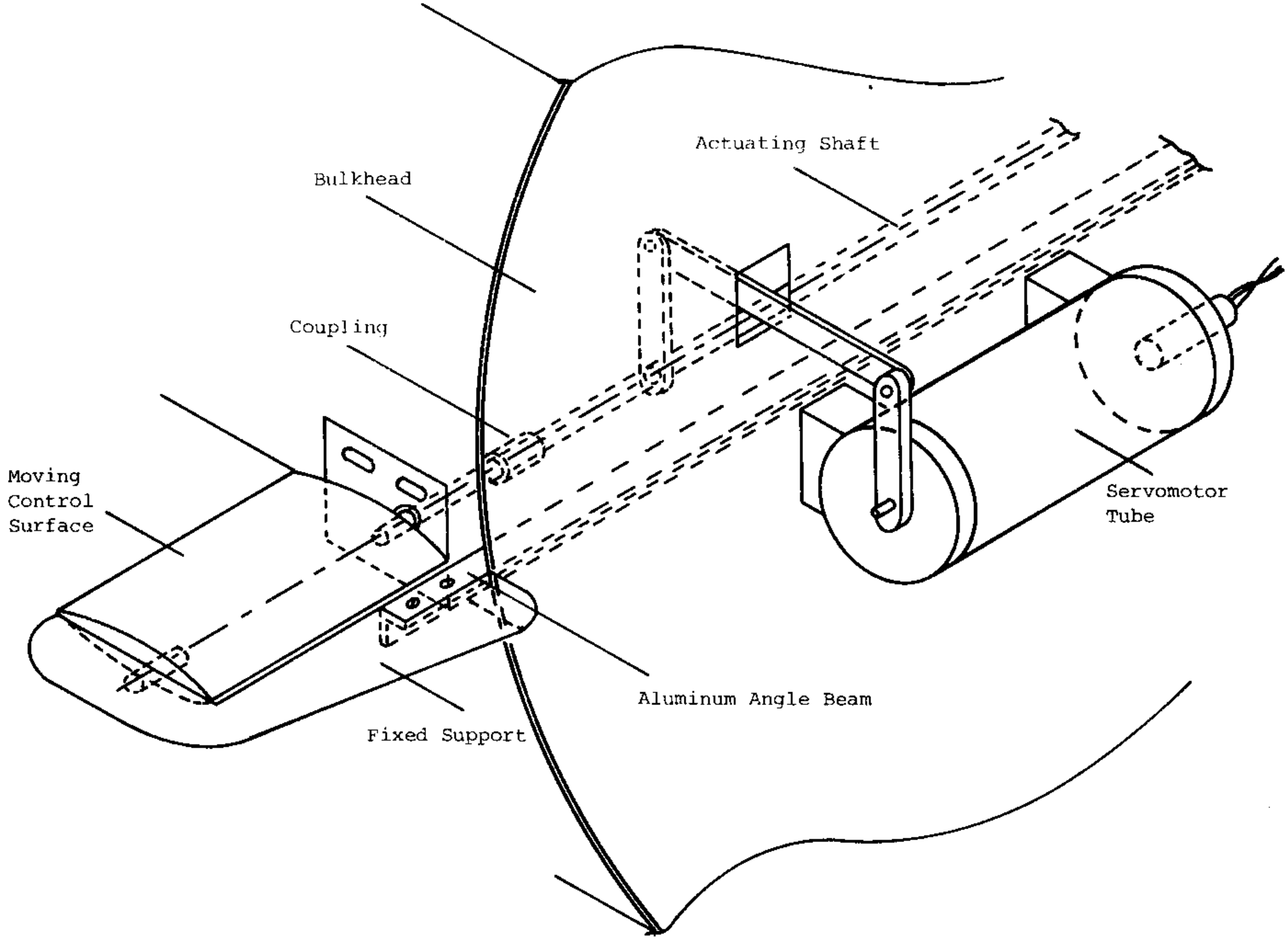


FIGURE 3.2 The Actuation of the Bow Diving Planes

The overall alignment and structural strength of the fixed sections of the control surfaces is maintained by an aluminum beam of right angle section which is placed transversely across the submarine at the horizontal centerline and screwed to the forward bulkhead, as described earlier. This aluminum beam was machined from a larger channel section. During operation of the submarine the beam was twisted by an unfortunate underwater collision during the early successful operation of the robot. The beam was straightened and returned to the submarine.

3.3.2 The Stern Control Surfaces

The servomotors for the stern diving planes and the rudders are placed in the motor tube. The diving planes have one servomotor each which track together while the two rudders are driven by a single servomotor. The outputs of the servomotors are taken through dynamic "O" ring seals in the aluminum endcap of the motor tube. On the outside of the endcap there are 4:1 bevel reduction gears which transmit the drive to the control surfaces, as shown on Figure 3.3. The bevel reduction gears are fabricated from stainless steel components.

The drive to the top rudder is directly from the bevel gear while the bottom rudder is driven by a yoke which permits the drive to cross the propeller shaft, as shown on Figure 3.3.

The stern controls surfaces, like the bow planes, have fixed sections and actuated sections. The fixed sections of the control surfaces were fabricated in PVC and bolted to the fiberglass tail cone. The moveable control surfaces are supported in bearings machined in the PVC.

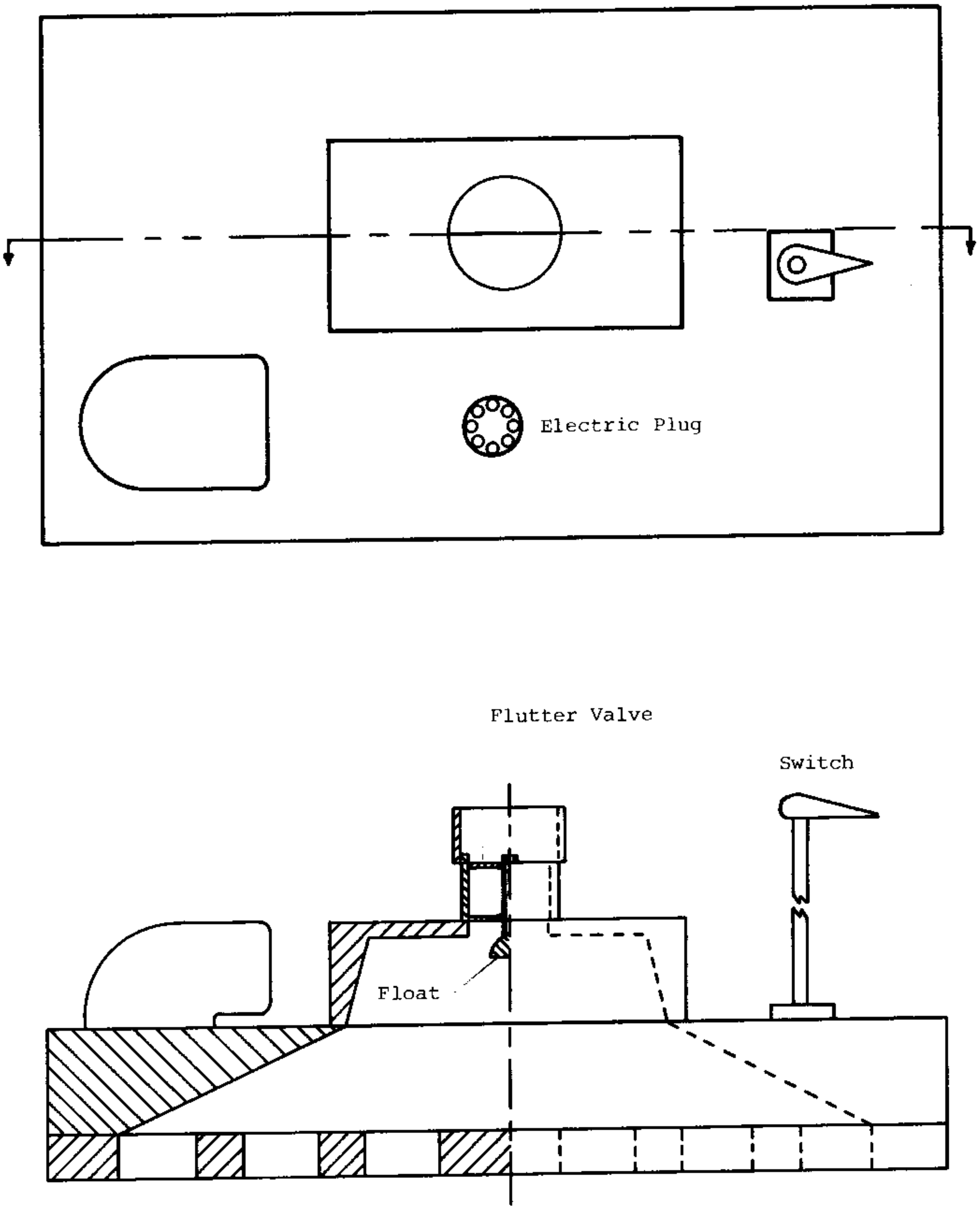
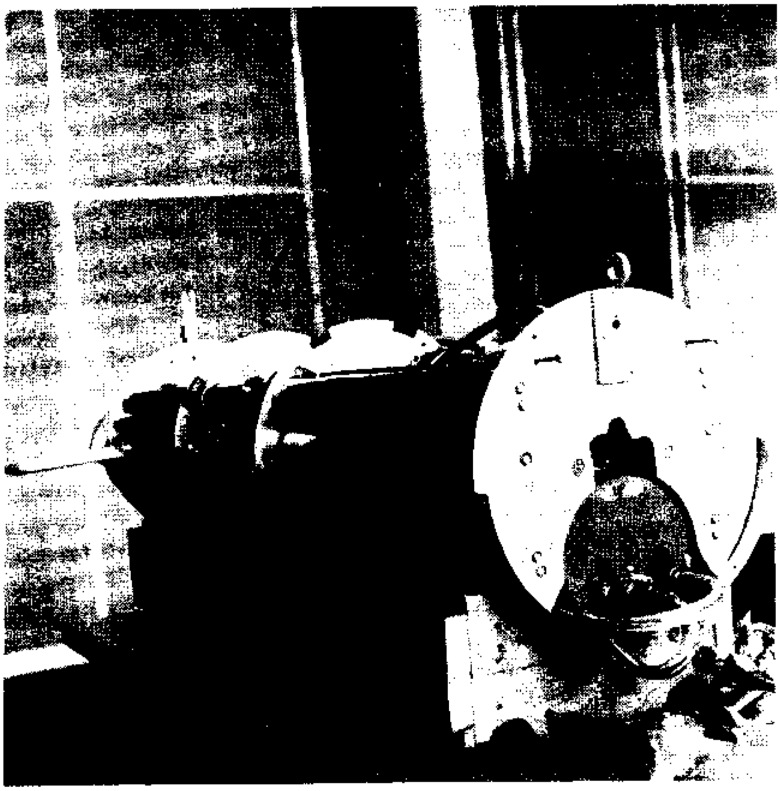


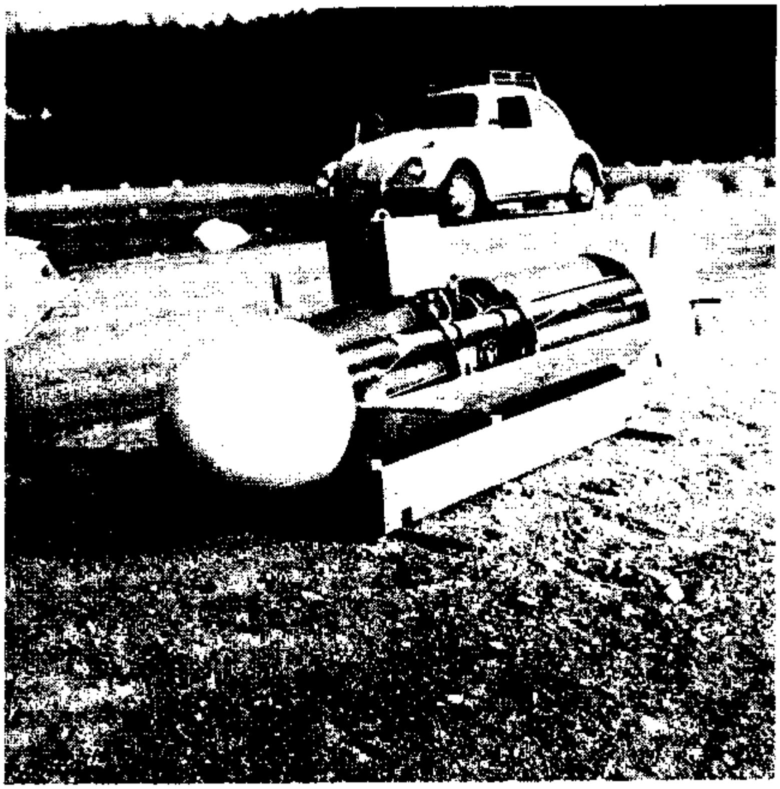
FIGURE 3.4 Battery Cover and Vent System

3.4 THE COMPENSATED BATTERY

The battery supplying the electrical power for the robot is a 96 ampere-hour automotive battery, modified to allow it to be immersed in sea water. The battery system has remained one of the more troublesome problems with the robot. The difficulties are associated with the pressure compensation of the battery and the continual production of hydrogen in lead-acid batteries. In order to maintain the battery at the local ambient pressure it is necessary to fill the space above the electrolyte with oil and to transmit the pressure to the oil by means of a rubber container. The hydrogen produced must be vented to environment while the oil must be retained. Partial success was achieved by building a special top for the battery to contain the oil and to vent the gas, Figure 3.4. In the vent valve an attempt was made to discriminate between oil and gas. The valve contains a float and rubber flutter valve. As gas is produced at the plates of the battery it displaces oil above it as it rises. The float then rises and closes the valve. When the gas has risen to the valve it allows the float to fall and when the gas pressure has risen sufficiently to open the flutter valve the gas blows off. This valve system has been found to reduce the outflow of oil although it has not completely eliminated the problem.



a. Viewed With Tail Cone Removed, Showing Computer Tube and Internal Arrangement



b. With Top Skin Removed With Showing Control Panel

FIGURE 3.5 The Robot Submarine

4. THE ROBOT ELECTRONICS

The purpose of the electronic system for the robot is to control all the functions of the robot. These functions include the testing, checkout, and programming of the robot before an operation and also the control and navigation of the vehicle when underway. The main components of the electronics system are the computer, the interfaces, and the autopilot.

Before each operation the computer programs required to control the submarine are transmitted to the computer memory from a paper tape reader or magnetic tape recorder. Immediately prior to the mission the operation of the servomotors, propulsion motor, sensors, and any instrumentation are checked-out manually by means of a control box on the dock. This box is coupled to the various components by the interface. On completion of the check-out any final instructions for the operation are sent to the computer by the control box via the interface and the computer is set to run. After a suitable pause to allow the control box to be disconnected and the robot to be released, the computer then instructs the propulsion motor to start, the autopilot to set the desired depth and the desired course, and scientific measurements to be made and recorded in memory. After the prescribed time has elapsed the computer instructs the autopilot to change course and depth and eventually to stop. The robot is returned to the dock where new instructions would be transmitted to the computer. Eventually, at the end of operations, the instrumentation data are retrieved from memory and printed out or put onto paper tape for transcription and analysis.

4.1 THE COMPUTER

The architecture of the computer is similar to 12 bit PDP 8 series (Digital Equipment Corporation). However, the 16 bit wide data paths give it some capabilities of the Nova series (Data General Corporation). Due to the requirement of low power consumption in the robot, the computer is much slower than the Nova. Typical instructions are 21 microseconds (μs) compared with 1.5 μs for the Nova, however, the total power consumption of the computer is only 3.5 watts.

In parallel with the construction of the computer hardware has been the development of the software to make the programming easier. The availability of this software has enabled several subroutines to be developed which permit the control of the robot.

The robot computer, in common with most computers, has three main parts:

1. A central processing unit which executes instructions.
2. A memory unit, which stores data and instructions for processing.
3. Input/output interfaces which exchange information between the computer and its environment.

These three units are mainly housed on separate circuit boards in the lower stern 6 inch PVC tube, although a large section of the interface is in the autopilot tube.

4.1.1 The Central Processing Unit (CPU)

The purpose of the CPU is to execute the instruction coded in a 16 bit digital form. These instructions are of three types:

1. Input/output, for communication with the interfaces.
2. Memory reference, arithmetic and program control operations to the memory.
3. Accumulator, operations upon a special register which can change the program flow depending on its contents.

The circuits that execute the instruction are of three types:

1. Control Logic
2. Data Paths
3. Registers

The control logic circuits adjust the data paths so that the data flows between register and to-and-from the memory and the various interfaces. The data paths consist mainly of mulitplexers and transmission gates through which the data flows. The registers have many purposes but they are essentially temporary stores for data and instructions.

4.1.2 The Computer Memory

It is described as a 4K 16 bit memory as it has 4096 locations and each location can contain 16 bits of information. The memory hardware includes the sixteen 4K by one bit memory chips together with clock drivers, logic chips and transistors for changing the voltage level to that of the memory (0-5 volts) from the level in the rest of the computer (0-10 volts).

4.1.3 The Interfaces

The internal interface in the submarine connect the computer to the autopilot and to the servo-amplifiers. The external interfaces allow the computer to be connected to the control panel, the teletype, and the tape recorder. These internal and external devices require different interfaces because of the various forms of the data transmitted to and from them and because they have different modes of operation. Serial transmission of data and multiplexing are used to reduce the numbers of interconnecting wires between the computer and the interfaces. Serial transmission involves moving data along a single wire one bit at a time. Multiplexing allows a single wire to be used for various functions.

The submarine interface:

The main purpose of the submarine interface is to send commands to the autopilot and the controllers and to receive data back. Since the computer operates with binary numbers while the rest of the submarine utilizes mainly analog voltage levels, an important function of the interface is to convert to and from these different systems. There are digital-to-analog converters (D → A) to change the digital number coming from the computer into voltage levels between 2.25 volts and 7.75 volts as used by autopilot and controller. Voltage outputs from the autopilot are changed to binary numbers in the analog to digital converter (A → D) and then transmitted to the computer.

The computer can transmit three types of instructions to the submarine interface:

1. An order, which can set the depth command, course command, and control the motor.
2. A direct command, which can directly control the servomotors coupled to the control surfaces.
3. A readout instruction, which transmits information back to the computer from the autopilot.

The first two bits in the 16 bit instruction define which of the three types of commands is required. Bits 2-7 define the device instructed (e.g. bow diving plane, or depth required), while bits 8-15 contain any digital data conveyed by an order or direct command. The interface is called upon to interpret the instructions from the computer, to select the correct path to carry out the command, convert the form of the data if necessary, and then to pass the instruction to the device.

The external interface:

These interfaces are all different since they involve interfacing the robot computer with the control panel, the teletype, and the tape recorder.

The control panel has 16 data switches, 16 function switches and a 16 bit data display using light emitting diodes. The main purpose of the control panel is to send the instructions to check-out all the main systems in the robot before a mission and to send the final information for a particular mission. In addition, when turning the computer on it is necessary to send a short instruction program (termed the bootstrap loader) in order to enable the computer to accept programs from the teletype, papertape, or tape recorder.

The data from the control panel is sent by serial transmission and the function and data signals to the computer are multiplexed. In this way the total number of wires from the panel to the computer is reduced to five. In addition to the send line, there is a return line, a clock line, an "end of transmission" line, and common.

The teletype interface has been designed to allow two-way communication between the computer and the teletype or between the tape recorder and the computer. It has been arranged to make the recorder look like a very fast teletype. The information is transmitted between the computer and teletype in serial form and requires four wires and common.

4.1.4 Computer Software

The robot computer, like other computers, is essentially a device capable of storing and manipulating information presented in binary form. This is termed machine language. Both the data and the instructions to manipulate the data are in this confusing binary format. The programmer can simplify his program writing procedure by changing from binary to octal numbers which reduces the 16 bit binary representation to octal numbers from 0 - 177777. A further simplification to assist the programmer is to devise a letter code to represent operational steps. These codes are (more-or-less) standard for small computers and the instructions are termed the assembly language. As an example, the operation "load accumulator with the number 2" is represented in the assembly language as "LDA #2" and in machine language with a 16 bit binary representation of the octal number "142002". Commercial computers utilize higher level languages such as Fortran and Basic to make the process of programming somewhat easier.

The efficient conversion of a program written in assembly language to machine language and then the operation of this program by the computer requires a series of software programs. The software for the robot computer was developed during the designing, building, and check-out of the computer. This process was facilitated by utilizing simulator computer programs operated on a PDP 11 computer. With this simulator representing the robot computer the software was developed and available when the computer became fully operational. The software is described in the following paragraphs.

The "Text Editor" permits the teletype interface to be operated as an editing typewriter and enables the edited program language to be transcribed onto paper tape. This program allows insertions, deletions, and changes to be made on the text in memory. When the editing is complete a print-out of the revised program and a paper tape are produced. Although this is a general editing program it is normally used to produce edited programs in assembly language.

The "Assembler" translates programs in assembly language into machine language and allows a paper tape of the program to be produced in machine language.

The "Loader" loads a machine language tape into the computer memory. The loaded program is then ready for execution.

The "Debugger" allows the examination and modification of machine language programs in memory via the teletype. In addition, it permits the controlled execution of the program for error checking.

The "Core Dump" arranges for selected areas of memory to be typed out by the teletype; this permits instrumentation data to be printed out at the end of a robot operational run.

During the operation of the robot only the "Loader" and "Debugger" of the software system are in memory together with the operational programs. At the end of an operation the "Core Dump" is inserted to extract the recorded data from memory.

4.1.5 Robot Operating Computer Programs

The computer programs developed to operate the robot had the following main objectives:

1. To carry out instructions at prescribed times.
2. To give control to the autopilot with set values of depth and course.
3. To have direct control of the submarine for special maneuvers.
4. To record data in memory.

These tasks are made easier by the provision of a set of subroutines which can be called. These subroutines are as follows:

1. SEND (command): this sends the specified command to the autopilot.
2. GET (command) (storage address): this sends a read command and stores the information at the specified address.
3. WAIT (seconds): this is essentially a pause to permit program instructions that follow the WAIT instruction to be carried out after a specified number of seconds.
4. REPEAT (n times)(instruction sequence): this allows repeated measurements to be recorded in memory. The instruction sequence following REPEAT would normally include a WAIT instruction so that the repeats would occur at specified intervals.

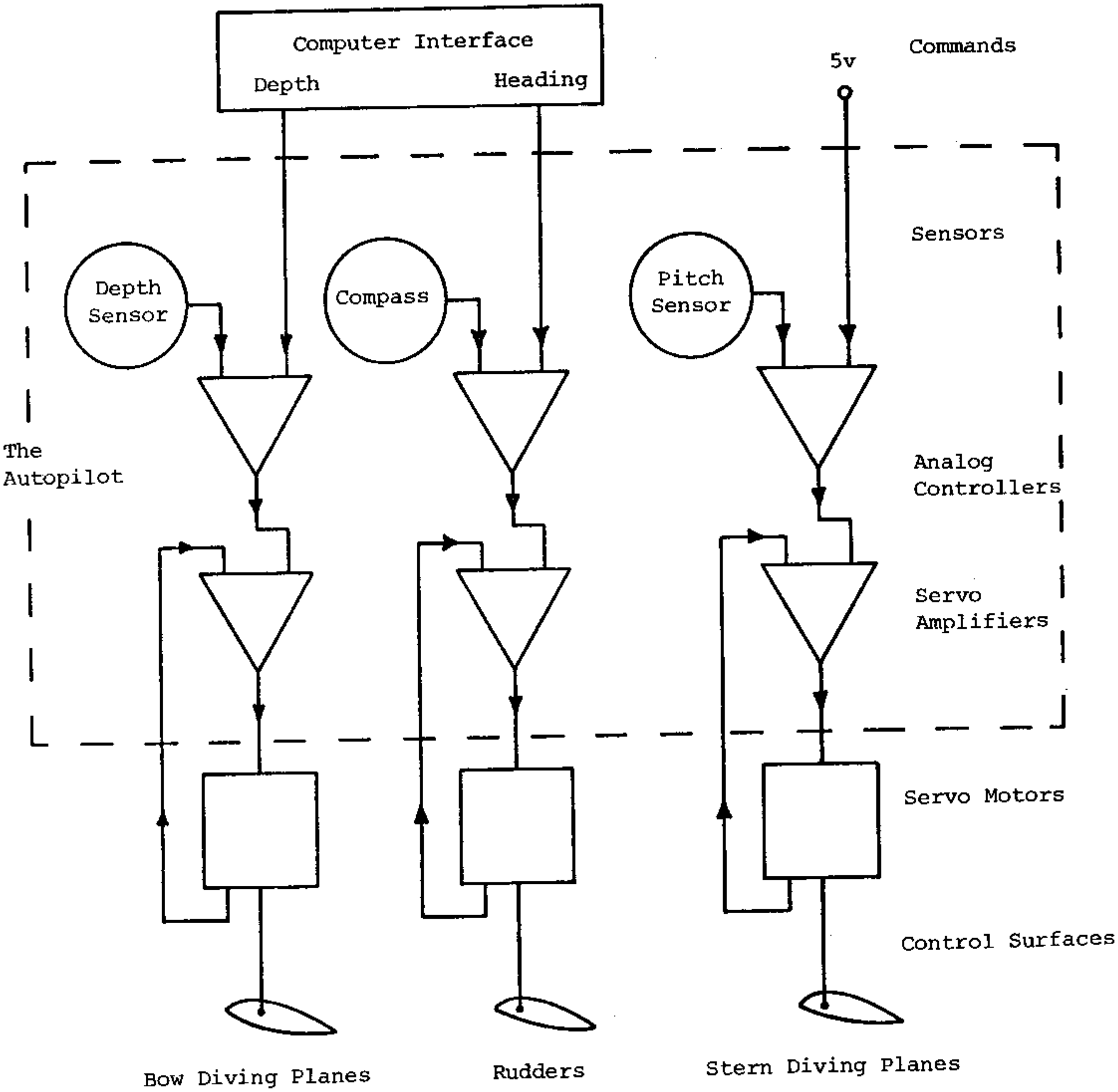


FIGURE 4.1 The Arrangement of the Autopilot

With these subroutines an operation of the robot can be programmed very simply as a series of statements calling these subroutines. Modifications to the instructions can be made in the field with the aid of the control panel. Such instructions would be to change course, depth or timing of a mission.

4.2 THE AUTOPILOT

The autopilot has real-time control of the robot; it carries out the computer instructions with regard to course and depth and in addition it controls the pitch attitude of the vehicle. In the original design the autopilot also controlled the roll attitude but this was eliminated when it was observed that the vehicle was very stable in roll.

The autopilot has three sections as shown in Figure 4.1.

1. The sensors, which sense the depth, attitude and heading of the vehicle.
2. The analog controller, which provides the control signals to instruct the control surfaces to move, depending on the differences between the desired and sensor determinations of the depth, attitude, and heading.
3. The servo-amplifiers, which utilize the signals from the analog controller to provide the power necessary to drive the servomotors.

4.2.1 The Sensors

The sensors on the robot determine the depth, the pitch angle, and the heading of the robot. The outputs from the sensors are voltages between 2.25 volts and 7.75 volts required by the analog controller.

Depth is determined by a commerical semiconductor transducer which measures absolute pressure. This transducer is temperature compensated and has a linear response in the region of interest. The device has a working range equivalent to 135 feet of sea water and would be replaced if the robot were required to operate at its maximum design depth of 200 ft. The transducer would be corroded by sea water so that the ambient water pressure is sensed by a neoprene rubber bladder filled with air. The output from the transducer is passed to an operational amplifier circuit to provide a signal making the surface correspond to 2.25 volts and 100 feet correspond to 5 volts.

Pitch angle is sensed by two separate sensors. The first using pressure difference measurements and the second using a pendulum.

The semiconductor pressure differential transducer is connected to small rubber bladders filled with air, one is mounted near the bow and the other near the stern. This instrument senses the slight pressure difference due to pitch. It was found in operation that the instrument required continual adjustment and recalibration. However, when the system was dismantled it was found that one of the air bladders was not filled with air.

The pendulum attitude sensor has a lead pendulum attached to a low friction potentiometer. The pendulum is place in an oil filled container to provide damping.

The pendulum, depth sensor, and pressure difference sensor were all placed in one housing and attached to the forward bulkhead.

The compass was developed to provide an output signal that varied approximately linearly with heading. The compass uses an opaque compass card on which a spiral is scratched to allow light through. A light source is placed above the card and photo-potentiometers are placed below. The output from the photo-potentiometers depend on the position of the light arriving at them, which is a function of the angular position of the compass card. Two photo-potentiometers 180 degrees apart were utilized to overcome the overlap at the ends of the spiral. The computer selects the appropriate photo-potentiometer to utilize.

4.2.2 The Analog Controller

The analog controller is a proportional-derivative controller which utilizes the differences between the command signals and the sensor outputs to generate the control signals; these are transmitted to the servo-amplifiers. The depth and heading commands come from the computer while the attitude command requires that the robot should remain horizontal. This is provided in the controller as a 5 volt signal corresponding to zero pitch angle.

In the original design the bow and stern diving planes were coupled together to control depth while the stern diving planes controlled pitch attitude. It was found to be very difficult to develop a stable control system with this arrangement. Successful operations were finally obtained when the two functions were decoupled so that the bow diving planes controlled depth and the stern diving planes controlled pitch.

The values of the gains and time constants in the controller were predicted from theoretical analysis and by 1/4 scale model tests in the propeller tunnel. These constants were adjusted during the experimental program to provide a satisfactory controller.

4.2.3 The Servo-Amplifiers

The purpose of the servo-amplifiers is to utilize the signals from the analog controllers, which specify control surface positions, and then to provide the power to the servomotors to reach the commanded positions.

The first stage of the servo-amplifier is a differential amplifier which has an output proportional to servo-position error. The output from this amplifier goes to the servomotor drivers which are essentially solid state switches. During early testing of the servo-amplifiers with their servomotors it was observed that small oscillations occurred. The oscillations were inhibited by switching off the servo-amplifiers for a few milliseconds several times per second.

4.3 THE POWER SUPPLIES

The 12 volt automotive battery is connected directly to the propulsion motor. The supply is then taken to the autopilot tube where several of the regulators are placed. These regulated supplies drive the electronics and the servomotors. There is an additonal regulator in the computer tube with small rechargeable batteries to provide an emergency supply for the computer.

There are three power supplies placed in the autopilot tube. The first regulator delivers 10 volts at 2 amps for use in the autopilot and the computer. The second supply delivers 5 volts to the operational amplifiers in the autopilot, while the third power supply provides 5 volts and 2 amps for the servomotors.

The power supply in the computer tube takes the regulated 10 volts from the autopilot tube and the 11-16 volts from the emergency batteries and outputs the following dc supplies:

1. - 12 volts for the teletype interface.
2. ± 5 volts for the memory.
3. + 10 volts for the computer, memory and interfaces
4. + 12 volts for the memory.

The 12 volt supply consists of a 30 kHz oscillator and drivers driving a toroidal autotransformer. The - 12 volts and - 5 volts are also derived from the autotransformer. The + 5 volt supply is a series pass regulator using the main 10 volt supply.

The 10 volt auxiliary supply uses batteries to supply a regulated voltage slightly lower than 10 volts. The auxiliary batteries only deliver power when the main power supply falls below 9.5 volts. It can deliver about one amp until the auxiliary batteries are discharged.

4.4 MISCELLANEOUS ELECTRONICS

In addition to the main electronics described above there are additional electronic systems associated with the positioning and the safety of the robot. These have been built and installed but not utilized during the development of the vehicle. They are planned to be used in the future.

4.4.1 The Pinger

The "pinger" is a separate system housed in a small PVC tube placed in the battery compartment. It could be isolated from the remainder of the vehicle, however, since it has a quartz crystal tuned to 200 kHz it was decided to utilize this as a precise clock for the computer.

The pinger circuit provides an 8 millisecond burst at 8.33 kHz precisely every second. The transducer, placed in the robot nose, is tuned to 8.33 kHz by a series inductor. The position of the robot is determined on the shore by means of a wet paper recorder with a precise one second sweep utilizing two hydrophones.

During normal operation the pinger runs on the 10 v main power. In case of power failure the pinger is supplied from two 9 volt transistor radio batteries to keep the pinger operational for about two days.

4.4.2 The Optical Coupler

The purpose of the optical coupler is to provide a convenient two-way transmission path from the on-board computer to the teletype or the control panel with the robot in the water. This avoids the problems of breaking and resealing watertight connections.

The optical coupler is in two halves which are brought together and aligned when data is to be transmitted. On the robot side there is a small PVC block in which there are three light emitting diodes (LEDs) and five photo transistors. On the shore side there is a mating PVC block with 5 LEDs and three photo transistors. In addition to the optical system there are four magnetic reed switches.

This coupler was designed and built but unfortunately damaged during testing. It has been rebuilt and can be used.

5. THE ROBOT EMERGENCY SYSTEMS

There was some concern during the design of the robot about the possibility of losing the robot due to failure of critical components. The most probable failures were defined and designs were considered which would minimize the resulting damage and facilitate the recovery of the vehicle in the event of such failures.

The situations envisaged were as follows:

1. Collision with a fixed object.
2. Leakage of water into a critical tube.
3. Loss of battery power.
4. Operation at excessive depth.

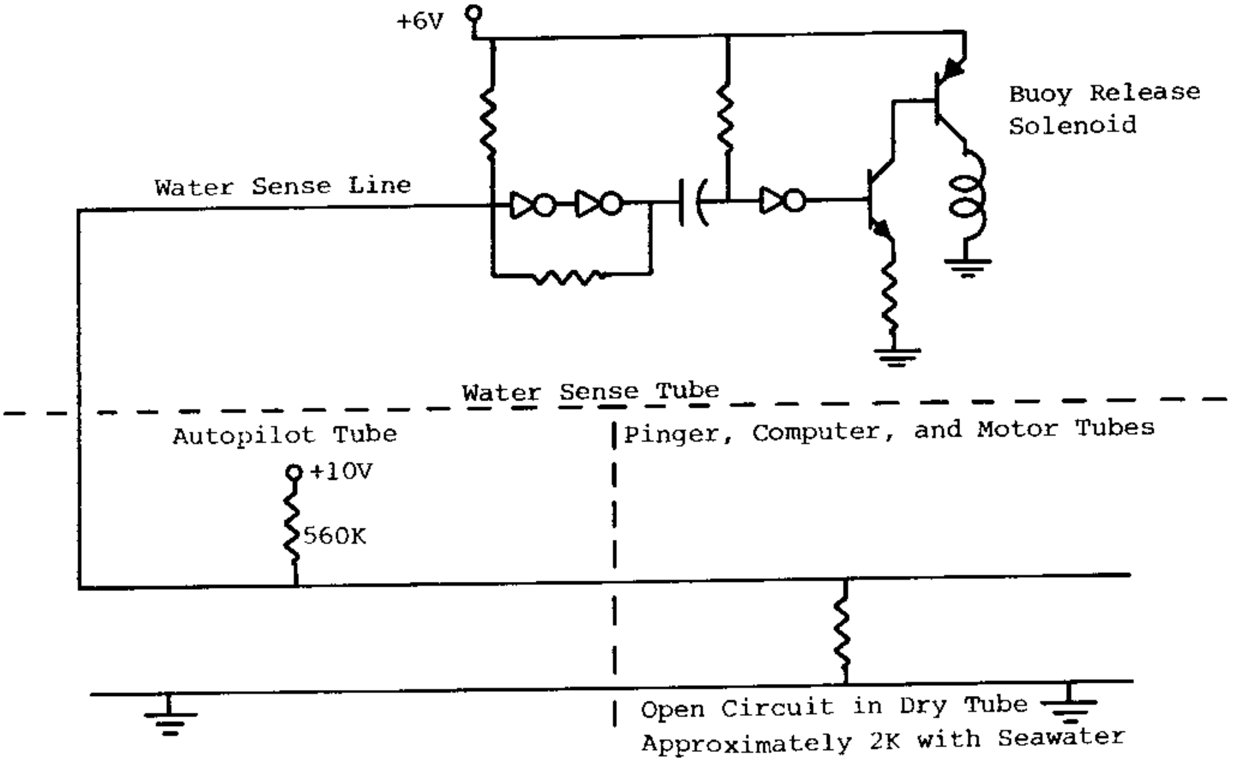
To avoid fixed objects in the water it is necessary to have an active sonar system with the avoiding action controlled by the computer.

The problems of water leakage, loss of power, and excessive depth required systems to detect the problems and then to assist possible recovery by releasing a tethered buoy and ballast.

5.1 COLLISION AVOIDANCE

The collision avoidance sonar sends a pulse at 140 kHz in a 30^o beam ahead of the robot. It receives any echo on the same hydrophone and transmits to the interface of voltage proportional to the delay between the original and the return signals. This system is not fully operational and is being developed. There have been problems with responses from surface waves.

The Water Sense Circuit



The Water Sense Tube

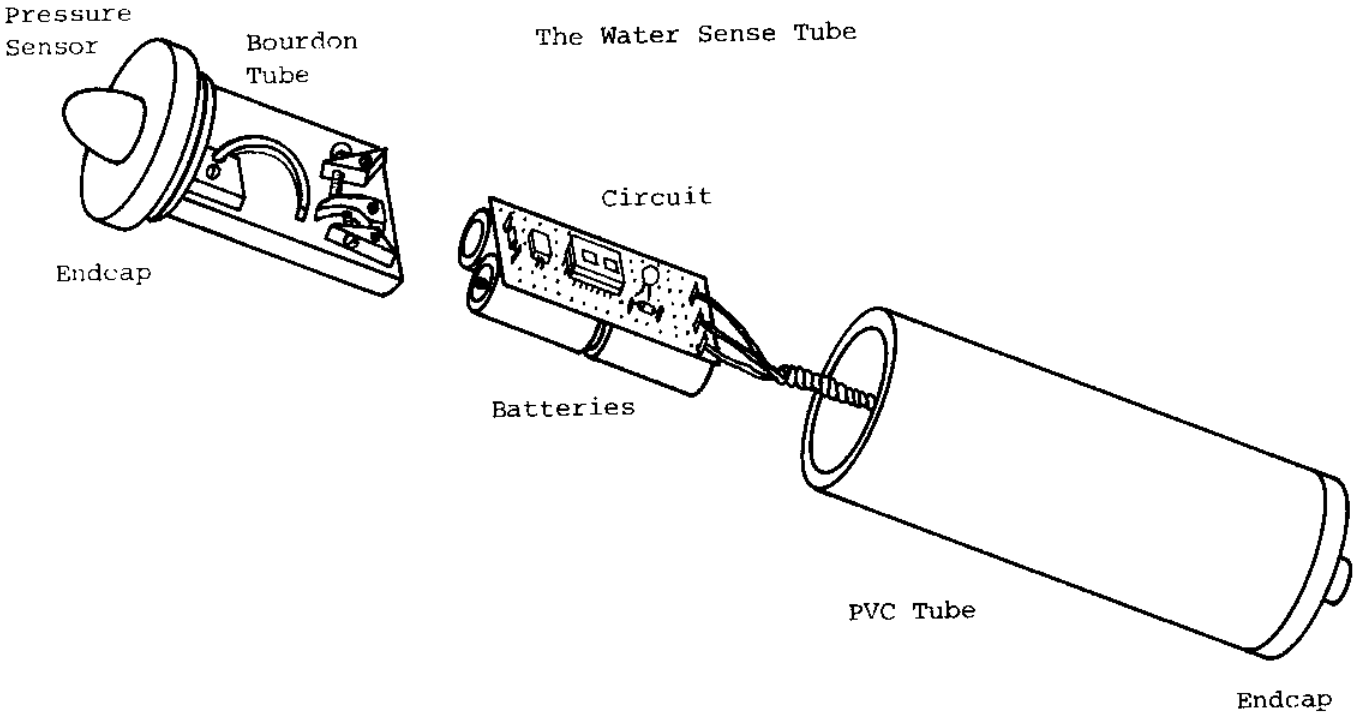


FIGURE 5.1 The Emergency Systems

5.2 THE MISSION EMERGENCY SENSING SYSTEM

The leakage of sea water into the critical PVC tubes is detected by two bare wires placed in grooves at the bottom of each tube. One of the wires is grounded and the other (termed the water sense line) is connected by a large resistor to the + 10 volts supply. When there is no water in the tubes the "water sense line" is at 10 volts while in the presence of sea water it is grounded. The loss of battery power also drops the water sense line to zero volts. This system, therefore, senses two emergency conditions.

When the limiting depth is reached the pressure sensor would record the excessive pressure. An additional system based on a bourdon tube and simple limit switches connected to the water sense line was also designed and built. However, this device requires further development as it is not reliable.

When the water sense line goes to ground for any reason this is signaled to the computer through the submarine interface. In addition a simple circuit was devised to provide power to a solenoid which would release the emergency marker and ballast system as shown on Figure 5.1. This solenoid would be powered by C cells placed with the releasing circuit in the "pinger" tube.

5.3 THE MARKER BUOY AND BALLAST RELEASE

During preliminary design of the emergency recovery arrangements various alternatives were considered including ballast tank "blowing", the inflation of rubber bags, and the release of a marker buoy and weights. This last named method of recovery was finally decided upon for several reasons. First, the submarine sits very low in the water and is difficult to spot, so that the method of recovery should include a clearly visible marker, namely a buoy. Secondly, the combined release of a buoy and a ballast weight was a much simpler mechanical system than blowing ballast tanks or the gas inflation of a bag.

The design finally selected uses a streamlined marker buoy mounted on the top skin of the submarine in a fiberglass cradle. The buoy is weighted to float vertically when it is released. One end of the buoy is attached to a 100 ft. line which comes from a reel placed in the battery compartment. A release mechanism placed on the rear bulkhead has a series of spring loaded levers which simultaneously release the marker buoy and a five pound mass of scrap metal mounted under the battery. This release system was nearly operational towards the end of the experiments. The mechanism had been designed and built and is being trimmed to provide reliable operation.

5.4 RECOVERY SYSTEM USED FOR OPERATIONAL MISSIONS

During the actual missions of the vehicle, since the emergency system were not operational it was decided that the robot should tow on the surface a small streamline float. This was a satisfactory solution for development operations.

6. THE ROBOT TEST PROGRAM

The test program for the robot vehicle was completed in several phases. The individual components were first developed, then assemblies were tested and finally the complete vehicle was operated.

The main development of the mechanical system was associated with the drives for the control surfaces. The bow diving plane assembly was operated for many hours in a water tunnel. The bow servo-system was coupled to the computer interface and programmed to provide changes in angle of attack of the control surface. This test demonstrated the reliability of the system.

The electronic systems were calibrated before assembly and simulated missions were conducted in the laboratory. These missions tested the software and the hardware.

6.1 INITIAL OCEAN TESTING

The initial test program for the robot was conducted to determine the basic operational characteristics of the vehicle. The concern was the inherent stability and maneuverability. The vehicle was operated before the computer, autiopilot and software were functioning reliably, the control surfaces were therefore set at fixed positions. The propulsion motor was controlled by a simple electronic timer.

The robot was first ballasted with a lead sheet in the battery compartment. It was decided that the vehicle should have approximately one pound positive buoyancy. A relatively simple procedure was devised to facilitate ballasting. The vehicle was submerged horizontally to a depth of one foot and then released. The elapsed time to surface was determined. A simple theoretical analysis showed that the vehicle should take approximately seven seconds to reach the surface with one pound of positive buoyancy. The ballasting was adjusted to that the robot surfaced horizontally with approximately the correct elapsed time.

The first operational tests were conducted to determine the minimum turning radius. On the surface it was found that this was about 25 feet. The turning radius underwater was later found to be smaller than this value because the rudders were fully immersed.

These initial tests confirmed the mechanical integrity of the vehicle and indicated that the rear control surfaces were adequately sized for stability and maneuverability. There was some doubt about the effectiveness of the bow diving planes as these had half the surface area of the rear control surfaces.

6.2 DEVELOPMENT OF THE CONTROLLED VEHICLE

The computer and autopilot were installed and the vehicle was operated in a large sea water swimming pool and also in a cove near Castine using the specially designed catamaran to transport the robot. A series of surface maneuvers were first attempted including circles and figures-of-eight. These simple operations were successful with the propulsion motor starting and stopping as required and the control surfaces moving as commanded. Initial attempts at making the robot dive were irratic. There were occasions when the robot would not dive, while on other occasions the vehicle would not stay on the surface. It was concluded that the autopilot was not functioning as designed and that the bow diving planes were too small.

At this point it was decided to redesign the bow diving planes and increase their size and also to make changes in the autopilot.

After these changes were made the robot operated successfully. Further simple maneuvers were carried out and the robot was sent out-and-back on prescribed headings and at shallow depths. Unfortunately, during one of the early successful operations the vehicle struck an underwater object which damaged the bow planes. Repairs were made after the accident but the operation of these planes were impaired until the whole structural arrangement was later straightened.

6.3 DATA COLLECTING MISSIONS

The robot was programmed to go and return on preset heading and record the water temperature and the operating depth every second. The temperature was measured by thermistor. It was put in series with a resistor, placed across the 10 volt supply and calibrated to provide output voltage as a function of temperature. In the robot the thermistor was arranged to measure water temperature just outside the nose. It was coupled to the computer interface through one of the spare leads in the autopilot tube.

During the final test the robot pulled away from the pier after being given the start instruction. It turned to its preset course which was parallel to the shore and dived to its preset depth

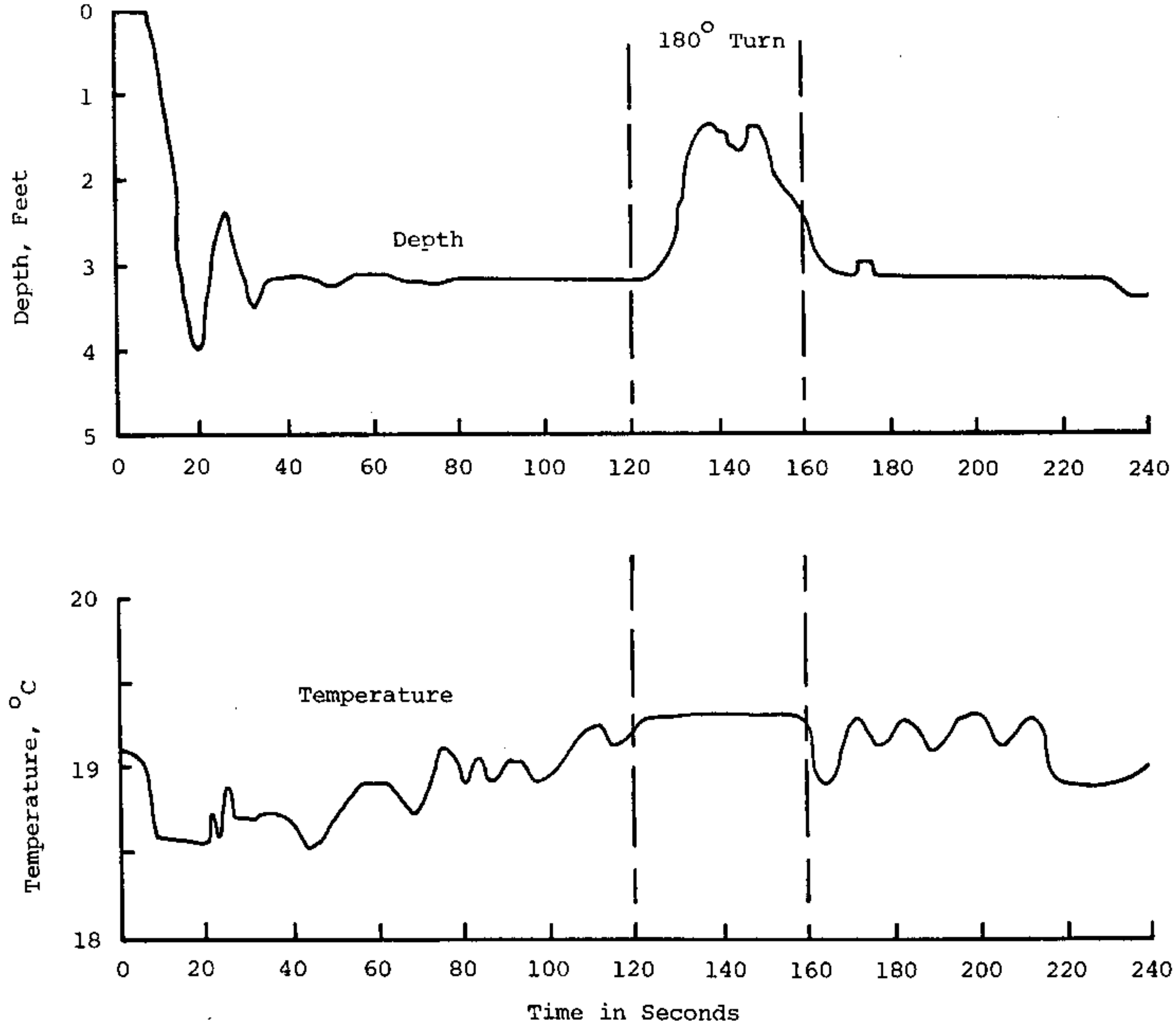


FIGURE 6.1 Robot Measurements of Water Temperature

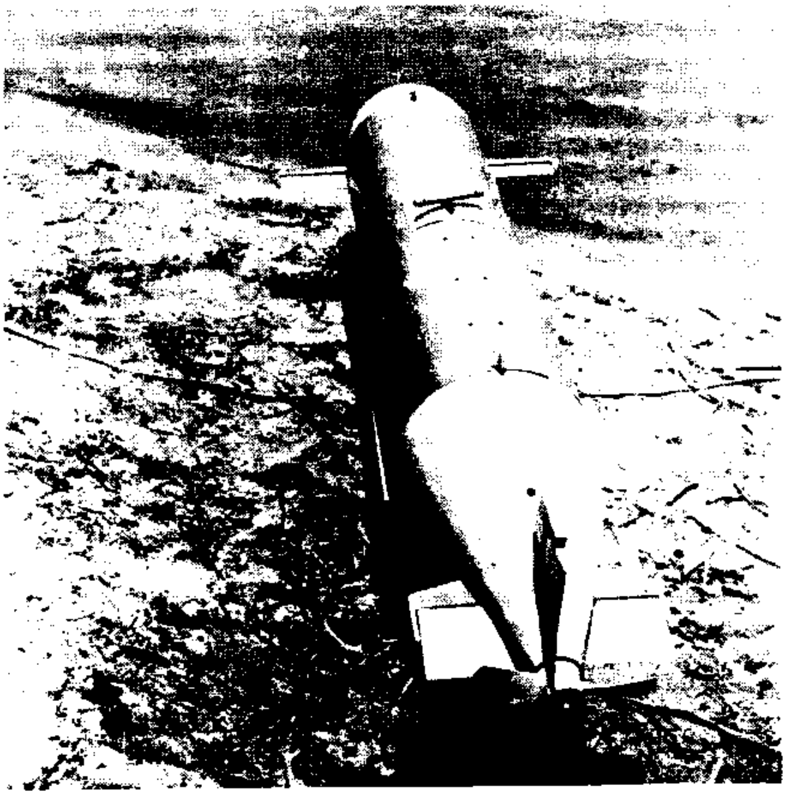
of three feet. It continued on this course for two minutes and then turned through approximately 180 degrees to return. It finally surfaced about 100 feet from the pier.

The robot was then returned to the laboratory where the data stored in the memory was printed out as octal numbers and also punched on paper tape in binary form. These data were changed to decimal numbers and recorded.

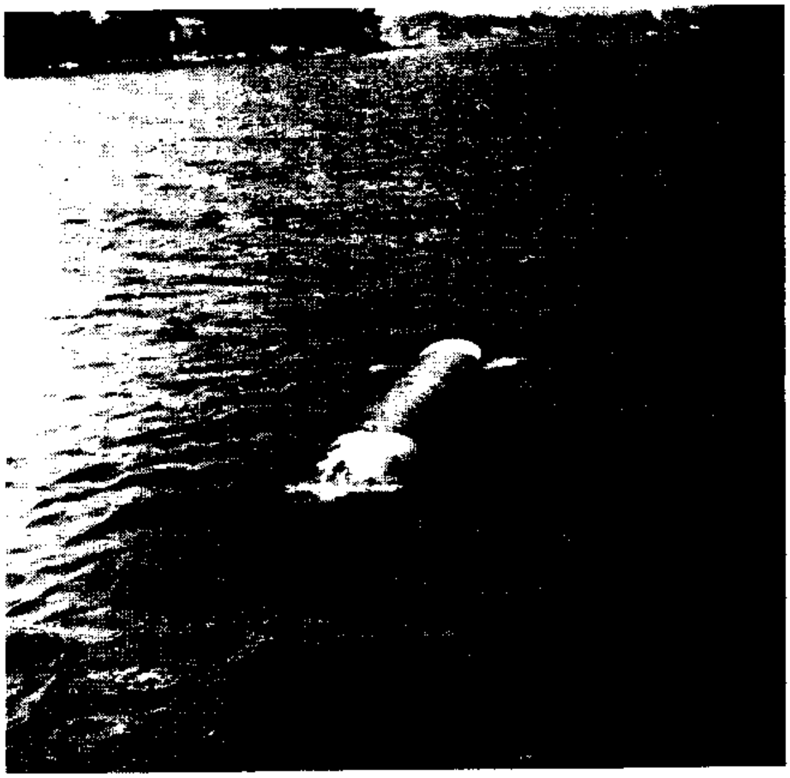
The measurements of depth and temperature as functions of time for one data collecting operation are presented on Figure 6.1.

The temperature was remarkably uniform for the operation, with a temperature variation of less than one degree. The variation of depth during the mission shows several interesting features. The robot begins diving after about 8 seconds from start, it overshoots the preset depth by a foot and then settles down to the prescribed depth after one or two oscillations. During the 180° turn the vehicle rises 1 1/2 feet and then returns to preset depth after completing the turn.

A scuba diver stationed near the path of the robot observed that it was very stable both in pitch and heading.



a. On the Beach Before Launching



b. Underway with Computer Control

FIGURE 6.2 The Operational Robot

7. A WINDMILL POWERED BUOY

Many buoy systems require electrical power to perform their functions. For these installations, simple battery systems actuated by environmental controls are used. However, for certain larger buoys a larger, reliable energy source is required to provide the power to collect and transmit data.

Wind power is readily available on most parts of the ocean's surface and coupled to a battery storage system could provide the power for these large buoys. Windmills are a proven practical source of power for remote applications, such as pumping water on farms. It was therefore decided to design and build a simple inexpensive windmill system placed on a buoy.

7.1 EQUIPMENT DESIGN

The design problem was separated into two areas, the buoy and the windmill.

7.1.1 The Buoy

The buoy must serve as a stable platform for the windmill and associated test equipment. It should be simple, inexpensive and allow various mounting arrangements for the windmill and experimental equipment. It was decided that the windmill should be attached to a pylon placed in the middle of the buoy.

Various methods of constructing the buoy were considered and fianlly a design utilizing an available inner tube was selected. A truck inner tube of five feet diameter with a wooden frame of

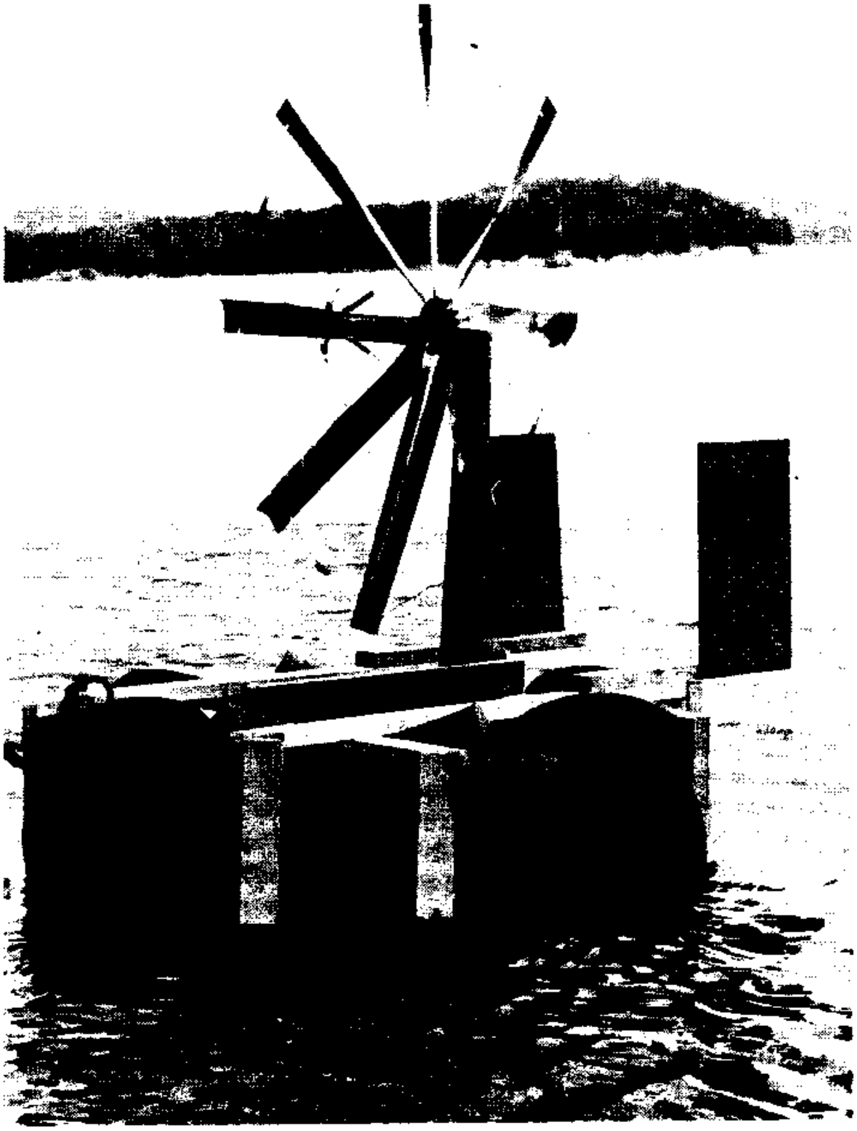


FIGURE 7.1 The Windmill Buoy

2" x 4" placed across it was used, as shown in Figure 7.1. A section of aluminum mast from a sloop was used as the pylon. Two vanes were placed aft to provide directional stability.

The buoy was moored by means of a chain bridle hung on the center line and attached to a swivel and line leading to the anchor.

7.1.2 The Windmill

Several methods can be used to generate power from the wind. Vertical axis windmills such as the Savonius rotor may be used in addition to several types of axial axis designs.

The Savonius rotor is simple and rugged, but it is inefficient and requires large areas of material to generate power.

Horizontal axis windmills can be roughly catagorized as multibladed or propeller type. The multibladed has good starting characteristics but is not as efficient as the propeller type. It was felt that good starting characteristics were important for a remote windmill so that the multibladed windmill was selected.

The windmill was designed to drive a hub-generator removed from a bicycle. The characteristics of the generator were first measured by mounting it in a lathe chuck and driven at various speeds by the motor. The reaction torque was determined with a spring balance and the voltage and current were measured with electrical meters. The generator load was provided by a 400 ohm rheostat and it was found that the most efficient load was about 50 ohms. A fixed 50 ohm 10 watt resistor was then attached to the generator. The starting torque was measured with the lathe chuck stationary as

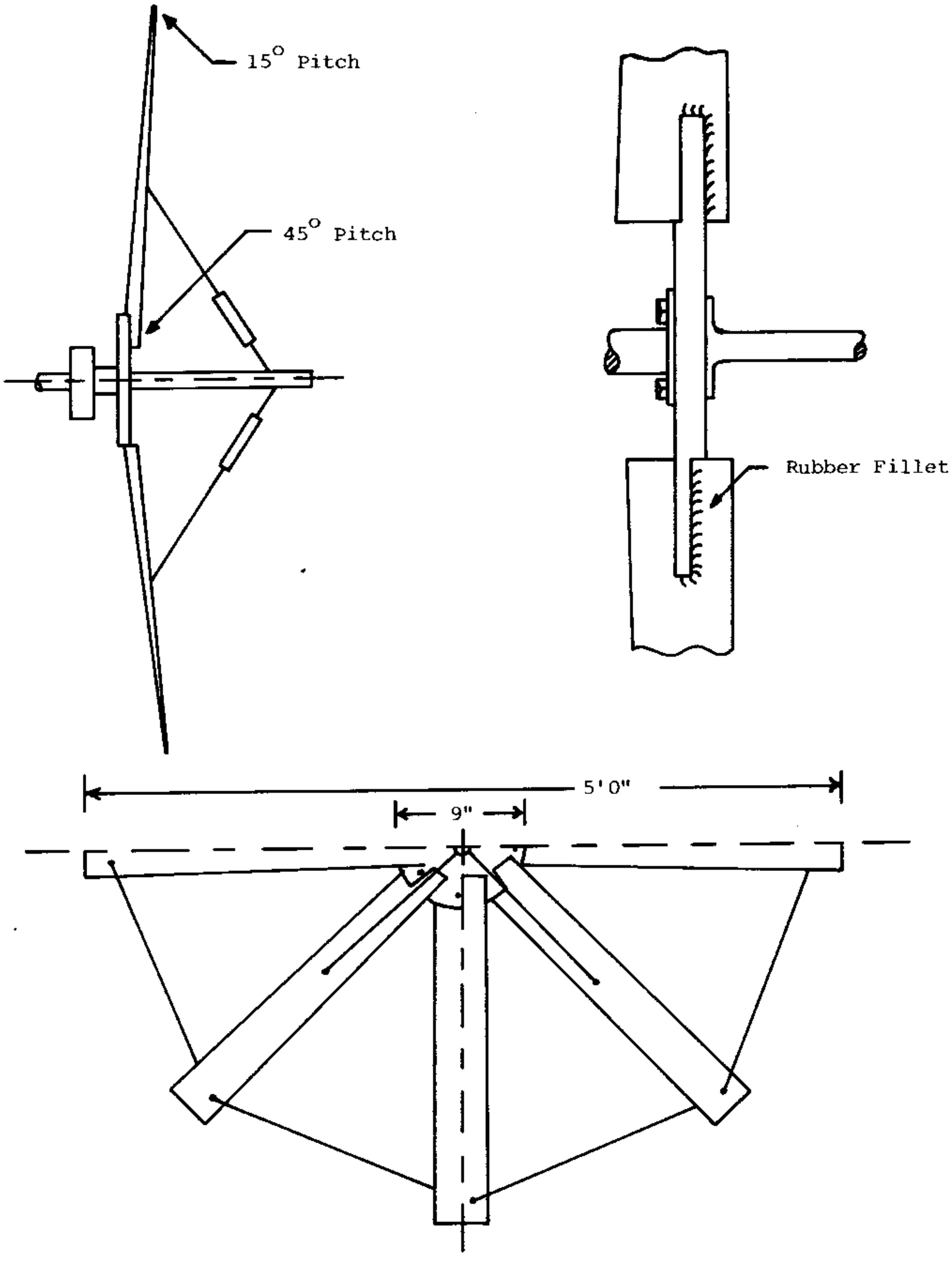


FIGURE 7.2 The Windmill Design

.20 lb ft. This value was used to estimate the size and number of windmill blades that would start with a wind of five knots.

The blades of the windmill were modeled as flat plates and it was found that the optimum leaving angle to give the best starting conditions was about 36 degrees from the tangential direction. With this angle and the measured starting torque for the generator, it was determined that eight blades thirty inches long and 7 1/2 inches wide would start at just below 5 knots.

The blades were made from 1/32" aluminum formed over a wooden template to give camber and added stiffness. The blades were twisted to prevent stalling. The blades were attached to a plywood hub carried by the generator. They were supported by lacing wires at the tips and by wires from a 12 inch post placed at the center of the hub, (Figures 7.1 and 7.2). The whole assembly was attached to the pylon on the buoy.

7.2 EXPERIMENTAL PROGRAM

The windmill powered buoy was moored in 30 feet of water near the dock at Castine. In this position it was exposed to the prevailing south westerlies. The mornings tend to be calm with the wind increasing to 10-15 knots by early afternoon. The windmill was removed from the pylon at night.

The buoy proved capable and stable and the vanes directed the windmill into the wind regardless of the original direction.

The windmill was found to start at 4 knots with no electrical load and operated in winds of 25 knots. During handling four blades were bent. These were repaired but the blades were weakened. On the second day of testing before test data was taken the windmill failed in a 20 knot wind. One of the lacing wires parted and the blades made contact with the pylon.

7.2.1 Conclusions and Recommendations

The buoy and windmill design proved that a simple system could be used to generate power. The buoy was entirely satisfactory but the windmill construction was not rugged enough. However, to produce a more sturdy design would require thicker blade material which would be difficult to fabricate without special facilities.

8. CABLE STRUMMING EXPERIMENTS

"Cable strumming" is the name given to the self-excited vibration of cables caused by ocean currents. This strumming is important to the oceanographic community because the movements of the cables can cause incorrect reading of instruments supported by such cables. In addition, the "fish bite" damage found on many cables in the ocean may be aggravated by these vibrations.

The cause of the strumming is considered to be the regular shedding of vortices from the cable. These vortices form the "Karman vortex street" which occurs downstream from cylinders at low Reynolds numbers. The shedding of a vortex induces a transverse force which moves the cable perpendicular to the current. Another vortex of opposite sign is then shed, producing an opposing force and opposite cable movement. This alternate shedding of vortices sustains the strumming action. The vortex shedding between nodes of the vibrating cable appears to be synchronized by the cable's own movements.

A large number of experiments have been performed by other experimenters with rigid cylinders in wind tunnels and water tunnels. A few wind tunnel and water tunnel experiments have also been carried out with short lengths of cables. These experiments have produced a considerable amount of data concerning rigid cylinders and short cables, but an extrapolation of these results does not necessarily correspond to the realities of cables thousands of feet long in the ocean environment. Recent experiments have been conducted on such long cables in the ocean. However, the experimental data have not yet been adequately analyzed because of the complications of various mass loadings and varying current velocities along these cables. In 1974 preliminary experiments on 250-yard and 50-foot cables were conducted and reported in reference 1. These experiments were carried out on cables which were not well isolated from outside vibrations and there was doubt about the current velocity measurements. The experiments described here used an improved test arrangement and testing technique.

8.1 THE TEST ARRANGEMENT

It was decided that approximately 75-foot-long test cables would be used. It was expected that the data from these experiments would assist in the interpretation of information from very long cables. The main emphasis of the experiments was the provision of solid end supports for the cable and the development of good instrumentation and recording techniques.

8.1.1 Cables Tested

The cables tested in this experiment were as follows:

1. 7/16" Sampson "Blue Streak".
2. 0.275" U.S. Steel wire rope.

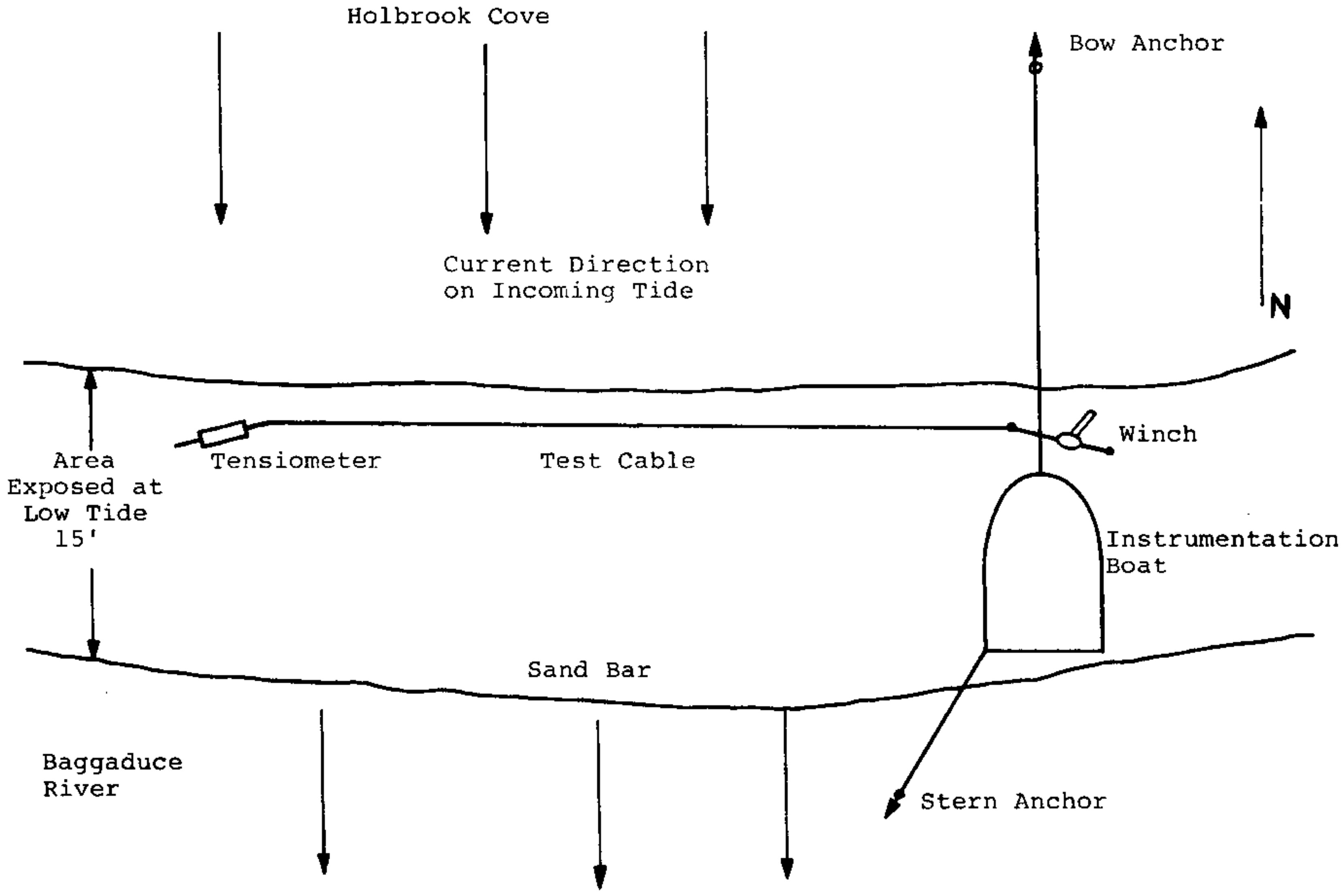


FIGURE 8.1 Test Arrangement at the Sandbar

3. Philadelphia Resin Corporation "Phillystran" Kevlar rope.

4a. 0.154" Philadelphia Resin Corporation Kevlar rope with 3 twisted conductor center, and anti-strumming fairings woven around the outside of the rope.

4b. Same as above but with fairing removed.

For technical details, see Table 8.1.

8.1.2 The Experimental Site

The controlled conditions necessary for the cable strumming experiment were as follows:

1. A region in which to place the test cable where the current would be uniform along the length of the cable and perpendicular to it at any given moment.
2. The current would vary slowly as a function of time over a large velocity range.
3. The site would have to be dry at low tide so that the equipment could be set up.

A suitable test site at a sandbar near Castine, Maine, was used for the preliminary experiments of reference 1. The sandbar was exposed at low tide, as shown on Figures 8.1 and 8.5. As the tide came in, current velocity slowly decreased from a high of 3 ft/sec to a low of zero (at high tide). Several traverses of the test site were made with an electromagnetic current meter at various times while the tide was coming in. The current varied up to 2.5% about the mean along the test cable in a 3-minute round trip from one end of the cable to the other with several current measuring stops each way.

TABLE 8.1

Cables Tested

1. Sampson "Blue Streak"

12-strand single braid, polyester and propylene (half and half), 5,000-lb breaking strength, 7/16" nominal diameter, .39" measured diameter under tension, 64.78 g/m dry, 93.5 g/m wet.

2. U.S. Steel Wire Rope

3x9 torque balanced, polyethylene coated, closed swaged socked, galvanized plow steel, 4,000-lb breaking strength, .275" measured diameter, 108.3 g/m.

3. Philadelphia Resin Corporation "Phillystran" P_S 29-C395

Construction 7x7 (P_S 29-B105) "Kevlar" rope with a polyurethane jacket, 17,000-lb breaking strength, 3/8" nominal diameter, .485" measured diameter, 113.2 g/m.

4a. Philadelphia Resin Corporation Anti-Strumming Cable

Braided polyurethane impregnated Kevlar, with 3 twisted conductors down center, 2,000-lb breaking strength, anti-strumming fairing woven helically into Kevlar covering, .154" measured diameter under tension with anti-strumming fairing removed.

4b. Same as above, but with anti-strumming fairings removed.

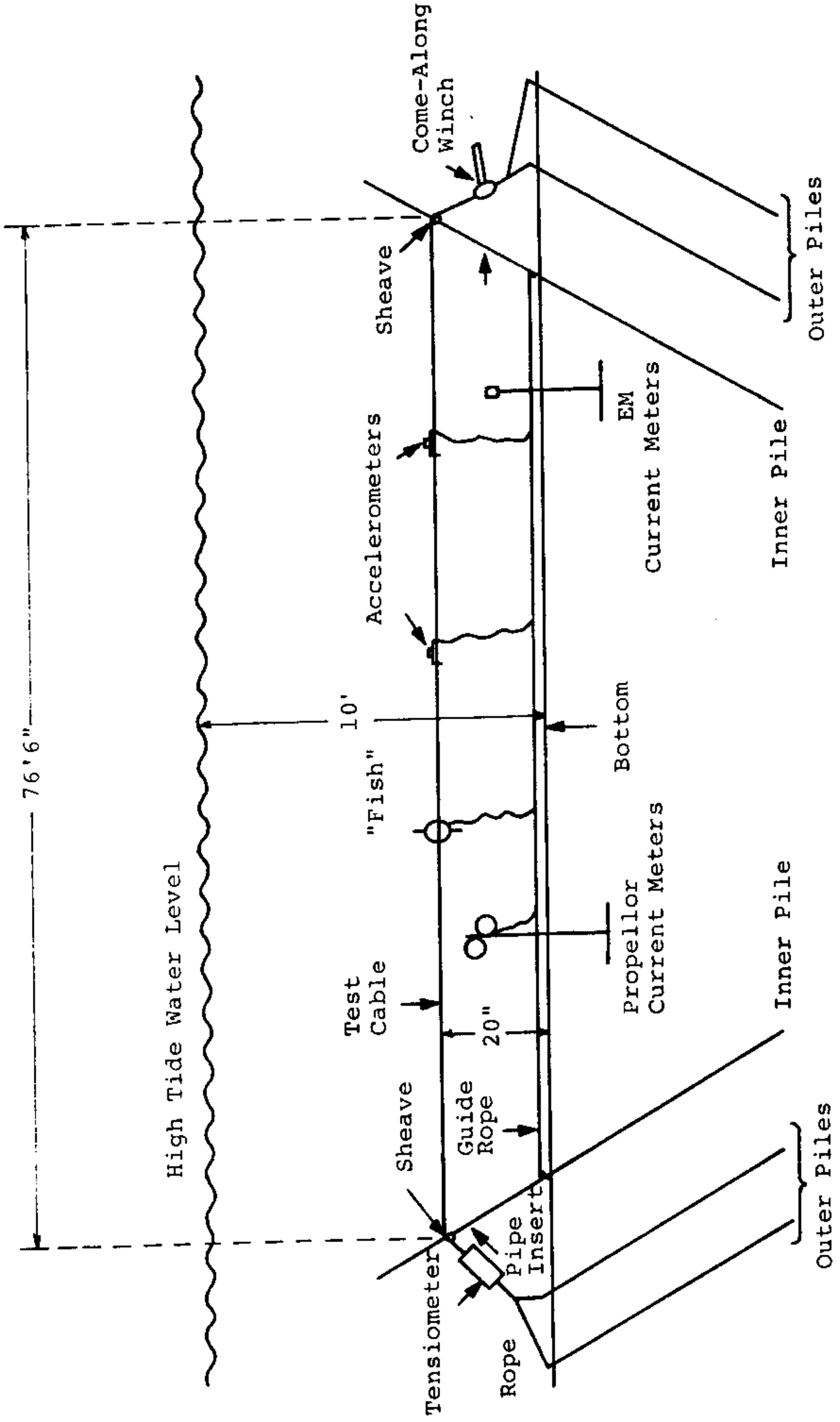


FIGURE 8.2 Test Cable Arrangement

8.1.3 Preparing the Test Site

It was decided to support the test cables using six piles driven into the sandbar, as shown on Figure 8.2. At each end of the test section, one pile (the inner one) was used to support the test cable and two outer piles were arranged to take the cable tension load. The piles were constructed from 10-foot-long steel pipes and these were driven into the sandbar with water jets so that only a few inches were left exposed above the sandbar.

A sheave attached to a length of pipe was bolted to the inner piles to support the cable about two feet above the sandbar. These sheave attachments were removed after the test runs to allow passage over the sandbar.

8.1.4 Instrumentation

Instruments were needed to measure the frequency and amplitude of the test cables, the speed of the ocean currents, and the tensions in the cables. In addition, a recording instrument was required for the various instrument outputs.

Frequency and Amplitude Measurements

The frequencies and amplitudes of the cable vibrations were measured with accelerometers and with a special direct reading device, described later, termed the "fish".

The accelerometers were single-axis, general-purpose, damped accelerometers made by Entran Devices Inc. These instruments had a range of ± 10 g and were attached to sheet metal mounts which enabled them to be clamped to the cables and moved along the cable when necessary.

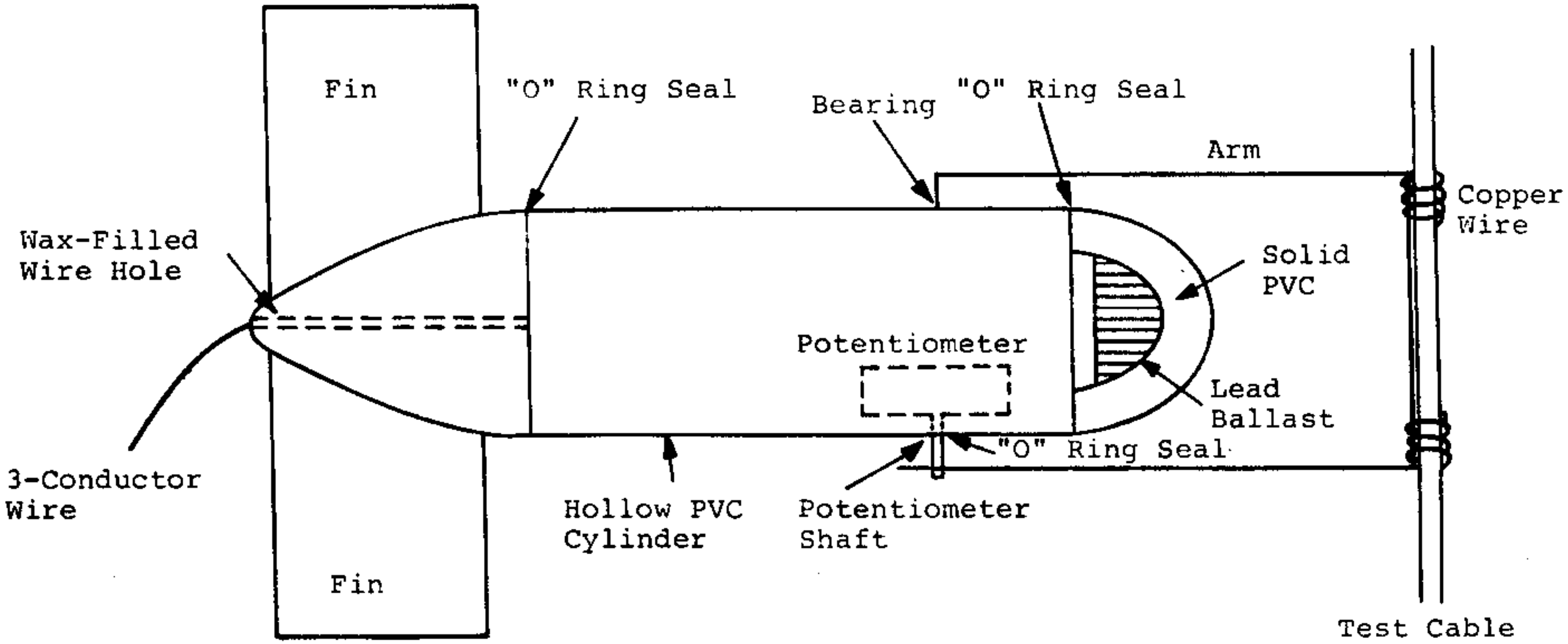


FIGURE 8.3 The "Fish" Amplitude Transducer

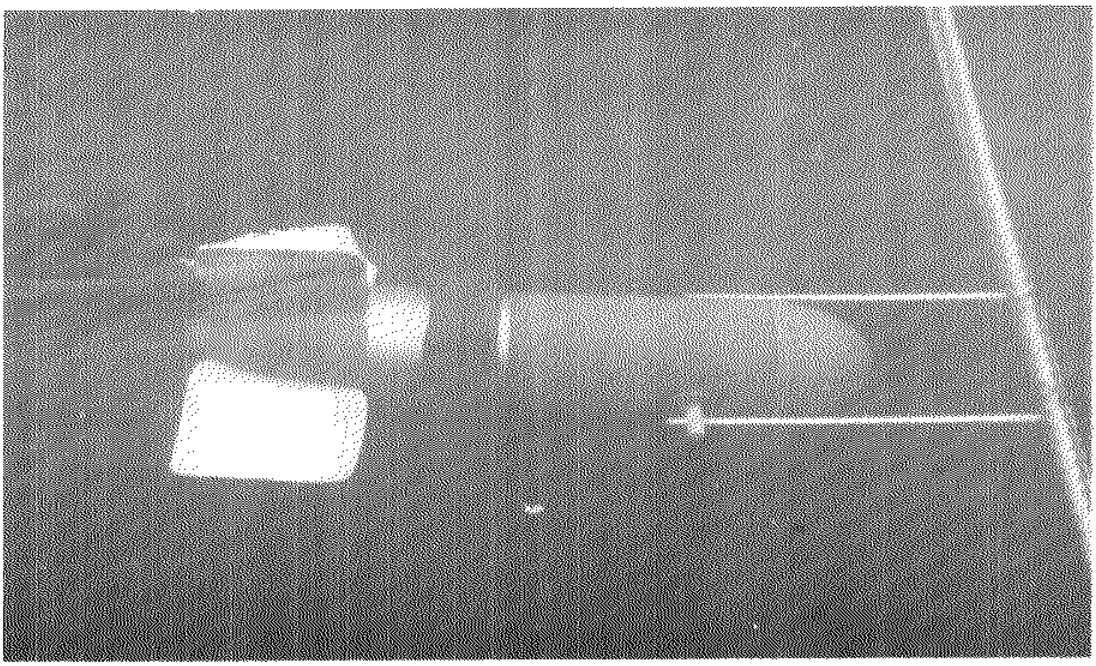


FIGURE 8.4 The "Fish" Attached to the "Blue Streak" Cable

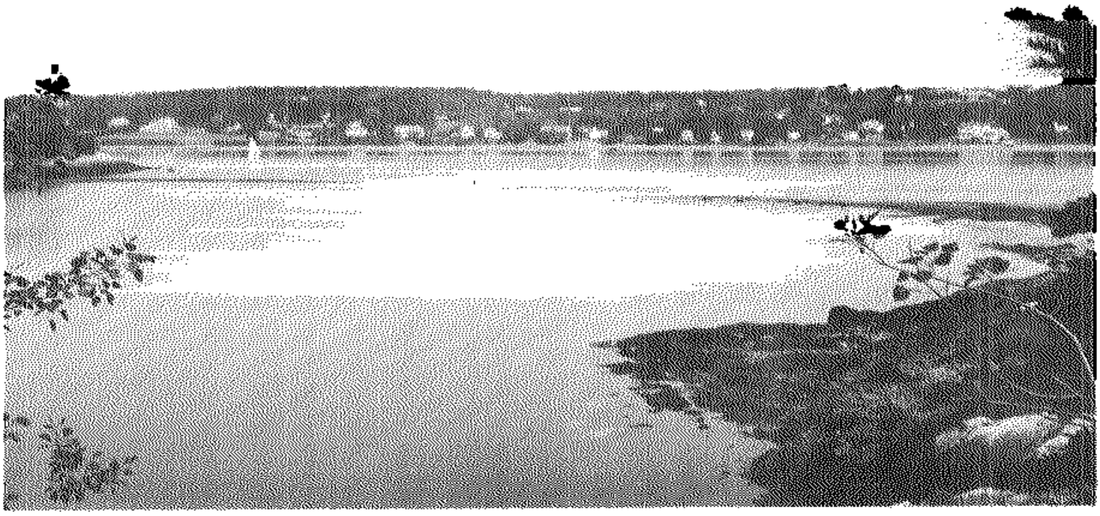


FIGURE 8.5 The Experimental Site from Holbrook Cove

The amplitude and frequency of the test cables were also measured directly using a transducer built for the purpose, as shown on Figures 8.3 and 8.4. This transducer consisted of a rotary potentiometer connected by an arm to the cable. The potentiometer was housed in a streamlined and neutrally buoyant fairing with tail fins for stabilization termed the "fish". A second hinged arm was made to stabilize the fish as it streamed behind the cable. The fish remained essentially at rest behind the cable as the vibrating cable moved the supporting arms and the potentiometer shaft. This device was designed and developed using a small water tunnel. The calibrations of the transducer in the test arrangement show that it had 0.66 volts/inch of cable deflection.

Current Meters

The main current meter used in the experiment was an electromagnetic (EM) current meter with a sensitivity, after signal processing and amplification, of 2.75 ft/sec per volt. This instrument used an electromagnetic coil to produce an a.c. magnetic field and a pair of electrodes in the flowing water to measure the potential difference produced by the moving conducting fluid in the magnetic field.

Two small propeller current meters were occasionally used as back-up meters.

The current meters were mounted on stands which were placed on the sandbar about two feet downstream of the test cables.

A survey instrument for traversing the current meters along the length of the cable was also constructed. The design of this device was similar to the "fish" described above. The current meter was supported by the body of the "fish" while the arms of the device were hooked around the cable. This device could be pulled along the cable to measure the current speed just downstream of it.

Tensiometer

A cylindrical tensiometer with a sensitivity of about 100 lb per volt was used to measure the average and the oscillating tensions in the cables. This device was calibrated in a testing machine and the calibration was confirmed from time to time by supporting known weights from the transducer.

Recorder

A four-channel Tanberg FM tape recorder was used to record the instrument measurements. One channel was used to provide vocal comments and descriptions of the signals being recorded, in addition to recording data.

8.2 EXPERIMENTAL TECHNIQUE

The procedure used in the cable strumming experiments was similar for each test series. The cable was set up on the sandbar at low tide; the test results were recorded on the rising tide and the apparatus was removed by divers near high tide. Two boats were used in the experiments; a 17-foot boat of special design with a large area at the stern for apparatus and equipment, and a small skiff.

8.2.1 Setting Up

The boats arrived around low tide and the test cables were set up with the various transducers, as shown in Figure 8.2. The setting-up procedure began with the insertion and bolting of the sheave arrangement in the inner piles. The "come along" winch was placed at one end of the test region and the tensiometer was placed at the other end. The test cable was placed over the sheaves and shackled to the winch and to the tensiometer. The various amplitude transducers were then attached to the test cable. A guide wire was fixed to the inner piles to support all the electrical wires from the instrumentation. As each transducer was set up, the electrical wires were taken to the guide wire and supported by twisted copper wire loops about every five feet. The instrument wires were brought aboard the instrumentation boat and connected to the instrument amplifiers and the tape recorder. Marker buoys were placed so that boats would not go over the test cable. Finally, divers took the boat anchors to suitable spots and firmly placed them into position to withstand the loads imposed by the currents over the sandbar.

8.2.2 Data Collection

During the setting-up procedure, the instrument zeros were recorded and the test cable was plucked in air. The zero for the EM current meters was obtained after the water had risen above the meter by placing a hand over the instrument.

Data were recorded as soon as the current meter output stabilized; this depended on the depth of water over the sandbar and the sizes of the waves. The two accelerometers and the "fish" transducer had separate channels on the recorder while the tensiometer or EM current meter were put on the remaining channel.

When the current velocity reached a plateau, divers went down to the winch to adjust the cable tension. Short data segments were recorded at different tension levels from 60 to 700 lbs (see Table 8.2).

At various times divers swam along the cable to adjust the orientation of the accelerometers, to remove seaweed, and to check the cable and instrumentation. In addition, some accelerometer transverses were made by moving one accelerometer relative to the other.

When the current velocity was low enough so that the cable strumming stopped, scuba divers went down and plucked the cable to determine the response in still water.

8.2.3 Dismantling

It took two scuba divers approximately 20 minutes to dismantle the testing apparatus at high tide with no current.

The divers swam to the accelerometers, took them off the test cable, coiled their wires, and brought them aboard the boat.

TABLE 8.2

Test Data With Tension Varied Kevlar Cable, 0.485" Diameter

Run No.	V_d ft/sec	f_d	S_d	T_d lbs
a	2.17	12.0	.2235	120
b	2.17	11.5	.2142	128
c	2.17	11.7	.2177	131
d	2.17	11.5	.2142	135
e	2.17	11.5	.2142	152
f	2.17	12.0	.2235	164
g	2.17	11.6	.2161	186
h	2.17	12.1	.2247	209
i	2.17	11.25	.2095	228
j	2.17	11.4	.2119	250
k	2.17	11.25	.2095	280
l	2.06	10.38	.2037	304
m	2.06	10.5	.2060	328
n	1.84	10.1	.2219	350
o	1.84	9.0	.1977	378
o'	1.84	9.38	.2060	378
p	1.51	7.88	.2109	425

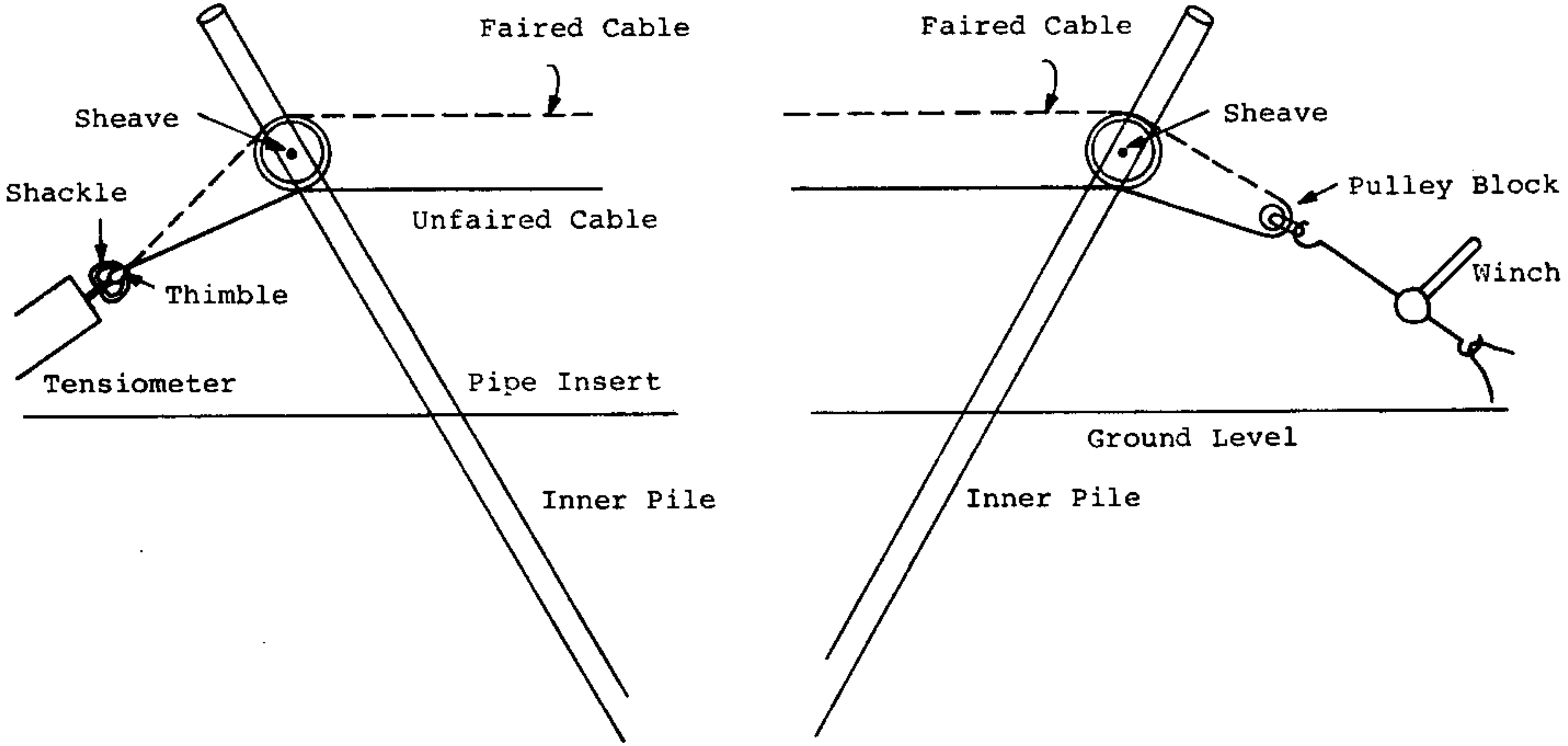


FIGURE 8.6 Arrangement for the Anti-Strumming Tests

The other instruments were also carried to the boat. The pipe inserts were then unbolted and handed up to those on board. These pipe inserts unfortunately could not be left on the sandbar because they would have been a hazard to navigation. The marker buoys, guide rope, test cable and winch were then brought to the boat. Finally, the divers loosened the stern anchor and climbed aboard.

8.2.4 Anti-Strumming Experiment

The last cables tested were cables #4a and #4b. It was decided that the effectiveness of the anti-strumming fairing could be best evaluated if both cables could be tested under exactly the same conditions. The problem was to place both cables in the same current, with the same tension, at the same time.

The arrangement of the cables was the major difference between this test and the previous tests, as shown in Figure 8.6, 8.7 and 8.8 a pulley block was hooked to the winch. The faired and unfaired parts of the original cable were not separated, and the cable was threaded through the pulley to the point where the cable changed from faired to unfaired. The faired part of the cable was stretched across the tops of the sheaves on the pipe inserts. The unfaired part was wrapped once around each of the two sheaves so that the unfaired cable was separated from the faired cable by the diameter of the sheaves. Both the faired and unfaired cables were terminated at the western end beyond the sheave by being cable-clamped to the same thimble. The thimble was then shackled to the tensiometer.

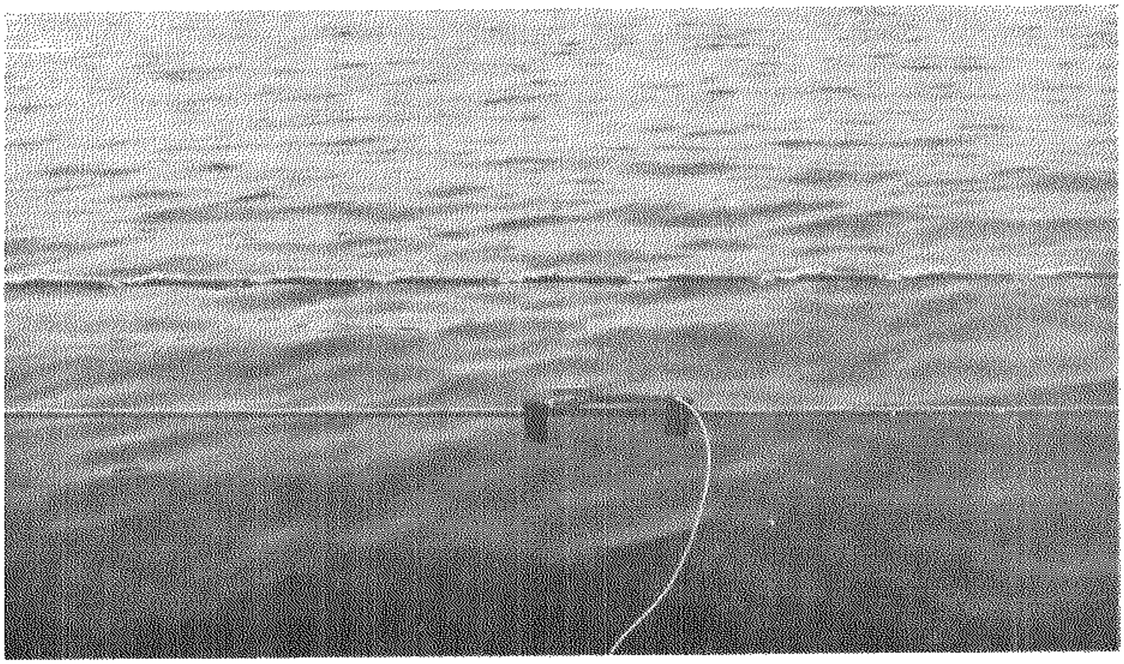


FIGURE 8.7 The Anti-Strumming Experiment Accelerometer is Attached to Unfaired Cable

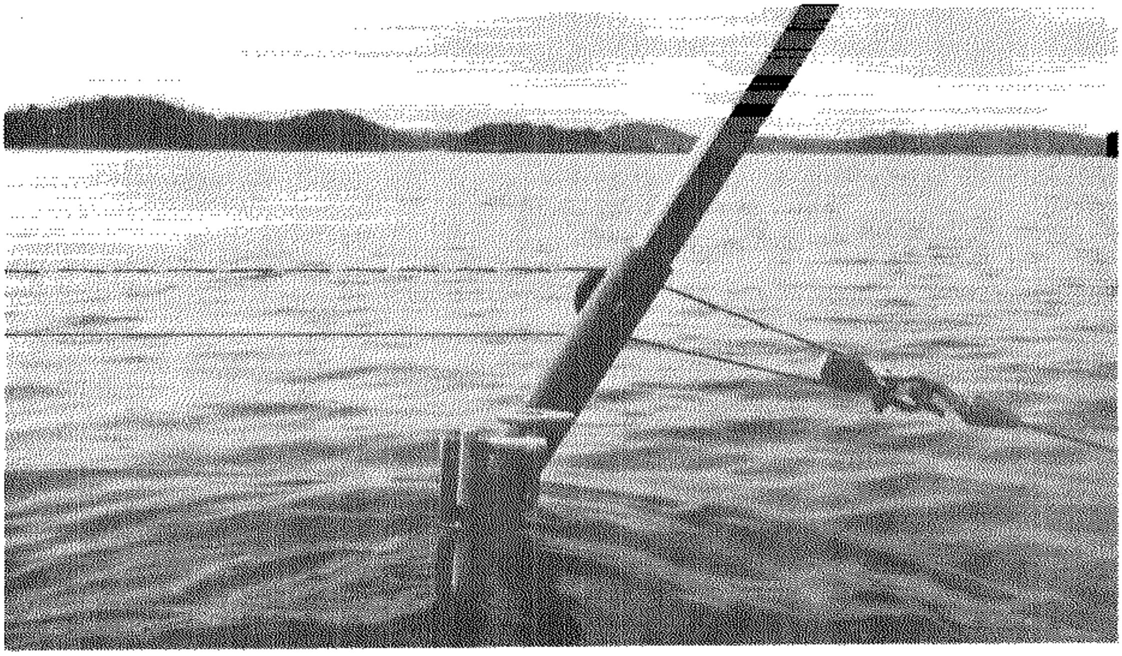


FIGURE 8.8 Anti-Strumming Experiment Eastern End

The "fish" was attached throughout the experiment to the same spot on the unfaired cable. Only one accelerometer was functioning so it was traversed along the unfaired cable, and also positioned on the faired cable, above the "fish", or above the point where data had recently been taken on the unfaired cable. To determine the tension on each of the cables, the tension shown on the tensiometer had to be divided by two.

8.3 EXPERIMENTAL RESULTS

The recordings made in Castine, Maine, were played back through a four-channel strip chart recorder at M.I.T.; a sample is shown in Figure 9. The analysis is not yet complete. Many sections of data must be processed through a spectrum analyzer. Only preliminary results are therefore reported here.

Preliminary analysis indicates that the strouhal numbers ($d f_d/V_d$) computed for the "Blue Streak" ranged from .14 to .18 with .17 dominant. By dominant it is meant that the number is the average non-lock-in observed strouhal number. The .485" diameter Kevlar cable's strouhal numbers ranged from .2 to .22 with .21 dominant. The unfaired anti-strumming cable's strouhal numbers ranged from .16 to .18 with .17 dominant. The faired anti-strumming cable's strouhal numbers ranged from .12 to .13 with .123 dominant, using the same diameter for strouhal calculations as the unfaired cable. The fairing was irregular so that accurate diameter measurements could not be taken.

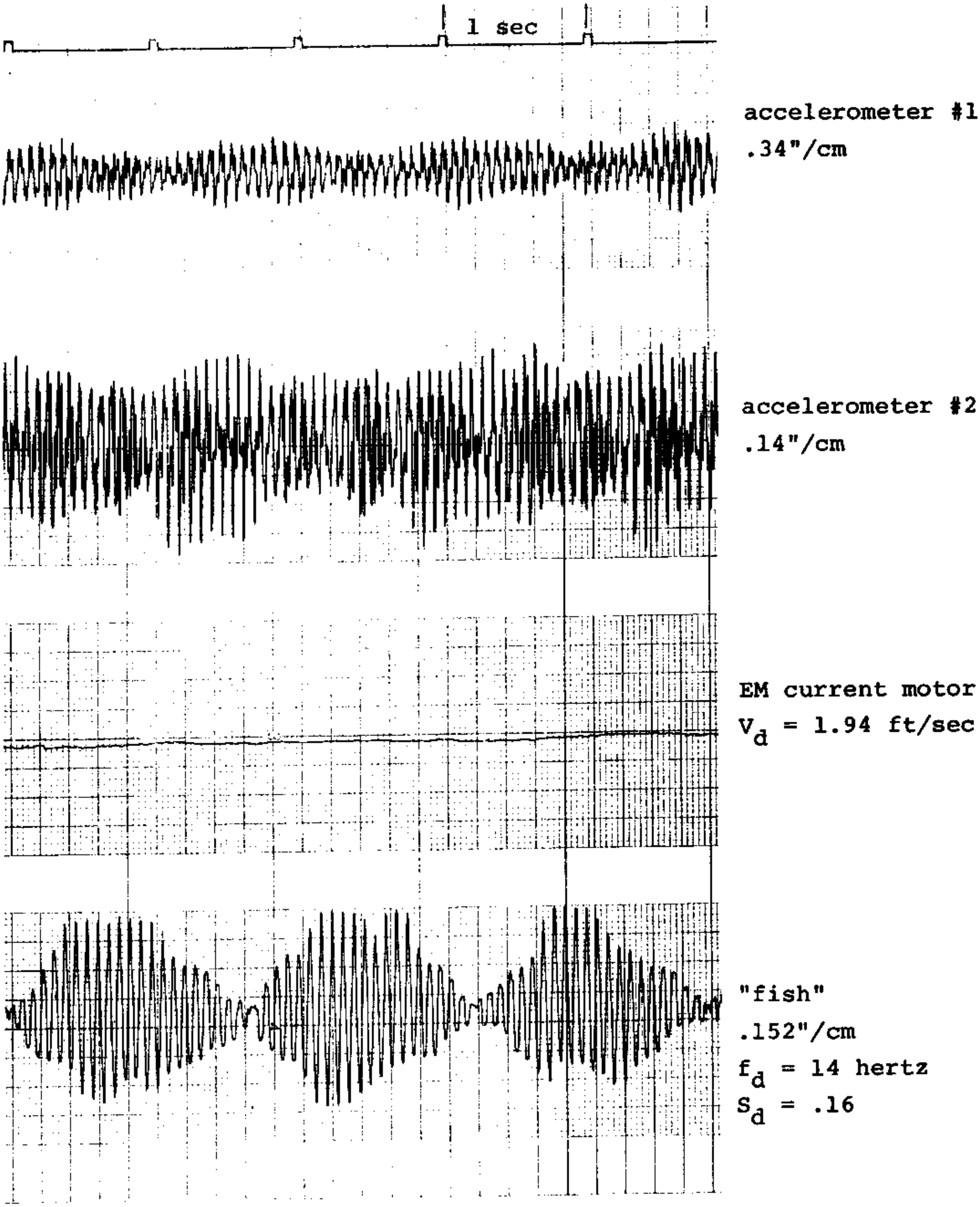


FIGURE 8.9 Representative Transducer Outputs for the Wire Rope, Tension 190 lb.

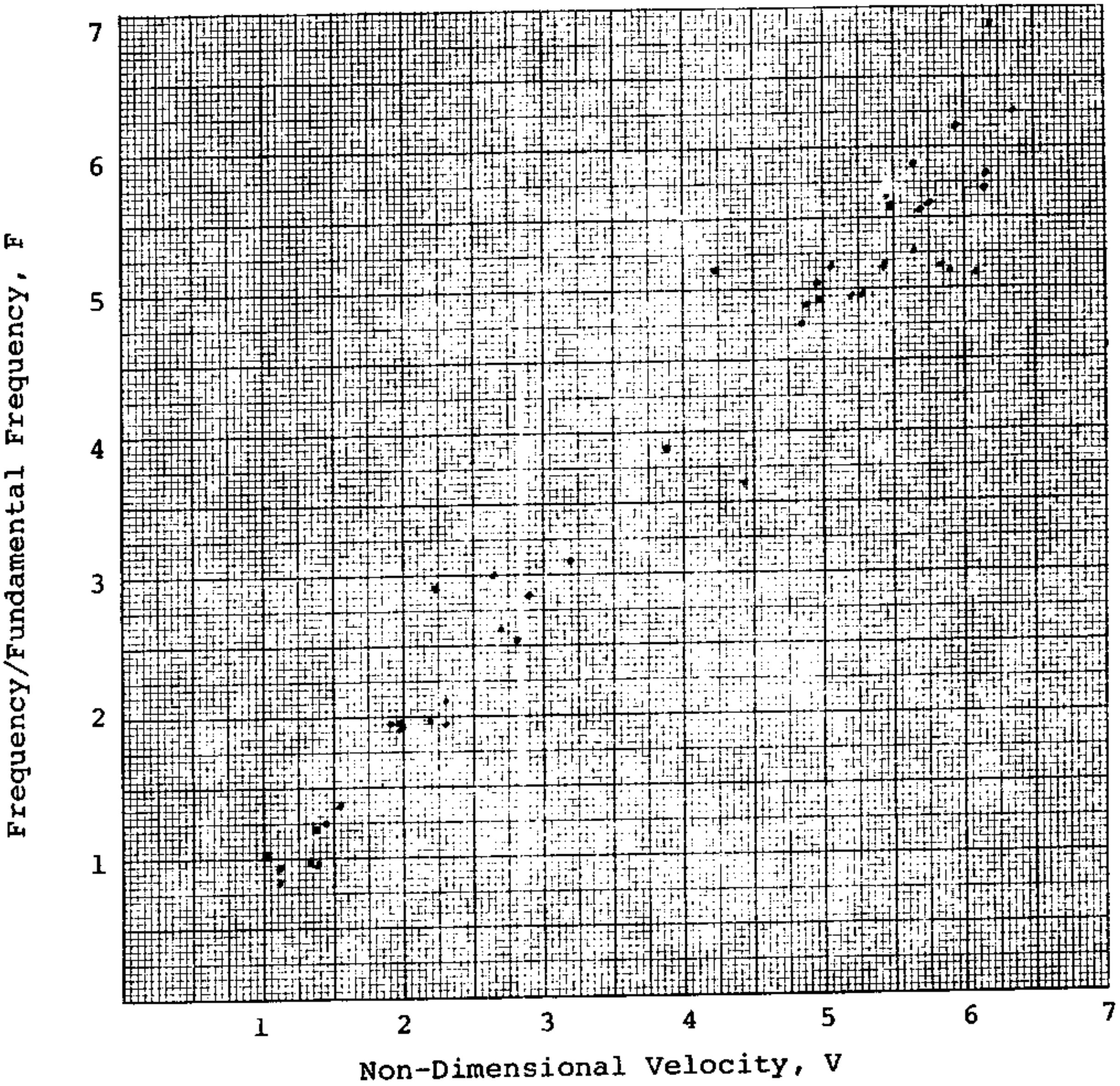


FIGURE 8.10 The Results of a "Blue Streak" Cable Test, Diameter 0.39".

Varying cable tension, while keeping at a constant velocity, did not alter the frequency of vibration a significant amount, as shown in Table 8.2.

Lock-in phenomena were observed at modes 1 through 5. Lock-in is said to occur when the cable continues to vibrate at a multiple of its fundamental natural frequency in water while the current velocity varies. Or, whenever the cable vibrates at a mode rather than at the frequency of shedding predicted by the strouhal number, current velocity and cable diameter ($f = SV_d/d$).

Figure 8.10 plots a nondimensional frequency F against a nondimensional current velocity V. The nondimensional frequency is the ratio of the observed frequency f_d to the fundamental natural frequency in water f_1. F therefore corresponds to the mode of the cable's vibration, assuming a constant added mass. The nondimensional velocity is the ratio of the observed current velocity V_d to that velocity which would cause the cable to shed vortices at its fundamental natural frequency in water ($V_1 = fd/s$). For details of calculations, see Symbols and Definitions.

The anti-strumming fairing decreased the strouhal number from .17 to .123; a strip chart recording is shown in Figure 8.11. Another way of looking at this is to say that the effective diameter was increased from .154" to .213" by adding the anti-strumming fairing. The maximum amplitude of the unfaired cable was .114" and the average amplitude was approximately .085", or 74% of the cable's diameter maximum and 55% of the diameter average. The maximum

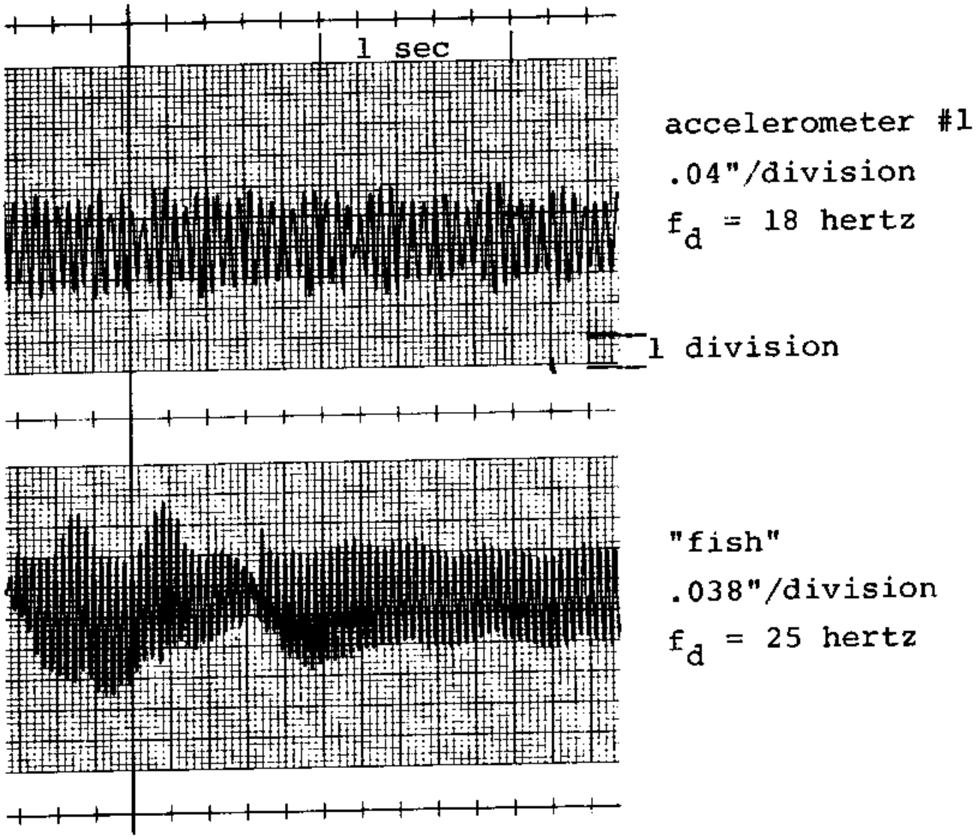


FIGURE 3.11 Anti-Strumming Experiment. Accelerometer #1 is on the Faired Cable. The "Fish" is on the Unfaired Cable. The Tension is 74 lb, Current Velocity is 1.88 ft/sec.

amplitude of the faired cable was .08" and the average amplitude was .06", or 38% of the effective diameter maximum and 28% of the effective diameter average. The anti-strumming fairing therefore had the effect of reducing the strumming amplitude, but it did not eliminate the problem.

8.4 CONCLUSIONS

Measurements of the amplitudes and frequencies of strumming cables were carried out in the ocean environment. The strumming action was vigorous and energetic, with amplitudes up to three-quarters of a cable diameter. Both the "fish" transducer and the accelerometers gave excellent results. The measured strouhal numbers for the "Blue Streak" and unfaired anti-strumming cable were approximately .17 which agrees with other experiments concerning freely vibrating cables. The .21 observed strouhal number for the Kevlar has not yet been explained. "Lock-in" phenomena were observed at low current velocities, as shown in Figure 8.10. Frequency of vibration was found to be independent of tension at high current velocity, as shown in Table 8.2.

Tests were conducted on an anti-strumming cable. The anti-strumming fairings were found to decrease the amplitudes by 30% and increased the effective diameter by 26%, but the faired cable still strummed at 3/8 of its effective diameter. This is still an energetic vibration. It appears that this anti-strumming design is not effective enough for most purposes.

8.5 RECOMMENDATIONS

Cables tested in this study were perpendicular to the current. Future tests should be conducted with yawed cables, and with mass loaded cables.

Other anti-strumming cable designs should also be tested.

8.6 REFERENCES

1. N. B. Davis and S. D. Jessup, Cable Strumming Experiments, Massachusetts Institute of Technology, Ocean Engineering Report No. 74-19, 1974

SYMBOLS AND DEFINITIONS

V_d = observed current velocity

f_d = observed frequency

T_d = observed tension

u = mass per unit length in water, including "added mass"

L = length of cable

$f_n = (n/2L)(\sqrt{T}/\sqrt{u})$ = frequency at nth mode

f_1 = fundamental frequency in water. In practice, the fundamental was observed at one tension, and scale from the above formula for other tensions.

$\therefore \quad f_1 = f_{1,\text{observed}} \sqrt{T_1}/\sqrt{T_{1,\text{observed}}}$

d = diameter of cable

$S_d = d\, f_d/V_d$ = observed strouhal number

S = dominant strouhal number for cable tested

$F = f_d/f_1$ = the mode of the cable's vibration

$V_1 = f_1 d/s$ = the current velocity which would drive the cable at its fundamental natural frequency

$V = V_d/V_1 = V_d S/f_1 d$ = a dimensionless velocity

9. A PORTABLE FLOATING BREAKWATER

In 1973 Dr. Buckminster Fuller approached the Summer Laboratory with a proposal for a floating breakwater. He assumed the breakwater would be of cylindrical form, portable and environmentally safe.

The first attempt used inner tubes from automobile tires, three quarters filled with water and pressurized with air. A plastic cover was placed over the tubes to form the cylinder. After deployment in Castine Harbor seas ripped the cover. In 1974 a larger model using truck inner tubes was built with a stronger cover. This model was 60 feet long and 6 feet in diameter. Due to the weight and the instability of the water filled tubes this model could not be properly assembled.

9.1 BREAKWATER DESIGN

The third model used plastic water pipe to form the hoops. Plastic couplings were used to join the two ends of each pipe to complete the ring. Weights were placed on the hoop to provide stability so that the rings would float in a vertical plane.

Preliminary calculations showed that with 1 1/2 diameter pipe, weights of approximately 6 lb should be added to each hoop to make the breakwater float with one quarter of the diameter above the surface.

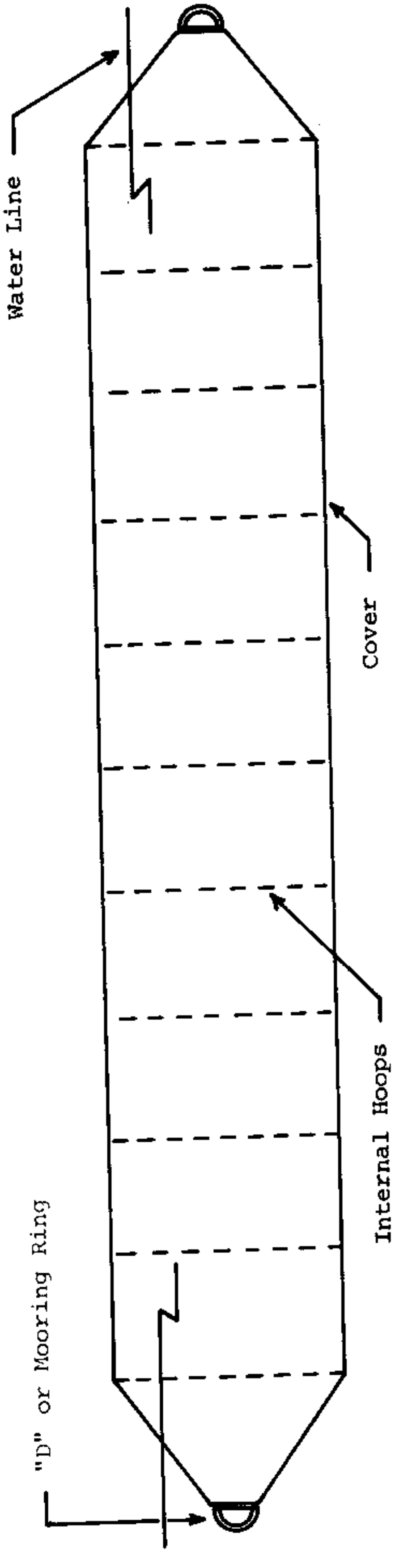


FIGURE 9.1 The Breakwater

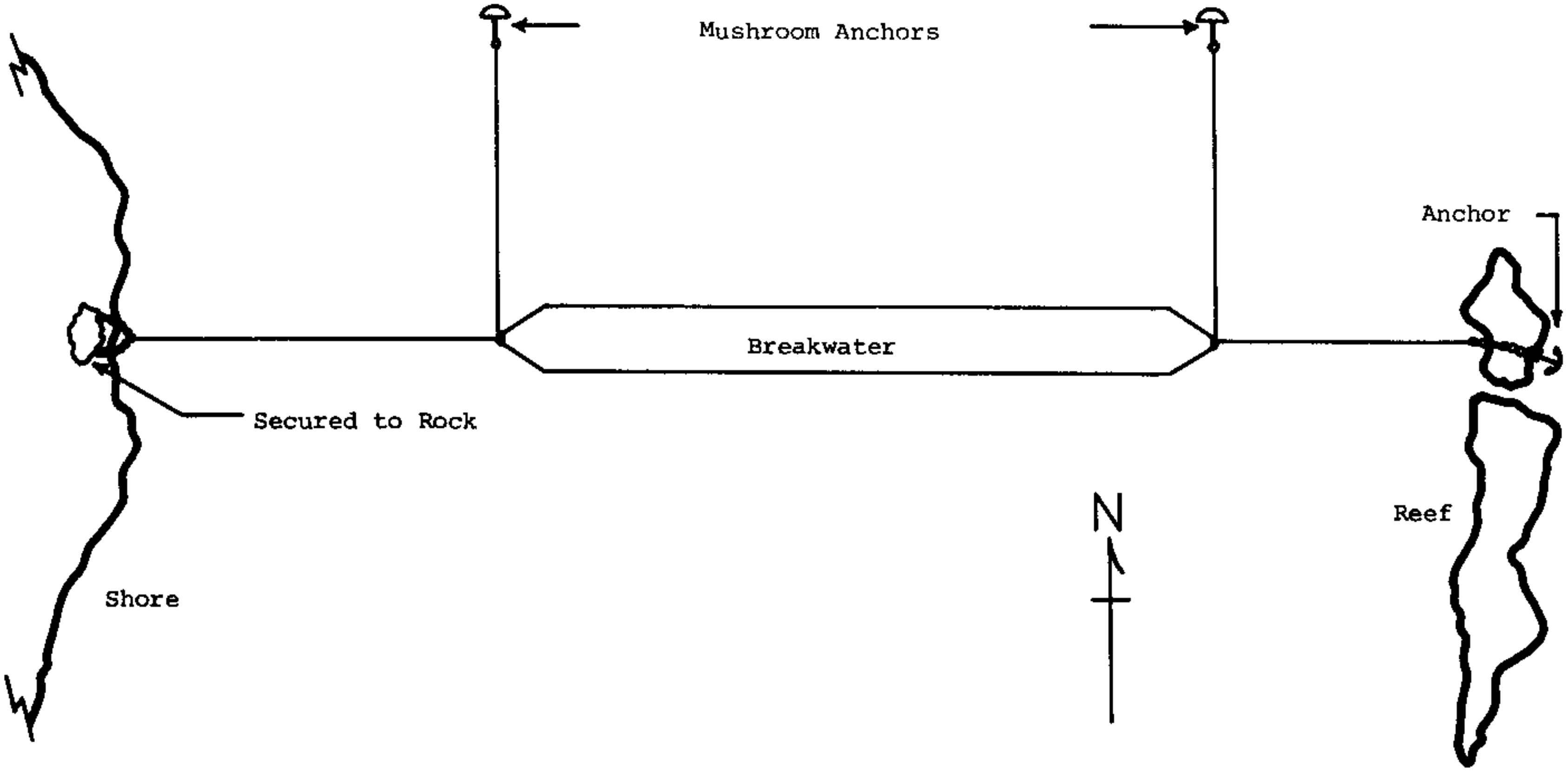


FIGURE 9.2 The Mooring System

The cover used the previous year was again utilized. Grommets were placed in rows every 6 feet along the cover to secure the hoops, as shown in Figure 9.1. "D" rings were placed at the ends of the cover to take the mooring lines.

The breakwater was assembled on land and deployed with two men using a rowboat. It was placed between an island and a rock reef at the testing site. One end of the breakwater was attached by a rope and chain to a rock on the island while the other end was secured by an anchor in a ledge of the reef. Swivels were placed at the ends of the breakwater. Two additional mushroom anchors were placed as shown on Figure 9.2 to prevent over-stressing of the mooring lines.

9.2 TEST PROGRAM

The breakwater was set up at the test site and simple wave height indicators built and installed upstream and downstream of the breakwater. However, during the twelve days that the breakwater was installed no significant waves were observed so that the effectiveness of the breakwater was not determined.

During the deployment structural problems occurred. It was found that plastic pipe deformed too easily, especially where the loads were high, at the two ends of the breakwater. Hoops of larger diameter 2 inch pipe were then used for the end rings. In addition water leaked into the pipes when the tubes were buckled.

9.3 CONCLUSIONS AND RECOMMENDATIONS

The breakwater design has been improved but there are several possible improvements. The plastic pipe used is obviously not strong enough and should be replaced with stiffer pipe. It has been suggested longitudinal strength members should be used. This would however, decrease the portability and ease of storage.

10. PRELIMINARY SONAR AND MAGNETOMETER SURVEY FOR VESSELS DESTROYED IN THE PENOBSCOT EXPEDITION OF 1779

During July 1975 a preliminary survey was conducted to determine the feasibility of locating additional vessels from the ill-fated Penobscot Expedition of 1779. The survey was conducted in two parts. First, a detailed survey of the DEFENCE (a Revolutionary War privateer of approximately seventy-five feet in length) to gather background data on target characteristics of a known vessel of this fleet and to get a better understanding of the DEFENCE site, and secondly, a preliminary survey of possible sites up the Penobscot River to investigate the feasibility of surveying in the river and to locate targets for further investigation.

10.1 BACKGROUND

In the summer of 1779 the State of Massachusetts formed an expeditionary force of forty ships to capture Fort George at Castine (Maine) in what was then the eastern part of Massachusetts. The fleet consisted of three Continental Naval Vessels, three vessels of the Massachusetts State Navy, one from New Hampshire, twelve privateers and twenty-one transports which laid siege to Castine on July 24, 1779. There were sporadic attacks made on Fort George but without success. On August 14, 1779 a British force of six large ships arrived at Castine and the American fleet immediately took flight up the Penobscot River

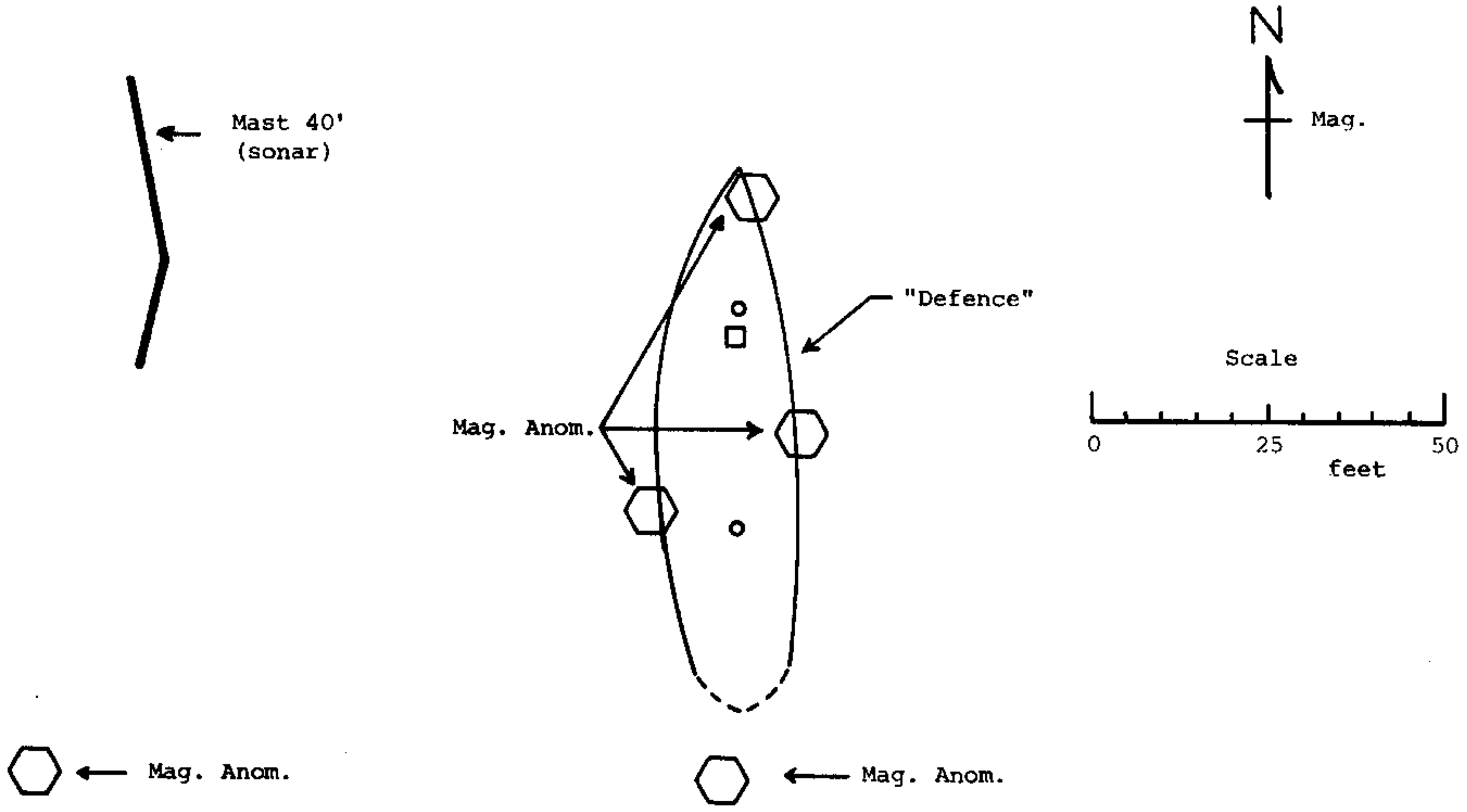


FIGURE 10.1 Sonar and Magnetic Survey of the "Defence"

Most of the ships were subsequently burned and/or blown up by their crews to prevent their capture by the British. This was a major disaster for the Revolutionaries, but it now provides us with invaluable historical artifacts from the Revolutionary War.

The DEFENCE, a Revolutionary War privateer was located four years ago by the Ocean Engineering Summer Laboratory. Since its discovery a limited amount of archaeological work has been accomplished consisting of mapping of the site, limited excavation of the hull and a limited recovery of artifacts.

10.2 THE SURVEYS

The wooden hull appears to have been burned down to the waterline, but below that, the wooden hull which sits in the mud is in very good condition. The extensive side scan sonar surveying of the site shows the hull, which barely projects above the mud bottom to be a very good target. A mast from the vessel was found about sixty-five feet to the west of the site, and a one-foot diameter by twenty-two foot long oak log partially buried in the mud which is not related to the wreck was the only other object found in the area.

A rotary side scan sonar developed by Dr. Edgerton proved very valuable in surveying the site. This device allows the boat to anchor near a suspected target, the rotary side scan sonar is rigged and slowly rotated so that distance and bearing to any target is read. If this information is plotted, a good site plan of bottom targets can be produced. It can also be used to direct divers to a target for investigation.

The DEFENCE site was also surveyed with a proton precession magnetometer owned and operated by Martin Meylach. The survey of the area was made by a series of close parallel paths over the site towing the sensor at low speed. A number of magnetic anomalies were discovered. These magnetic anomalies have not been investigated but are believed to be large iron objects such as cannons or piles of cannon balls. This survey of the DEFENCE site proved that a vessel of this fleet can be detected on both the sonar and magnetometer instruments that were used. The general site plan of the DEFENCE, Figure 10.1 is a composite of information gained from the side scan sonar and magnetometer surveys of the area.

The second part of the survey was to investigate the feasibility of surveying the Penobscot River for additional wrecks of this ill-fated fleet. A great deal of historical investigation has been completed with probable locations and general descriptions of the ships prepared. With this in hand, each of the proposed sites as indicated on the rough map of the area were briefly investigated. Surveying conditions were good for both the sonar and the magnetometer. The river bottom has some sonar targets but not so many as to make searching impossible. The background magnetic characteristics of the area did not interfere with the operation of the magnetometer. A number of magnetic anomalies were discovered as shown on Figure 10.2, some of which have a real potential when coupled with the sonar and historical data.

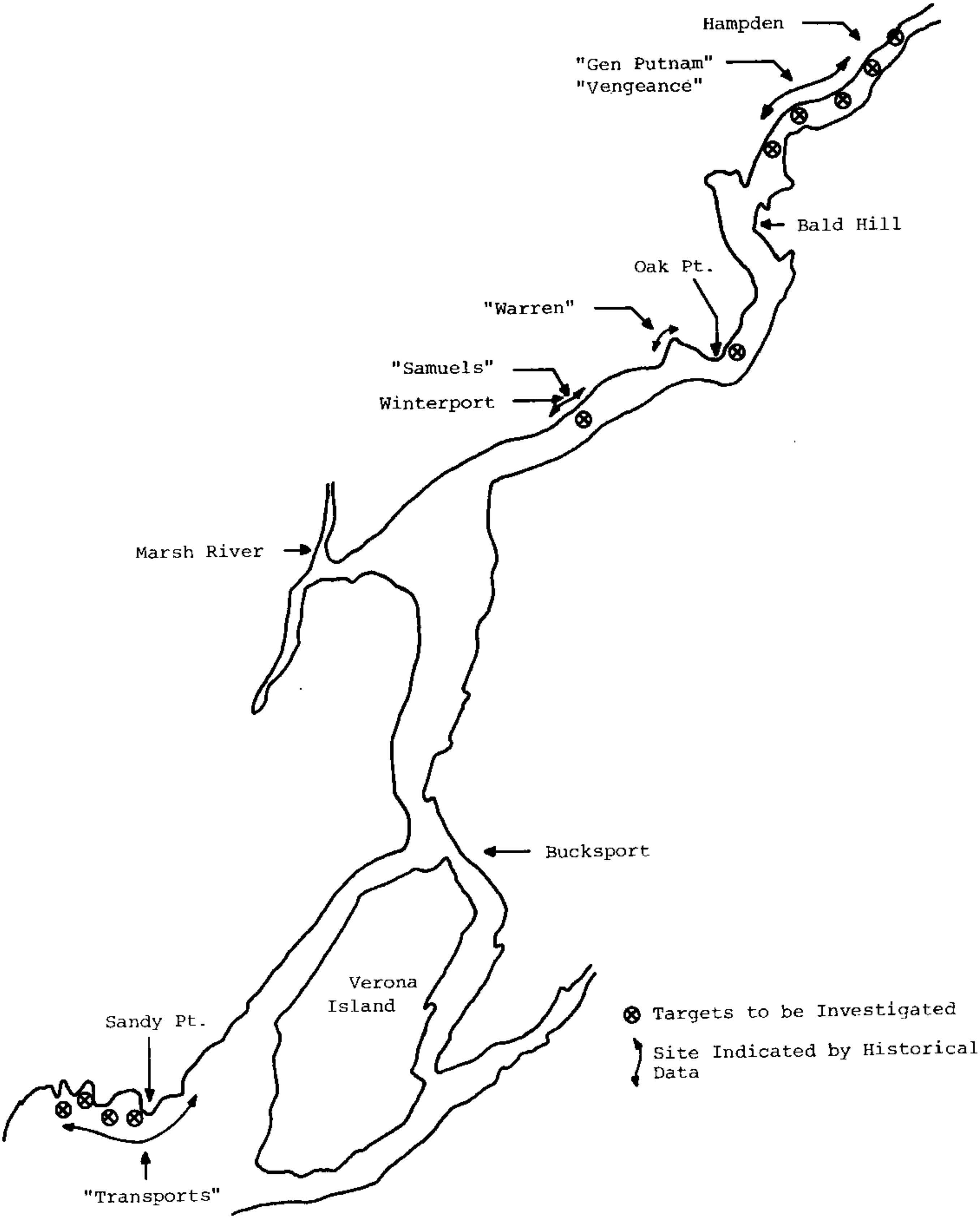


FIGURE 10.2 Preliminary Survey of the Penobscot River

A complete survey of the Penobscot River site should be made with special emphasis on the few promising targets discovered in the preliminary survey. Diver investigation of the targets was not conducted due to time limitations. This is an important aspect of the survey which can be facilitated by the use of rotary side scan sonar which allows the divers to be directed by the surface command right to the target without a detailed diver search of the area.