2

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

DESIGN AND CONSTRUCTION
OF A
SECOND GENERATION AUV

by

Michael R. Good

December, 1989

Thesis Advisor:	A.J. Healey
Second Reader:	Glenn N. Reid

Approved for public release; distribution is unlimited.

CLASSIFIED

RITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

EPORT SECURITY CLASSIFICATION LASSIFIED	1b. RESTRICTIVE MARKINGS
ECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited
ECLASSIFICATION/DOWNGRADING SCHEDULE	
RFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)

IAME OF PERFORMING ORGANIZATION al Postgraduate School	6b OFFICE SYMBOL *(If applicable)* 52	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
DDRESS *(City, State, and ZIP Code)* terey, CA 93943-5000		7b. ADDRESS *(City, State, and ZIP Code)* Monterey, CA 93943-5000
IAME OF FUNDING/SPONSORING ANIZATION	8b OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DDRESS *(City, State, and ZIP Code)*		10. SOURCE OF FUNDING NUMBERS

Program Element No	Project No	Task No.	Work Unit Accession Number

ITLE *(Include Security Classification)*
gn and Construction of a Second Generation AUV

ERSONAL AUTHOR(S) Good, Michael Richard

TYPE OF REPORT ter's Thesis	13b TIME COVERED From To	14. DATE OF REPORT *(year, month, day)* December 1989	15. PAGE COUNT 149

UPPLEMENTARY NOTATION
views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. rnment.

OSATI CODES			18. SUBJECT TERMS *(continue on reverse if necessary and identify by block number)*
LD	GROUP	SUBGROUP	Autonomous Underwater Vehicle, AUV, Unmanned Untethered Underwater Vehicle, UUV, Underwater Vehicle Systems Design

BSTRACT *(continue on reverse if necessary and identify by block number)*

The design and construction of an Autonomous Underwater Vehicle (AUV) for use as a research and development testbed at the Naval Postgraduate School (NPS) is presented. Design objectives, analysis and trade-offs are discussed with respect to a generic AUV and specifically detailed for the case of the NPS AUV II. System integration and flexibility is emphasized in the subject vehicle to support presently planned and future research employment. Hull, mobility, sensor, automatic control, and energy subsystems are described. Design and fabrication techniques for the NPS AUV II vehicle hull and equipments are documented.

ISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS REPORT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
NAME OF RESPONSIBLE INDIVIDUAL hony J. Healey	22b TELEPHONE *(Include Area code)* (408) 646-2586	22c OFFICE SYMBOL 69Hy

FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Design and Construction
of a
Second Generation AUV

by

Michael R. Good
Lieutenant, United States Navy
B.S.M.E., Marquette University

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING
from the
NAVAL POSTGRADUATE SCHOOL
December 1989

Author: Michael R. Good
Michael R. Good

Approved by:
A.J. Healey, Thesis Advisor

Glenn N. Reid, Second Reader

A.J. Healey, Chairman
Department of Mechanical Engineering

ABSTRACT

The design and construction of an Autonomous Underwater Vehicle (AUV) for use as a research and development testbed at the Naval Postgraduate School (NPS) is presented. Design objectives, analysis and trade-offs are discussed with respect to a generic AUV and specifically detailed for the case of the NPS AUV II. System integration and flexibility is emphasized in the subject vehicle to support presently planned and future research employment. Hull, mobility, sensor, automatic control, and energy subsystems are described. Design and fabrication techniques for the NPS AUV II vehicle hull and equipments are documented.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Anthony Healey and the members of the AUV group, in general for their suggestions and contributing ideas to this work. LCDR Tom Saunders and Dave Marco are thanked for their contribution to the detail design of the thruster units. Mr. Glenn Reid is thanked for his input to the sonar systems detail and other practical suggestions and enthusiasm on overall design issues. Tom Christian is particularly recognized for his expertise in the design of the electrical circuitry, and Jim Selby, for his contributions to the construction of the hull and the fiberglass nose.

The completion of this endeavor owes much to the love, support and encouragement of my wife, Nancy Helland. I will always be grateful for your assistance in meeting this challenge.

The author wishes to acknowledge financial support from the NPS Direct Research Fund with technical sponsorship from Naval Surface Warfare Center - White Oak Laboratories.

I. INTRODUCTION

A. INTRODUCTION

The Naval Postgraduate School (NPS) has engaged in research with Autonomous Underwater Vehicles (AUVs) since 1987 under the sponsorship of the Naval Surface Weapons System (NSWC) at White Oak, Maryland [Ref. 1]. This interdepartmental research has been aimed at developing a prototype expert system controller for an AUV, a critical technology for Navy applications. Actual vehicle trials have been a fundamental aspect of the program, confirming laboratory efforts and computer simulation.

While underwater vehicles of many diverse types are used in the military and commercial arenas, the important new feature of AUV's lies in the increased use of onboard automation. Thus the special features of the research at NPS lie in the development of advanced control concepts and surrounding issues in real-time control, autonomous mission planning (replanning) and navigation, guidance and autopilot functions.

Previous research into advanced autopilot design has shown the importance of a state observer when gyro signals are inoperative, even based on depth measurement only, (MacDonald, [Ref. 2]) and the usefulness of the robust control methods using Sliding Modes (Sur, [Ref. 3]). The importance of a good vehicle dynamic model cannot be overstated, however, and other work beginning with simulation of the six-degree-of-freedom behavior of the Swimmer Delivery Vehicle (SDV IX), led to studies of maneuvering controls (Boncal, [Ref. 4]), reduced parameterization (Larsen, [Ref. 5]), and system identification from model testing (Brunner [Ref. 6]).

Furthering the understanding of the dynamics of underwater vehicles, and the development of real-time control systems, however, has reinforced the need for a test vehicle that will conduct autonomous operations, having its own internal power, sensor processing and decision making capability.

1. Previous Vehicle - AUV I

The first underwater vehicle constructed at the Naval Postgraduate School by Glenn Brunner provided valuable service as a platform for the development of AUV automatic control techniques. AUV I was designed to be hand carryable and small enough to operate in a 4′ x 4′ x 40′ long test tank located in the Mechanical Engineering (M.E.) building. These size constraints limited the vehicle's internal load significantly, so that it had to rely on external equipment for its operation. Control was provided by an offboard IBM-AT type digital computer which transmitted maneuvering command signals through radio control hardware to the vehicle's control surfaces. This equipment was comprised of commercially available RC model aircraft components which were modified for the vehicle installation. Besides relying on the radio control link, the vehicle had an umbilical to convey vehicle sensor data to the computer. The umbilical also connected an external power supply to the vehicle since no room was available onboard for batteries.

2. Need for Second AUV

Several alternatives aimed at upgrading the capabilities of the AUV I were considered, including adding a midsection to the vehicle body for battery storage and installing a radio telemetry device to eliminate the requirement for a tether. Each modification had its drawbacks however, and it became clear that a second vehicle should be designed and built with the primary mission of demonstrating the feasibility of truly autonomous operation.

B. OBJECTIVES OF THIS THESIS WORK

The work described in this thesis was aimed at the design issues surrounding the development of the second model AUV. Because of the greater sophistication inherent in this vehicle, as a result of the mission to demonstrate fully autonomous operation, the tasks relating to its design brought out new considerations, not routine factors. The integration of the hardware and software for the increased levels of automation make the design of AUV's in general, somewhat unique.

The objectives of this work are twofold. First, the development of a design process with its necessary considerations for AUV vehicles was felt to be worthwhile and is discussed in Chapter II. Secondly, the application of that process to the design of the second generation model AUV, having the mission to demonstrate autonomous behavior within the confined space of a pool (or similar available body of water), was a goal. Chapter III of this thesis records the methodology and detail design of this second generation vehicle, and Chapter IV details the special considerations made for its construction and assembly. While the construction is about 75% complete at this time, sufficient confidence as to its final operational performance is now established.

II. GENERAL CONSIDERATIONS FOR AUV DESIGN

A. INTRODUCTION

This chapter will give a discussion of a general approach to the design of AUV's for supporting various mission scenarios. The design process for an autonomous vehicle, as with any total ship system, must begin with an assessment of the mission or series of mission objectives, that the vehicle must support, and the operational and technical requirements that must be achieved.

It is recognized, however, that this is only the first of perhaps many iterations of the process, since setting of competing requirements often implies that difficult trade-offs have to be made, with possibly large impacts on overall costs. As the design progresses, the technical specifications will have to be adjusted, and sometimes conflicts can only be resolved by modification to the mission requirements. This process is shown symbolically in Figure 1.

While this figure shows the overall design activity relating mission definition, vehicle design, and cost definition, it is the middle activity that has the task of defining the vehicle subsystems, the interface variables, the significant effects, the details of the major design trade-offs, and these major subsystems are the subject of the

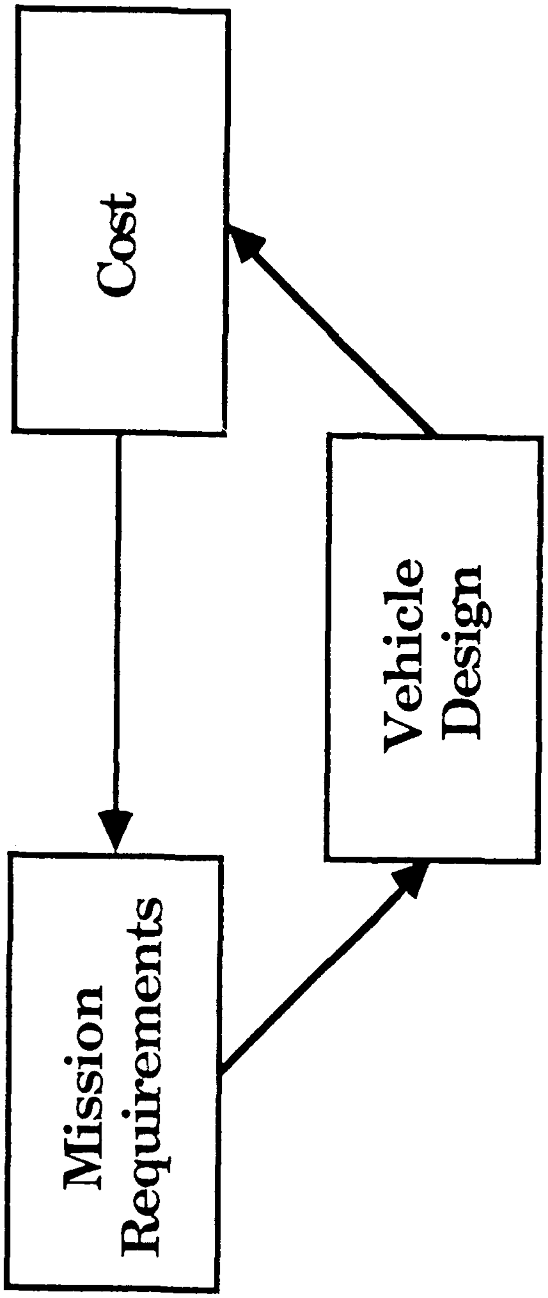


Figure 1 Basic Trade-offs in Design

rest of this chapter. This is provided as a preliminary to the follow-on chapter which addresses the specific details of the design of the second generation vehicle, the NPS AUV II.

B. MAJOR SUBSYSTEMS OF AN AUV

Depending on the nature of the vehicle mission, one or another subsystem may dominate the design considerations, although the need for autonomous operations will undoubtedly indicate that control functions will play a key role. For relatively long mission durations of more than one hundred hours or so, the energy system may be the dominant consideration. For long duration missions, overall AUV reliability may be the dominant consideration, and will demand high reliability and possibly redundancy in both the computer hardware and software areas, as well as in the vehicle hardware systems. For special missions, the sensor integration that is commonly done by human operators will need to be done by automated means, and this may dominate the design process. In general, the subsystems below have been identified as common to many vehicle mission needs, and Figure 2 is provided to illustrate the design spiral that in this case includes a counter rotation through the vehicle hardware considerations and the mission dictated information systems considerations:

1. Hull (Containment System)

2. Energy Storage and Power Plant (Energy System)
3. Vehicle Motion Control System (Mobility System)
4. Sensor Suite (Environment Awareness Systems)
5. Obstacle Avoidance, Navigation and Guidance Systems
6. Autonomous Mission Planner / Replanner
7. Machinery Health Monitor
8. Workpackage Subsystems

C. HULL SUBSYSTEM

The hull, as a subsystem must have sufficient strength and size to safely contain all the internal systems of the vehicle, and is strongly dependent on mission requirements for depth. In present practice, Remotely Operated Vehicle (ROV) hulls are distinguished by their frame type structure, wet, with buoyancy as needed, to which various self contained pressure proof units are attached. A more hydrodynamically shaped version of this is used when external power from a mother ship is not available, as found in the US Navy's Deep Submergence Rescue Vehicles (DSRV), where separately contained systems are attached to a frame over which a faired skin defines the outer shape. Human life support systems, in this case, are contained in the three titanium sphere pressure chambers, interlocked together. This approach, by the way, is favored with many of the deep sea vehicles.

For moderate depths of a few hundred meters or so, integral containment structures may be chosen, although some

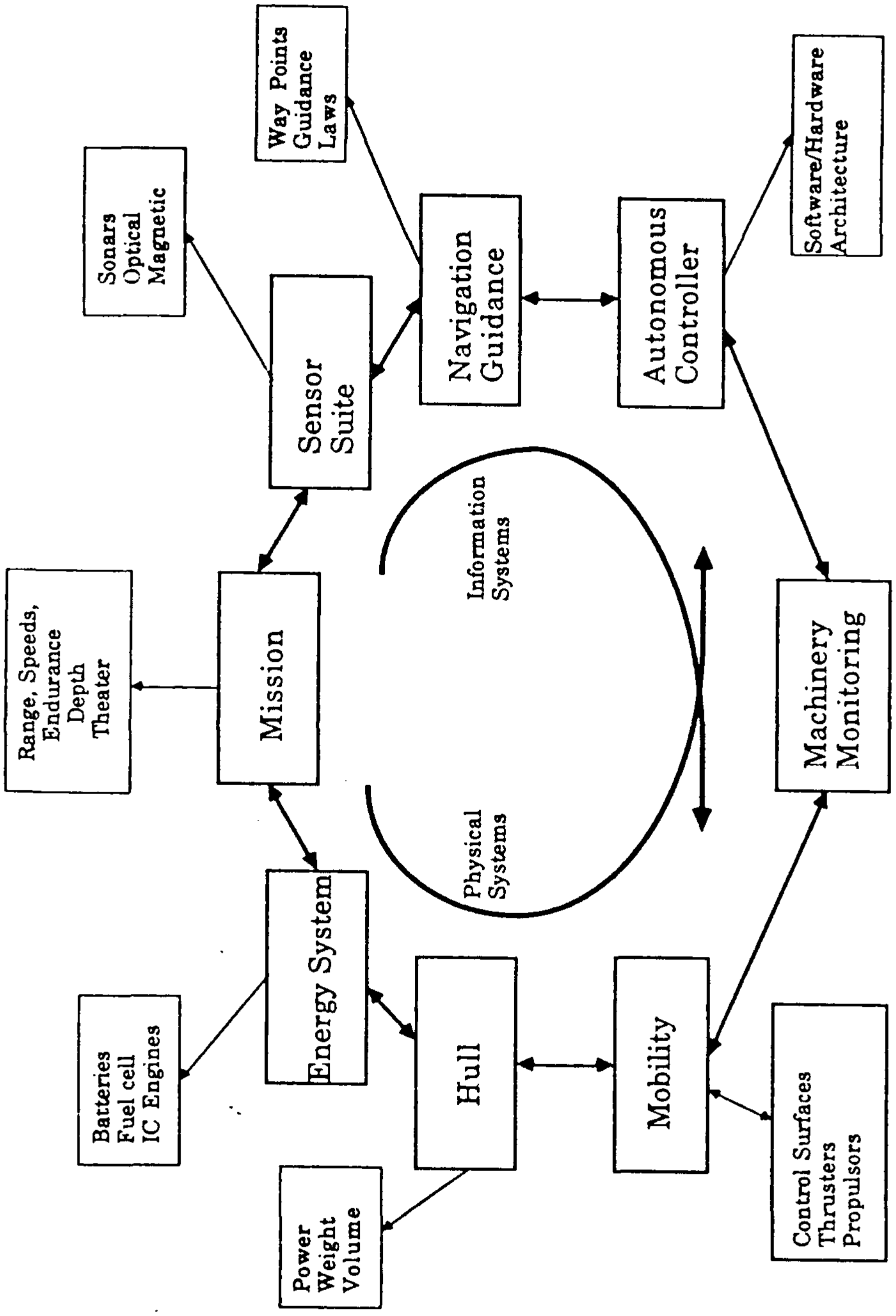


Figure 2 AUV Design Spiral

form of pressure chamber is likely to be needed to house those components that favor atmospheric pressure for their operation. Assuming the foregoing, strength design boils down to the design of pressure vessels for collapse strength under external pressure loading. For very shallow operation, the dominant strength considerations may arise in transportation and handling operations. The design of ring stiffened shells/cylinders has been the subject of a great many investigations over the past several years [Ref. 7] [Ref. 8] and will not be repeated here except by reference. Suffice it to say that failure modes that must be considered in designing stiffener ring parameters include column buckling, higher mode buckling for 'thin-shell approximants', panel buckling, and collapse. Special care must be exercised if hull form transitions occur. This topic will be revisited in the next chapter with reference to the NPS AUV II vehicle.

D. POWER PLANT / ENERGY SYSTEM SELECTION AND DESIGN

AUV power plants and energy systems depend strongly on the mission requirements as far as range, endurance, and speed are concerned. Generally for short duration missions -say a few hours- batteries, either standard or advanced high density variants would be preferred. Moderate to long missions up to 100 hours or more, require significant amounts of energy storage, stored in compact form. Short of using small size nuclear plants, these missions will require the use of advanced fuel cell technology, or the use of other liquid fuel technology such as a closed cycle diesel power plant. Key design parameters are the weight and volume needs to support the total mission. A good discussion of these issues can be found in [Ref. 9].

E. VEHICLE MOTION CONTROL SYSTEM

The vehicle motion control system provides mobility for the vehicle and is comprised of combinations of propellers, either as a traditional propulsor, or in the form of thruster units, and control surfaces that are active when the vehicle is under way. The functioning of this system is to take commands for deflection or force from the vehicle autopilot system and establish the proper forces on the vehicle body consistent with the necessary motion. This system clearly has a double facet in the role of the computer software algorithms for the autopilot, and the operation of the hardware involved. This system also includes the sensors that are required to monitor the actual motion of the vehicle providing inputs to the autopilot. In general, sensors required measure the state of the vehicle in terms of its angular rates, positions, and including doppler sonar if necessary, corrections to global position data from the equivalent of an inertial navigation system suite. The division of the function of 'Autopilot', 'Navigation', and 'Guidance' is somewhat arbitrary and subject of current issues in control software architecture.

The sizing of control surfaces is a subject familiar to the maritime industry, as is the specification of thruster units. However, these issues are not that simple in the case of AUV's because of the small sizes involved. Special attention, for example [Ref. 10], must be given to small thrusters. Part of this work will devote time to the development of such small units.

The specific detail of control actuators is determined by the mass, and hydrodynamic behavior of the particular vehicle, and the needs for maneuverability, acceleration and deceleration rates, in both horizontal and vertical planes.

Certain rules of thumb are available for rapid sizing of control surfaces as will be described in more detail in the later sections of this work, although a comprehensive design from first principles, including the development of hydrodynamic force functions, becomes a major undertaking, involving a full understanding of the overall vehicle dynamics. The sizing issues are addressed further later in this work. The control algorithms, have been [Ref. 2] [Ref. 3], and are continuing to be, addressed.

F. SENSOR SUITE

The sensor suite carried by any AUV is a function of the contemplated mission. A variety of sensors could be configured for AUV operation and perhaps the basic set will include obstacle avoidance sonar; needed to maintain safety of the vehicle, video and tactile sensors for mission related activity, doppler sonar to enhance navigation, side-scan sonar for survey work, magnetic sensors for survey work, as well as radio communication link equipment for unloading results.

Design rules for the incorporation of these items are not available and the subject of research.

G. OBSTACLE AVOIDANCE, NAVIGATION AND GUIDANCE

Design considerations for the installation of obstacle avoidance sonar, to sense the impending danger of collision, are not easy to generalize. Navigation, in the form of an Inertial Navigation System (INS) is well studied and will not be repeated here. Guidance laws, for both collision avoidance and mission related guidance, including the aspects of path planning and path replanning are the subject of recent research, see for example [Ref. 11], [Ref. 12].

H. AUTONOMOUS MISSION PLANNING / REPLANNING

Design considerations relative to the issues of autonomous mission planning are clearly the subject of research. Recent activity is underway for the case of mobile land robotics, and similar work in the area of underwater robotics has been conducted at this institution as described in [Ref. 13] [Ref. 14] and [Ref. 15].

I. MACHINERY HEALTH MONITORING

Machinery health monitoring is important to any hardware intensive facility, and is commonplace in Naval vessels. In this case however, the additional demands of autonomy place added burdens on the need for reliable sensors to indicate the status of key machinery elements.

J. WORKPACKAGE SUBSYSTEMS

The systems are separate packages, determined directly by the mission needs and include items such as manipulators, arrays to be deployed, particular sensor packages and items that may be needed on board to assist the launch, recovery and communications aspects of the AUV mission.

Each item must be designed to be consistent with key parameters, such as space, weight, power, and the computational and data storage capability of the vehicle system. It will not be sufficient to simply "add-on" these systems as their needs must be integrated into the vehicle system design. Since, however, individual items are mission specific, further discussion will not be provided here.

III. ACHIEVING OBJECTIVES FOR AUV II THROUGH DESIGN

A. INTRODUCTION

This chapter describes the design of the AUV II test vehicle from its initial concept through detailed system design. AUV II was devised to conduct research in simple autonomous operations. The swimming pool located on the grounds of the Naval Postgraduate School was designated as a test area. The pool would afford the vehicle with adequate maneuvering room while still providing a controlled environment for research. A plan view and depth profile of the pool are shown in Figure 3.

Preliminary investigation would focus on elementary vehicle mobility. A mission for the vehicle at this stage will be to conduct several safe transits along the pool's length, turning at a specified distance from any wall encountered. Later work will involve identifying objects in the pool by shape or position and retaining information about the object for retrieval at the launching site.

B. VEHICLE REQUIREMENTS

The fiscal year 1989 proposal for research [Ref. 1] outlined a preliminary plan for AUV II. Compared to AUV I, it would be a larger scale vehicle with similar shape and about

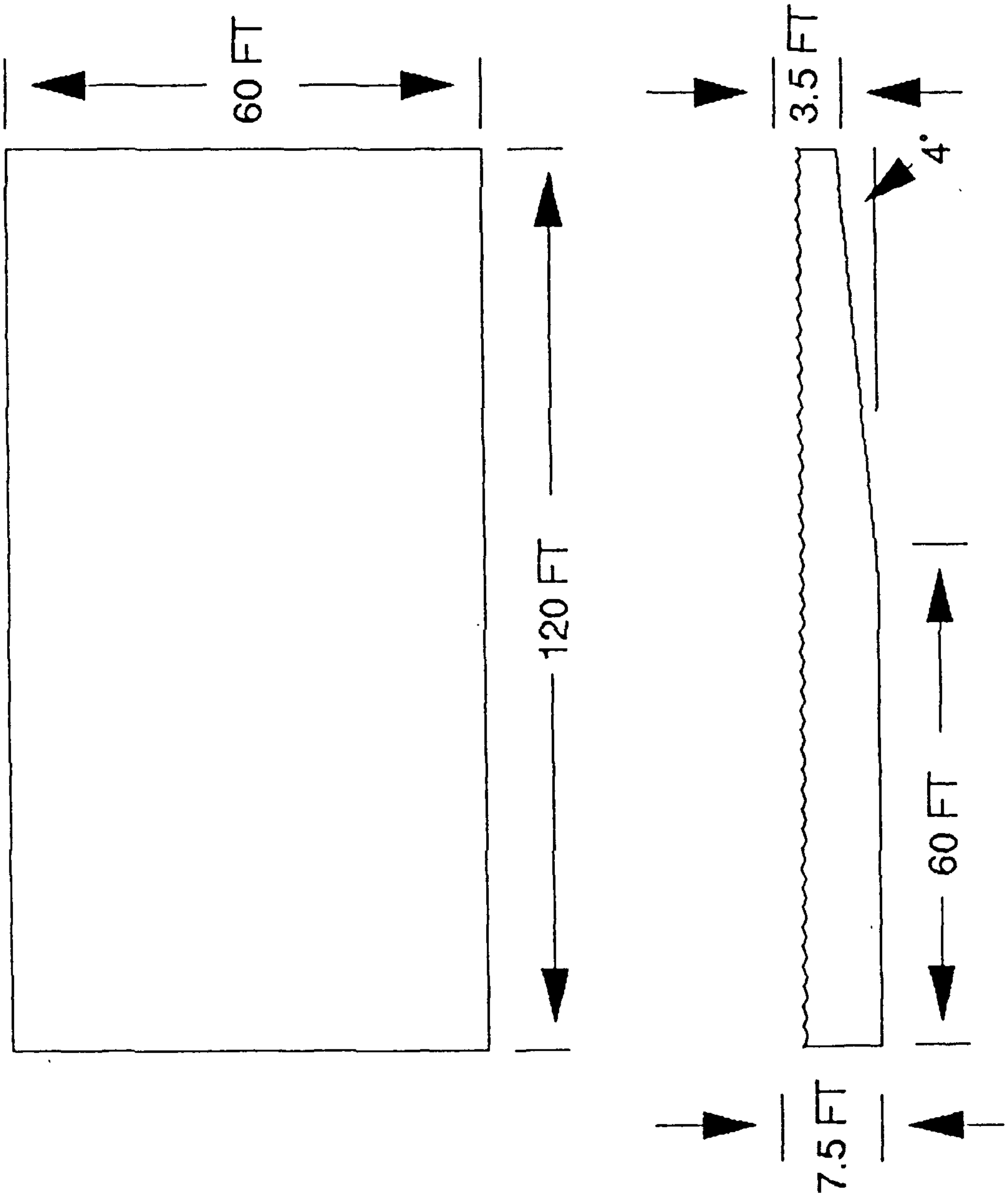


Figure 3 NPS Swimming Pool

twice the length, with a displacement of about 150-200 pounds, to accommodate its own power supply and computational capability. Vehicle power would be supplied by batteries carried internally and an onboard digital computer would provide real time automatic control as well as collect and process data from vehicle sensors. An endurance of about one hour was determined to be desirable for moderate test run speeds of 2 feet per second.

It was thought that the vehicle hull would be fabricated from aluminum or possibly a honeycomb composite sheet material[1]. A detachable fiber optic data transmission link from the vehicle computer to a remote computer was envisioned in order to output data from the vehicle and to monitor the progress of research activities. No commands that would affect the mission were to be transmitted to the AUV.

Discussions on areas of particular importance to vehicle performance focussed on mobility, integration of key subsystems, vehicle reliability and mission capability. Some of the specific topics addressed in this chapter resulted from specified requirements; the hull had a design depth of 25 feet and would incorporate compartmentation to isolate possible water damage; the energy system would provide 1 hour of endurance at a speed of 2 feet per second; mobility design had

---

[1] A composite sandwich material of phenolic honeycomb between two layers of preimpregnated fiberglass cloth.

to specifically address concerns related to the confined operating environment of the swimming pool.

C. VEHICLE BODY

1. Introduction

The AUV II hull form corresponds roughly to that of the SDV IX Swimmer Delivery Vehicle, though the proportions differ due to internal equipment space requirements. A rectangular cross-section hull having a width twice the height was initially envisioned to closely match the body shape of the SDV IX. An early adjustment to this body form occurred when a width of 14 inches, height of 8 inches and a length of 50 inches were chosen for the vehicle. These dimensions were selected after an initial layout of the computer and a prototype thruster was accomplished with an estimate made of the battery compartment size. A plywood mock-up of this vehicle shape was fabricated to facilitate a verification as to whether enough space was available in the hull before construction was initiated. The plywood AUV II model is shown in Figure 4.

Many components by necessity were still being selected during the design phase and estimates had to be made of their sizes. Among the equipment carried in the vehicle, it was expected that the computer system and batteries would be the largest individual pieces. These bulkier items would require more careful placement than circuit cards or sensors, since

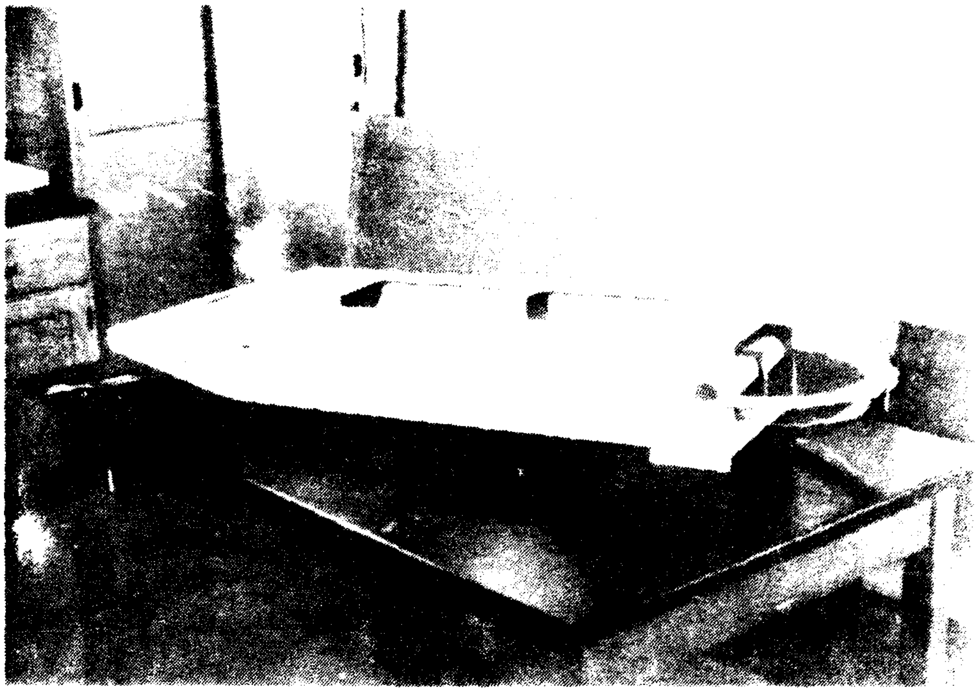


Figure 4 Plywood AUV Mockup

they would have a greater effect on vehicle dynamics by virtue of their mass and location. A key question at the early design stage involved the trade-offs between the number of batteries required and their sizes. The answer to this question required an analysis of onboard power requirements[2].

Once an estimate of vehicle energy requirements was established and more equipment selected (particularly the vehicle gyro sensors), use of the plywood mockup pointed out the need for additional room onboard for battery placement and mounting the vertical gyroscope unit. It was decided that some reserve space should also be provided for unexpected growth and future research equipment. An expanded vehicle

---

[2] Discussed in Section D.

body (less the nose) having dimensions of 10 inches in height, 16 inches in width and 68 inches in length was agreed on for construction planning. The nose was considered to be an individual piece and would be designed separately to house the sonars and other equipment.

2. Hull

a. *Material and Configuration*

Hull design was initially approached with several criteria in mind; fabrication, strength and internal equipment arrangement. Fabrication concerns had the greatest emphasis since they reflected the most practical aspects of the hull design. As previously mentioned, aluminum and a honeycomb composite material were suggested as hull material alternatives. While the composite held much interest as a newer technology, only one member of the machine shop staff had any practical experience with its use. Aluminum, of course, was well known and often used.

Although preparation, cutting and fitting of composite hull pieces could be accomplished with simple shop tools [Ref. 16], the final stages of fabrication would require more specialized methods and equipment which was not held by the machine shop. In particular, it was anticipated that a composite body would have to be nearly complete and then sent to a commercial facility for a final curing treatment in a vacuum oven [Ref. 17]. While this was not prohibitive from the standpoint of cost or capability, it would require a great deal more time and effort to complete a detailed design which had reliable strength characteristics.

Unlike the composite, aluminum presented no technical production challenges. Aluminum also had a great ability to act as a heat sink for the electronic components and motors, an issue of concern given the estimated level of power consumed in the vehicle and the moderately warm temperatures expected in the swimming pool. Aluminum was chosen for hull construction since it offered several advantages over the composite material and few drawbacks. Further investigation [Ref. 18] suggested several favorable Aluminum alloys[3] for consideration as a construction material, from which Al 5052 was selected based on weldability, availability and ease of fabrication.

Once the selection of an aluminum body had been made, three alternatives were considered relating to the vehicle body structural design; an aluminum bar frame with inset aluminum plate panels; a thin aluminum sheet bent to shape with an internal framework; and an aluminum plate bent to shape.

The first alternative was **initially** favored because it could be built entirely in the M.E. machine shop using

---

[3] Aluminum alloys 5052, and 5086 were particularly considered for corrosion and workability, but 6061 was suggested if cost or availability became an issue since it also had good qualities.

basic forming and fastening methods. Though simpler in this respect, it was also the most time consuming of the three options and the shop had limited personnel resources. Because of the desire to move ahead expeditiously with a design when it was **finally** established, a local firm specializing in metal fabrication was consulted [Ref. 19].

Subcontracting the preliminary fabrication to a capable metal working firm made the second and third body structure alternatives possible, with the direct gain of the elimination of several seams that would otherwise have required mechanical fastening and sealing. These two structures were also simpler to build, especially the third choice, since there were fewer parts to fit together. It was decided that the simplest choice, alternative three, would be pursued.

An analysis of the various strength characteristics which were previously listed would begin the process of selecting the material thickness and overall design strength. The vehicle body was modeled as a beam with several different cases of loading. The greatest bending stresses were expected when the vehicle was being handled outside the water, rather than in the pool where hydrostatic pressure would act to support the body evenly from underneath. For the design, a worst case was chosen with the vehicle body being simply supported only at each of its endpoints (bow and stern).

In order to establish what amount of load should be used in the analysis, a calculation of the vehicle's buoyancy was made from the volumes expected for the vehicle's nose, midbody and tail. The vehicle would be perhaps five pounds buoyant, so this was subtracted from the buoyancy figure to give an estimate of what the vehicle would have to weigh. A weight of about 365 pounds was estimated. A completely distributed load and a combined distributed / multiple point source loading were the two loading cases analyzed using this value. The multiple point loads were given values for the heavier individual pieces of equipment anticipated, at estimated locations.

Three different beam cross-sections were considered to portray the midbody structure of the vehicle. A hollow rectangle, a C-channel and an open channel section were chosen for analysis, as depicted in Figure 5. The hollow rectangle represented the ideal body section as one continuous piece. However, the metal fabrication shop was unable to bend plate or sheet so that four full walls of a rectangular section could be achieved. The most complete section that could be bent as one piece was a C-channel, having two lips which would extend toward each other but not touch to complete a side. This restriction meant that the body would have at least two parts, a lower hull in the form of a large C-channel, and an upper piece of metal plate acting as a lid to be fastened to the channel along the two lips. The last body section, the

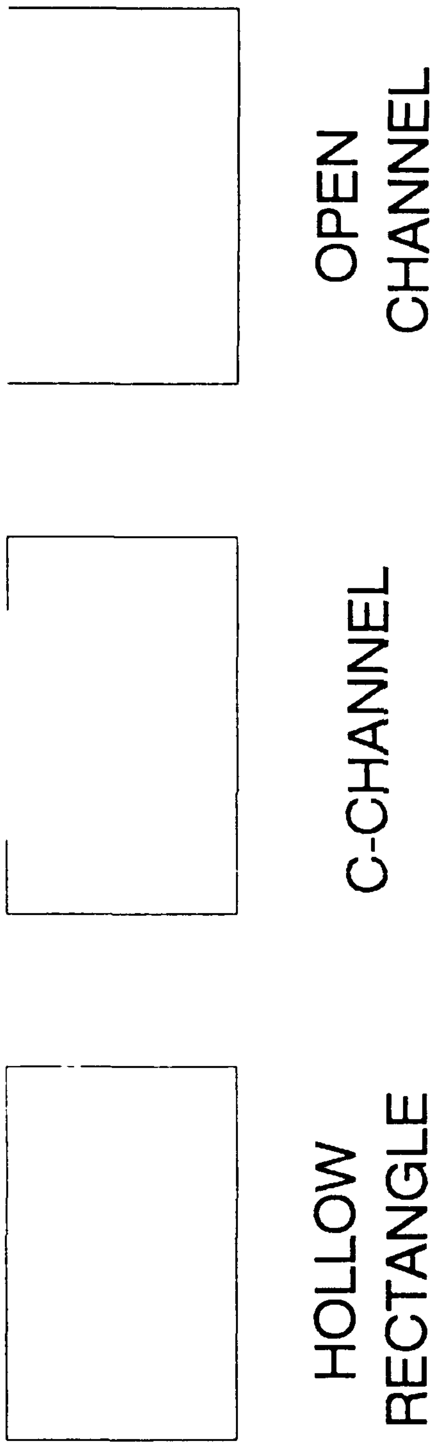


Figure 5 Hull Cross-sections

open channel, represented a minimal structure to withstand loading. It was thought that using the three variations for comparison would give the evaluation a more qualitative reference.

Besides bending strength, the rectangular cross-section's resistance to hydrostatic pressure is important - especially from the point of view of maintaining seals at section interfaces that are not welded. This means that, not only stress levels, but also deflections under load are important. The greatest deflection produced by a uniform water pressure at 25 feet of depth was expected in the center of the large horizontal panels in the vehicle midbody, while angular deflections occurred at the edges. Using the rectangular plate lid with all edges simply supported as a worst case, a value for maximum vertical deflection at a pressure of 10.83 psi was calculated using the formula [Ref. 20]:

$$Y_{Max} = \frac{-\alpha q b^4}{E t^3}$$

where

α = factor from table [Ref. 20:p. 458]
q = load per unit area
b = panel width
E = modulus of elasticity for plate
t = plate thickness

Similar elastic deflections for angular distortions were found.

The third hull strength criteria was the body's resistance to a torsional loading, which might result from mishandling. The following formula describing the angle of twist in a thin walled hollow rectangular section was used [Ref. 20:p. 352]:

$$\Theta - \frac{TL}{KG}$$

where

Θ = angle of twist (radians)
T = twisting moment (in-lb)
L = beam length (in)
K = factor in table
G = modulus of rigidity (psi)

A spreadsheet[4] was devised to allow rapid calculation of each of the sections in different loading configurations at the same time for a given plate thickness. The spreadsheet included the bending, hydrostatic pressure and torsional strength analyses. Table I is an example of one of the spreadsheets produced, for a wall thickness of 0.25 inches. In the balance of the considerations, this was the thickness chosen for construction of the vehicle.

When the strength appraisal had been completed, each of the three hull structure options was considered for a final hull configuration. Alternative one was considered to be a manpower intensive choice and eliminated. Time was

---

[4] LOTUS 123 spreadsheet software was used.

Table I SPREADSHEET ANALYSIS OF HULL STRENGTH

```
AUV HULL THICKNESS SPREADSHEET

THIS SPREADSHEET WILL ASSIST THE DESIGNER TO DETERMINE THE OPTIMAL
THICKNESS OF THE SECOND GENERATION AUV HULL THRU 'WHAT IF ' ANALYSIS.

ALUMINUM CHARACTERISTICS                                  THICKNESS OF PLATE
ALLOY:     AL 5052    AL 5086                               2.500E-01
E.MODUL    1.030E+07 1.030E+07


GEOMETRY OF CROSS-SECTION
CASE:      H. RECT    CHANNEL    C-CHANNEL
BASE       1.600E+01 ,1.600E+01 1.600E+01                 TORSION EFFECT ON HOLLOW RECT VEHICLE BODY
OVL HT     1.000E+01 1.000E+01 1.000E+01                  FORMULA:     THETA = T*L/K*G  -  ROARK P352
LEG HT     9.500E+00 9.500E+00 9.500E+00                  K            4.624E+02 IN^4
LIP                            2.000E+00                  T (TWIST)    3.000E+05 MOMENT (LB-IN)
AREA       1.275E+01 8.750E+00 9.750E+00                  G (RIGID)    3.750E+06 PSI
YIA                  4.850E+01 3.413E+01                  THETA        8.651E-03 RADIANS
Y1         5.000E+00 2.771E+00 3.500E+00                               4.957E-01 DEGREES
Y2         8.000E+00 8.000E+00 8.000E+00
I1         2.259E+02 8.735E+01 1.326E+02
I2         4.653E+02 3.799E+02 4.293E+02
                                                          HYDROSTATIC PRESSURE EFFECT ON HORIZ HULL PLATE
                                                          MAX VERT DEFY=-ALPHA*q*b^4/E*t^3
                                                        α FROM ROARK, 2.800E-02
LOAD:      AIR-DIST  AIR-COMB                             q(psi load):1.083E+01
Q(LOAD)    3.650E+02 1.800E+02                            Y (vert defl1.235E-01
LENGTH     5.000E+01 5.000E+01
CONC LD1             3.130E+01
LOCATE1              1.200E+01
CONC LD2             6.000E+01
LOCATE2              2.500E+01
CONC LD3             3.130E+01
LOCATE3              3.800E+01

DEFLECTION AT MID-BODY IN INCHES - 'BEAM LOAD'
           AIR-DIST  AIR-COMB
H. RECT    2.553E-04 2.396E-04
CHANNEL    6.603E-04 6.197E-04
C-CHANNEL  4.349E-04 4.082E-04
```

valuable to the project and the labor involved with installing fasteners to connect all the pieces was prohibitive. It was thought that alternative three, with a solid 0.25 inch plate hull might be overly heavy, whereas the thin sheet with internal skeleton option might give enough structural strength and watertightness without such weight. However, the complexity of the internal structure might make construction of the internal skeleton body style more time consuming.

The choice between the two remaining options was based on the need for solid ballast. Since the hull material volume of the 0.25 inch solid plate was approximately 80 pounds, and the total weight of all equipment to be installed in the vehicle was about 150 pounds (batteries accounted for almost 80 pounds of this), a great deal of lead ballast would still be required even with the heavier hull, leaving the solid aluminum plate structure as the most desirable.

b. Interior / Component Accessibility

Providing access to the interior of the vehicle for modification and repair was seen as an important aspect early in design, and two portholes were located in the midbody section with the third in the angled surface of the tail. The larger openings would accommodate removal of most equipment.

The final design incorporated an integrated frame and window top[5] which was built into the lower hull piece,

---

[5] Discussed in detail in Subsection A-1 of Chapter IV.

removing the necessity for an aluminum plate lid. This scheme allowed removal of even the laptop computer as well as the large batteries.

c. *Equipment Arrangement - SUBCALC Program*

As an aid to the hull design studies performed in this project, a FORTRAN program was written to perform hull characteristics calculations for a user defined vehicle. SUBCALC is a conceptual design aid which provides tangible estimates of vehicle parameters to reduce the burdensome work of iterative design. Appendix A contains user guidelines for the SUBCALC program. The finalized arrangement of internal equipment is shown in Figure 6.

3. Nose

The nose structure for AUV II was expected to enhance the smooth flow around the vehicle and serve as a housing for various vehicle sensors, most notably sonar. Although a **dry** nose interior was initially envisioned, after sensor layout and sonar performance were considered it became evident that a **wet** nose would be desirable. This approach was also facilitated by the choice of construction material. The discussion that follows includes consideration of configuration and materials, sensor placement, sonar, speed paddle wheel, and flooded effects.

a. *Material and Configuration*

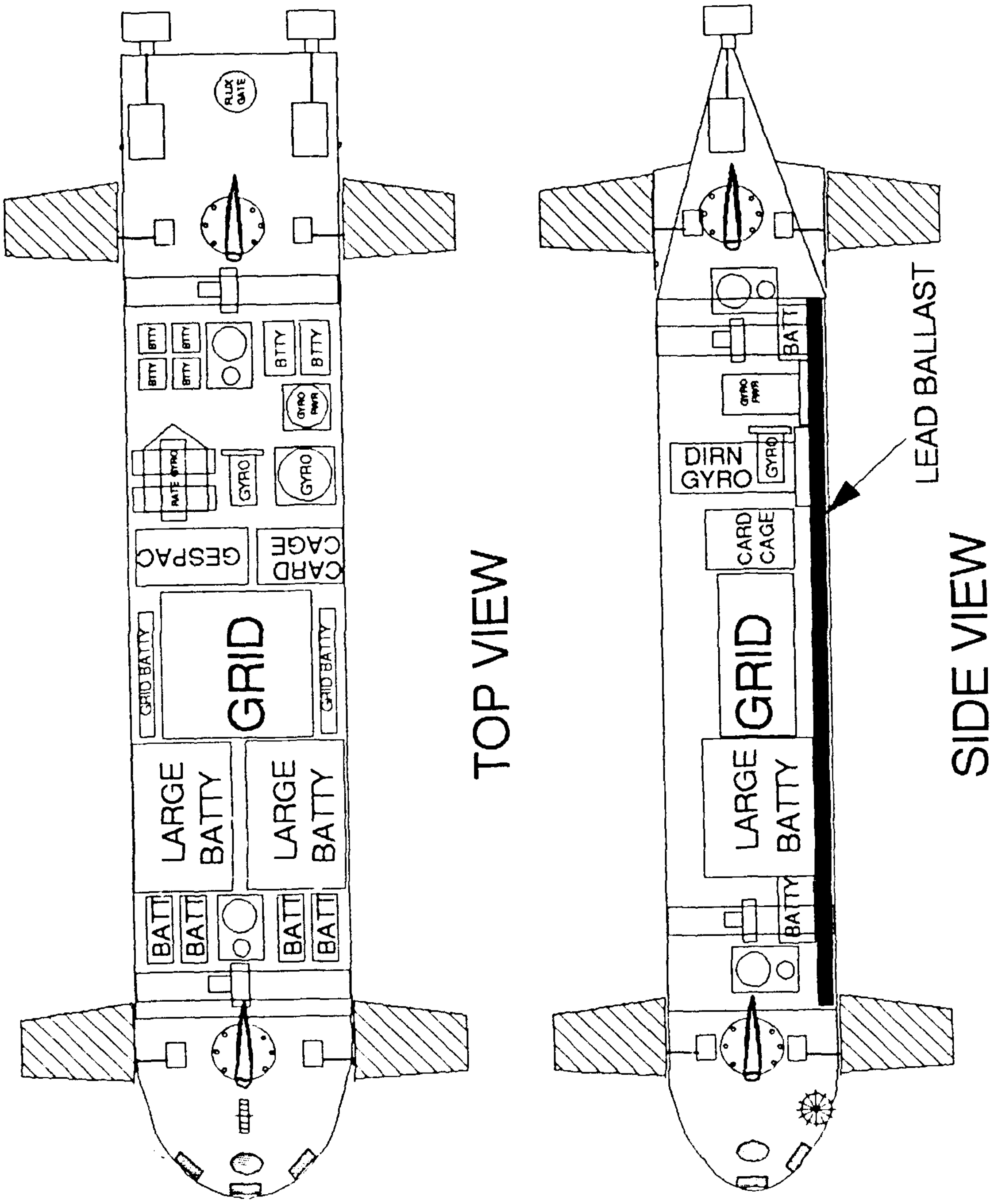


Figure 6 AUV Equipment Arrangement

To reduce pressure drag effects and provide a smooth hydrodynamic front end, it was decided to use a nose shape which was essentially half of an ellipsoid faired into a rectangular base. The ellipsoidal contour would help improve flow over the nose surface, while the modification to a round cornered rectangular base would facilitate a simple mating connection between the nose and aluminum body.

The question of a suitable material for the nose was discussed and it was apparent that metal would be difficult to form in the complex shape desired, and that a glass fiber reinforced plastic nose shape could be produced through the use of an open mold process with contact molding techniques [Ref. 21][Ref. 22].

One concern has to be the nose strength, particularly the resistance to impact, and although finite element analysis of the GRP material is possible[6] [Ref. 23], it was beyond the scope of this effort. A thickness of 0.10 inch was selected for reasons other than impact, related to sonar equipment.

b. *Sensor Placement*

Experience with the initial testing of AUV I demonstrated the importance of proper pressure cell location. An optimal location for improved accuracy would allow contact

---

[6] GIFTS (Graphics-Oriented Interactive Finite-element Transportable System) code was installed on the Aeronautical Engineering curriculum's VAX computer system.

with water at depth in a region of undisturbed flow. Contemplation of this aim led to the idea that the cell could be located in a flooded nose shell which had free communication with the water. Though this location was not free of flow effects, these would be minimal when compared with other locations considered.

c. Sonar Equipment

The wet nose concept was particularly beneficial to sonar performance [Ref. 24]. Since the air-fiberglass-water interfaces would be eliminated, the significant signal attenuation that would take place when sound was reflected as it tried to pass between these dissimilar materials could be reduced. Although some attenuation was still likely with the water-fiberglass-water path due to the same phenomena, the transmission losses could be substantially decreased by controlling the laminated thickness of the fiberglass nose. Building the fiberglass up to a thickness corresponding to a half wavelength of the sonar transducer frequency would minimize loss. A thickness of about 0.17 inch corresponds to a half wavelength for the 212 kHz Datasonics transducer. The fabricated thickness was specified to be less, about 0.125 inch, to allow for changes in the mounting angle of the transducer. When the angle was finally set, a fiberglass patch could be bonded to the inside surface of the nose to provide a mounting surface of the correct thickness. The

0.125 inch thickness was also expected to provide the nose with enough rigidity to serve structural needs.

d. *Speed Sensor*

When additional equipment housing in the nose was evaluated, it appeared that a paddlewheel-type speed through water sensor could also be built into the nose shell. This arrangement would take great advantage of the wet nose. Not only would sensor hull mounting and sealing cease to be a problem, but the opening in the nose for the paddlewheel would help equalize the water pressure in the nose with that of the environment.

e. *Flooded Nose Considerations*

The decision to have a flooded nose brought along with it an unusual strategy to the problem of sealing the vehicle. As well as the necessity to prevent water intrusion into the midbody, the complete circulation of water in the nose was important. Mounting the water speed paddlewheel in an opening cut into the fiberglass nose would assist. Several small openings were also required in the upper half of the nose to allow trapped air to vent. All openings, including the open mating area of the shell were to be reinforced with fiberglass to retain stiffness. These penetrations are adequate for the present design, but will need to be evaluated based on later experience.

D. VEHICLE ENERGY

1. Power Requirements

A key to achieving basic vehicle autonomy for pool operations was having an adequate energy system onboard AUV II so that it could sustain all vehicle functions for at least one hour of operation. The approach taken to ensure this took several criteria into consideration. Electrical power had to be available to run vehicle 'hotel' systems such as the computer, sonars and other electronics, in addition to power for mobility.

An estimate of mobility power requirements had to be made to support the varying operating characteristics that might be expected in a given pool mission. The primary power requirement was to overcome hydrodynamic drag for motion in transit, although additional needs for thrusters in maneuvering also had to be included. AUV II would have to be capable of full speed cruising with active control surfaces as well as extended hovering using four maneuvering thrusters. The two maneuvering systems were not expected to run at rated capacities simultaneously. This simplifying assumption made the task of estimating power loads more workable.

Propulsion power for transit conditions is closely tied to vehicle hull form. In surfaced submarines, their drag-weight resistance ratios are slightly higher than those of other displacement ships due to skin friction drag, but when deeply submerged, they may have a low drag coefficient [Ref. 25]. To estimate the energy needed to propel AUV II through the water, the fluid dynamic drag of the hull had to be examined. The first step in this analysis was calculating the expected Reynolds number over a range of vehicle speeds. Table II lists Reynolds number and Froude number values corresponding to various speeds and shows the vehicle parameters used in the calculation.

Table II REYNOLDS AND FROUDE NUMBERS FOR VARIOUS SPEEDS

VELOCITY (FT/SEC)	REYNOLDS NUMBER	FROUDE NUMBER
0.000	0.000E+00	0.000
1.000	6.333E+05	0.067
2.000	1.267E+06	0.135
3.000	1.900E+06	0.202
4.000	2.533E+06	0.270
5.000	3.167E+06	0.337

In describing the fluid dynamic drag of the blunt body AUV II shape, several different aspects had to be considered together, including the wave drag, friction drag, surface area drag, frontal area drag and drag due to appendages. Hoerner [Ref. 25:p. 11.18] shows in Figure 18 that wave drag is minimal at depths below about half a vehicle length. Since AUV II is expected to operate at mid-depth or near the bottom of a pool which is up to 8 feet deep, the wavemaking drag component for the vehicle is not contemplated. A methodology for estimating the drag of aircraft fuselages [Ref. 25:pp. 13.1-13.5] showed promise for estimating the drag of AUV II. The prescribed techniques were followed with AUV II specific values.

The friction and area components of the overall drag coefficient are based on the geometry of the body and Reynolds number. A body fineness ratio describes the geometry where, for the case of a rectangular cross-section:

$$\frac{l}{d} = \frac{2l}{(b+h)}$$

A fineness ratio of 6.154 was obtained using the planned values for height and width of 10 inches and 16 inches. For fuselages with tail surfaces, Table E [Ref. 25:p. 6.18] specifies an optimal fineness ratio of 6.

The velocity chosen for drag calculations was 2 feet per second, which was anticipated as a moderate operational speed in the swimming pool. From Table II, a Reynolds Number of 1.267×10^6 corresponds to this velocity. The maximum velocity that AUV II might achieve was expected to be less than 5 feet/sec.

Chapter VI of Fluid Dynamic Drag addresses the drag of streamline shapes. A minimum drag coefficient is found from two frictional drag ratios given in Equations 28 [Ref. 25:p. 6.17] and 31 [Ref. 25:p. 6.18]. For drag based on the wetted surface area:

$$\frac{C_{Dwet}}{C_f} = 1 + 1.5\left(\frac{d}{l}\right)^{\frac{3}{2}} + 7\left(\frac{d}{l}\right)^3$$

and for drag based on the frontal area of the body:

$$\frac{C_{Do}}{C_f} = 3\left(\frac{l}{d}\right) + 4.5\left(\frac{d}{l}\right)^{\frac{1}{2}} + 21\left(\frac{d}{l}\right)^2$$

These values were calculated to be 1.1283 and 20.83 for AUV II.

Skin friction drag was examined next. Total friction drag is a combination of the skin friction drag and the drag due to three dimensional flow, which is expected in typical submerged operation. The skin friction drag is found using Equation 27 [Ref. 25:p. 2.5] for a plane wall:

$$C_f = \frac{0.427}{(\log_{10}Re - 0.407)^{2.64}}$$

The three dimensional turbulent flow term is found using Equation 32 [Ref. 25:p. 2.7]:

$$\Delta C_f = 0.0016\frac{\left(\frac{l}{d}\right)}{Re^{\frac{2}{5}}}$$

The total friction drag is then:

$$C_{f_{TOTAL}} = C_f + \Delta C_f$$

The total surface area drag is found using the value found for drag on the wetted surface area and the total friction drag:

$$C_{D_{WET}} = \left(\frac{C_{D_{WET}}}{C_f}\right)\left(C_{f_{TOTAL}}\right)$$

Similarly, the total frontal area drag is found:

$$C_{D_o} = \left(\frac{C_{D_o}}{C_f}\right)\left(C_{f_{TOTAL}}\right)$$

The total drag is represented by a sum of the individual components found thus far:

$$C_D = C_{D_o} + C_{D_{WET}} + C_f$$

$$= 0.106 + 0.005754 + 0.00507$$

The total coefficient drag of AUV II was calculated to be 0.12.

Hoerner describes the drag of numerous vehicle bodies of different shapes. One of those which bears some resemblance to the shape of AUV II is the depiction of the Heinkel-177 aircraft found in Figure 10 [Ref. 25:p. 13.3]. The aircraft has a rectangular frontal cross-section with a blunt nose. Hoerner examines the effects on drag that three different tail shapes have. The tail turret case seemed to correspond best with the AUV II blunt tail. The drag coefficient of 0.137 compares with that previously calculated for AUV II.

Given the added drag effects of a non-smooth (real life) hull and appendages such as the control surfaces and stern propeller gear, a drag coefficient in the range of .15 - .20 seemed appropriate for AUV II. Using this range for drag, Figure 7 shows how drag force varies with vehicle velocity. Figure 8 shows the result of converting the force-velocity character of the vehicle to estimate the power required to overcome drag.

While details of the stern propulsors and thrusters are given in more detail in Subsection E-3, the need for additional thrust and power based on vehicle acceleration and deceleration was indicated. Based on the motion of a longitudinal total vehicle mass close to 400 pounds, and a required stopping distance of 2 vehicle lengths (12 ft) from a speed of 2 ft/sec, a net deceleration of about 0.167 ft/sec^2 required a total thrust of about 2 lb force (1 lb thrust each propeller).

Table III lists the equipment chosen for the vehicle and their power requirements.

2. Power Supply

The desire to maintain high reliability with system simplicity made battery power the best choice as an energy source for AUV II. It was proposed that lead acid gel cell batteries should be used, if possible, since they were easily obtained and inexpensive. The deciding factor in whether

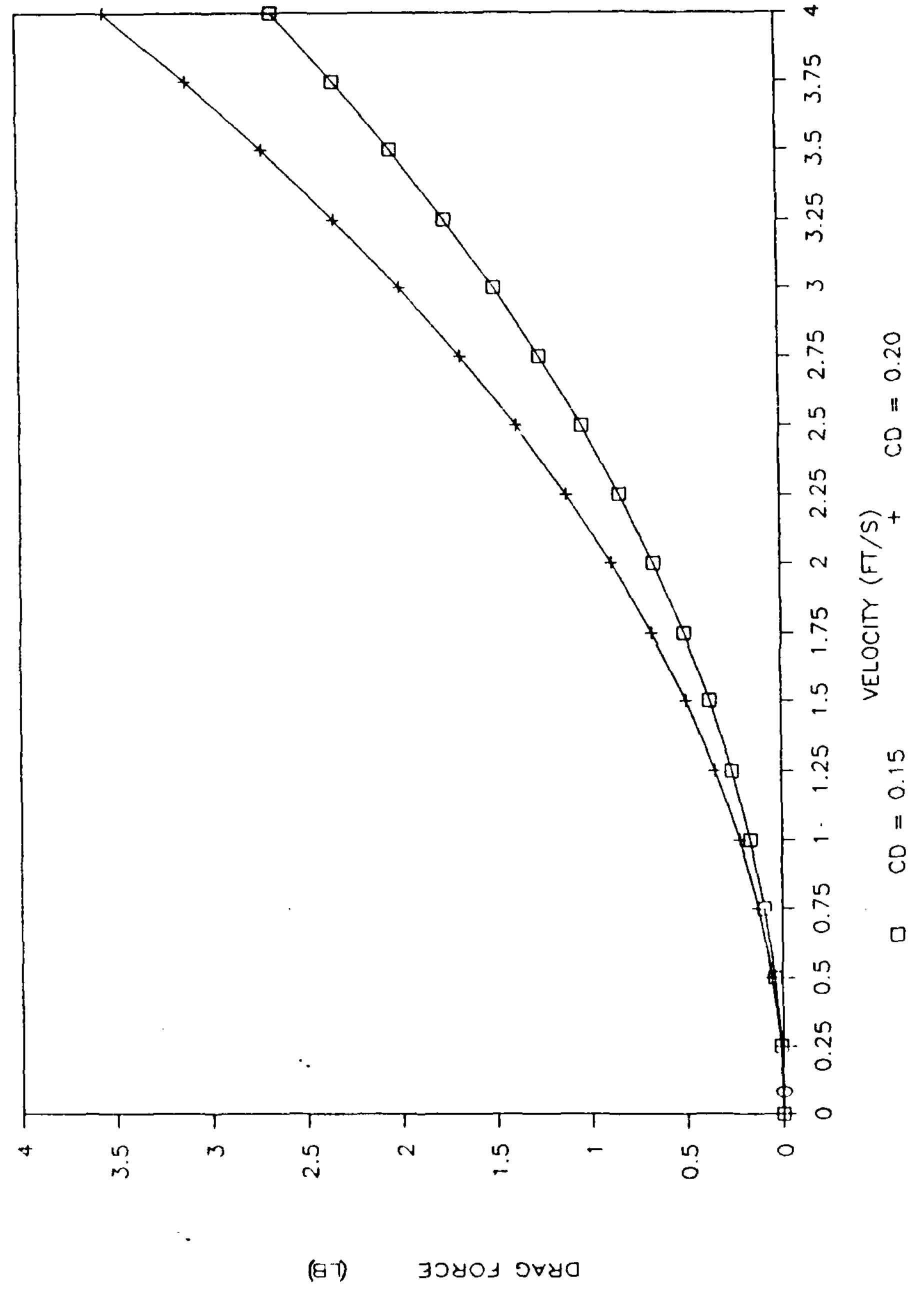


Figure 7 Vehicle Drag Force Versus Velocity

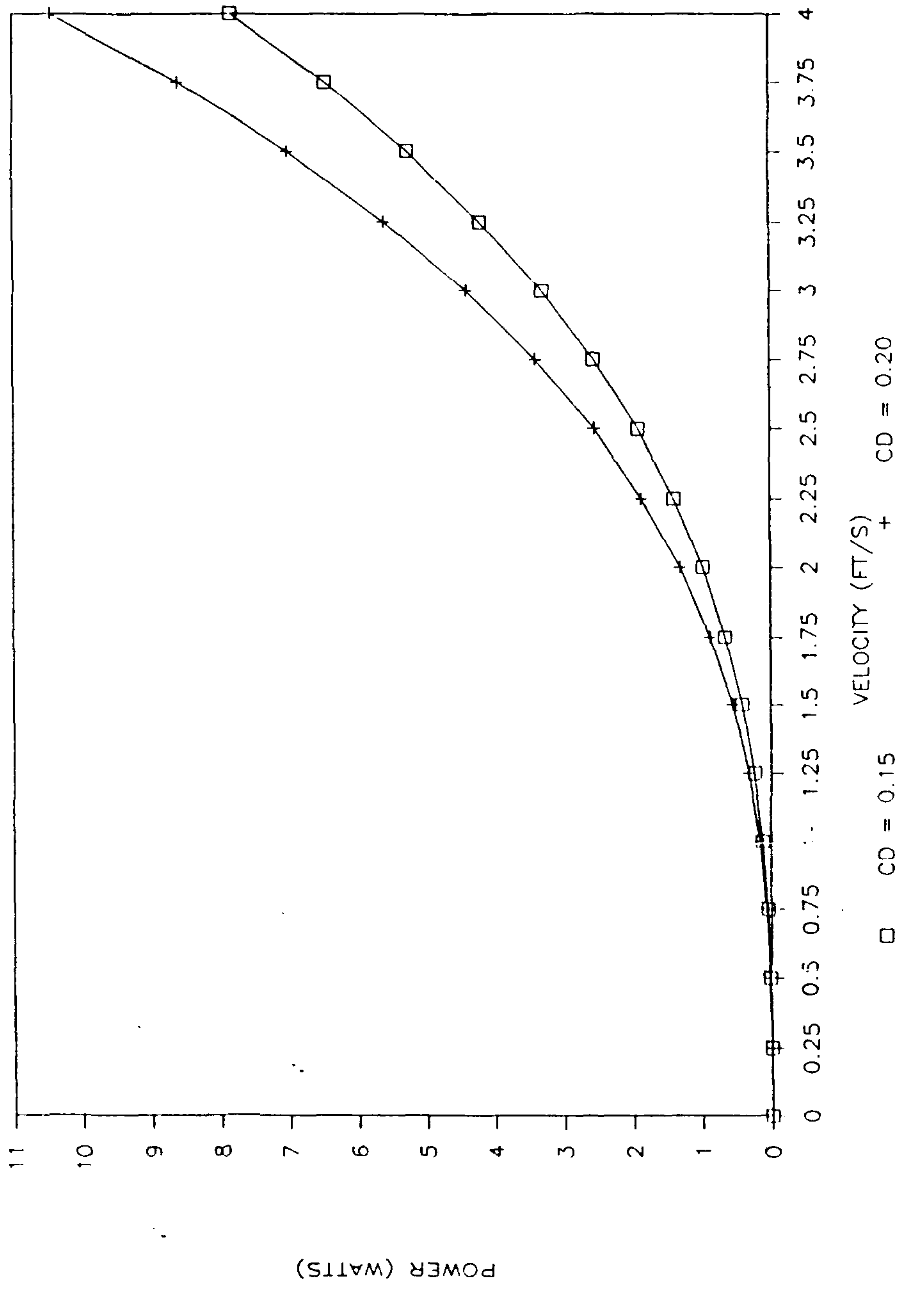


Figure 8 Vehicle Power To Overcome Hydrodynamic Drag

Table III POWER REQUIRED FOR ELECTRICAL EQUIPMENT

EQUIPMENT	VOLTAGE	CURRENT	SOURCE	# UNITS
GRID LAPTOP COMPUTER	---	---	OWN BATTERY	1
GESPAC COMPUTER	5 VDC	3.3 AMP	BATTERY	1
	+12 VDC	0.085 AMP	BATTERY	---
	-12 VDC	0.095 AMP	BATTERY	---
DIRECTIONAL GYRO	115V 400Hz	---	POWER SUPPLY	1
	26V 400 Hz	---	POWER SUPPLY	---
	28 VDC	0.15 AMP	BATTERY	---
GYRO POWER SUPPLY	27.5 VDC	1.8 AMP	BATTERY	1
VERTICAL GYRO	28 VDC	0.6 AMP	BATTERY	1
RATE GYRO PACKAGE	28 VDC	1.0 AMP	BATTERY	1
STERN PROP MOTOR	24 VDC	13.8 AMP	BATTERY	2
THRUSTER MOTOR	24 VDC	5.91 AMP	BATTERY	4
SONAR TRANSDUCER	15-28 VDC	0.1 AMP	BATTERY	4
SERVO	6 VDC	0.1 AMP	BATTERY	8

this type would be used was the size of the batteries required to power the vehicle for the specified endurance of one hour. If the amount of room required for the batteries was considered to be excessive, an alternative such as silver-zinc batteries would have to be evaluated. An advantage to using lead-acid cells existed in terms of the possibility for future growth of power requirements. If at some point the vehicle needed much greater power, necessitating a source of greater density, a step up to a more advanced battery could be made to achieve the power boost with the same relative volume of batteries. Table IV lists the specifications of the batteries selected for AUV II.

The total weight and volume of the lead acid batteries was considered to be reasonable. Weight was not a problem

Table IV BATTERY DETAILS AS SELECTED

Panasonic

RECHARGEABLE SEALED LEAD-ACID BATTERIES

Model Number	Nominal Voltage	Nominal Capacity		Dimensions				Weight (Approx.)	Standard Terminals or Connectors
		10 hour rate	20 hour rate	Length	Width	Height	Total Height (including terminals)		
	(V)	(Ah)	(Ah)	inch (mm)	inch (mm)	inch (mm)	inch (mm)	lbs. (g)	
LCR6V1.2P	6	1.1	1.2	3.82(97)	0.94(24)	1.97(50)	2.20(56)	0.66(300)	FASTON Type 187
LCS-386P	6	3.8	4.0	2.03(51.5)	1.88(47.7)	4.67(119)	4.67(119)	1.52(690)	Pressure Contact
LCR6V6.5P	6	6.0	6.5	5.95(151)	1.34(34)	3.70(94)	3.94(100)	2.54(1150)	FASTON Type 187 or 250
LCR12V6.5P	12	6.0	6.5	5.95(151)	2.54(64.5)	3.70(94)	3.94(100)	4.85(2200)	FASTON Type 187 or 250
LCL12V38P	12	34.0	38.0	7.76(197)	6.50(165)	6.89(175)	6.89(175)	31.3(14.2kg)	M6 Bolt and Nut Type

since the vehicle needed ballast to achieve a condition near neutral buoyancy. Lighter, more advanced batteries would probably reduce the volume required, but then more inert lead ballast would have to make up the weight difference in this design.

A preliminary drawing of a system of battery sources matched to the various pieces of equipment on the vehicle is shown in Figure 9.

Several guidelines were set for installation of electrical equipment:

1. Battery sources will be located as close as possible to the equipment they serve to minimize wiring run length.
2. All two conductor wiring will be installed as twisted pairs to minimize generation of an electromagnetic field.
3. Equipment connections will be made for quick disconnection to facilitate repair or recharging.

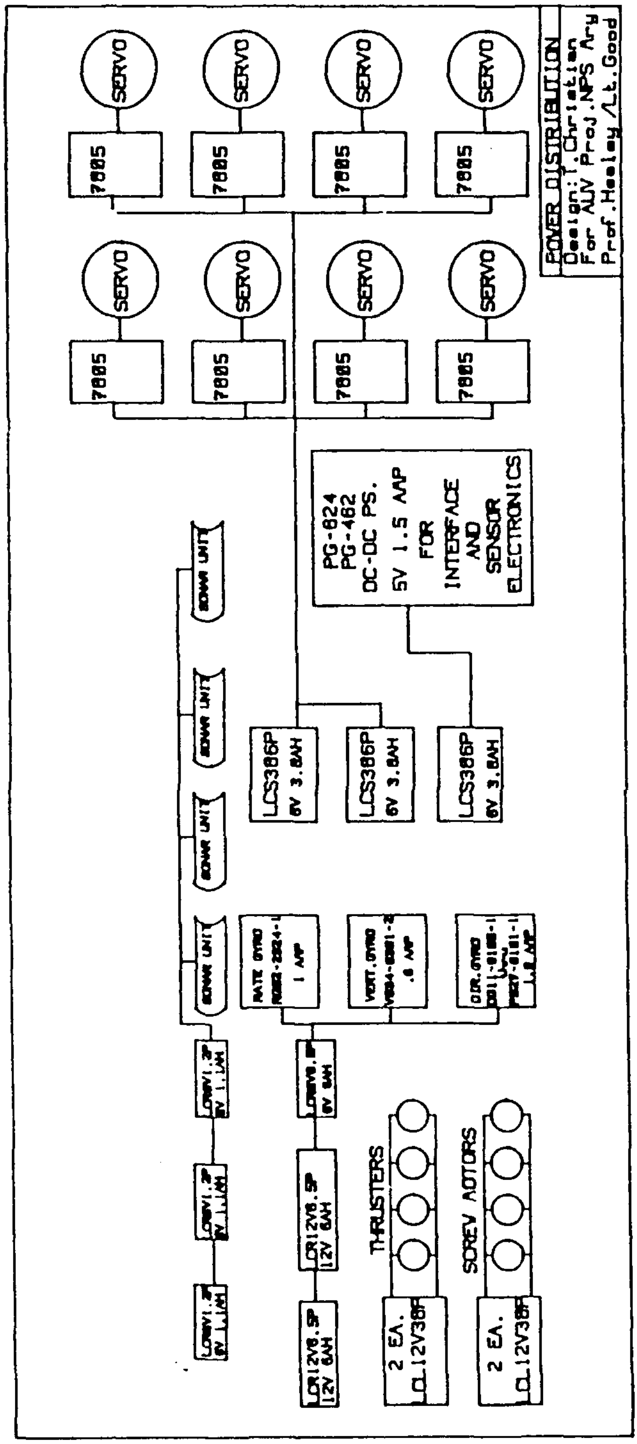


Figure 9 Battery Sources for Equipment

Appendix B contains circuit drawings for the electrical distribution and control systems resulting from detailed design for the motor power and control requirements; servo power and radio control emulation requirements; sensor power and control requirements.

E. MOBILITY / MANEUVERING PERFORMANCE

1. Introduction

Achieving superior maneuverability was an important goal of the design effort since the NPS swimming pool was a relatively confined environment and the vehicle needed the ability to execute accurate path following as well as respond rapidly to course changes due to obstacles. It was clear that several different devices, including control surfaces and propulsors would be needed.

Like the SDV IX and AUV I, a simple twin stern propeller arrangement would be followed, however one main difference between AUV II and the earlier vehicles would lie in the use of maneuvering thrusters. A system employing four tunnel thrusters in an arrangement similar to that used in the Navy DSRV was envisioned, and a more detailed design effort on control surfaces was foreseen.

Because some hydrodynamic similitude with the SDV IX body shape was retained, it was felt that the SDV IX as well as the AUV I could provide some qualitative reference for the

AUV II maneuvering studies. The hydrodynamic model for this body shape was available in the form of FORTRAN code which could be implemented to simulate the dynamic response of the vehicle. It was felt that this hydrodynamic model could be extended in some respects to the new vehicle, and provide a starting point for the eventual development of a set of coefficients specific to AUV II.

2. Control Surfaces

a. *Background*

The precise shape and size of the control surfaces was an issue that required some research. AUV I used bow and stern planes[7] purchased from 32nd Parallel[8], a manufacturer of radio controlled and specialty model submarines. The rudders were of a basic flat plate design, fabricated by the M. E. Machine Shop. It was felt that AUV II might benefit from the added performance that a more sophisticated dive plane or rudder set could provide, and it was decided that a set of all moveable control surfaces would be fabricated in-house with a reasonable attempt made at producing a foil shape.

---

[7] From Pre-Fabricated Control Surfaces Kit # 01-200 for the Type VII German U-Boat radio controlled submarine.

[8] 32nd Parallel, P.O. Box 804, Pismo Beach, California 93449, Telephone: (805) 481-3170.

b. Foil Shape

An assessment of the literature [Ref. 26] [Ref. 27] yielded recommendations to use a NACA 0015 foil section for naval applications. As a result of previous experimental work to support the use of this configuration on naval vessels [Ref. 28], the lift, drag, and center of pressure characteristics for this shape were well known.

A detailed analysis would be required to determine the magnitude and location of lift and drag forces produced by the selected control surface. The actuator shaft could be located so that the plane would be well balanced and produce a minimal amount of resisting torque for the servo to overcome. This torque is due to the distance from the centerline of the shaft and the point of action of lift, which is complicated by the movement of the centers of pressure along the plane's surface over the operating range of angles of attack.

Figure 10 [Ref. 27:p. 495] shows the characteristics of the NACA 0015 foil section chosen. The changing parameters of the foil are clearly plotted with respect to angle of attack. Figure 11 shows the region of the generic control surface within which the centers of pressure act and the relative location of the actuator shaft chosen to minimize resisting torque[9].

---

[9] Shaft location analysis is found in Servo Control Subsubsection f.

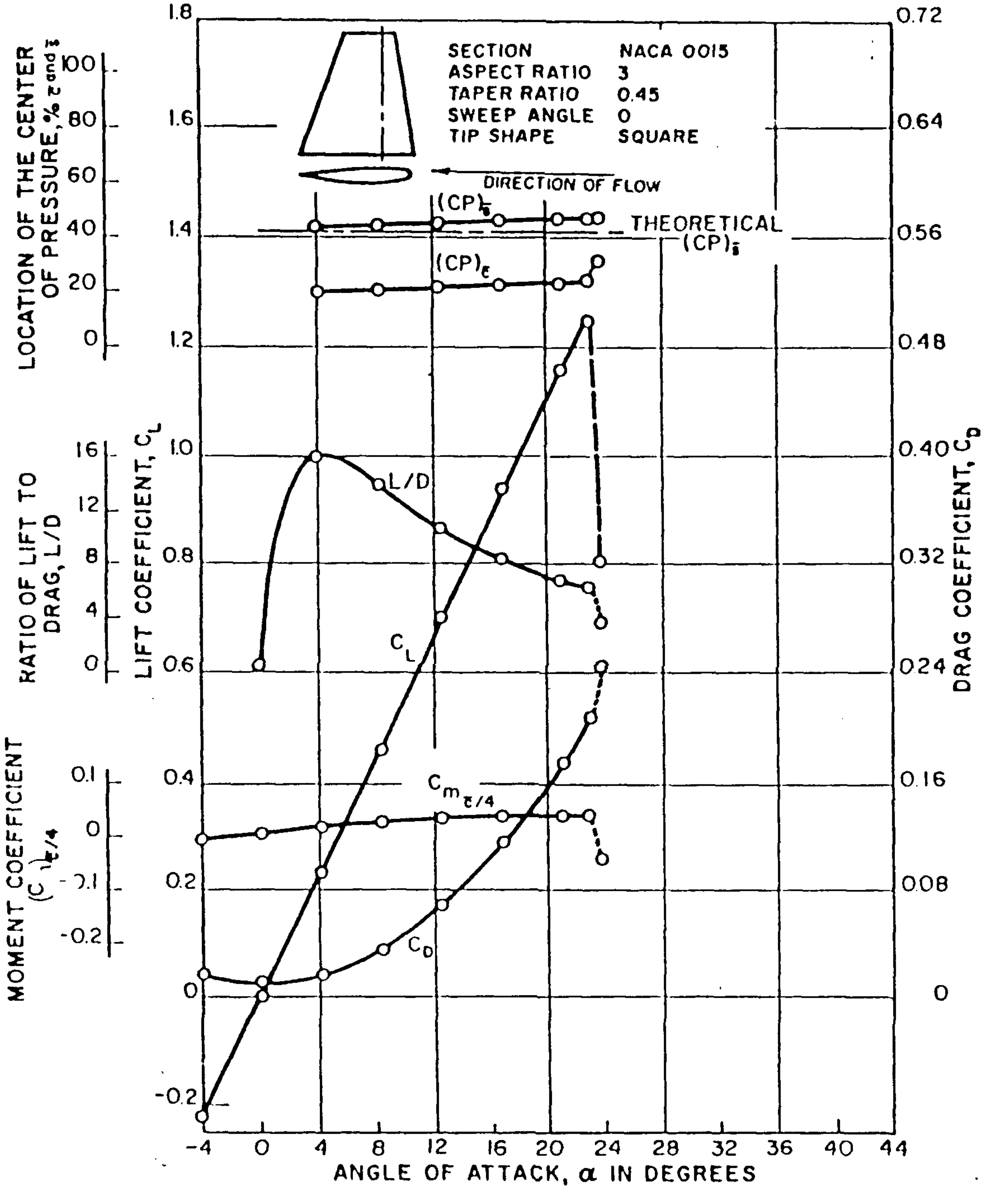


Figure 10 Characteristics of NACA 0015 Airfoil

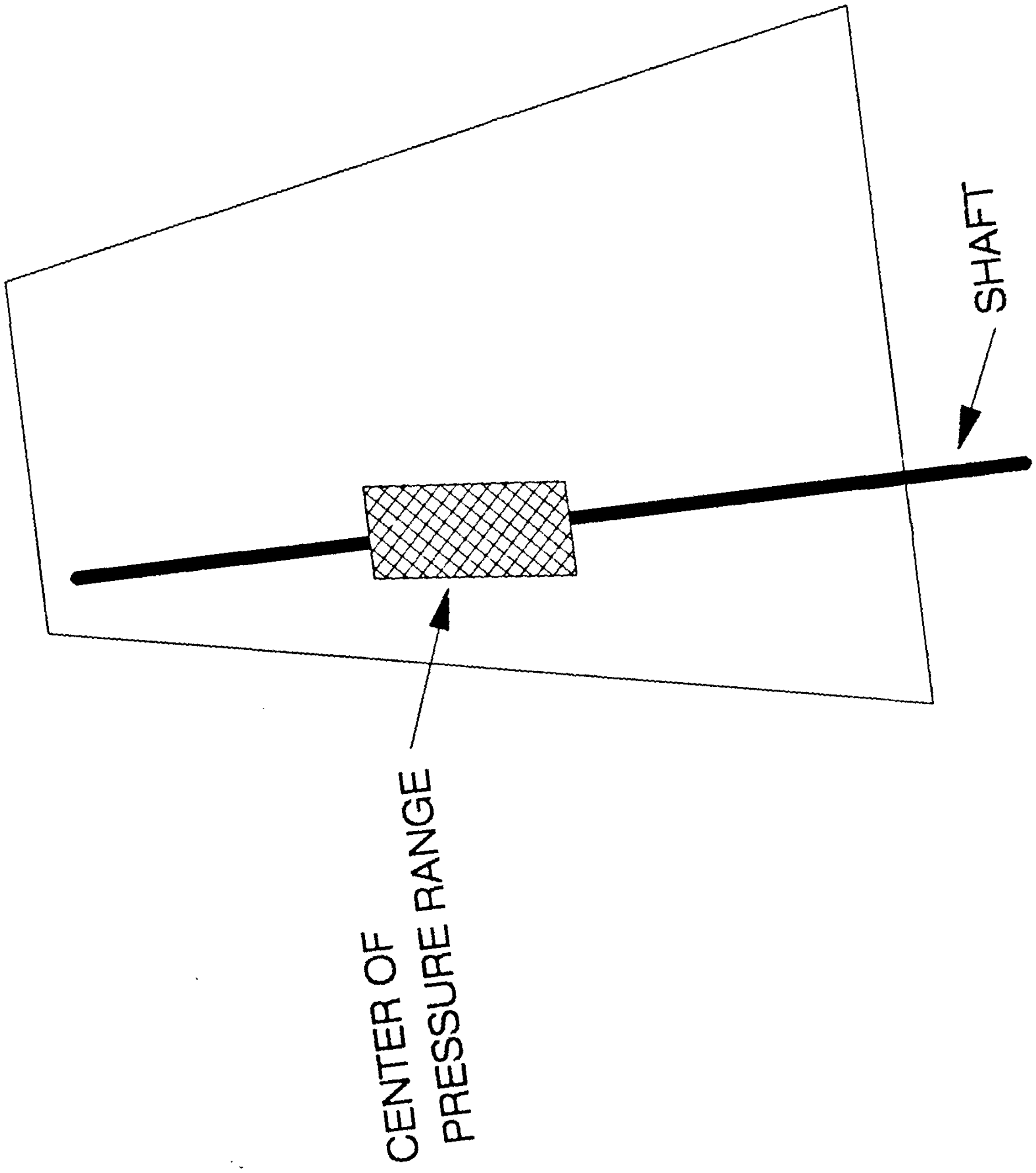


Figure 11 Range of Center of Pressure

c. *Sizing*

Several analytic methods were pursued to help determine the correct sizing of the rudders and planes for AUV II. These results are presented in Table V. The SDV IX and AUV I were included in the analysis to help characterize the results obtained with each technique. Figures 12 and 13 show the control surfaces used on these vehicles.

(1) DnV Method. Landsburg [Ref. 29] recommends that the Det norske Veritas (DnV) method is a good first step in minimum rudder area determination. The area is found using the equation [Ref. 29:p. 370]:

$$A = \frac{TL}{100}\left[1 + 25\left(\frac{B}{L}\right)^2\right]$$

where

A = Area of the rudder
T = Draft (Vehicle height is substituted)
L = Length between perpendiculars
(Vehicle body length is used)
B = Beam

for the situation where the rudder is located directly behind the propeller. When the rudder is located outside the screw race, the area found with the above equation must be multiplied by a factor of 1.3. This factor applies toward the SDV IX and AUV II, but AUV I had twin rudders mounted behind twin screws.

For this analysis, the DnV rudder area did not correlate well with the actual service rudder found on either SDV IX or AUV I. The rudder for the SDV IX specified by DnV

Table V CONTROL SURFACE SIZING

CONTROL SURFACES SIZE CALCULATION SPREADSHEET

VEHICLE	CONTROL SURFACE	ACTUAL AREA	AREA COEF %	AREA CALCULATION METHOD				
				DnV	JACKSON	SCALE 1	SCALE 2	SCALE 3
SDV IX								
	BOW PLANES	459.00	—	—		—	—	—
	RUDDERS	264.62	3.78%	360.82	273.55	—	—	—
	STERN PLANES	684.64	4.11%	329.88	650.16	—	—	—
AUV I								
	BOW PLANES	9.50	—	—		5.54	5.74	5.37
	RUDDERS	6.80	7.33%	2.55	3.62	3.20	3.31	3.10
	STERN PLANES	6.40	3.45%	2.66	7.25	8.27	8.57	8.01
AUV II								
	BOW PLANES	65.00	—	—		46.39	39.46	39.90
	RUDDERS	65.00	7.83%	21.72	32.43	26.74	22.75	23.00
	STERN PLANES	65.00	4.80%	24.29	52.85	69.19	58.85	59.52

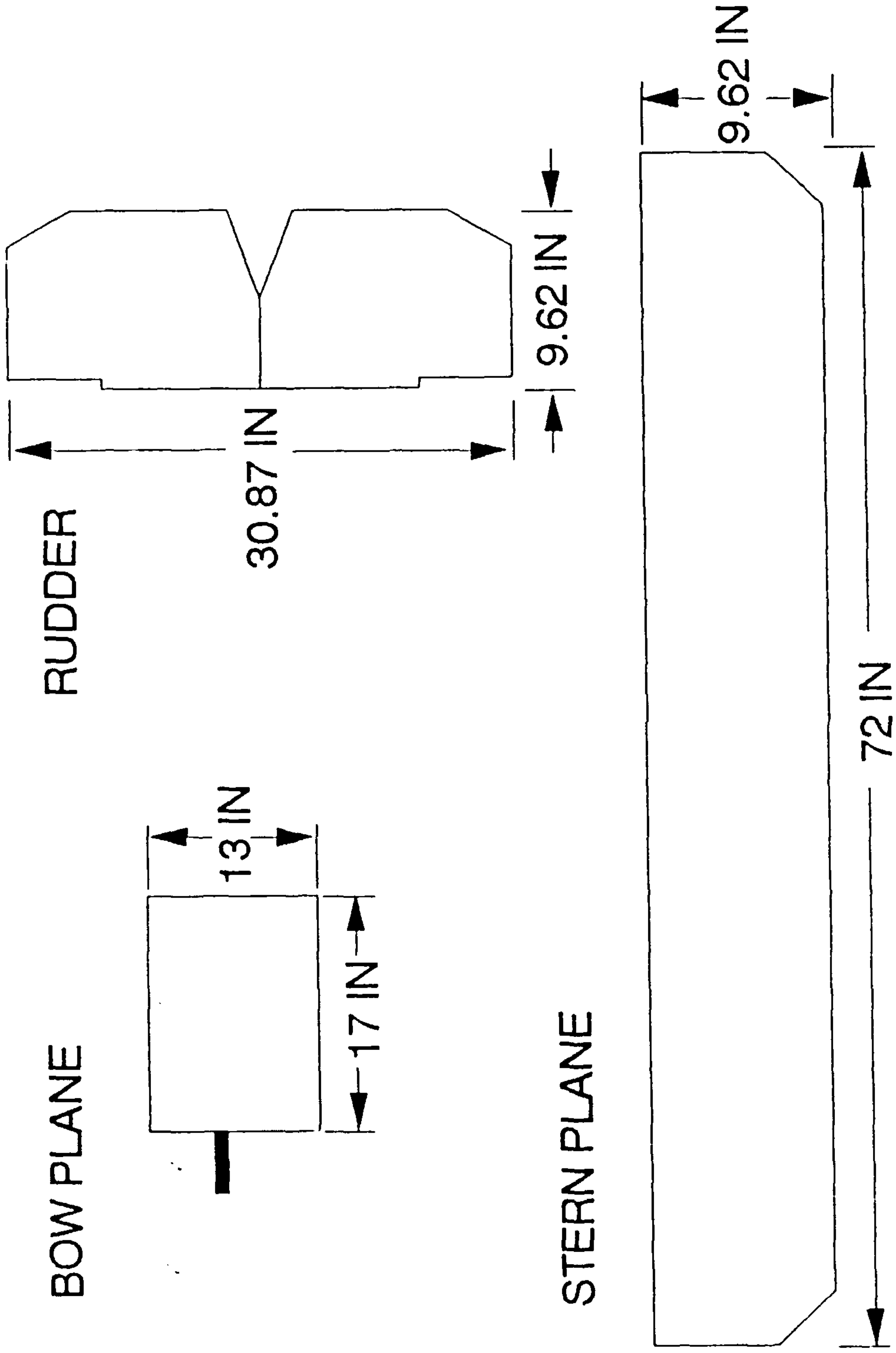


Figure 12 SDV IX Control Surfaces

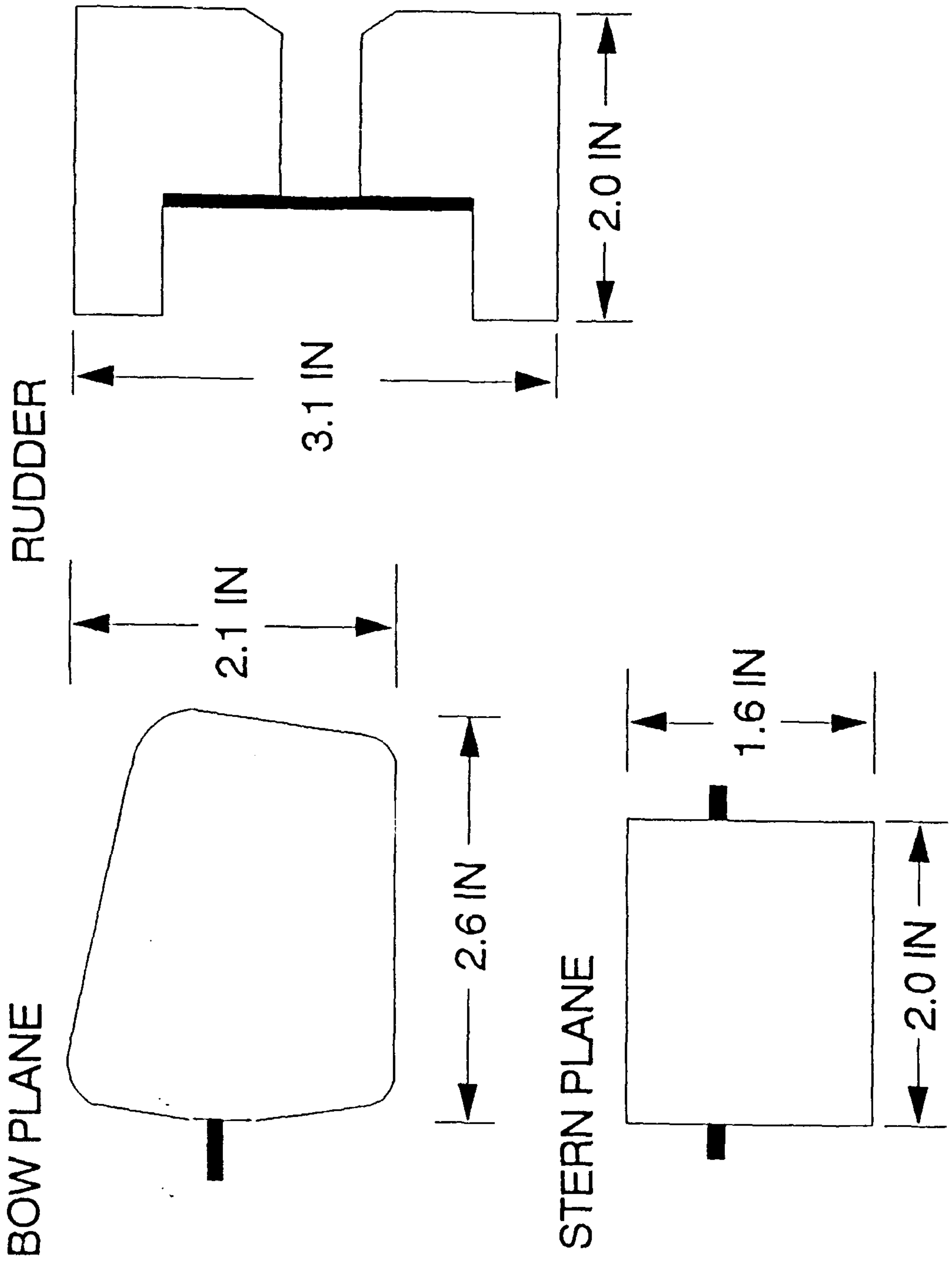


Figure 13 AUV I Control Surfaces

was one and one-third times the size of the actual vehicle's rudder. In contrast, the rudder area suggested for AUV I was over two and one-half times smaller than the area used. It would seem that the rudder system for AUV I therefore, should have made the vehicle quite maneuverable, and trial runs with the model in the 4' x 4' x 40' tow tank did prove that it was reasonably sensitive to rudder control.

In addition to rudder surfaces, the DnV method was extended to examine stern plane sizing. A modification was made in the use of the DnV formula, where the beam of the vehicle was substituted for the draft in the first term of the equation and draft was used in the numerator of the last term. Suggested Dnv areas for both SDV IX and AUV I were less than half the size of the stern planes used on the respective vehicles. The question is raised as to the applicability of the DnV code for submarine design.

(2) Rudder Area Coefficient. Landsburg also recommends the use of a rudder area coefficient [Ref. 29:p. 370] for comparison with typical values for a vessel type. The rudder area coefficient is a comparison of rudder area versus underwater profile area (Length x Draft) given as a percentage. The vessel types listed in Table 11 of the subject paper do not include submersibles, but it was thought that the maneuverability of the vessels being studied could be characterized by a coefficient in the range of 3.0-5.0 %. The

values for the SDV IX proved to be in this range, as did the stern planes for the AUV I. The rudders for AUV I again seemed to be oversized, at almost twice the relative size of those on the SDV IX.

(3) Scale Ratios. Using the idea of scale ratios from Froude's law of comparison, three ratios were examined as another approach to control surface sizing. The three ratios described by number in Table V correspond to the power of the exponent used with the scale factor which describes the length, wetted surface area and volume ratios. In this method, the SDV IX assumed the role as ship with the AUV I and AUV II as two models having different scale ratios to the SDV IX, with:

$$\lambda = \frac{L_S}{L_M} \qquad \lambda^2 = \frac{A_{S_{WETTED}}}{A_{M_{WETTED}}} \qquad \lambda^3 = \frac{\nabla_S}{\nabla_M}$$

where

L_S = *Ship Length* L_M = *Model Length*

$A_{S_{WETTED}}$ = *Wetted Ship Area* $A_{M_{WETTED}}$ = *Wetted Model Area*

∇_S = *Ship Volume* ∇_M = *Model Volume*

Results for AUV I were consistent between the three scale ratio powers, but did not match well with any of the control surfaces installed on the vehicle. As with previous methods, the suggested rudder area was less than half the size of that installed. In the case of the bow and stern planes, the recommended plane areas were alternately lower and higher than the actual areas. The recommended areas do seem more appropriately proportioned than those used, with a larger stern plane compared to those at the bow to produce a desirable dominating effect on vehicle control. This is also consistent with the SDV IX configuration.

Applying the scale ratios to AUV II yielded estimates for the control surface areas which were higher than the DnV, and like those for the AUV I, consistent with the SDV IX form.

(4) Jackson Method. The last method used for control surface sizing was devised by CAPT Harry Jackson, USN (Ret) [Ref. 30], where for a control surface located in the stern of a vessel, the relationship holds that;

$$M = \frac{L\,D}{A}$$

where

M = 25.6
L = Vehicle hull length
D = Maximum hull diameter
A = Area of two planes

Since the vehicles of this study are not bodies of revolution, having rectangular cross-sections, the diameter term was replaced by a measure of the vehicle draft (height) or beam for calculation of the rudder or stern plane areas, respectively. This seemed appropriate since these dimensions were in the active plane of the particular control surface and a component of the area which would provide resistance to the body moment provided by the appendage.

The "Jackson" method gave the best agreement with actual control surface sizes used in the SDV IX. For the AUV I, the calculated areas retained consistency with the SDV IX proportions, but did not compare well with either rudders or stern planes as equipped. Like the other methods, the suggested rudder size was half the area of those found on the vehicle. The proposed stern plane was slightly larger, promoting dominance over the bow surfaces in diving control.

Applying the Jackson method to AUV II yielded values for rudder and stern plane areas which were considered to be sound estimates. It was thought that these would produce a maneuvering character similar to that of the SDV IX.

d. Turning Performance

In order to gain an additional awareness for the vehicle's maneuverability, the FORTRAN hydrodynamic model of the SDV IX was normalized by vehicle length to provide a comparison of tactical diameters associated with rudder size. Computer simulation was performed for the scaled vehicle with a rudder of nominal size (Jackson Method) to give an estimate of the tactical diameter of AUV II. The resulting turning circle is shown in Figure 14.

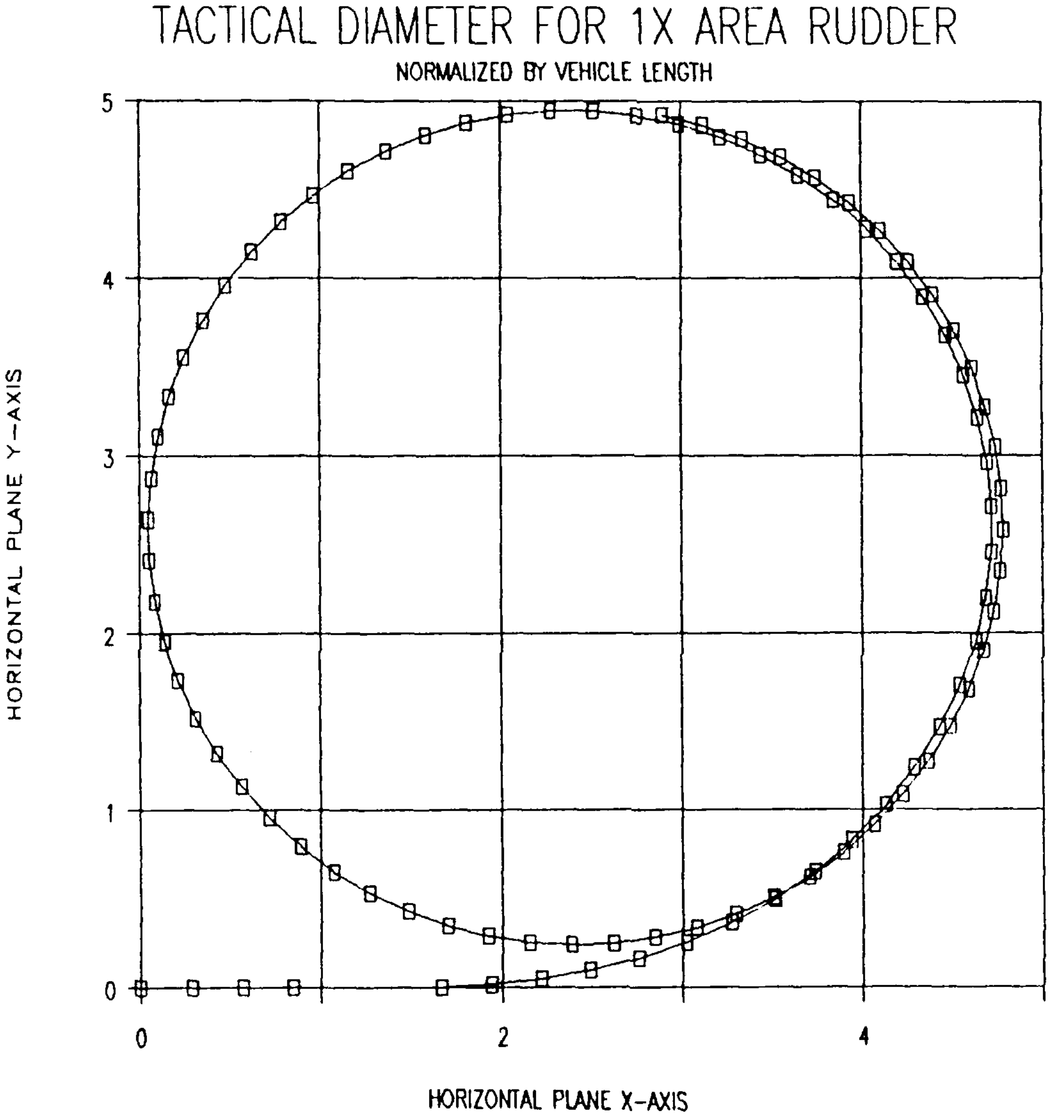


Figure 14 Tactical Diameter for Nominal Area

The tactical diameter of almost 5 vehicle lengths was considered to be to large for NPS pool operation (only 60 feet wide), confined to 8.83 vehicle lengths. With a nominal Jackson area (32.5 in^2) rudder, this meant that the vehicle would be limited to a single racetrack type turn around the pool. It was decided to conduct further dynamic simulation to examine how multiplying the rudder area might effect maneuverability. Doubling the area of the rudder reduced the AUV's tactical diameter down to about 3 vehicle lengths. Tripling the area yielded a further decrease to less than 2.4 vehicle lengths. Figures 15 and 16 show the results obtained in the dynamic simulation for the larger areas.

It was decided that the tactical diameter for the doubled area would be the maximum to allow. With this tactical diameter, the vehicle would be able to perform a full "S" type turn across the width of the NPS pool with some room to spare. This seemed like a minimum goal to strive for in the design.

e. Arrangement Alternatives

The original concept for the control surface arrangement was much like that for the SDV IX and AUV I, with the exception of the stern surfaces being arranged in a cruciform like modern submarines. Two bow planes were planned to enhance vertical plane maneuverability. Figure 17 depicts this arrangement concept. After the turning performance of

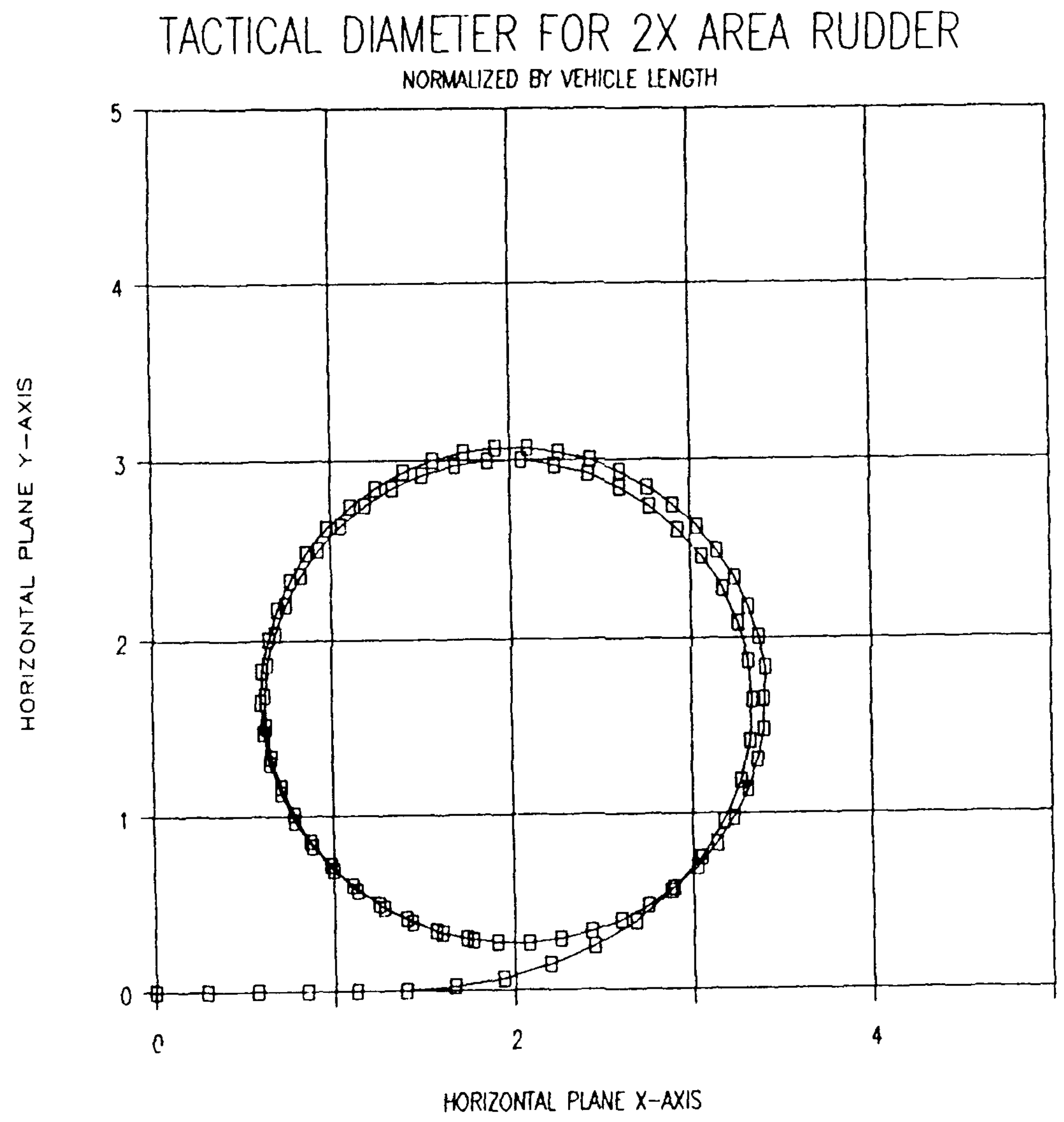


Figure 15 Tactical Diameter for Doubled Area

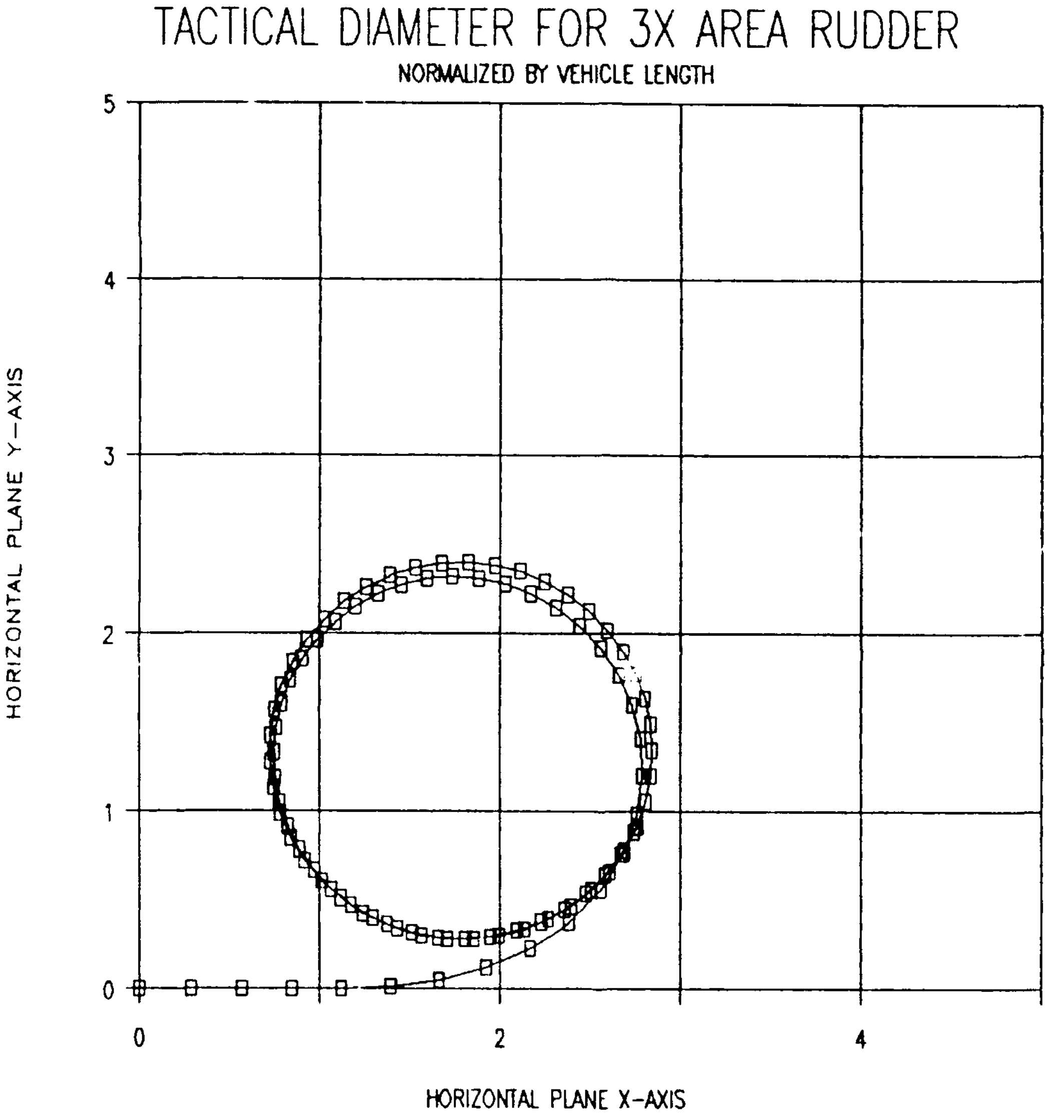


Figure 16 Tactical Diameter for Tripled Area

AUV II was demonstrated in simulation, some imaginative ideas were suggested to enhance horizontal plane turning. One of these, dubbed the Highly Maneuverable AUV, is shown in Figure 18.

Consideration was given to the effect that such an arrangement might have, and it seemed worth pursuing. It was thought that the action of the forward rudders would induce a dynamic instability to the vehicle's motion and help make turning more rapid. This type of performance is demonstrated by ferries which use bow rudders for improved backing and turning control [Ref. 31]. The effect would add to the maneuverability produced by a larger rudder area and could produce an extremely agile vehicle. This scheme was adopted and a suitable arrangement was studied.

The first decision in the process of determining a control surface arrangement was to make all the control surfaces the same size for simplicity. Though this meant that the bow mounted surfaces would be larger than originally conceived, it was thought that the automatic control system could compensate for the difference and performance would not be adversely effected. Vehicle trials would demonstrate the validity of this assumption.

The second recommendation was to mount the four bow surfaces in the fiberglass nose, where ample interior space was available. The aft section of the nose was fairly even with the midbody, so the rotation of the surface would not be

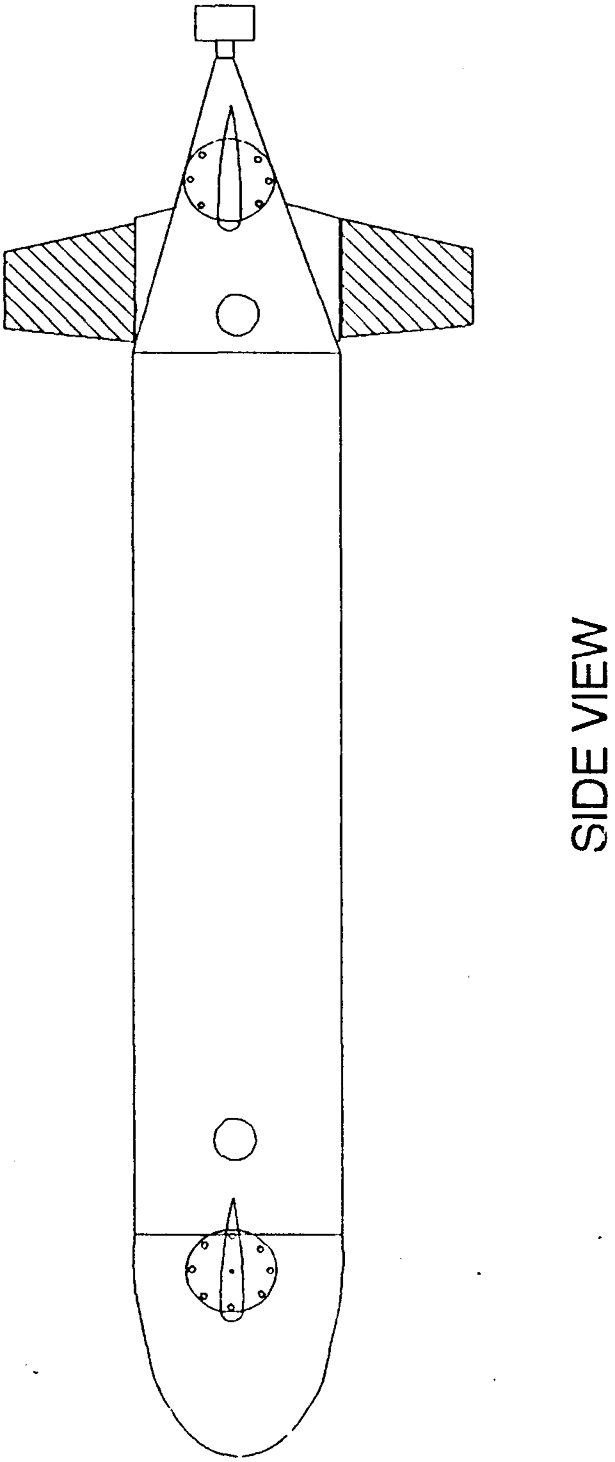


Figure 17 Original Concept Arrangement

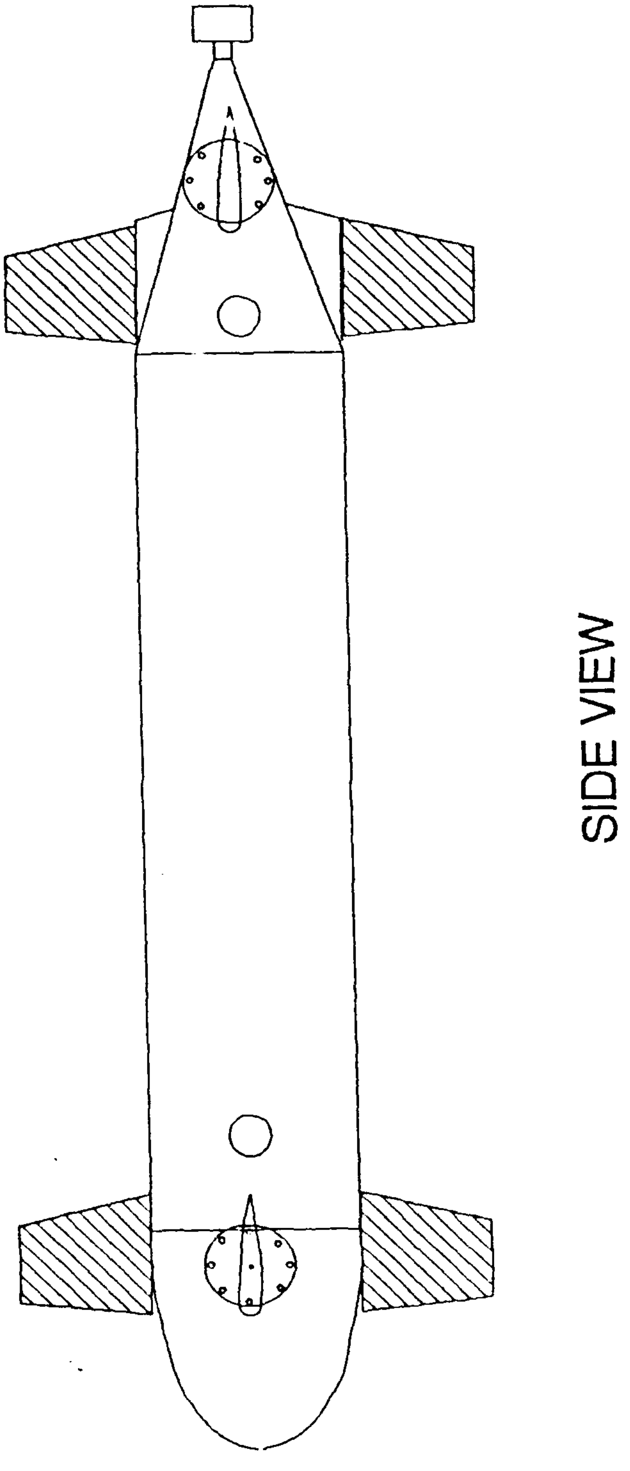


Figure 18 *Highly Maneuverable Arrangement*

impaired. The flat outside surface of the nose would offer suitable placement with respect to flow as well.

A third decision, which was a direct result of the second, was to combine the servo, bearings, shaft and control surface as an assembly in an interchangeable pod. Since a reliable waterproof seal was needed around the shaft of each servo unit, it was thought that a common waterproof enclosure would help insure this and be easy to fabricate. The bow control surface servo equipment pods would be mounted to the outside of the hull's front bulkhead, while the stern units would be placed internally and flush mounted with the skin. Figures 19 and 20 depict the two servo housing variants.

Interference with other systems due to the placement of the control surfaces was also examined. In particular, the interaction of a control surface edge with flow into and out of the tunnel thrusters was considered. Maintaining a distance of at least 2 inches between the tunnel lip and the leading or trailing edge of the wing root was considered necessary to minimize the deleterious effects of partial flow obstruction.

f. Servo Control

Airtronics radio control aircraft servos[10] had been used with success in AUV I, and three spare units were held for possible use in AUV II. To determine their

---

[10] Model # 94732.

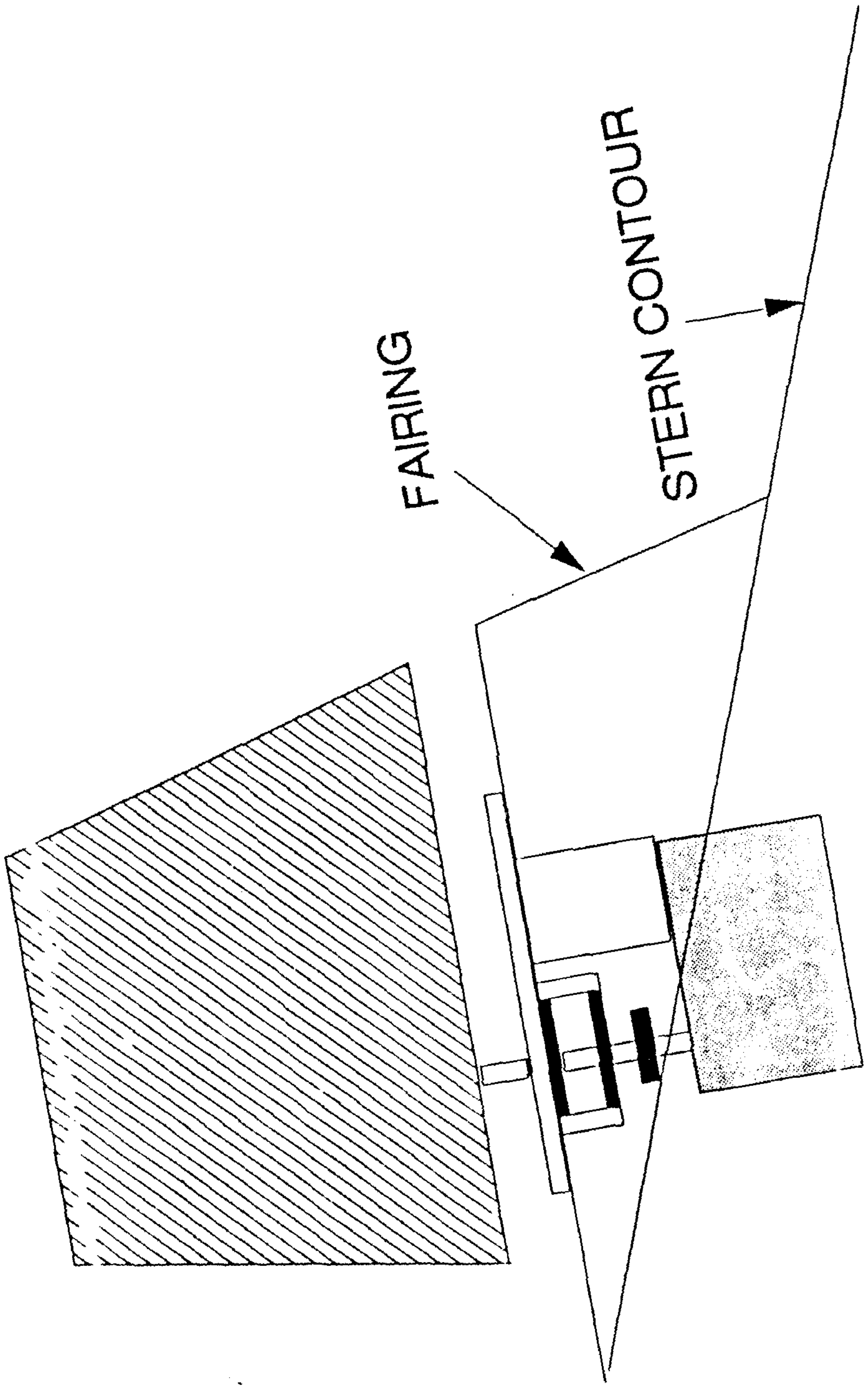


Figure 19 Stern Servo Housing

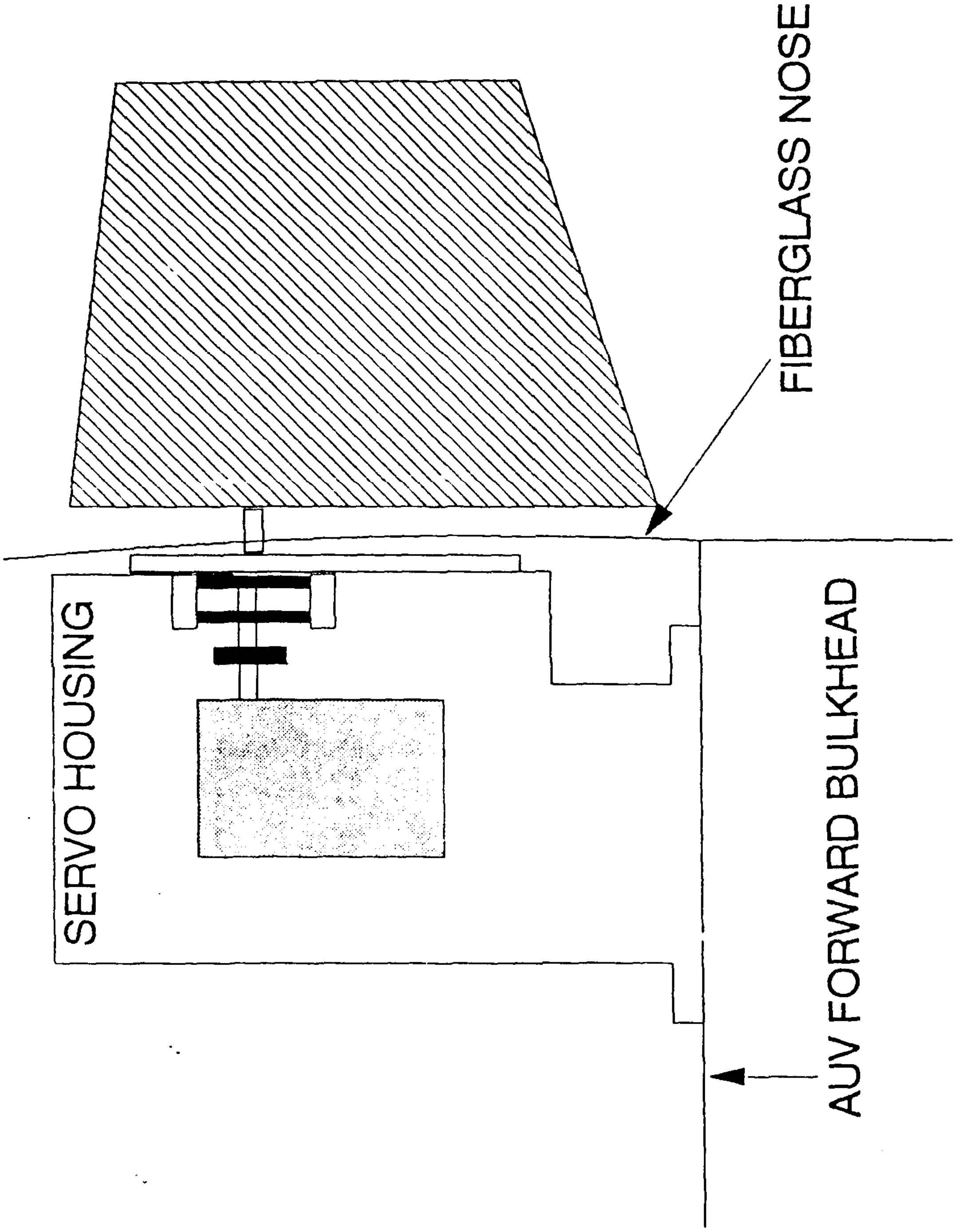


Figure 20 Bow Servo Housing

suitability, it was important to estimate the load that a control surface might put on the servo assembly. To expedite this analysis, a spreadsheet was created with lift, drag, and center of pressure information. These values were used to calculate the torque due to the chordwise and spanwise locations of the center of pressure.

The chordwise torque exerted on the shaft joining the wing and servo was of greatest concern in the servo examination. If the resisting torque values overcame the output torque of the servo, a replacement unit would have to be found. Several shaft locations along the chordwise direction at the mean span were investigated. An optimal location was considered for selection with two criteria:

1. Have the lowest average of the absolute value for torque over the range of angles of attack.
2. Have the lowest maximum value over the effective range of angles of attack (below 23°).

The case where the shaft was placed at 21% of the chord distance appeared to meet these criteria best. Figure 21 shows the torque character at this location. The diagram shows a maximum resistive torque of about 1.7 pound-inches would be encountered at this location. Some additional torque, perhaps 1 pound-inch, would be required to overcome the friction in the watertight O-ring seal envisioned. With a rated torque capacity of 67 ounce-inches (4.188 pound-inches), the servo would easily meet the estimated maximum torque of less than 3 pound-inches, although in the final analysis, a larger unit, Model # 94510 was selected with a 110 ounce-inch (6.875 pound-inches) rating and a response time of 0.5 seconds for 0 to 90° movement (Figure 22).

The effect of spanwise torque was considered as a criteria for shaft sizing. The maxim for shaft design was "Keep it simple and make it rugged". A maximum possible lift value of 82 pounds was obtained from the control surface spreadsheet for the foil at a 23 degree angle of attack with a velocity of 5 foot per second. Although this was an extremely overdesigned speed from the standpoint of vehicle powering, it seemed like a solid upper bounding reference for this analysis.

A calculation for the bending moment of this cantilever beam case showed that a steel shaft with yield strength of 30 ksi would need to be 0.46 inches in diameter at an absolute minimum. The shaft would have to be 0.58 inches in diameter to accommodate a factor of safety of 2. In order to purchase cheaper off the shelf bearings, a shaft of about 0.50 inches was desirable. A steel shaft of 0.50 inches gave a factor of safety of 1.33, which was considered marginal.

Since mild steel would not give much design safety, other materials were considered. The M.E. shop had a supply of stainless steel 0.50 inch rod which looked promising. Such a shaft would conservatively provide a factor of safety of 1.75. In light of the desire for simplicity, this was considered adequate.

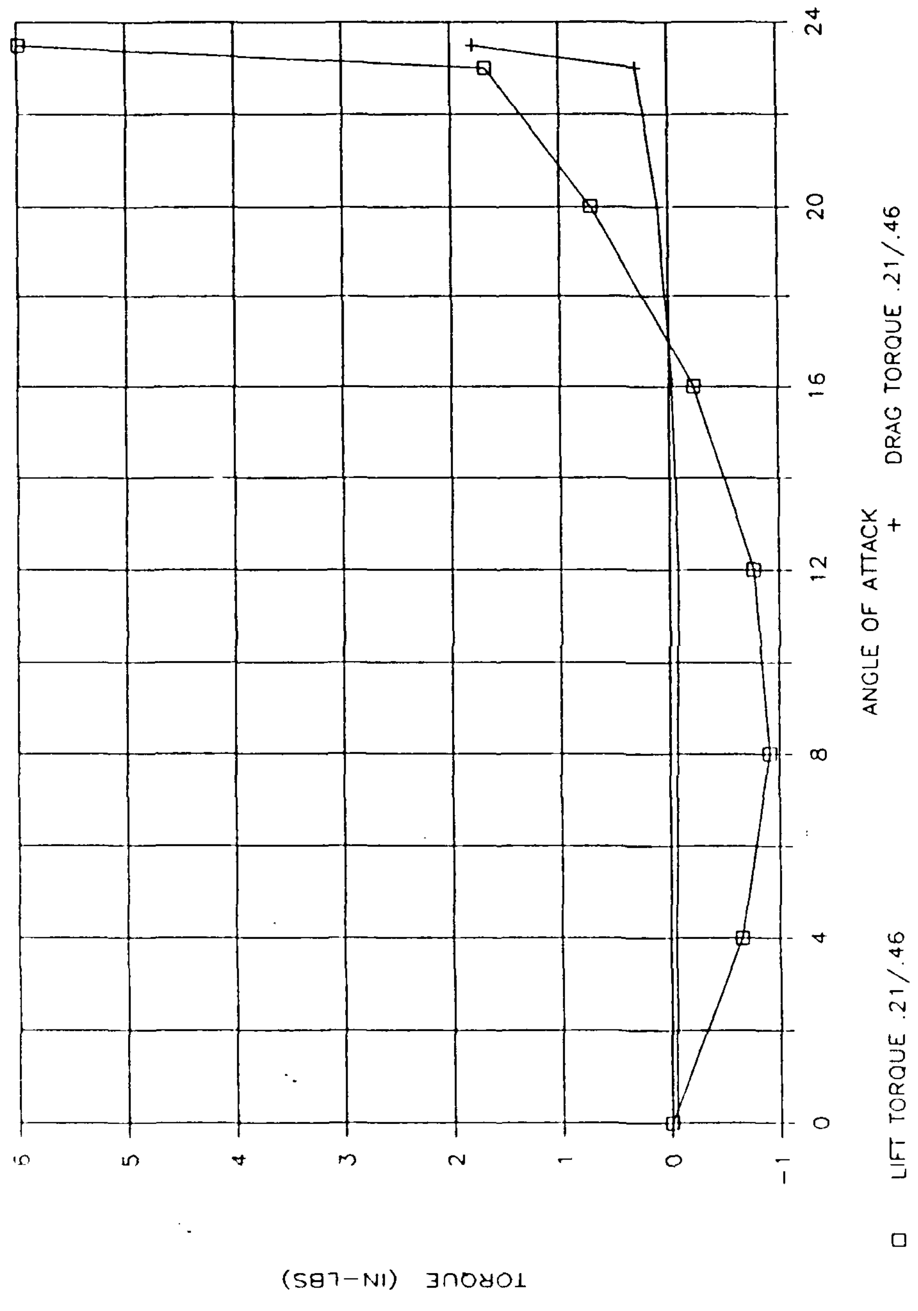
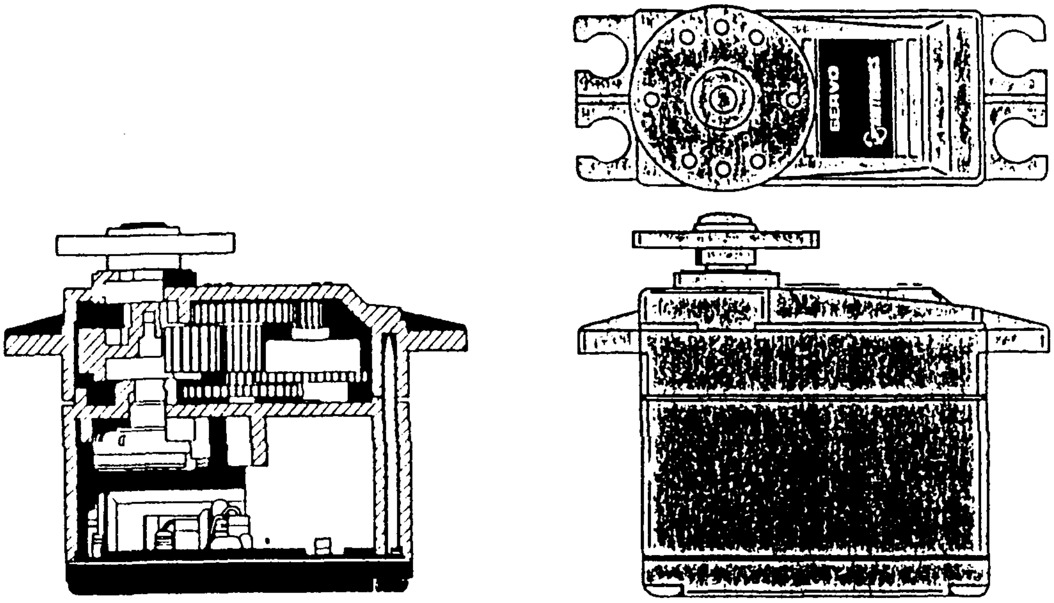


Figure 21 Resistive Torque Due To Shaft Location



94732 Heavy Duty Contest Aircraft Servo

A high performance servo designed for pattern type airplanes, 1/4 scale and any fixed wing application requiring small size, narrow deadband characteristics and high torque.

SPECIFICATIONS: 94732	
L: 1.55" x W: 0.80" x H: 1.40"	
Torque:	67 oz./In
Transit Time:	0.19 seconds for 60° rotation
Weight:	1.8 oz.
Dead Band:	1.3 Micro Seconds

Figure 22 Airtronics Servos

3. Stern Propulsors

a. *Running Gear*

The successful operation of the stern propulsion equipment used in AUV I influenced the choice of similar running gear for AUV II. A suitable kit[11] was purchased from 32nd Parallel for modification. Included were: two stainless steel propeller shafts, two 3 inch brass propellers and brass stuffing tubes.

b. *Propellers*

Preliminary testing with the 3 inch propeller demonstrated that it might not be capable of driving the estimated weight of AUV II and providing at least 1 lb of thrust for each shaft. A 4 inch diameter propeller was fabricated and subsequent testing showed it would provide adequate thrust.

c. *Motors*

Electric motors were chosen to provide propulsion for AUV II. Experience with AUV I had proven the reliability of quality servo motors and their suitability to the marine environment. AUV I had two Pittman 9513 series 12 volt DC motors for stern propulsion. These had been provided by 32nd Parallel, which uses them in their submarine models. The small 9513 series motor is shown in Figure 23.

---

[11] Gato/Balao Running Hardware Kit # 07-100.

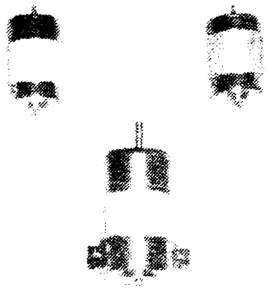


Figure 23 Electric Motors

It was anticipated that two different motor drive systems would be used in AUV II for stern propulsion and thrusters. The powering requirement for the vehicle in cruising mode was expected to be higher than that for hovering. A prototype drive system was built and tested to determine the thrust produced by a given motor system. The initial stern drive system was an arrangement with two Pittman 9513 series motors ganged together by a cogged belt. This setup was designed by 32nd Parallel for use in their 9 foot 9 inch long Gato / Balao submarine model kit.

Testing conducted by, and the subject of an upcoming thesis, Saunders [Ref. 32] showed that the drive system could provide about 1.5 pounds of thrust per screw in a bollard pull condition. However, the two ganged motors were being driven toward the high end of their operating capability and susceptible to performance degrading heat generation. Figures 24, 25 and 26 show the motor arrangement and test apparatus.

As a result of Saunder's findings, a single larger stern drive motor was decided on for installation as a prime mover on each shaft in AUV II. The Pittman 14202 series 24 volt motor chosen is also shown in Figure 23. Further details are forthcoming in Ref. 32.

*d. **Kort Nozzle.***

Some sort of shielding ring was considered for installation around the screw to prevent fouling of the planned fiber optic output data cable. After some

Figure 24 Flexiglass Stern Drive Housing

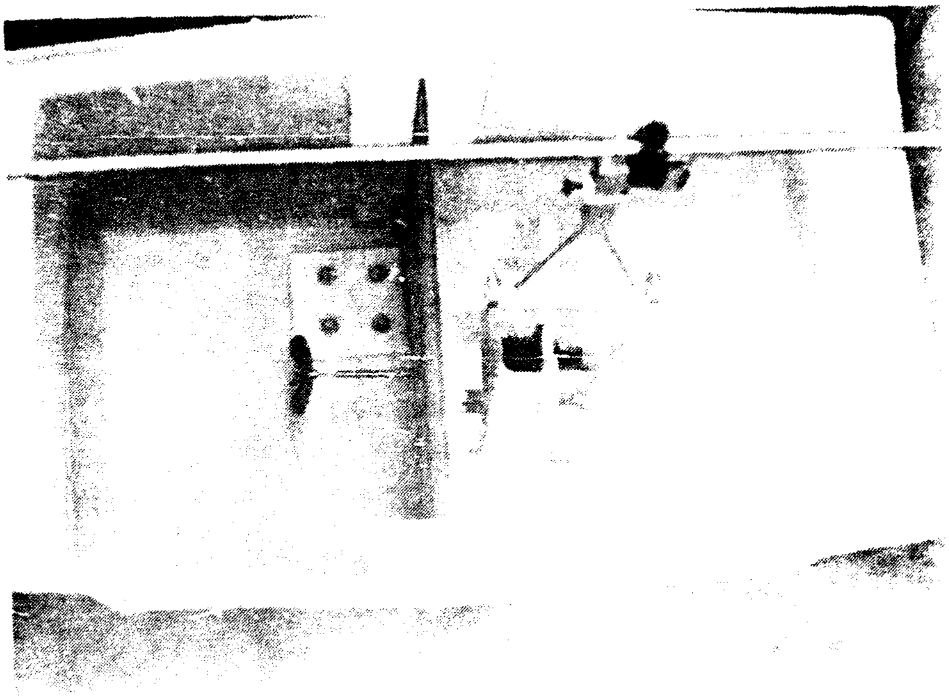


Figure 25 Testing Tub

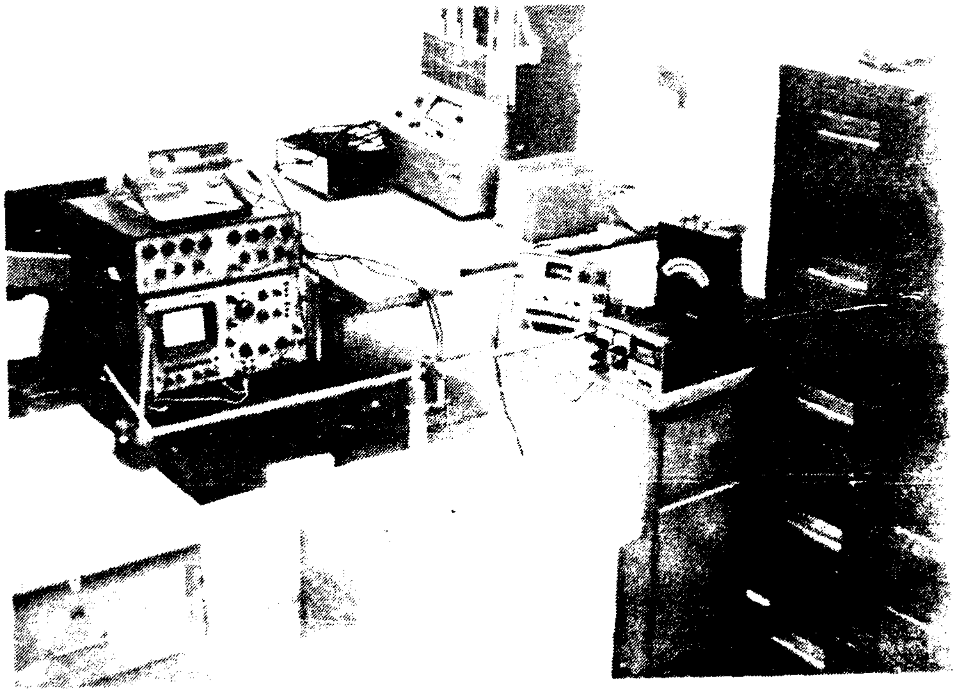


Figure 26 Test Apparatus

alternatives were discussed, it was decided to incorporate a Kort nozzle into each stern propeller assembly. This device would enhance low speed thrust as well as protect the cable. Design of the Kort nozzle was taken up by Saunders.

4. Thrusters

The DSRV-like arrangement of four through body tunnel thrusters was appealing from the standpoint of hull hydrodynamics as well as the ability to impart an effective body moment on the vehicle with combined operation of fore and aft units. The modeling of this system for hovering control purposes also seemed fairly direct due to the orthogonal nature of the thrust vectors produced. In order to take advantage of these traits, placement and sizing of the thrusters needed to be examined carefully.

a. *Physical Arrangement*

The thrusters would be arranged in pairs, forward and aft, in the vehicle. Each horizontal thruster would be located nearest the bow or stern to impart the greater effective moment on the vehicle. This position was chosen because it was thought that the vehicle would perform more sideways or horizontal rotation thrusting at a constant depth when performing a sonar scan of an object in the pool. Vertical thrusters would be inside of the horizontal ones, toward the midpoint of the vehicle. It was expected that these would act primarily to counter the vehicle's slight positive buoyancy and maintain depth while the vehicle was moving too slowly to achieve depth keeping with the control surfaces. In order to meet the movement requirement, and noting that no current requirements would be present in the pool, it was thought that the thrusters would have to produce at least 1 pound of thrust per unit.

b. Prototype unit

A prototype thruster was designed by Marco and the author, and built for testing on the same apparatus used for the stern drive. Figures 27 and 28 show views of the thruster unit. The prototype thruster used a single Pittmann 9513 series 12 volt motor with a belt and pulley drive system to provide rotation to a Kaplan type impeller. The housing and most parts were fabricated from plexiglass to enable observation of the internal workings of the unit. Testing quickly showed the inadequacy of the smooth drive belt in water. When the thruster motor was powered above about 5 amperes at a constant 12 volts, the belt would begin to hydroplane on a layer of water between it and the impeller's pulley surface. The resultant loss of driving force above this level called for a redesign of the thruster drive system. The maximum force achieved with this motor and drive system was 0.25 pounds of thrust.

A novel direct gear driven thruster, with a Kaplan type impeller, fabricated in plexiglass, was designed for

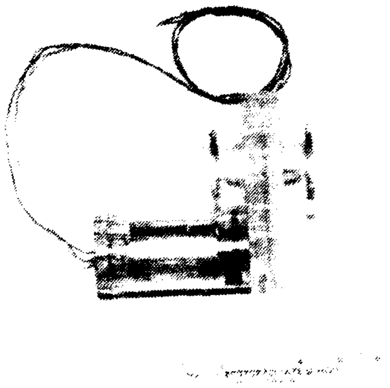


Figure 27 Prototype Thruster Side View

Figure 28 Prototype Thruster End View

testing and prospective vehicle installation. Figure 29 shows a view of the proposed arrangement. A motor with greater power was also chosen for the thruster. Figure 26 includes the Pittman 9514 series 24 volt motor selected.

F. AUTOMATION & INTELLIGENT VEHICLE CONTROL

1. Introduction

The task of providing real time control of the AUV II systems was addressed by other participants in the project and will be the subject of an upcoming thesis by Cloutier [Ref. 33]. Software conducts the processing of sensor data and provides vehicle control. Implementation of the control techniques was part of the vehicle mechanical design. In particular, the hardware used to accomplish control had to be selected and integrated.

2. Software Role in Control

Analog sensor information on the vehicle's environment, motion or equipment status is fed to through a circuit board which converts it to digital signals. Software conveys the digital sensor information from the converter board to the appropriate guidance module. This module, in turn, will generate desired heading, depth and speed signals for the vehicle controller to implement. The controller is also a software system which acts to reach the specified objective. It originates the command signals received by the control surface servos and propulsion units.

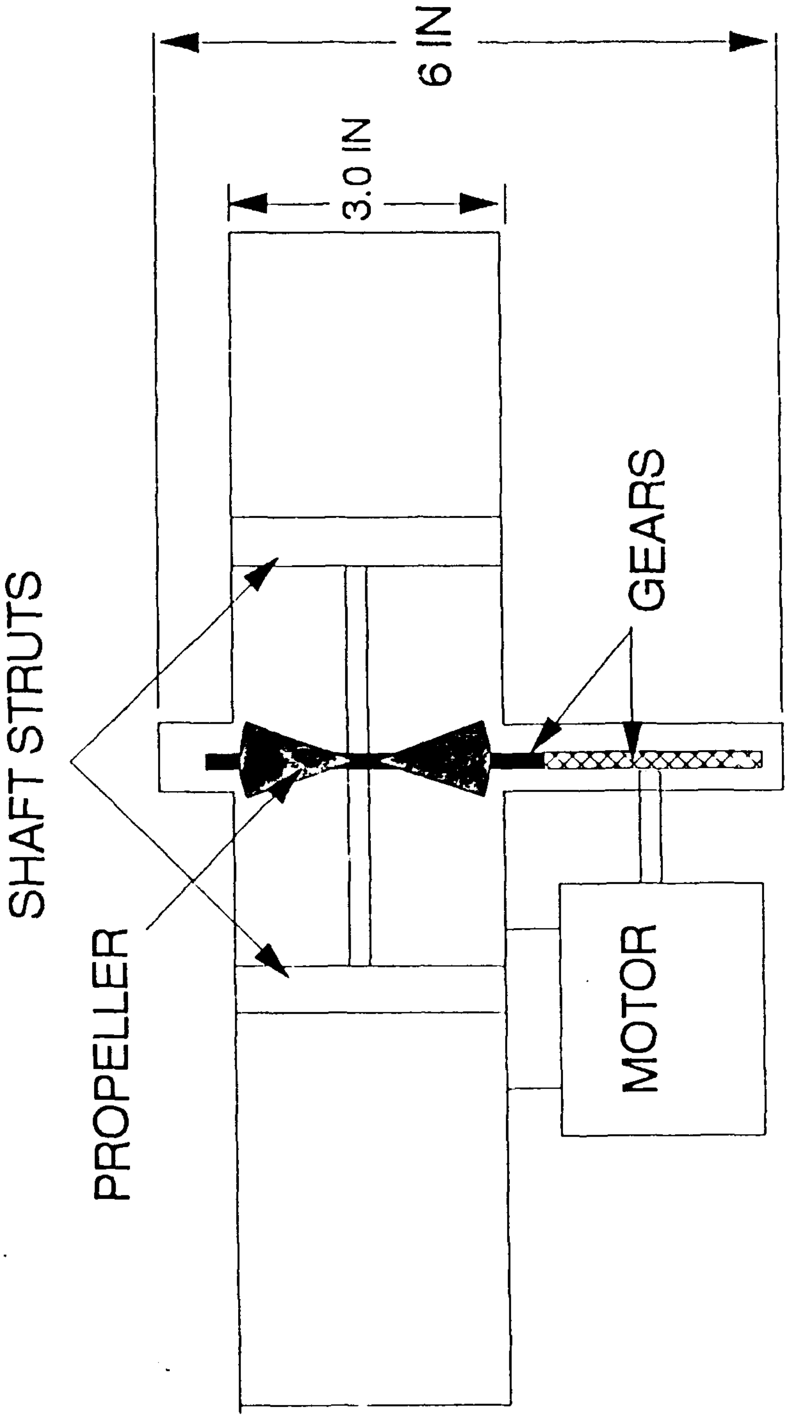


Figure 29 Proposed Gear Driven Thruster

3. Multi-Tasking Capability

Experience with AUV I demonstrated the capability of an IBM-AT type digital computer to provide autonomous control in diving plane operations. The evolution to a vehicle which would operate in three dimensions would require a more advanced microprocessor to achieve the complexity of control desired. A rugged multi-tasking computer was necessary to perform the myriad of vehicle control functions in the marine environment.

a. *GRiDCASE 80386 Laptop*

A survey of available systems which would suit various needs of the AUV project resulted in the choice of a GRiDCASE 1535 EXP Intel 80386 based microprocessor laptop computer. It could serve capably in the vehicle for system control and in the lab as a vehicle software development tool. An expansion tray and detachable battery were also purchased to allow the computer to interface with and power the analog-digital conversion circuit cards. These accessory units are designed to attach directly to top and bottom of the laptop chassis. Figures 30 and 31 show different configuration views of the laptop computer.

b. *GESPAC 68000 System*

Late in the design stage, and because of problems encountered in direct operation of the Data Translation A/D converter boards from the MS-DOS operating system,

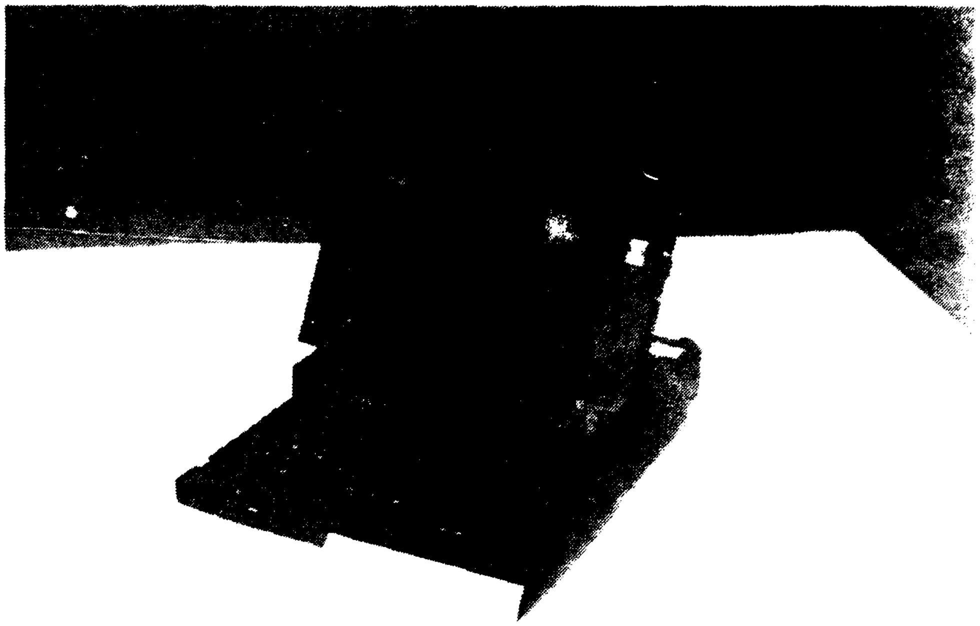


Figure 30 Laptop Standard Configuration

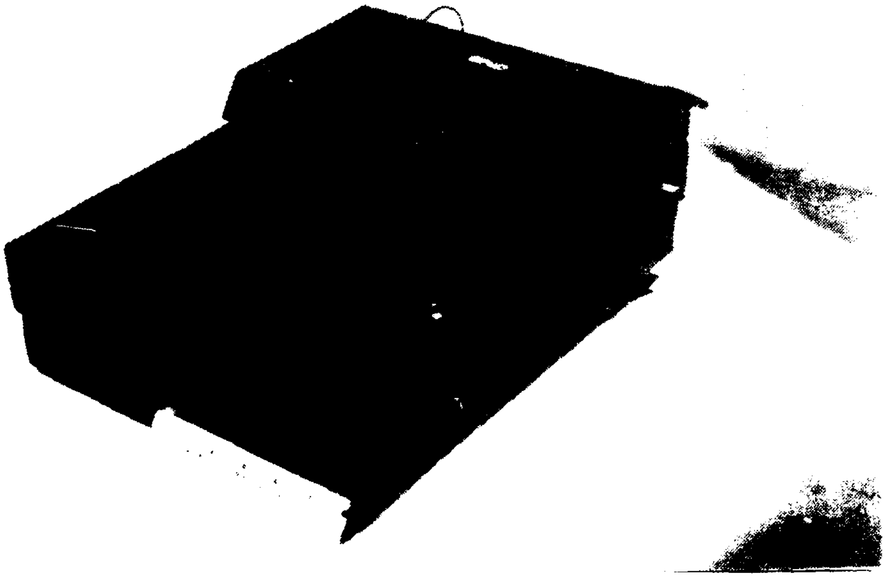


Figure 31 Laptop Enhanced Configuration

consideration of a second computer system, employing a Motorola 68000 series microprocessor, is expected to enhance the **real-time** decision making and control capability of the vehicle. A revisitation of the vehicle's equipment layout plan yielded a different packing scheme that provided a small space for the new computer. The GESPAC universal G-64 bus card cage package was selected for integration into the existing computer hardware plan for AUV II. The GESPAC computer system is expected to enable real-time multi-tasking signal processing to keep up with an autopilot update rate of 25 Hz.

G. SENSOR REQUIREMENTS

1. Introduction

Experience with AUV I demonstrated that control could be provided in the absence of some vehicle motion information. Although this was true for the limited operation of that vehicle, a complex autonomous system like AUV II has a great need for accurate sensor data concerning its environment and its own motion. Sensors must be carefully chosen to provide reliable measurement of the desired parameters.

2. Sensor Selection

a. *Environment - Active Sonar*

A high frequency sonar unit was identified for possible use in the vehicle and purchased. The Datasonics Model PSA-900 Programmable Sonar Altimeter offered arrangement flexibility and compact size. Subsequent testing [Ref. 34] confirmed its suitability for the swimming pool environment and provided recommendations for use in the vehicle.

The arrangement of four transducers in the nose of the vehicle was considered from the viewpoints of beam coverage, internal mounting and accessibility for mounting adjustment. The beam pattern of each transducer was approximately 10 degrees, in a conical shape as described in Lorhammer [Ref. 34]. This would provide accurate definition of an obstacle, but did not serve the need for area coverage ahead of the vehicle. This latter consideration was important for detection and avoidance of an obstacle during transit.

It was found that mounting four units at different angles in the nose would be difficult in the confined space, due to the size of the metal housing which came attached to the rubber transducer. The need for this housing was examined and it was determined that it could be eliminated. The housing was standard equipment which allowed the transducer to be used at depths approaching 2000 meters. For the shallow operation of AUV II, the rubber transducer piece could be used alone. Figures 32 and 33 show the Datasonics transducer electronics and a disassembled transducer.

The concerns related to adequate sonar beam coverage of the pool were discussed and a compromise proposed. An initial configuration would be built into the nose which

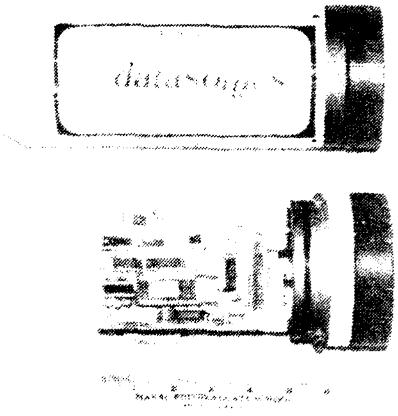


Figure 32 Sonar Electronics

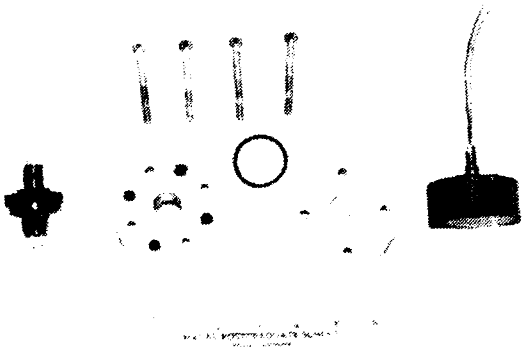


Figure 33 Disassembled Sonar Transducer

would allow easy adjustment of transducer orientation. In this way, the vehicle could be assured of operating during initial trials in a form similar to that which would be used in phase one testing. Figures 34 and 35 show the initial configuration and operating concept.

b. Vehicle Sensors

Vehicle motion, environment and equipment status sensors are critically important to the proper navigation and control of an AUV. An array of sensors including gyroscopes, a pressure transducer, velocity sensor, motor speed sensors, and vehicle health sensors was proposed for AUV II. The integration of these sensors into the vehicle and their interfacing with the vehicle computer system was a task which required thorough consideration.

(1) Gyroscopes. Gyroscopes are the key sensors for vehicle navigation. Autopilot design ideally requires feedback of vehicle angular rates and position, in addition to depth data. The system proposed for AUV II would employ units to measure 3-axis vehicle orientation angles and angular rates.

A directional gyro[12] with flux gate compass was designated for use in the horizontal plane. The gyro would provide vehicle yaw angle information and the north seeking flux gate would provide an averaged direction to magnetic

---

[12] Humphrey Gyro Model DG11-0105-1.

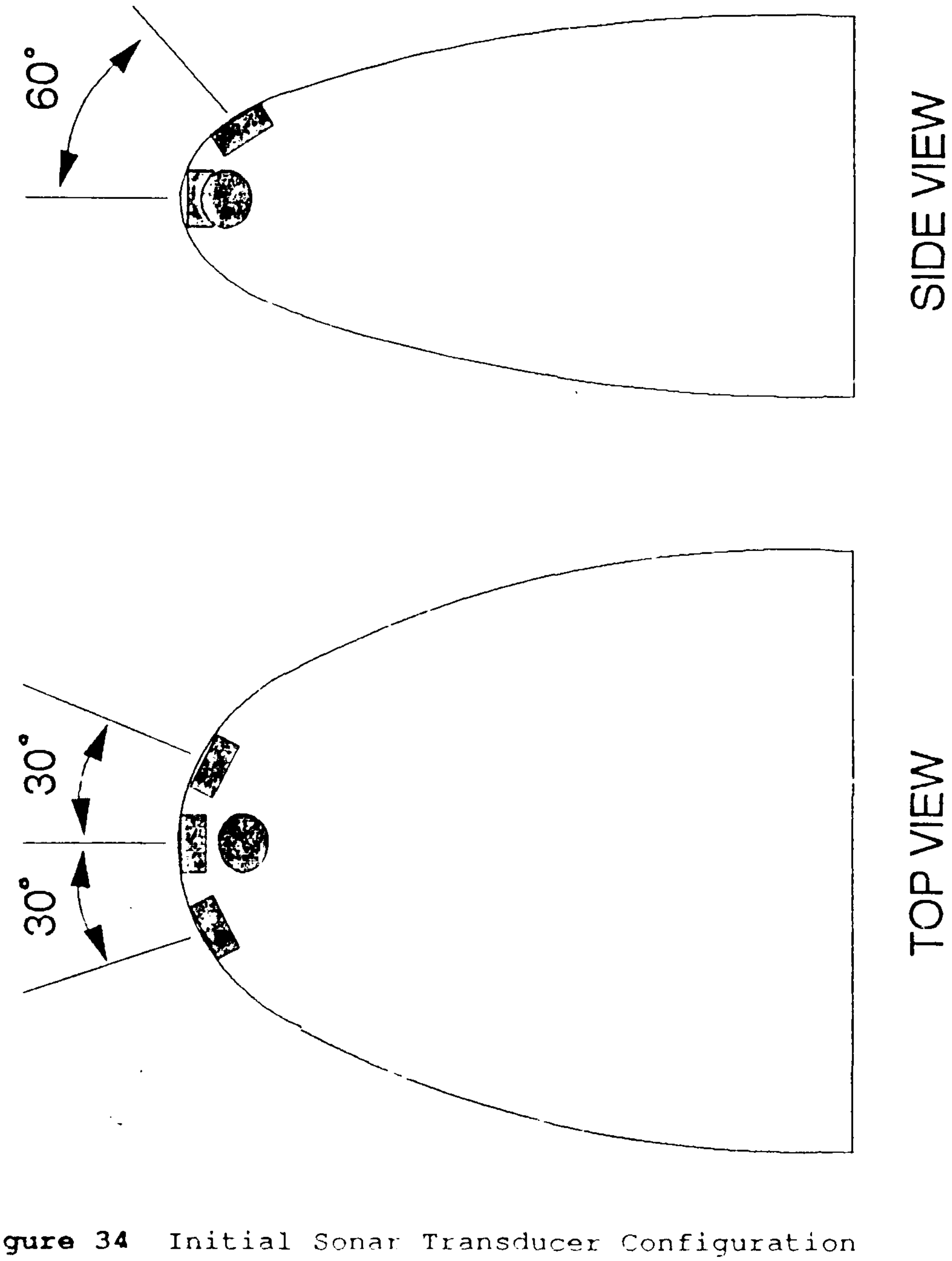


Figure 34 Initial Sonar Transducer Configuration

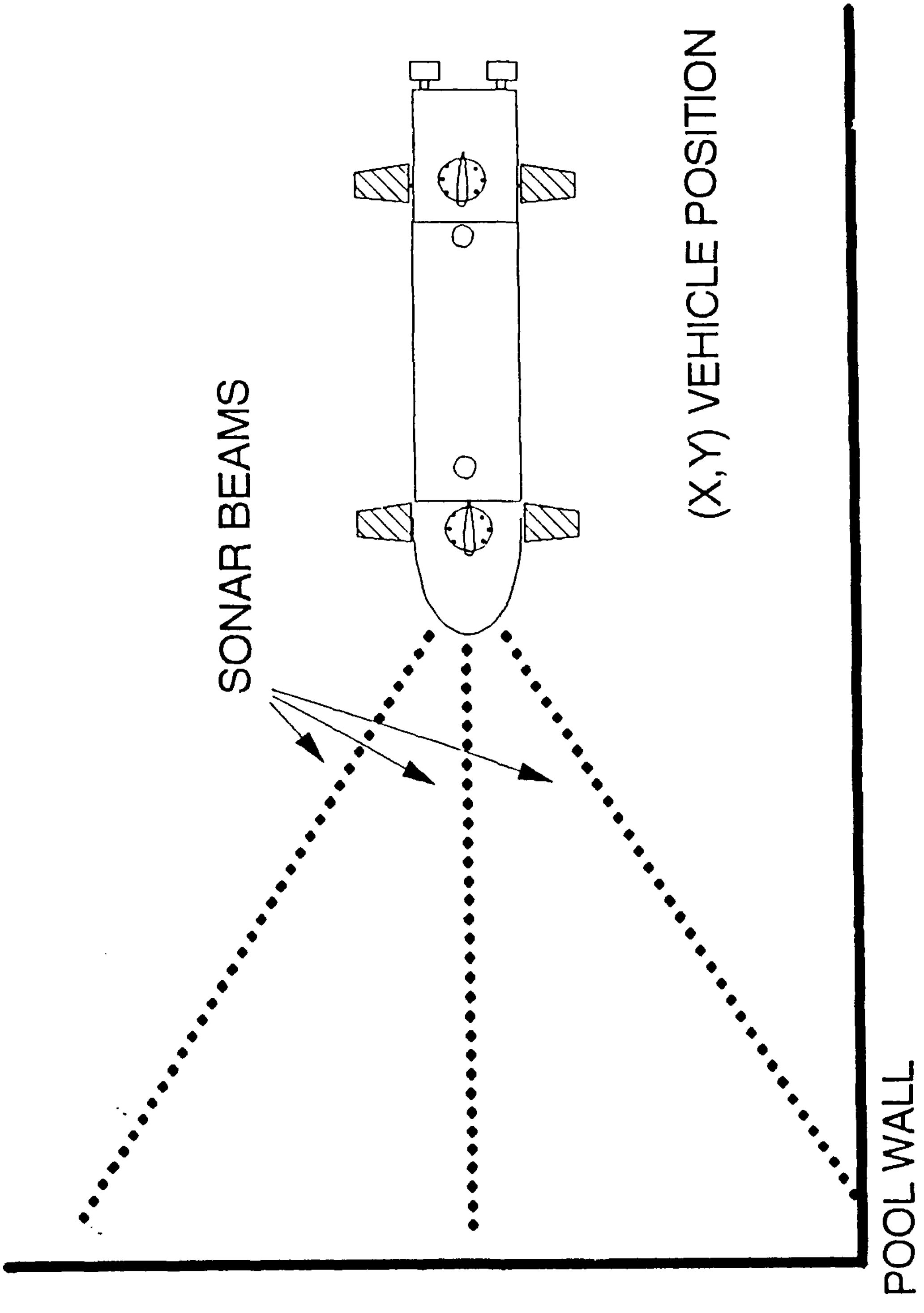


Figure 35 Pool Navigation

north. A compact vertical gyro[13] was selected for pitch and roll angle indication, and a 3-axis rate gyro package[14] was chosen to provide all the angular rate information. A valuable feature to the rate gyro setup was the precise mounting orientation of the units. Since they were aligned as a group, this would make vehicle installation easier. [Ref. 35]. Figure 36 shows the three gyroscopes and a power supply required for the directional gyro.

Integration of the gyroscopes into AUV II was not merely a matter of ordering the units from a catalog and bolting them into the hull, however. The selection of the

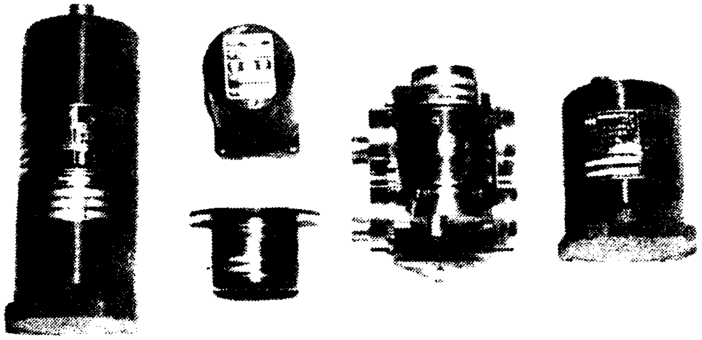


Figure 36 Vehicle Gyroscope Equipment

---

[13] Humphrey Gyro Model VG24-0636-1.

[14] Humphrey Gyro Model RG02-2324-1.

directional gyro precipitated a revisit of the design spiral and system interplay. This sensor's size required the height of the hull to be increased from 8 inches to 10 inches in order to accommodate installation of the 8.4 inch tall unit.

Selecting an installation site for the flux gate device raised concerns about the influence of electromagnetic fields on its accuracy. Investigation into the consequences of this effect pointed to the possibility that some shielding would be required around strong electromagnetic sources such as motors. A quantity of appropriate shielding material[15] was identified a sample of it was satisfactorily formed and spot welded in accordance with the manufacturer's fabrication guide [Ref. 36]. Vehicle trials will determine the amount of this material required to shield the motors.

(2) Pressure Transducer. A suitable pressure transducer was known as a result of the experience with AUV I. The Celesco LCVR[16] differential pressure transducer was selected for use with a LCCD[17] circuit board to provide an analog voltage output corresponding to depth. The sensor offers rugged construction in a small size package which will

---

[15] CO-NETIC AA alloy (high permeability) annealed sheet, approximately 0.030 inches in thickness.

[16] Low Cost Variable Reluctance.

[17] Low Cost Carrier Demodulator.

measure pressure between 0.75-400 inches of water [Ref. 37]. The pressure transducer will compare the water pressure inside the flooded nose with that of air trapped inside a sealed tube at atmospheric pressure.

(3) Velocity Paddlewheel. A simple paddlewheel arrangement was decided on for a speed-through-water sensor. A small paddlewheel with square notches cut into its perimeter would protrude into the flow outside the nose of the vehicle and be spun by the fluid at a rate corresponding to its velocity. An infrared source and photoreceiver would be aligned so that the square notches would pass through the infrared light beam, interrupting it regularly as the wheel rotated. The light source interruptions would be counted and compared to a standard clock signal to provide the velocity of the wheel for a close approximation of the fluid velocity. An important aspect of this design is the mass of the paddlewheel. Styrene plastic like that used in hobby models would be used to minimize bulk as well as simplify fabrication and avoid corrosion.

(4) Vehicle Equipment RPM Sensors. It was thought that speed information from the propulsors would be useful as feedback for the automatic controller. A scheme similar to that used for the water speed sensor was envisioned to determine the rotation rate of the propulsor's driving shaft. This information could be used to verify the system's

correspondence to command signals and report on its operating status. It would indicate to the automatic controller that a propulsor was unable to rotate, for example, and the controller could declare a propulsion system fault. This action might have consequences in the mission planner's determination of vehicle's ability to accomplish a mission or conduct impaired operation.

(5) Vehicle "Health" Sensors. Discussion with Blidberg [Ref. 38] highlighted experiences with previous vehicle systems and arrived at a recommendation for a vehicle health monitoring system on AUV II. Two simple sensors were incorporated in the initial design of the vehicle to support this end. The danger of damage to electronic systems seemed greatest from flooding and overheating of the vehicle, so these hazards were addressed in this first step.

A simple humidity detection circuit was found [Ref. 39] for testing and prospective implementation. Figure 37 shows the suggested circuit.

Since electronic equipment is susceptible to overheating, it was important to incorporate a thermal sensor which could monitor the ambient temperature inside the vehicle. A thermistor circuit was envisioned for a simple system to detect a temperature above a given maximum value. An examination of computer equipment operating temperature specifications [Ref. 40] listed an upper limit of

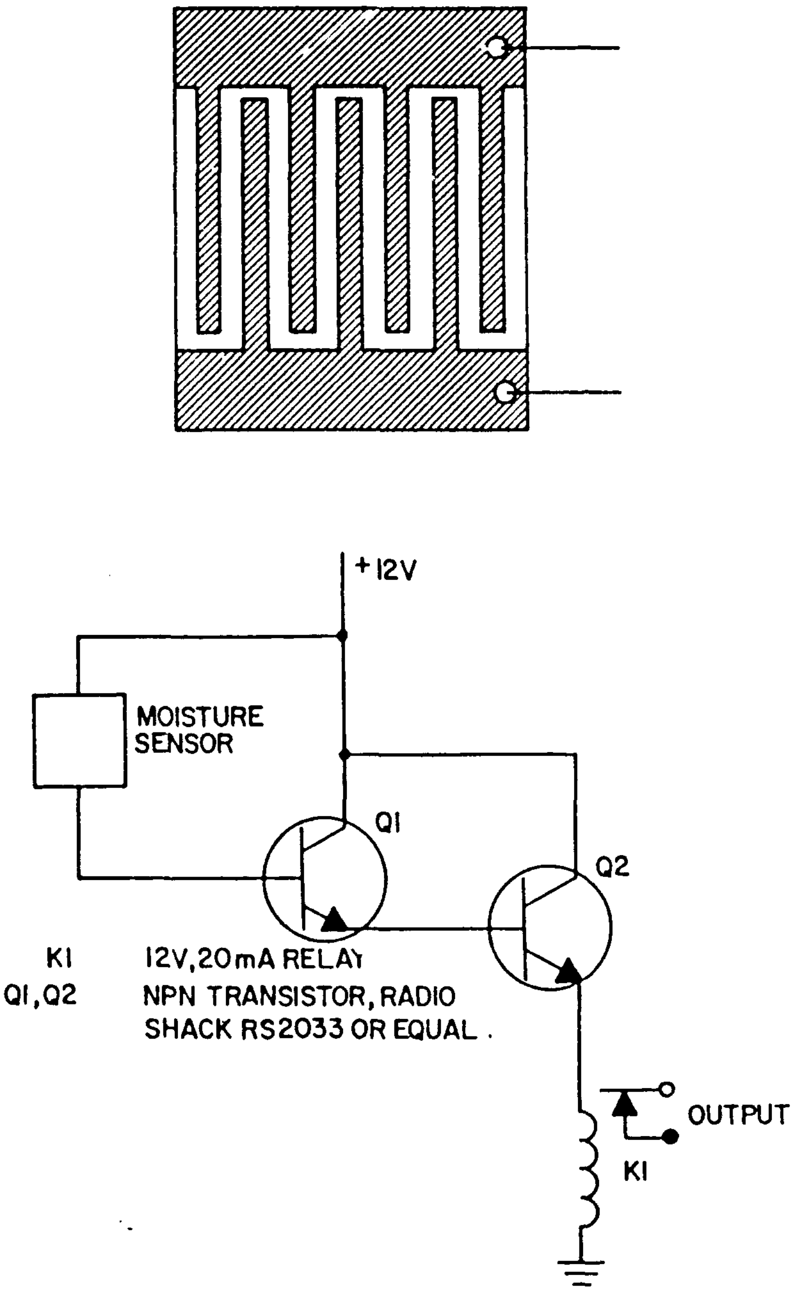


Figure 37 Moisture Sensor and Circuit

35°C (95°F). This value was adopted as the vehicle system alarm setpoint. Several intermediate levels were considered to provide warning of imminent overheating danger. These are shown in Table VI.

Table VI OVERHEATING DANGER LEVELS

Temperature	System Operating Level
70°F	No Overheating
80°F	Minimal Overheating
85°F	Moderate Overheating
90°F	High Overheating
93°F	Critical Overheating
94°F	System Overheating Alert
95°F	System Overheating Alarm
96°F	System Overheating Shutdown

c. ***Sensor Integration***

Sensor integration involved the development of a interface with the automatic control system and prioritization of signal information. This is accomplished using advanced D/A and A/D conversion boards.

(1) Signal Conversion. Data acquisition experience with AUV I suggested suitable electronic hardware for analog to digital sensor signal conversion. A Data Translation DT2821 series high speed analog and digital input/output board was selected to perform this function. The board accepts 16 channels of signal input with 12-bit

resolution [Ref. 41]. Two of these signals can be sampled by the microprocessor using DMA[18].

(2) Input Data Channel Assignment. Consultation with the other project participants helped define the signals needed for vehicle control. 18 signals were identified without having discussed the vehicle health sensor system. Since the DT2821 board could only accommodate 16 individual input lines, some technique had to be employed to combine inputs or a few of them would have to be eliminated. The propulsor speed sensors were considered to be the least critical to vehicle operation so they were in jeopardy.

A discussion of methods to combine the signals [Ref. 42] yielded a proposal to fabricate a secondary multiplexing circuit to be connected to one of the 16 DT2821 channels. The secondary circuit could receive 8 channels of input and convey their signals in a time sharing fashion to the DT2821 connection. Connecting the propulsor speed inputs to six of these would provide adequate monitoring and yield five spare channels. These unused lines were split between the two boards; two on the sub-mux circuit board and three on the DT2821 board. Figure 38 is a schematic showing this arrangement.

---

[18] Direct Memory Access.

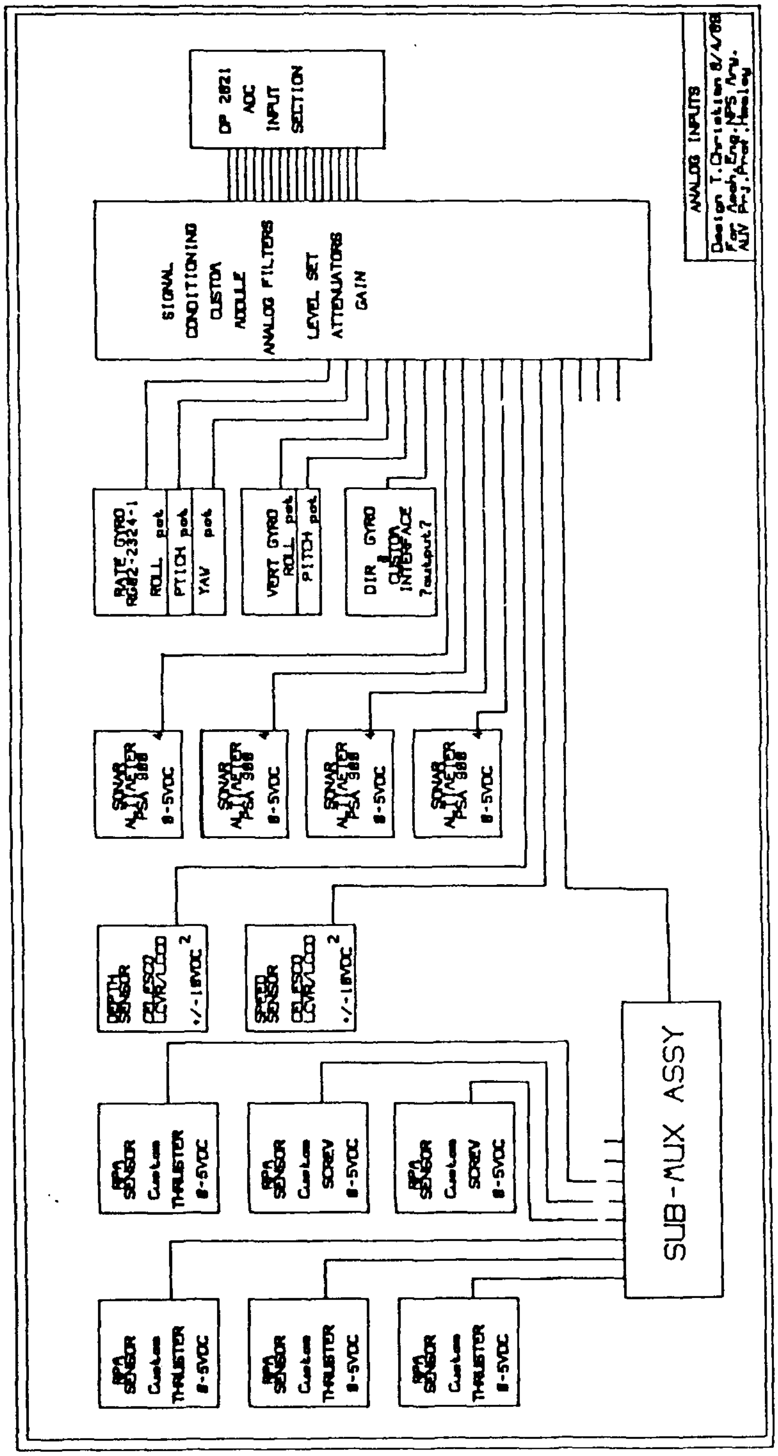


Figure 38 Sensor Inputs

(3) Future Expansion. The two spare channels on the sub-mux board are designated for connection to the vehicle health sensors mentioned previously. Future research is expected to utilize the three DT2821 channels for 3-axis accelerometer signal information. In order to accept a greater number of sensors beyond these additions, the integration process must be reinitiated and new hardware investigated.

H. Communications Link

A one way communications link was desired to provide the researcher with the opportunity to monitor data from the vehicle while it was operating in the pool. A fiber optic system employing lightly shielded cable seemed a good choice from the standpoint of low drag with reliability and convenient handling. A set of LeCroy high speed digital fiber optic communication chips were available, remnants of a prior project. The HLP/HPL118 circuit chips [Ref. 43] could provide up to 100 megabits per second in data transmission. This was above any requirement considered for the AUV II system. The chips were printed circuit board mountable and could interface with the RS-232 port of the computer. These components were offered for use with ample fiber optic cable, which could be configured for the AUV application by the technician.

IV. VEHICLE CONSTRUCTION

A. BODY

1. Hull

Once the aluminum lower hull and lid had been fabricated, two 0.5 inch thick pieces of aluminum bar stock were machined into porthole dividers having a T-shaped cross-section. These were fastened to span between the two lips at equal intervals along the flat midbody section with the base of the T facing up, toward the outside of the vehicle and flush with the hull. Figure 39 shows a close-up of the porthole divider.

Four 0.5 inch thick rectangular lexan panels were machined as flanged access covers to drop into the recesses provided by the dividers. A backing frame fabricated from 0.25 inch plate was installed from the inside of the hull to provide a sealing surface for the lexan panels. The angled tail section did not require installation of a divider, but did receive a backing frame. Figures 40, 41 and 42 provide views of the backing frame installations.

Besides being mechanically fastened, the aluminum hull pieces were bonded together using a compound commonly used to seal automobile windshields. Sealing of the clear lexan panels to the backing frames was achieved using a special

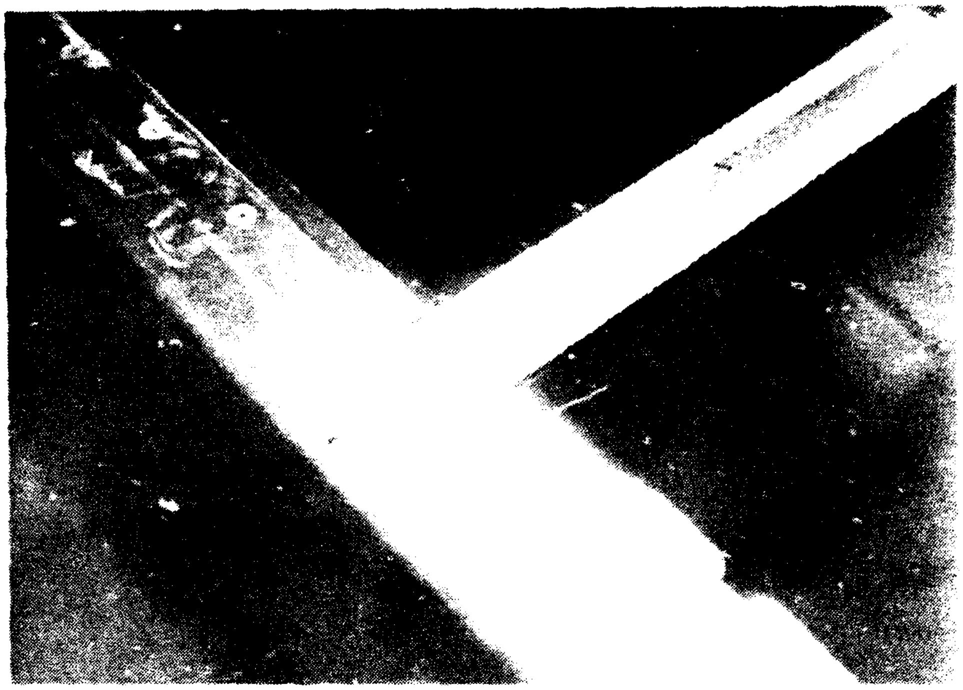


Figure 39 Porthole Divider Detail

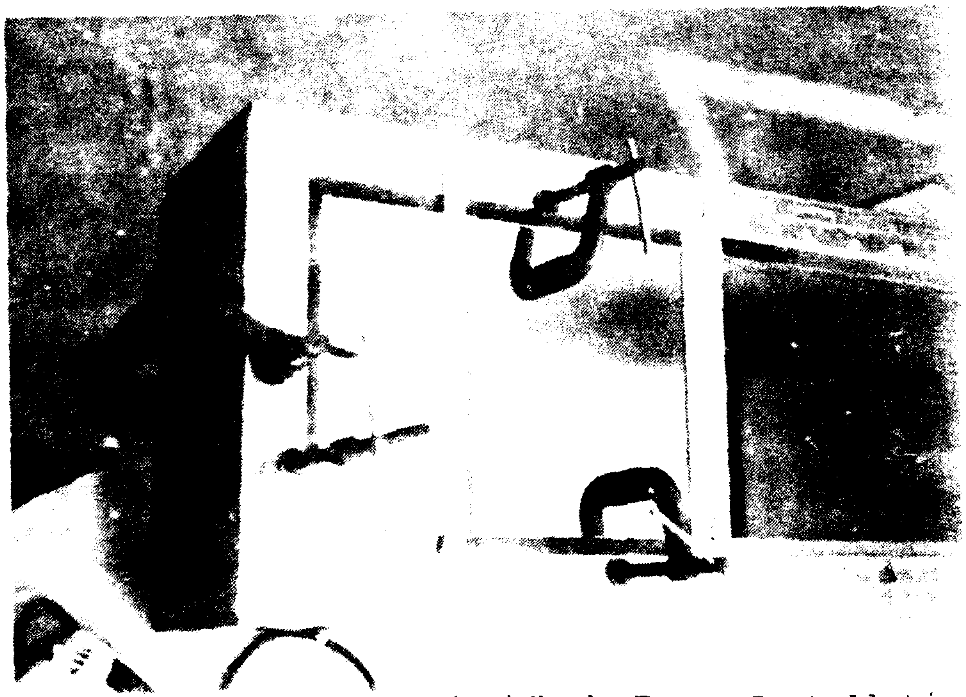


Figure 40 Forward Midbody Frame Installation

Figure 41 Tail Section Detail

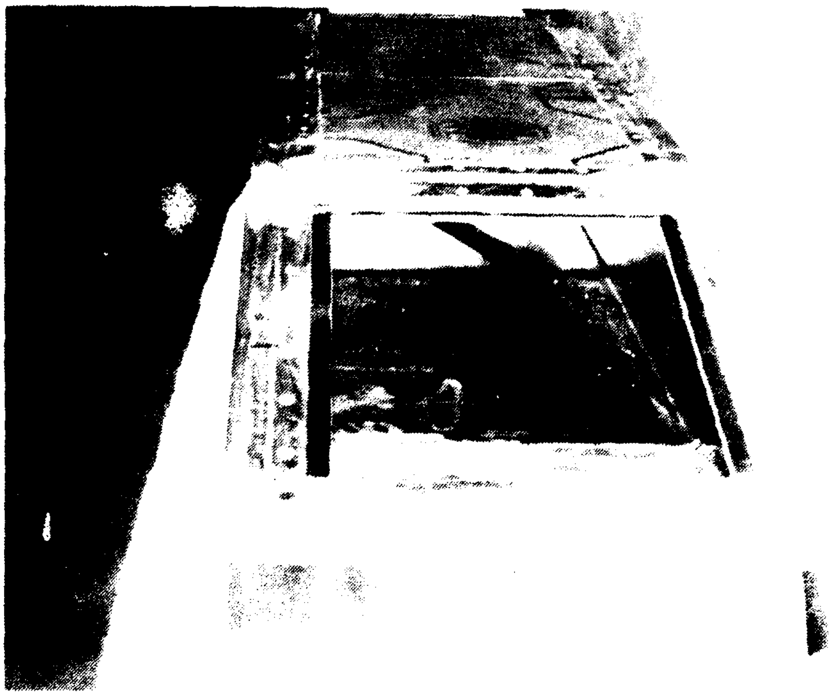


Figure 42 Lexan Panel Porthole Installation

putty supplied by NEODTC[19] where it is used for sealing an ROV[20]. This putty has a sticky consistency which does not degrade with exposure to air or water as others do. It can be peeled off, rolled in the hands and reapplied for sealing the panels.

2. Nose

The male mold for the nose was started as a series of thin plywood pieces glued to another centerline board, each one cut to form part of the ellipsoid shape. Figure 43 provides a glimpse of the framework at its early stage. Once the pieces had set, blue styrofoam was cut into small blocks and placed between the plywood framing pieces. The foam in the front half of the nose was roughly sanded to the desired ellipsoidal contour, as seen in Figure 44. The transition from the purely ellipsoidal shape at the tip of the nose to the rectangular base occurred aft of the middle section of the nose. In order to visualize the alteration in curvature, a string was attached to the tip of the male mold and stretched back along the ellipsoidal shape to the rectangular cut plywood shape fixed to the base. The gap resulting between the string and the ellipsoid shape was filled with smaller blocks of modeling foam and sanded until a three dimensional

---

[19] Naval Explosive Ordnance Disposal Training Center, Indian Head, Maryland.

[20] Putty was provided from a supply used for the PLUTO vehicle which underwent testing at NSWC-White Oak.

Figure 43 Plywood Mold Framework

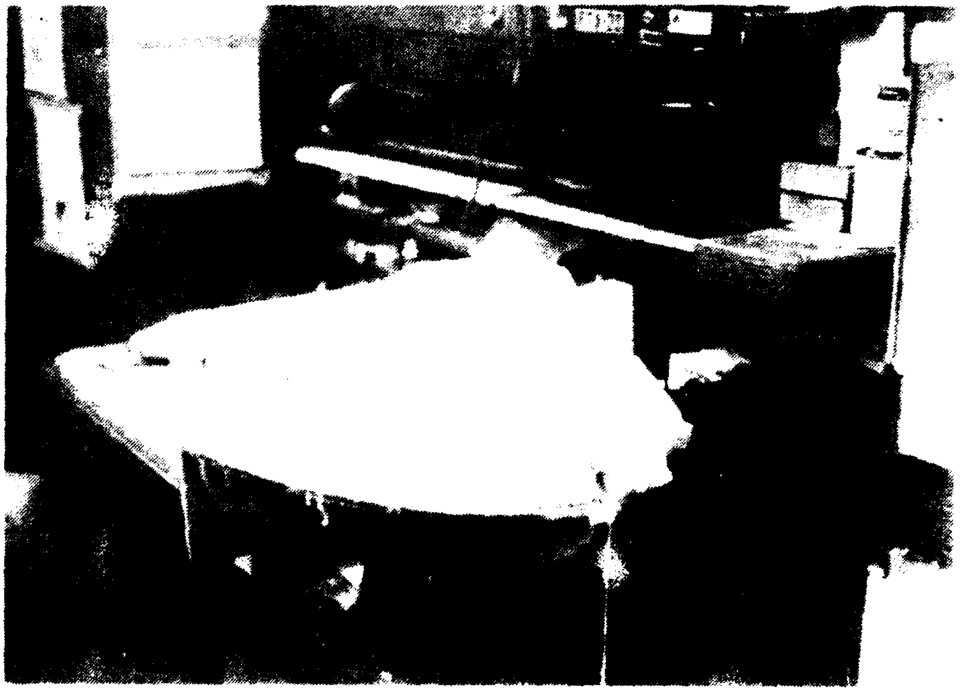


Figure 44 Rough Shaping of Styrofoam Blocks

male mold was achieved. An epoxy body filler like those used in auto body work was spread over the plywood and foam shape and sanded in several coats until a very smooth, consistent surface was obtained. The top half of the mold is shown at this stage in Figure 45.

Subsequent to finish sanding, the male mold for the nose was sprayed with a thick enamel paint to seal the porous surface of the body filler. The paint provided the smooth, shiny coating seen in Figure 46. After this coating had dried thoroughly, the mold was prepared for the application of fiberglass. Several coats of wax were applied to the smooth surface and a mold release agent was painted over the wax. When this had dried, 3 layers of fiberglass cloth were applied with an epoxy resin, smoothing out the residual epoxy constantly between layers. When the fiberglass had set, the nose shell was removed from the male mold. The shell had a thickness of approximately one tenth of an inch. Figures 47, 48 and 49 show the fiberglass nose shell after removal from the mold.

B. CONTROL SURFACES

A well known technique employed by composite aircraft builders was adopted for control surface fabrication [Ref. 44]. The wing shape was cut from styrofoam with a hotwire to the desired shape, mounted on a shaft, and covered with a layer of fiberglass to provide strength and

Figure 45 Creating a Smooth Surface With Body Filler

Figure 46 Nose After Sealing Coat

Figure 47 Fiberglass Nose

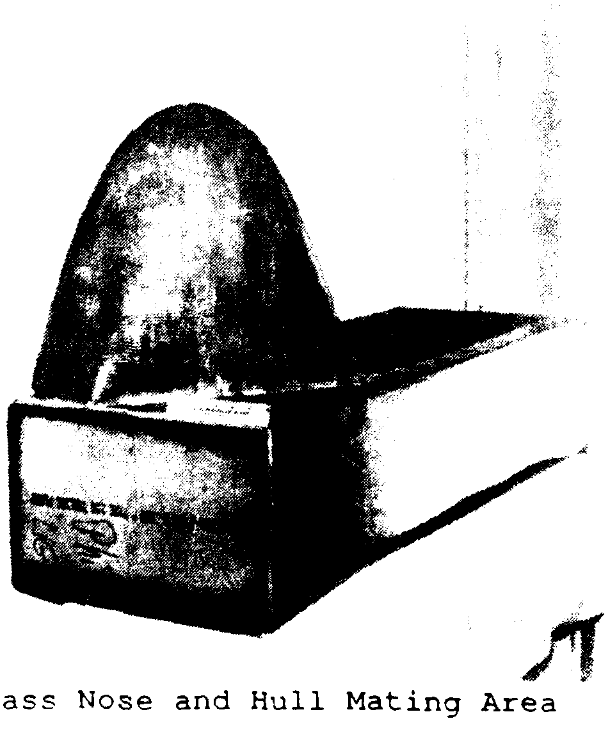


Figure 48 Fiberglass Nose and Hull Mating Area

Figure 49 View of Fiberglass Nose Interior

stiffness. In order to closely match the design shape of the control surfaces, Aluminum guide plates were machined in the shape of the NACA 0015 foil section and mounted to the ends of a block of blue styrofoam[21] cut to the correct span dimension. The block was slightly long in the chordwise dimension to make the cutting operation easier.

A foam cutting frame strung with a nichrome wire was used to create the wing shape. The wire is heated by an electrical current which is adjusted with a hand operated voltage controller. The hotwire apparatus easily melts through the styrofoam to produce a smooth contour between the aluminum guide pieces. Figure 50 shows the hotwire procedure followed

---

[21] Low Density (2 lb/ft^3).

for control surface fabrication. Figure 51 is a representative control surface produced by this method.

In order to accommodate the spanwise taper of the foil shape selected, the servo actuator shaft was machined with a 4.7 degree taper. The shaft would be cemented into the wing shape using an epoxy cement. To ensure that the shaft would not break loose under torque loading, three cross members were inserted into holes drilled through the shaft and silver soldered to it, as seen in Figure 52.

C. **ELECTRICAL / ELECTRONIC**

Circuit card organization and fabrication required a great amount of detailed design which was accomplished by the M.E. Electronics Technician. The fabrication drawings for the

Figure 50 Close-up of Hotwire Procedure

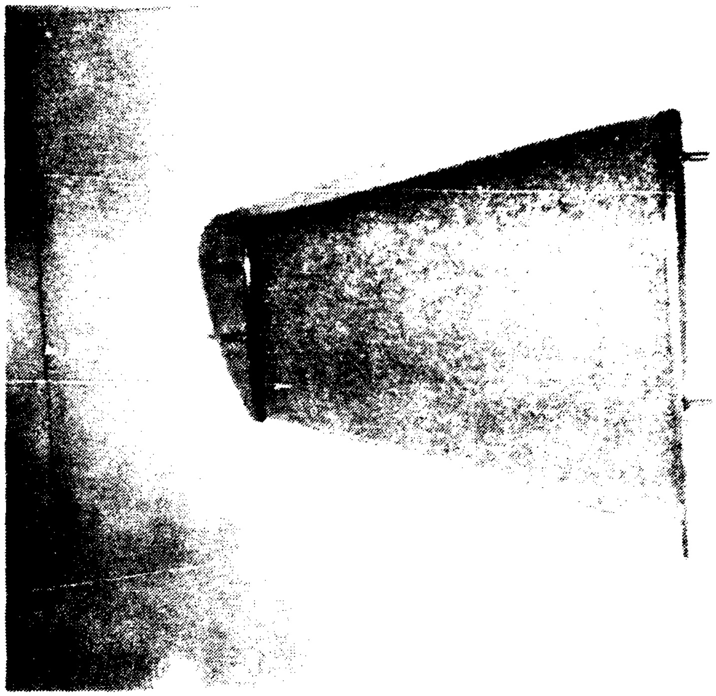


Figure 51 Control Surface After Hotwire Cutting

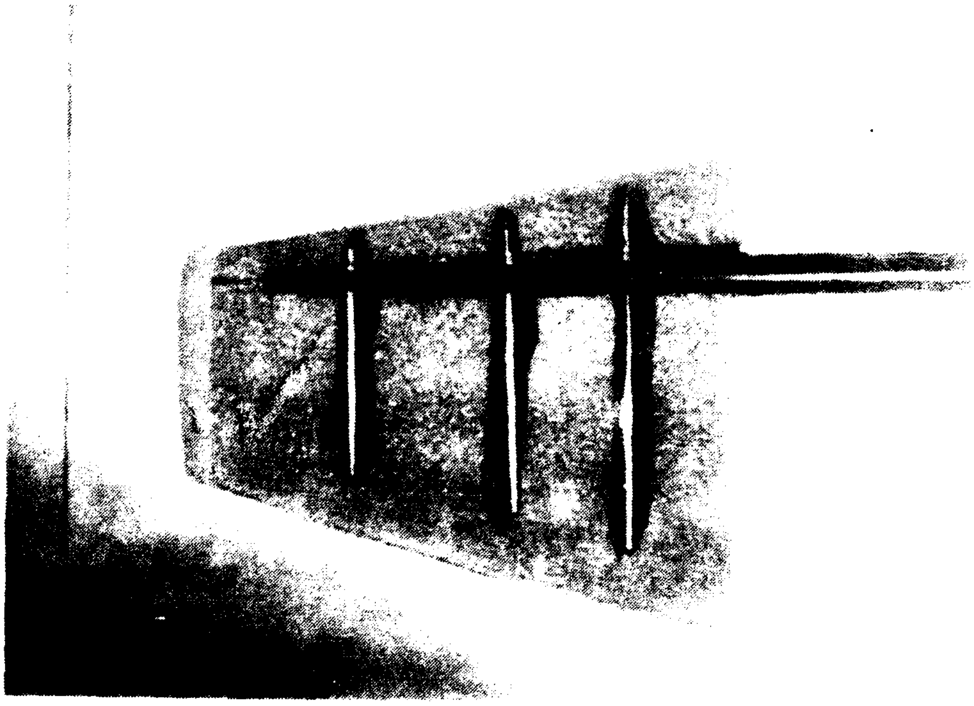


Figure 52 Control Surface with Shaft in Place

printed circuit cards to be installed in AUV II are included in Appendix B.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This work has presented a general procedure for designing an Autonomous Underwater Vehicle and has documented the detail design of one for a specific mission. The Naval Postgraduate School AUV II will be used as a testbed to demonstrate autonomous operation at a simple level within the confined environment of a pool. Several conclusions follow from this design effort:

1. The design has many elements of similarity to a submarine case, but there is more emphasis on maneuvering and the automation of controls.
2. There is no "cookbook" available, therefore the design relied heavily on fundamental engineering principles and ingenuity.
3. All of the systems integration issues in Total Ship Systems Engineering are present, even with this small sized vehicle.
4. There is every reason to believe that the AUV II design will work and meet the requirements as conceived.

B. RECOMMENDATIONS

Continuing research is recommended as described in the following:

1. Investigate maneuvering control schemes for AUV II which employ propulsors and control surfaces. Four thrusters are intended for hovering, while the eight control surfaces will operate while the vehicle is driven by the

two stern propellers. An area of particular interest is the transition stage between cruising and hovering.

2. Investigate and characterize the flow in the vicinity of the Kort nozzles used with stern propellers in AUV II. Kort nozzles are used to enhance low speed thrust for the vehicle, but modeling and vehicle testing is needed to identify performance aspects important to vehicle propulsion control.

3. Establish requirements for the AUV II sonar system, signal processing techniques and data storage capability as defined by the variety of missions envisioned for AUV II. Obstacle avoidance, object search and acoustic imaging of an object are a few of the specific mission related tasks which involve the sonar system.

4. Optimize the installation of sonar transducers in the free flooded nose of AUV II while meeting structural and mission requirements.

5. Investigate and implement modifications required to the PSA-900 sonar altimeter units used in AUV II in order to optimize their use for mission related tasks. The equipment operating frequency, time varying gain circuit and beamforming should be examined in addition to the use of raw sonar data.

6. Develop a versatile handling system for AUV II that will enable the research team to transport it to and from its operating site and stow it between tests. A design must take special consideration of appendages such as the control surfaces and stern propulsors in addition to the fiberglass nose which houses sensors. On site maintenance and repair must be facilitated as well as easy vehicle launch and recovery.

LIST OF REFERENCES

1. Healey, A.J., and others, "Navigation, Path Planning, Dynamics and Control of Generic Autonomous Underwater Vehicles" Research Proposal to NSWC for work under the Naval Postgraduate School Direct Research Fund, April 1988.

2. MacDonald, G.S., *Model Based Design and Verification of a Rapid Dive Controller for an Autonomous Underwater Vehicle,* Master of Science and Mechanical Engineer Thesis, Naval Postgraduate School, Monterey, California, March 1988.

3. Sur, J.N., *Design of a Dive Plane Sliding Mode Compensator,* Master of Science Thesis, Naval Postgraduate School, Monterey, California, July 1989.

4. Boncal, R.J., *A Study of Model Based Maneuvering Controls for Autonomous Underwater Vehicles,* Master of Science Thesis, Naval Postgraduate School, Monterey, California, December 1987.

5. Larsen, K.P., *Reduced Hydrodynamic Modeling for a Submersible Vehicle,* Master of Science Thesis, Naval Postgraduate School, Monterey, California, September 1988.

6. Brunner, G.M., *Experimental Verification of AUV Performance,* Master of Science and Mechanical Engineer Thesis, Naval Postgraduate School, Monterey, California, March 1988.

7. Gill, S.S., *The Stress Analysis of Pressure Vessels and Pressure Vessel Components,* Pergamon Press, 1970.

8. Timoshenko, S.P., Gere, J.M., *Theory of Elastic Stability* 2d ed., McGraw-Hill Book Company, 1961.

9. Sedor, Gerald, *A Conceptual Design of a Propulsion Plant for an Autonomous Underwater Vehicle,* Ph.D. Dissertation, Marine Systems Laboratory, University of New Hampshire, 1989.

10. David Taylor Research Center Report DTNSRDC-79/097, *An Inventory of Some Force Producers for Use in Marine*

Vehicle Control, by M.B. Wilson, and C. Von-Kerczek, November 1979.

11. Kanayama, Y., and others, "A Stable Tracking Control Method for an Autonomous Mobile Robot," paper submitted to IEEE Conference on Robotics and Automation, 1990.

12. Kanayama, Y., and Hartman, B.I., "Smooth Local Path Planning for Autonomous Vehicles," Proceedings of IEEE International Conference on Robotics and Automation, pp. 1265-1269, 14-19 May 1989.

13. McPherson, D.L., *A Computer Simulation Study of Rule-Based Control of an Autonomous Underwater Vehicle*, Master of Science Thesis, Naval Postgraduate School, Monterey, California, June 1988.

14. Naval Postgraduate School Report NPS 52-89-035, *A Computer Simulation Study of Mission Planning and Control for the NPS Autonomous Underwater Vehicle*, by D.B. Nordman, June 1989.

15. Rogers, R.C., *A Study of 3-D Visualization and Mission Planning and Control for the NPS Model 2 Autonomous Underwater Vehicle*, Master of Science Thesis, Naval Postgraduate School, Monterey, California, December 1989.

16. *1989 Catalog*, pp. 21-26, p.29, Aircraft Spruce and Specialty Company, 1989.

17. Interview between J. Selby, Progress Aero R&D Inc., Monterey, California, and the author, 10 March 1989.

18. Interview between T.R. McNelley, PhD, Professor of Materials Science, Naval Postgraduate School, Monterey, California, and the author, 9 June 1989.

19. Interview between M. Coury, Gabilan Iron and Machine Company, Salinas, California, and the author, 16 June 1989.

20. Young, W.C., *Roark's Formulas for Stress and Strain*, 6th ed., McGraw-Hill Book Company, 1989.

21. Nicholls, R., *Composite Construction Materials Handbook*, pp. 373-388, Prentice-Hall Inc., 1976.

22. Catherall, J.A., *Fibre Reinforcement*, pp. 30-35, 55-58, Mills & Boon Limited, 1973.

23. Interview between E.M. Wu, PhD, Professor of Aeronautics, Naval Postgraduate School, Monterey, California, and the author, 6 October, 1989.

24. Reid, G.N., "Acoustic Considerations for the AUV II Nose," paper discussed in AUV II construction issues meeting, Naval Postgraduate School, Monterey, California, 20 October 1989.

25. Hoerner, S.F., *Fluid-Dynamic Drag*, by the author, Midland Park, NJ, 1965.

26. Rawson, K.J., and Tupper, E.C., *Basic Ship Theory*, v. 2, p. 491, Longman Group Limited, 1976.

27. *Principles of Naval Architecture*, J.P. Comstock, Ed., The Society of Naval Architects and Marine Engineers, Chapter VIII, pp. 463-606, 1967.

28. David Taylor Model Basin Report 933, *Free Stream Characteristics of a Family of Low Aspect Ratio Control Surfaces*, by L.F. Whicker and L.F. Fehlner, May 1958.

29. Landsburg, A.C., and others, "Design and Verification for Adequate Ship Maneuverability," SNAME Transactions, v. 91, pp. 351-401, 1983.

30. Jackson, H.A., "Submarine Design Trends," Course Notes, Professional Summer at MIT, Charles Stark Draper Laboratory, Inc.

31. Saunders, H.E., *Hydrodynamics in Ship Design*, v. 3, p. 122, The Society of Naval Architects and Marine Engineers, 1965.

32. Saunders, T.E., Master of Science Thesis, Naval Postgraduate School, Monterey, California, March 1990, forthcoming.

33. Cloutier, M., Master of Science Thesis, Naval Postgraduate School, Monterey, California, 1990, forthcoming.

34. Lorhammer, D.N., *An Experimental Study of an Acoustic Ranging System for AUV Obstacle Avoidance*, Master of Science Thesis, Naval Postgraduate School, Monterey, California, September 1989.

35. Humphrey Incorporated, *Summary Catalog*, 1988.

36. Magnetic Shield Corporation, Perfection Mica Company, *Shielding Products Catalog*, 1989.

37. Celesco Transducer Products Inc., *Celesco VR Series Literature*, September 1983.

38. Interview between D. Richard Blidberg, Marine Systems Engineering Laboratory, University of New Hampshire, Durham, NH, and the author, 17 March 1989.

39. Cunningham, J.E., *Handbook of Remote Control & Automation Techniques*, pp. 48-49, Tab Books Inc., 1979.

40. GRiD Systems Corporation, *GRiDCASE 1535 EXP Technical Specifications*, 1988.

41. Data Translation Inc., *Data Acquisition Hardware Catalog*, pp. 8.12-8.13, 1988.

42. Interview between T. Christian, Electronics Technician, Mechanical Engineering Department, Naval Postgraduate School, Monterey, California, and the author, 14 July 1989.

43. LeCroy Corporation, *High Speed Digital Fiber Optic Link Product Literature*, 1989.

44. Interview between J. Selby, Progress Aero R&D Inc., Monterey, California, and the author, 17 October 1989.

APPENDIX A

SUBCALC PROGRAM INFORMATION

THIS FORTRAN PROGRAM IS WRITTEN AS AN AID TO PRELIMINARY DESIGN OF UNDERWATER VEHICLES. BY INPUTTING INFORMATION ABOUT HULL GEOMETRY (NOSE, MIDBODY & TAIL) AND UP TO 50 PIECES OF INTERNAL EQUIPMENT (WEIGHTS & THEIR RESPECTIVE XYZ LOCATIONS), THE USER CAN GAIN A SENSE OF THE PHYSICAL PARAMETERS ASSOCIATED WITH A GIVEN CONFIGURATION. IT IS POSSIBLE TO EXAMINE THE EFFECT OF EQUIPMENT PLACEMENT ON OVERALL VEHICLE CENTER OF GRAVITY BY TRYING DIFFERENT CONFIGURATIONS WITHIN THE SAME HULL FORM. IN ADDITION, THE USER CAN RETURN TO THE EQUIPMENT MENU AND ADD BALLAST WEIGHTS TO BRING THE VEHICLE'S CENTER OF GRAVITY AND RESERVE BUOYANCY INTO A DESIRED RANGE.

IT IS HOPED THAT THIS PROGRAM WILL ASSIST THE NAVAL POSTGRADUATE SCHOOL AUTONOMOUS UNDERWATER VEHICLE (AUV) PROJECT IN THE COMPLETION THE SECOND VEHICLE AND WILL ALSO SERVE AS A STARTING POINT FOR ANY FUTURE VEHICLE DEVELOPMENT.

THE FOLLOWING DOCUMENTATION IS PROVIDED AS A GUIDE TO THE USE OF THE SUBCALC PROGRAM. IT IS HOPED THAT IT HAS ADEQUATE DETAIL FOR THE DESIGNER WITHOUT BECOMING A PROTRACTED EXPLANATION OF THE MECHANICS OF THE PROGRAM.

BEGINNING THE PROGRAM

PLACE THE PROGRAM DISK IN YOUR COMPUTER DISK DRIVE AND ENTER **SUBCALC** AT THE PROMPT.

THE FIRST DECISION TO MAKE IS:

```
'WHAT TYPE OF WATER WILL VEHICLE OPERATE IN ?'
'ENTER (1) FOR FRESH WATER, (2) FOR SALTWATER '
```

THE PROGRAM ASSUMES THE FOLLOWING SPECIFIC GRAVITIES:

FOR FRESH WATER: RHOG = 62.41756
FOR SEA WATER: RHOG = 64.02626

DESIGNING THE HULL FORM

THE SECOND PHASE OF THE PROGRAM WILL ASK YOU TO:

```
'INPUT HULL PARAMETERS, SELECTING VALUES FROM MENUS'
```

THIS PROCESS WILL BE DIVIDED INTO THREE MAJOR STEPS. THE HULL WILL BE CONSIDERED AS BEING MADE UP OF A NOSE, MIDBODY AND TAIL, OR ANY COMBINATION OF THE INDIVIDUAL SECTIONS. IN OTHER WORDS, YOU CAN INPUT ALL THREE SECTIONS OR ONLY A NOSE AND TAIL OR ONLY A MIDBODY, FOR EXAMPLE. HEREIN LIES SOME HULL DESIGN FLEXIBILITY.

THE DESIGN IS THE PRODUCT OF THE USER, AND AS SUCH THE USER MUST ENSURE THAT THE SELECTIONS MADE WILL MAKE SENSE AND FAIRLY ACCURATELY REPRESENT THE TRUE VEHICLE. SUCH THINGS AS COMBINING A HEMISPHERICAL NOSE WITH A SQUARE CROSS-SECTION MIDBODY CAN BE INPUT, BUT MAY NOT BE A GOOD DESIGN IF HYDRODYNAMICS ARE IMPORTANT. BESIDES, THE DESIGNER MUST CONSIDER HOW TO JOIN THESE TWO SHAPES AT THEIR MATING PLANE. PERHAPS A SPECIALIZED BULKHEAD COULD BE USED, BUT THEN THAT WILL ADD TO VEHICLE WEIGHT AND COMPLICATE THE STRUCTURAL PROBLEM. THAT'S PROBABLY ENOUGH DISCUSSION ON YOUR RESPONSIBILITY IN DESIGN. THE KEY WORD HERE IS "TOOL". SUBCALC WILL BE A HELPFUL TOOL IF USED INTELLIGENTLY.

NOSE

YOU BEGIN INPUTTING THE HULL FORM WITH THE NOSE. THE PROGRAM WILL PROMPT YOU WITH:

```
'SELECT NOSE SHAPE FROM MENU'

     '0. NO "NOSE" DISCERNABLE FROM MID-BODY'
     '1. CONICAL'
     '2. WEDGE'
     '3. HEMISPHERE'
     '4. PARABOLOID'
     '5. PYRAMID'
```

YOU ENTER THE APPROPRIATE NUMBER AND HIT THE RETURN KEY. THIS IS FOLLOWED BY :

```
'ENTER NOSE HULL THICKNESS IN DECIMAL INCHES'
```

AND

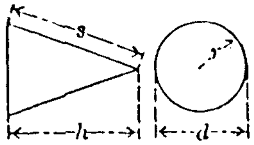
```
'SELECT NOSE MATERIAL FROM MENU'

'   MATERIAL            SPECIFIC WT (LB/FT^3)'

'1. FIBERGLASS               75'
'2. PLASTIC - NYLON          70'
'3. ALUMINUM  ALLOY         175'
'4. MAGNESIUM ALLOY         112'
'5. STEEL                   490'
'6. TITANIUM                280'
'7. CUSTOM MATERIAL'
```

AGAIN, ENTER THE APPROPRIATE NUMBER. IF YOU INPUT A 7, YOU WILL SEE ANOTHER QUESTION:

```
'ENTER SPECIFIC WEIGHT OF CUSTOM MATL IN LB/FT^3'
```

HERE YOU MUST INPUT THE SPECIFIC WEIGHT OF YOUR PARTICULAR MATERIAL WHICH DIFFERS FROM THOSE AVAILABLE IN THE MENU.

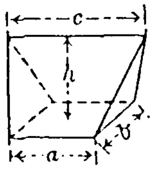
NOW WE BEGIN ENTERING HULL GEOMETRY FOR THE CHOSEN NOSE SHAPE. THE FOLLOWING SUMMARY WILL SHOW A DRAWING OF THE SHAPE AND CORRESPONDING DIMENSIONS.



Cone

'FOR A CONICAL NOSE SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "R" IN DECIMAL INCHES'



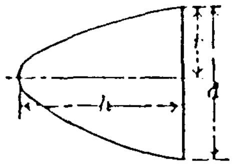
Wedge

'FOR A WEDGE-SHAPED NOSE SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "A" IN DECIMAL INCHES'
'ENTER DIMENSION "B" IN DECIMAL INCHES'
'ENTER DIMENSION "C" IN DECIMAL INCHES'

Hemisphere

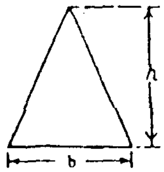
'FOR A HEMISPHERICAL NOSE SECTION'
'ENTER DIMENSION "R" IN DECIMAL INCHES'



Paraboloid

'FOR A PARABOLOID NOSE SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "R" IN DECIMAL INCHES'



Pyramid

'FOR A PYRAMID-SHAPED NOSE SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "B" OF SQUARE BASE
IN DECIMAL INCHES'

MIDBODY

NOW THAT YOU HAVE COMPLETED THE NOSE SELECTION, THE PROGRAM CONTINUES ON TO THE MIDBODY SECTION, PROMPTING YOU TO:

```
'SELECT MID-BODY SHAPE FROM MENU'

     0. NO DISTINCT MID-BODY'
     1. SPHERE'
     2. ELLIPSOID'
     3. CYLINDRICAL-PARALLEL BODY'
     4. CYLINDRICAL-BARREL BODY'
     5. SQUARE CROSS-SECTION "BOX" '
     6. RECTANGULAR CROSS-SECTION "BOX" '
```

YOU ENTER THE APPROPRIATE NUMBER AND HIT THE RETURN KEY.
THIS IS FOLLOWED BY :

```
'ENTER MID-BODY HULL THICKNESS IN DECIMAL INCHES'
```

AND

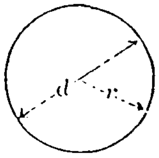
```
'SELECT MID-BODY MATERIAL FROM MENU'

'   MATERIAL            SPECIFIC WT (LB/FT^3)'

'1. FIBERGLASS                75'
'2. PLASTIC - NYLON           70'
'3. ALUMINUM  ALLOY          175'
'4. MAGNESIUM ALLOY          112'
'5. STEEL                    490'
'6. TITANIUM                 280'
'7. CUSTOM MATERIAL'
```

AGAIN, ENTER THE APPROPRIATE NUMBER. IF YOU INPUT A 7, YOU WILL SEE ANOTHER QUESTION:

```
'ENTER SPECIFIC WEIGHT OF CUSTOM MATL IN LB/FT^3'
```

HERE YOU MUST INPUT THE SPECIFIC WEIGHT OF YOUR PARTICULAR MATERIAL WHICH DIFFERS FROM THOSE AVAILABLE IN THE MENU.

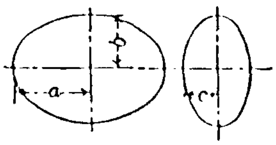
NOW WE BEGIN ENTERING HULL GEOMETRY FOR THE CHOSEN MIDBODY SHAPE. THE FOLLOWING SUMMARY WILL SHOW A DRAWING OF THE SHAPE AND CORRESPONDING DIMENSIONS.



Sphere

'FOR A SPHERICAL MIDBODY SECTION'

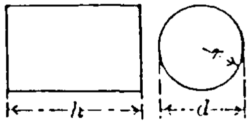
'ENTER DIMENSION "R" IN DECIMAL INCHES'



Ellipsoid

'FOR A ELLIPSOIDAL MIDBODY SECTION'

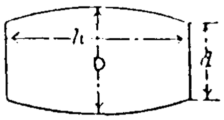
'ENTER DIMENSION "A" IN DECIMAL INCHES'
'ENTER DIMENSION "B" IN DECIMAL INCHES'
'ENTER DIMENSION "C" IN DECIMAL INCHES'



Cylinder

'FOR A PARALLEL-SIDED CYLINDRICAL MIDBODY SECTION'

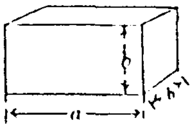
'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "R" IN DECIMAL INCHES'



Barrel

'FOR A BARREL-SIDED CYLINDRICAL MIDBODY SECTION

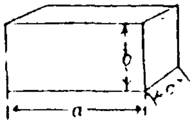
'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "DMID" IN DECIMAL INCHES'
'ENTER DIMENSION "DEND" IN DECIMAL INCHES'



Square Prism

'FOR A SQUARE CROSS-SECTION MIDBODY'

'ENTER LENGTH "A" IN DECIMAL INCHES'
'ENTER DIMENSION "B" IN DECIMAL INCHES'



Rectangular Prism

'FOR A RECTANGULAR CROSS-SECTION MIDBODY'
'ENTER LENGTH "A" IN DECIMAL INCHES'
'ENTER DIMENSION "B" IN DECIMAL INCHES'
'ENTER DIMENSION "C" IN DECIMAL INCHES'

TAIL

NOW THAT YOU HAVE COMPLETED THE MIDBODY SELECTION, THE PROGRAM CONTINUES ON TO THE TAIL SECTION, PROMPTING YOU TO:

```
'SELECT TAIL SHAPE FROM MENU'

     '0. NO "TAIL" DISCERNABLE FROM MID-BODY'
     '1. CONICAL'
     '2. FRUSTRUM OF A CONE'
     '3. PYRAMID'
     '4. WEDGE'
     '5. HEMISPHERE'
     '6. PARABOLOID'
```

YOU ENTER THE APPROPRIATE NUMBER AND HIT THE RETURN KEY. THIS IS FOLLOWED BY :

```
'ENTER TAIL HULL THICKNESS IN DECIMAL INCHES'
```

AND

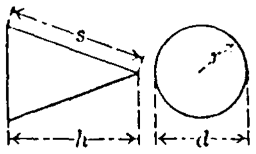
```
'SELECT TAIL MATERIAL FROM MENU'

'   MATERIAL            SPECIFIC WT (LB/FT^3)'

'1. FIBERGLASS               75'
'2. PLASTIC - NYLON          70'
'3. ALUMINUM  ALLOY         175'
'4. MAGNESIUM ALLOY         112'
'5. STEEL                   490'
'6. TITANIUM                280'
'7. CUSTOM MATERIAL'
```

AGAIN, ENTER THE APPROPRIATE NUMBER. IF YOU INPUT A 7, YOU WILL SEE ANOTHER QUESTION:

```
'ENTER SPECIFIC WEIGHT OF CUSTOM MATL IN LB/FT^3'
```

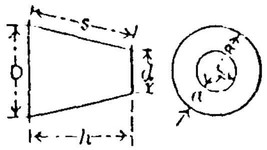
HERE YOU MUST INPUT THE SPECIFIC WEIGHT OF YOUR PARTICULAR MATERIAL WHICH DIFFERS FROM THOSE AVAILABLE IN THE MENU.

NOW WE BEGIN ENTERING HULL GEOMETRY FOR THE CHOSEN TAIL SHAPE. THE FOLLOWING SUMMARY WILL SHOW A DRAWING OF THE SHAPE AND CORRESPONDING DIMENSIONS.



Cone

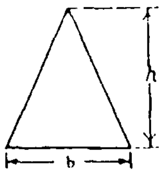
'FOR A CONICAL TAIL SECTION'
'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "R" IN DECIMAL INCHES'



Frustum of Cone

'FOR A FRUSTUM OF A CONE SHAPED TAIL SECTION'

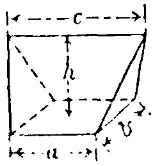
'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "DBASE" IN DECIMAL INCHES
'ENTER DIMENSION "DEND" IN DECIMAL INCHES



Pyramid

'FOR A PYRAMID-SHAPE (SQUARE BASE) TAIL SECTION

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER BASE LENGTH "B" IN DECIMAL INCHES'



Wedge

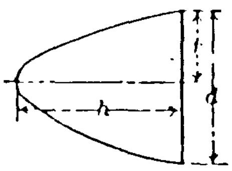
'FOR A WEDGE-SHAPED TAIL SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "A" IN DECIMAL INCHES'
'ENTER DIMENSION "B" IN DECIMAL INCHES'
'ENTER DIMENSION "C" IN DECIMAL INCHES'

Hemisphere

'FOR A HEMISPHERICAL TAIL SECTION'

'ENTER DIMENSION "R" IN DECIMAL INCHES'



Paraboloid

'FOR A PARABOLOID TAIL SECTION'

'ENTER DIMENSION "H" IN DECIMAL INCHES'
'ENTER DIMENSION "R" IN DECIMAL INCHES'

ADDING EQUIPMENT TO THE HULL

NOW THAT THE HULL FORM HAS BEEN SPECIFIED, INTERNAL AND EXTERNAL EQUIPMENT MAY BE ADDED TO IT TO EXAMINE THE EFFECT OF SUCH ADDITIONS TO CENTER OF GRAVITY AND BUOYANCY. YOU ARE QUERIED WITH:

'DO YOU WANT TO EVALUATE EFFECT OF INTERNAL EQUIPMENT?'

AT THIS POINT YOU CAN ENTER A (0) AND OBSERVE A DISPLAY OF THE COMPOSITE RESULTS OF THE VEHICLE HULL. AN EXAMPLE OF THIS DISPLAY IS SHOWN LATER. OTHERWISE, YOU CONTINUE:

'IF YES, ENTER A (1) AND PREPARE TO INPUT WEIGHT, (XYZ) LOCATION'

THE PROGRAM IS WRITTEN TO ACCEPT A NOMINAL NUMBER OF PIECES OF EQUIPMENT OR BALLAST:

'THE PROGRAM WILL ALLOW YOU TO INPUT UP TO 50 ITEMS'
'HOW MANY ITEMS DO YOU WISH TO INPUT?'

IF YOUR ANALYSIS REQUIRES THE CAPABILITY TO ACCEPT MORE ITEMS, YOU MUST ALTER THE SOURCE CODE **SUBCALC.FOR** IN SEVERAL PLACES AND COMPILE YOUR NEW VERSION FOR USE.

IT IS IMPORTANT THAT YOU INPUT ALL THE REQUIRED DATA IN THE CORRECT ORDER AND QUANTITIES:

'ENTER ITEMS IN THE FORMAT: (WT, X, Y, Z)'

'WEIGHT IN LBS'

'X POSITION IN INCHES FROM THE TIP OF VEHICLE NOSE'

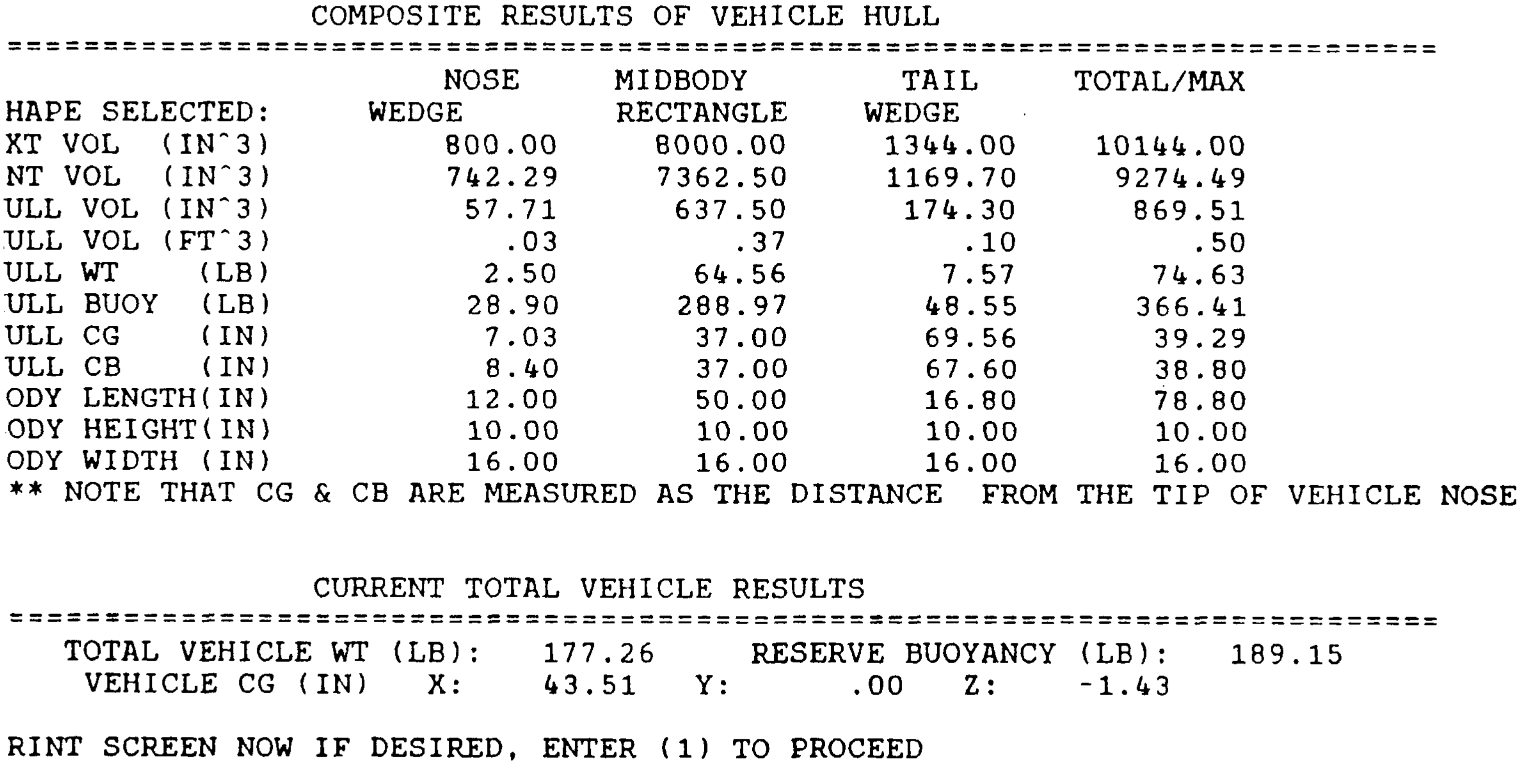
'Y POSITION IN INCHES STBD(+) OR PORT(-) FROM CENTERLINE OF VEHICLE

'Z POSITION IN INCHES ABOVE(+) OR BELOW(-) THE VEHICLE CENTERLINE'

AFTER EACH PIECE OF EQUIPMENT OF BALLAST IS INPUT, THE PROGRAM WILL RESPOND WITH THE ADDITIVE RESULT OF THAT PIECE:

'CURRENT VEHICLE CG (X,Y,Z):', VCGX, VCGY, VCGZ

WHEN YOU HAVE INPUT THE NUMBER OF ITEMS YOU SPECIFIED EARLIER, THE PROGRAM WILL PROVIDE THE SAME COMPOSITE RESULTS SUMMARY FOR THE VEHICLE HULL MENTIONED BEFORE (IF YOU HAD BYPASSED THIS EQUIPMENT SECTION). IN ADDITION, TOTAL RESULTS WILL INCLUDE THE EFFECT OF THE EQUIPMENT INPUT IN THIS SECTION. THIS INFORMATION WILL BE SPECIFICALLY TAILORED TO YOUR INPUT CHOICES AND CAN SERVE AS A USEFUL RECORD OF YOUR SUBCALC RUN. THE SHAPE SELECTED ROW AND THE BODY LENGTH, HEIGHT AND WIDTH INFORMATION ARE DIRECTLY RELATED TO YOUR INPUT GEOMETRY, BUT IT DID NOT SEEM PRACTICAL IN THIS FIRST VERSION TO INCLUDE AN EXTENSIVE RECORD OF ALL THE INPUT GEOMETRY FOR EACH COMPLEX SHAPE. PERHAPS IT MAY BE INCORPORATED IN THE FUTURE. THE OUTPUT WILL LOOK LIKE THIS:



```
                    COMPOSITE RESULTS OF VEHICLE HULL
==========================================================================
                          NOSE        MIDBODY        TAIL       TOTAL/MAX
HAPE SELECTED:         WEDGE         RECTANGLE      WEDGE
XT VOL   (IN^3)           800.00       8000.00      1344.00     10144.00
NT VOL   (IN^3)           742.29       7362.50      1169.70      9274.49
ULL VOL  (IN^3)            57.71        637.50       174.30       869.51
ULL VOL  (FT^3)              .03           .37          .10          .50
ULL WT     (LB)             2.50         64.56         7.57        74.63
ULL BUOY   (LB)            28.90        288.97        48.55       366.41
ULL CG     (IN)             7.03         37.00        69.56        39.29
ULL CB     (IN)             8.40         37.00        67.60        38.80
ODY LENGTH(IN)             12.00         50.00        16.80        78.80
ODY HEIGHT(IN)             10.00         10.00        10.00        10.00
ODY WIDTH (IN)             16.00         16.00        16.00        16.00
** NOTE THAT CG & CB ARE MEASURED AS THE DISTANCE  FROM THE TIP OF VEHICLE NOSE

                    CURRENT TOTAL VEHICLE RESULTS
==========================================================================
   TOTAL VEHICLE WT (LB):     177.26      RESERVE BUOYANCY (LB):    189.15
    VEHICLE CG (IN)    X:     43.51    Y:          .00    Z:     -1.43

RINT SCREEN NOW IF DESIRED, ENTER (1) TO PROCEED
```

END OF RUN OPTIONS

AT THE END OF A TYPICAL RUN, A SERIES OF "NEXT STEP" OPTIONS ARE AVAILABLE:

'ENTER A (0) TO QUIT'

'ENTER A (1) IF YOU WANT TO REPEAT FOR A NEW VEHICLE'

'ENTER A (2) IF YOU WANT TO USE SAME HULL, START ADDING EQUIPMENT TO IT

'ENTER A (3) TO DISPLAY CURRENT EQUIPMENT CONFIGURATION'

'ENTER A (4) IF YOU WANT TO CONTINUE WITH CURRENT EQUIPMENT CONFIGURATION

THESE ARE MOSTLY SELF EXPLANATORY. OPTION (2) IS USEFUL WHEN YOU BYPASS THE EQUIPMENT SECTION AFTER INPUTTING THE HULL. OPTION (3) PROVIDES A DISPLAY OF THE CURRENTLY HELD EQUIPMENT INVENTORY SUCH AS:

```
                    CURRENT EQUIPMENT CONFIGURATION
============================================================================
  ITEM        WEIGHT          X-POSIT         Y-POSIT         Z-POSIT
    1          24.60           36.00             .00           -2.00
    2          31.30           54.00            3.50           -3.00
    3          31.30           54.00           -3.50           -3.00
    4           4.70           14.00             .00           -3.60
    5           3.45           12.00             .00             .00
    6           2.80           72.00            4.50             .00
    7           2.80           72.00           -4.50             .00
    8            .56            1.00             .00             .00
    9            .56            3.00            2.50             .00
   10            .56            3.00           -2.50             .00

URRENT VEHICLE CG (X,Y,Z):           43.51           .00          -1.43

'RINT SCREEN NOW IF DESIRED, ENTER (1) TO PROCEED
```

NOTE THAT IN THIS AND IN OTHER SITUATIONS THROUGHOUT THE PROGRAM, A VALUABLE OPTION IS SUGGESTED:

'PRINT SCREEN NOW IF DESIRED, ENTER (1) TO PROCEED'

ADDING TO ORIGINAL EQUIPMENT LIST

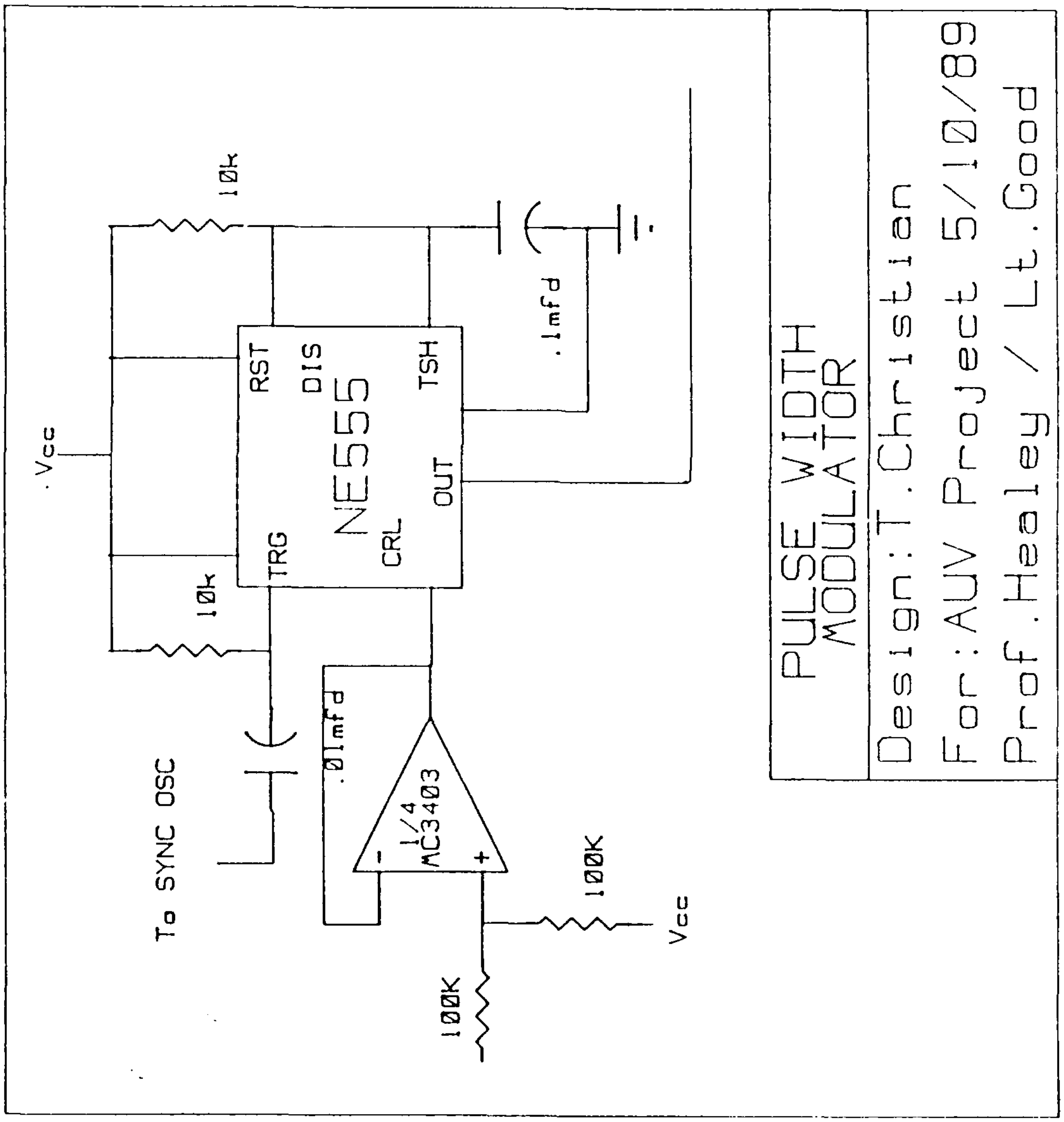
OPTION (4) ALLOWS YOU TO REENTER THE EQUIPMENT ADDITION SECTION AND ADD MORE EQUIPMENT, OR PERHAPS ADD BALLAST TO THE VEHICLE TO OPTIMIZE THE CENTER OF GRAVITY AFTER ALL EQUIPMENT HAS BEEN INPUT. AFTER SELECTING OPTION (4), THE PROGRAM WILL ASK:

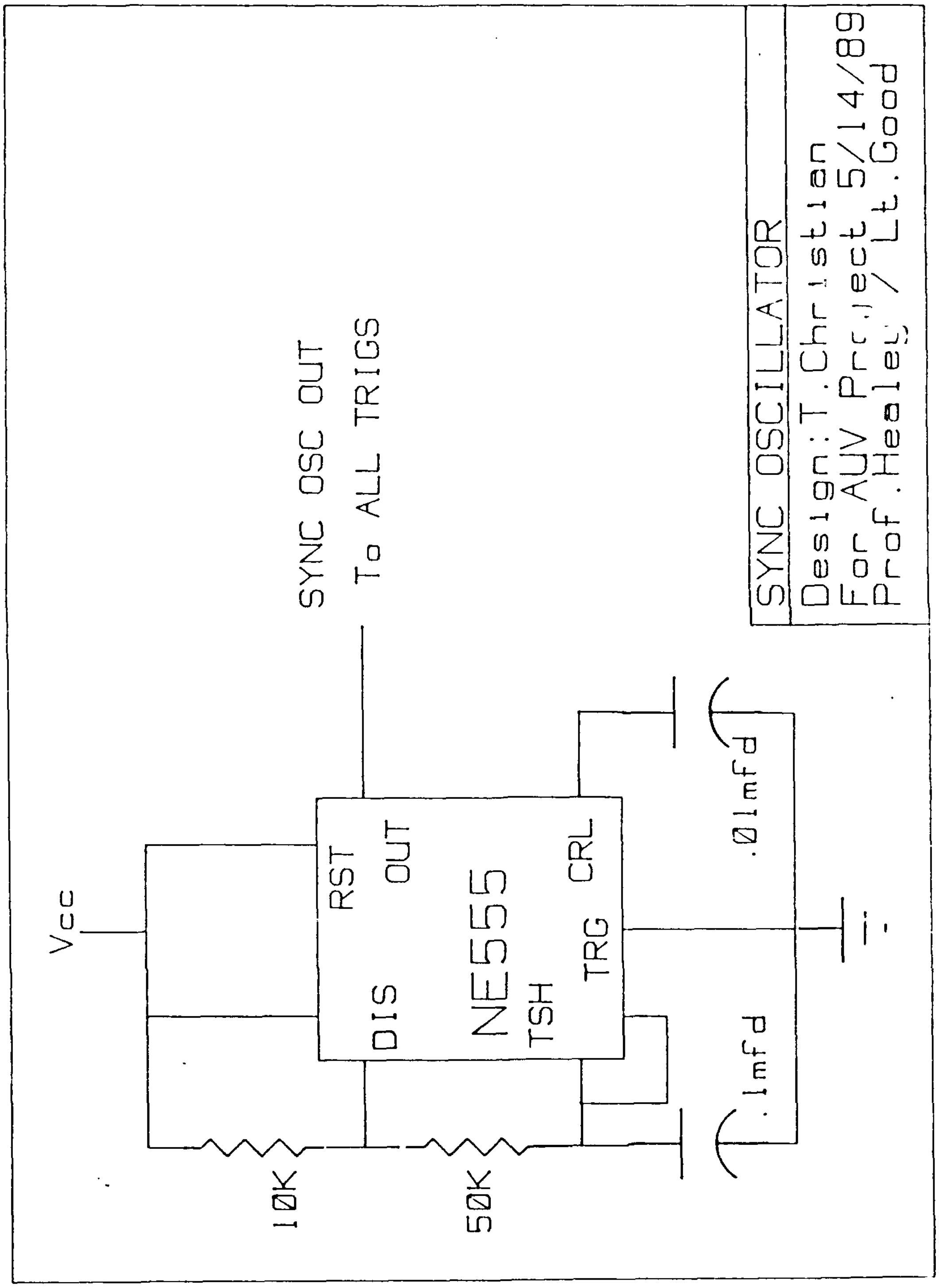
'HOW MANY ITEMS DO YOU WISH TO ADD TO CURRENT LIST?'

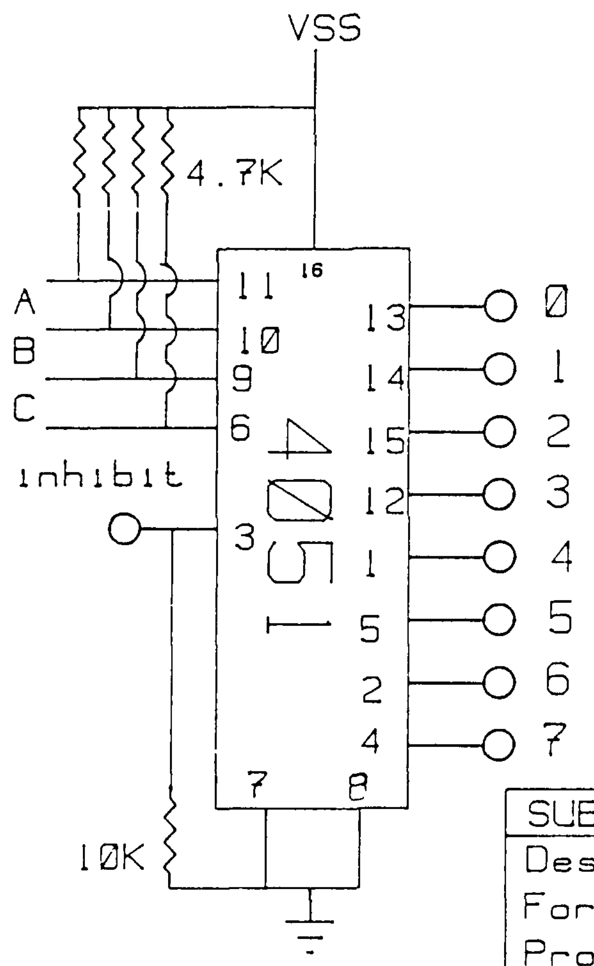
THIS ADDS TO THE NUMBER PREVIOUSLY INPUT AND SUBSEQUENTLY GIVES DIRECT ACCESS TO THE EQUIPMENT SECTION AS BEFORE.

APPENDIX B

CIRCUIT DRAWINGS

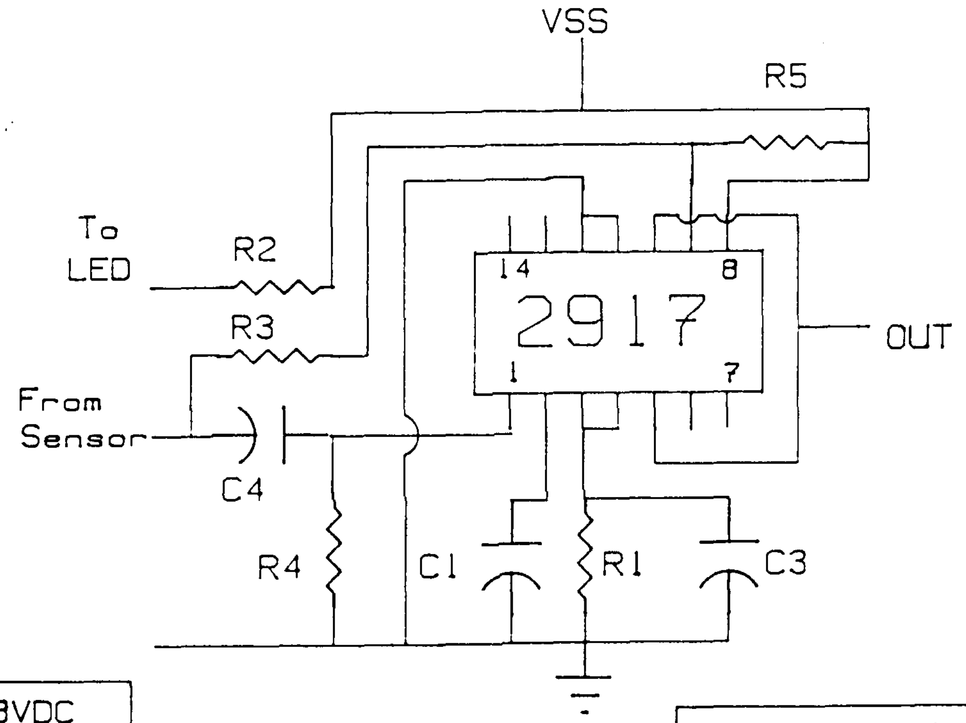



SYNC OSCILLATOR
Design: T.Christian
For AUV Project 5/14/89
Prof. Healey / Lt. Good
SYNC OSC OUT
To ALL TRIGS
Vcc
RST
OUT
NE555
DIS
TSH
TRG
CRL
.01mfd
.1mfd
10K
50K



SUB-MULTIPLEX ASSY

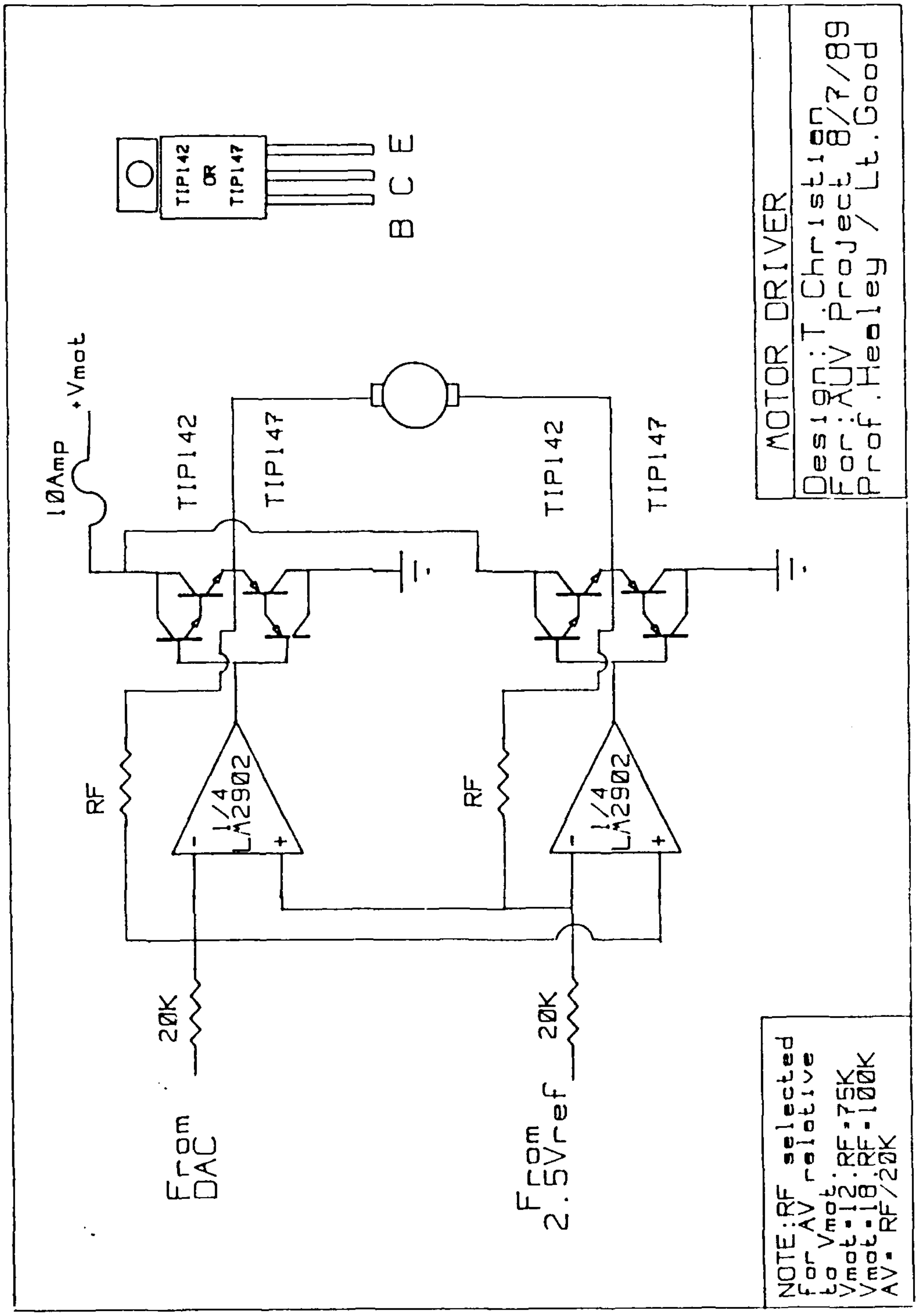
Design T.Christian
For:AUV Project 8/3/89
Prof.Healey /Lt. Good



NOTES: VSS=8VDC
R2:332
R3:10K
R4:1MEG
C3:1 mfd
C4:.1 mfd
R5:49
R1.C1 Selected
by TACH pgrm
re.TOMC 1980ver.

RPM To VOLTAGE
CONVERTER

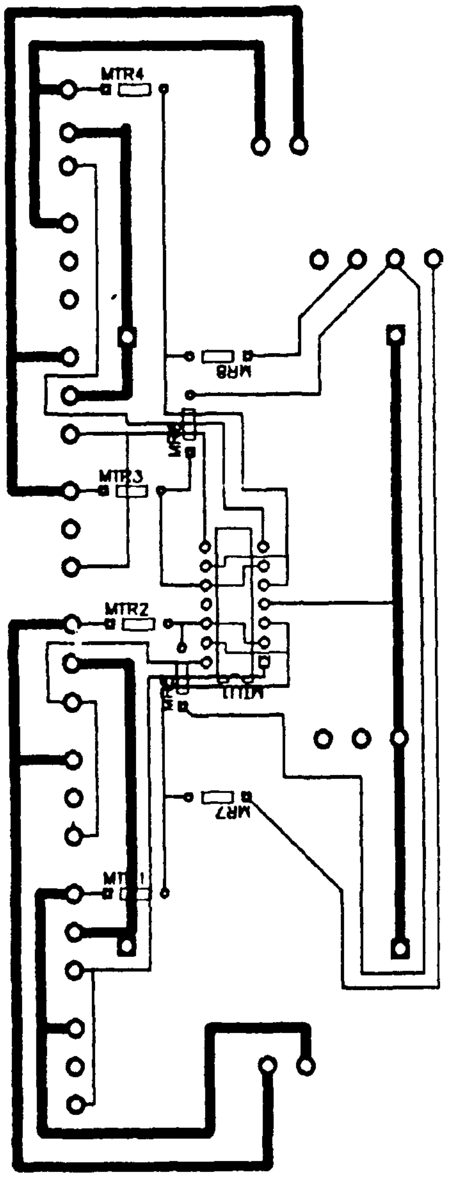
Design:T.Christian
For:AUV Project 8/4/89
Prof.Healey/Lt.Good


10Amp
+Vmot
TIP142
TIP147
TIP142
TIP147
TIP142
OR
TIP147
B C E
RF
RF
1/4
LM2902
1/4
LM2902
20K
20K
From
DAC
From
2.5Vref
MOTOR DRIVER
Design: T. Christian
For: AUV Project 8/7/89
Prof. Healey / Lt. Good
NOTE: RF selected
for AV relative
to Vmot:
Vmot=12: RF=75K
Vmot=18: RF=100K
AV= RF/20K

Bill of Materials [illegible]

DUAL SCREW/TRUSTER MOTOR DRIVE

Quantity	Type	Value	Ref Designators
1	LM3403P		MTU1
4	RN55	20K	MR5,MR6,MR7,MR8
4	RN55	75K	MTR1,MTR2,MTR3,MTR4

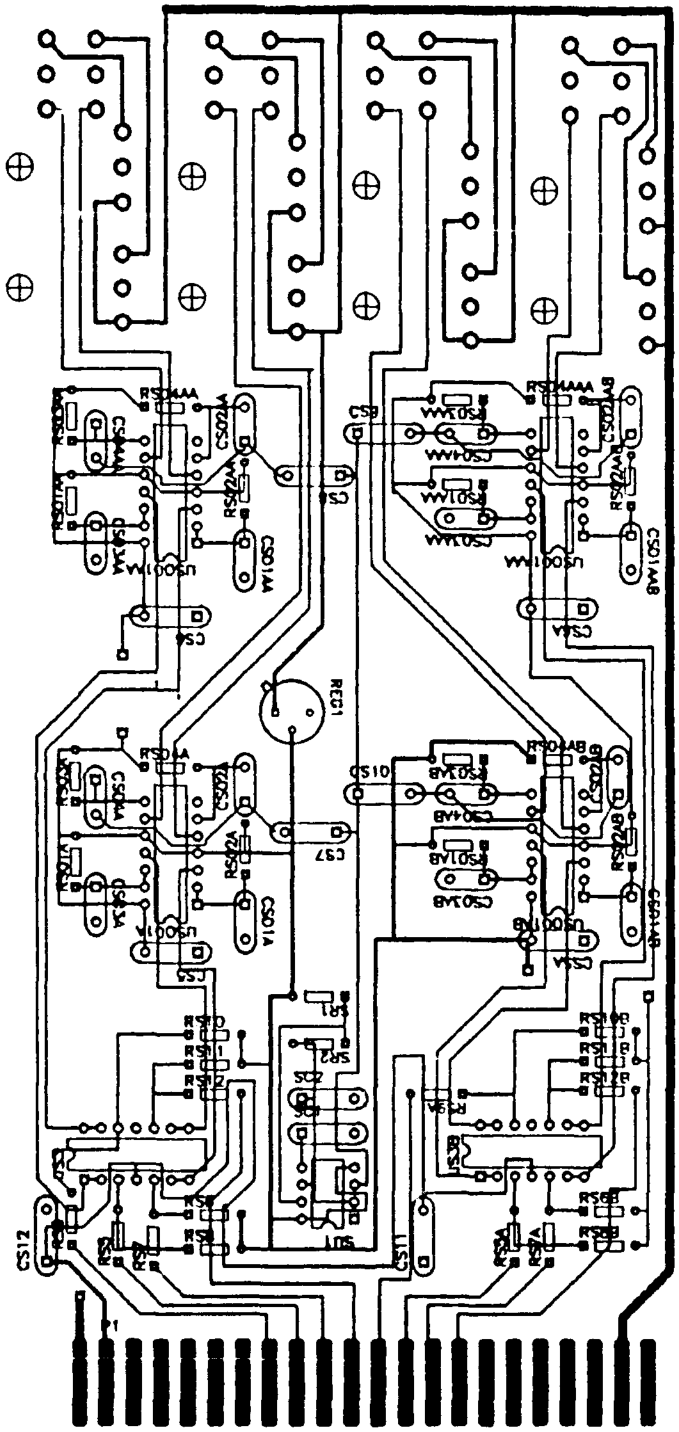


DUAL SCREW/TRUSTER MOTOR DRIVE

Bill of Materials AUVSRV1.PCB

8 CHANNEL SERVO CONTROL BOARD

Quantity	Type	Value	Ref Designators
1			P1
16		.1 MFD	CS01A,CS01AA,CS01AAB,CS01AB,CS02A,CS02AA,CS02AAB,CS02AB,CS03A,CS03AA,CS03AAA,CS03AB,CS04A,CS04AA,CS04AAA,CS04AB
10		.1MFD	CS5,CS5A,CS6,CS6A,CS7,CS8,CS9,CS10,SC1,SC2
2		1MFD	CS11,CS12
1	LM309	5V	REG1
1	LM555		SU1
4	LM556		USO01A,USO01AA,USO01AAA,USO01AB
2	MC3403		US3,US3B
1	RN55	10K	SR1
16	RN55	10KOHM	RS01A,RS01AA,RS01AAA,RS01AB,RS02A,RS02AA,RS02AAB,RS02AB,RS03A,RS03AA,RS03AAA,RS03AB,RS04A,RS04AA,RS04AAA,RS04AB
1	RN55	50K	SR2
16	RN55	100KOHM	RS5,RS5A,RS6,RS6B,RS7,RS7A,RS8,RS8B,RS9,RS9A,RS10,RS10B,RS11,RS11B,RS12,RS12B

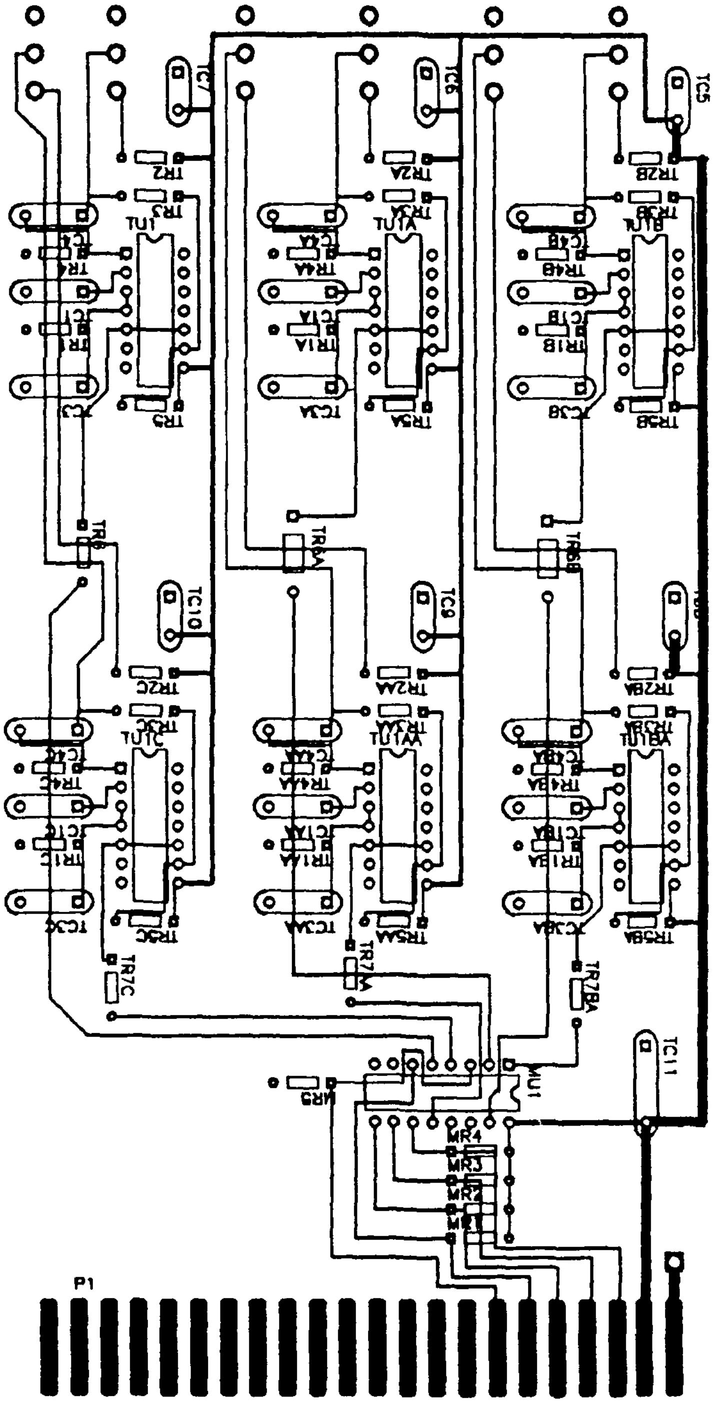


8 CHANNEL SERVO CONTROL BOARD

Bill of Materials [illegible]

6 CHANNEL TACH BD. W/MUX OUT

Quantity	Type	Value	Ref Designators
1			F1
12		.1 MFD	TC4,TC4A,TC4AA,TC4B,TC4BA, TC4C,TC5,TC6,TC7,TC8,TC9, TC10
6		1 MFD	TC3,TC3A,TC3AA,TC3B,TC3BA, TC3C
1		1MFD	TC11
6		49	TR5,TR5A,TR5AA,TR5B,TR5BA, TR5C
6		SELECED	TC1,TC1A,TC1AA,TC1B,TC1BA, TC1C
1	CD4051		MU1
6	LM2917		TU1,TU1A,TU1AA,TU1B,TU1BA, TU1C
6	RN55	1 MEG	TR4,TR4A,TR4AA,TR4B,TR4BA, TR4C
4	RN55	4.7K	MR1,MR2,MR3,MR4
7	RN55	10K	MR5,TR3,TR3A,TR3AA,TR3B, TR3BA,TR3C
6	RN55	100 OHM	TR6,TR6A,TR6B,TR7AA,TR7BA, TR7C
6	RN55	332	TR2,TR2A,TR2AA,TR2B,TR2BA, TR2C
6	RN55	SELECED	TR1,TR1A,TR1AA,TR1B,TR1BA, TR1C



6 CHANNEL TACH PD. W/MUX OUT

INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Technical Information Center Cameron Station Alexandria, Virginia, 22304-6145	2
2. Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3. Chairman, Code 69Hy Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5000	10
4. Dr. G. Dobeck, Code 4210 Naval Coastal Systems Command Panama City, Florida 32407-5000	1
5. Hal Cook, Code U25 Naval Surface Weapons Center White Oak, Maryland 20910	1
6. Paul Heckman, Code 943 Head, Undersea AI & Robotics Branch Naval Ocean Systems Center San Diego, California 92152	1
7. Dr. D. Milne, Code 1563 DTRC, Carderock Bethesda, Maryland 20084-50008.	1
8. RADM Evans, Code C92R Naval Sea Systems Command Washington, D.C. 20362	1
9. Dan Steiger Marine Systems Group Naval Research Laboratory Washington, D.C. 20032	1
10. Dick Blidberg Marine Systems Engineering Lab SERB Building 242 University of New Hampshire Durham, New Hampshire 03824	1

11. Jennifer Rau, Code U25 1
Naval Surface Weapons Center
Silver Spring, Maryland 20903-5000

12. Technical Library Branch, Code E23 1
Naval Surface Warfare Center
Silver Spring, Maryland 20903-5000

13. Naval Engineering Curricular Office 1
Code 34
Naval Postgraduate School
Monterey, California 93943-5000

14. LT Michael R. Good 1
Ship Superintendent, Repair Office
Puget Sound Naval Shipyard
Bremerton, Washington 98314