Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

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Ship Systems Integration & Design Department
Technical Report

Speed/Depth Recorder Project

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14. ABSTRACT

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The team developed a concept vehicle that met all the minimum requirements and exceeded some of the objective requirements. The vehicle contains an integrated stand-alone data logger and uses a combination of foam and free-flooded compartments to remain neutrally buoyant. The estimated fabrication cost is $8,200 per unit. Although the team demonstrated the feasibility of the concept, additional analysis is required to minimize risk and address aspects of the design beyond the scope of the team's mandate.

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Abstract

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Table of Contents

List of Tables

List of Figures

Nomenclature

A	Frontal Area
C_D	Drag Coefficient
D	Drag Force
I	Impulse
m	Mass
P_s	Static Pressure
P_o	Stagnation Pressure
V	Velocity
t	Time
ρ	Density

Section 1 – Introduction

Mission Statement

The design team was given the task of designing an economical and effective sub-surface vehicle for measuring speed and depth. This device will be part of an array that is towed behind a surface ship. The role of this vehicle is to deliver accurate measurements at depths of up to 1,000 feet, while remaining neutrally buoyant with a static trim of 0° or slightly nose down. The device must be simple and easy to use, with little or no daily maintenance required.

Background

A towed array is an array of sensor devices that is towed behind a vessel. It is essentially a long cable with passive sensors, active sensors or a combination of these devices that are towed behind the ship. They have little effectiveness near the surface and the ship's propeller, due to the turbulence and noise generated by the propulsurs and hence operate below and away from the towing vessel. A towed array is useful because it offers better range and resolution of measurements compared to hull mounted sensors.

Evaluation Criteria

Once a complete list of ideas was compiled, the team selected and eliminated ideas. The team narrowed the ideas generated in the brainstorming sessions into five major categories. These categories included depth gauge, speed sensor, data collection and storage, power, and clamp/attachments. At this point, ideas generated through brainstorming were subjected to the design review process to ensure that these ideas were sufficiently developed. These categories are discussed further in the section entitled Equipment Selection.

Section 2 – Design and Engineering

Threshold Requirements and Objectives

The Marine and Aviation Division (Code 5300) compiled a list of desired capabilities for the speed/depth recorder prototype. Table 1 indicates the threshold and objective requirements in addition to the concept vehicles achieved performance. The minimum requirements were met, and in some cases, the objective was exceeded.

Table 1: Stated and Achieved Requirements

Capabilities	Threshold	Objective	Achieved
Channels of Data	Speed Depth Time	Speed Depth Time Temperature Salinity	Speed Depth Time Temperature
Speed Range	3 – 30 knots	3 – 30 knots	0 – 50 knots
Accuracy	± 0.1 knots	± 0.1 knots	± 0.05 knots
Data Collection	1 Hz	20 Hz	6 Hz
Duration of Operation	-	8 hours	20 hours
Maximum Operational Depth	-	1,000 ft	2,400 ft
Fabrication Cost	$10,000	Less Than $7,000	$8,200 (est)

Overall Design

The final design is a modular arrangement that closely resembles a torpedo. This is due to the inherently superior hydrodynamic properties of torpedoes and the readily available data, which can be scaled from full size torpedoes and applied to the speed/depth recorder. The dimensions and placement of the fins require further research and design, as they are used for passive stability, rather than providing active control of the vehicle.

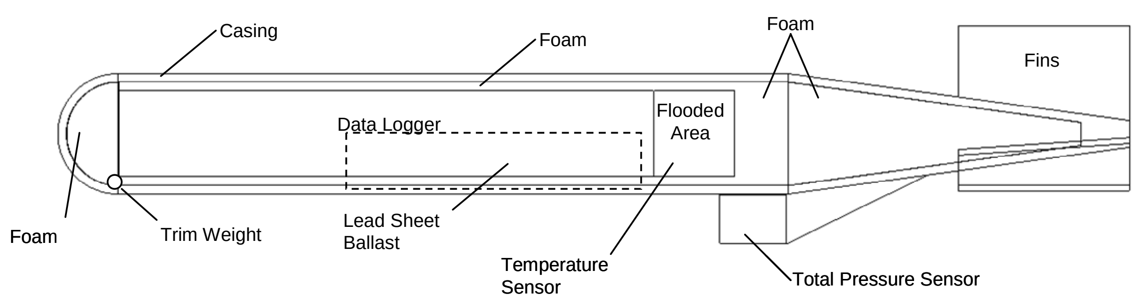

Figure 1:Schematic of the Vehicle

Early in the design process it was determined the vehicle should be free flooding. This solves a number of problems; most importantly is the issue of compression at depth. The considerable pressure at the maximum operating depth is roughly 30 atm. The vehicle must also remain neutrally buoyant at all depths and salinities, which means that any change in enclosed volume due to hull compression would affect the buoyancy. Making all compartments free flooding will negate these issues and result in a structural design that is simpler due to the lack of pressurized spaces.

In the vehicle's front section, the data logging system is encased in foam within the main hull to provide protection against accidental damage and shock. A stagnation pressure sensor protrudes from the hull in a faired body so that the sensor will be in the flow stream and generate a minimal amount of drag. A perforated flooded compartment is located aft of the logger to measure static pressure. The rear section is packed with foam and has three stabilizing fins at the stern.

The vehicle is packed with foam in order to provide buoyancy, although in waters with different salinity, weights will be required to alter the buoyancy so that neutral buoyancy is maintained.

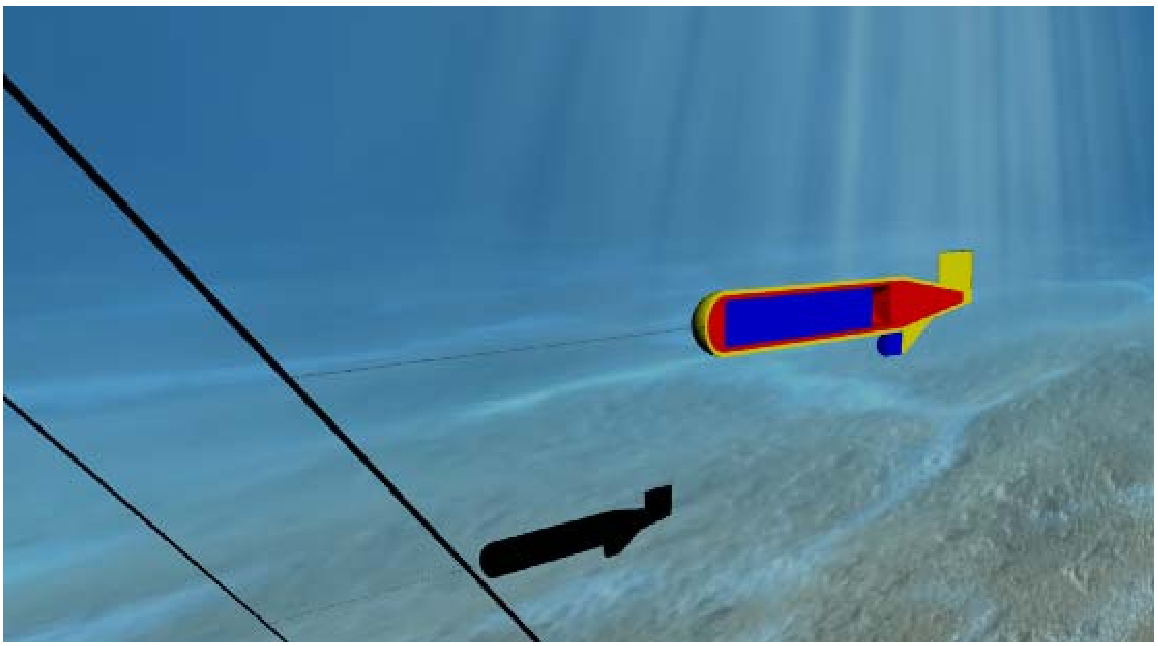

Figure 2: Cross-Section View of Vehicle during Use

Engineering Design

Material Selection

Because an operational depth of 1,000 ft is required, the team sought a casing material that can withstand the 440 lb/in^2 pressure at this depth. Numerous materials were evaluated and the team narrowed its selections to three options. Although it is readily available, stainless steel did not prove to be a satisfactory choice because it is expensive, difficult to machine and challenging to construct a neutrally buoyant device of a material with such a considerable density. Aluminum 6061-O is easy to machine and seemed a viable option because of its wide availability, but it is also too dense. Varieties of plastics were assessed and the design team determined that the specialty nylon Nycast 12 is the best casing material option. It has the required strength but with a density nearly that of seawater, allowing the team to offset weight elsewhere in the design (Appendix A: Calculations).

Table 2: Material Comparison

	Density		Weight in Air	
	lb/in^3	kg/m^3	lb	kg
Stainless Steel (SS 304)	0.2890	8,000	23.1574	10.5040
Aluminum (6061-O)	0.0975	2,700	7.8156	3.5451
Nylon (Nycast 12)	**0.0372**	**1,030**	**2.9815**	**1.3524**

There are several options for adding buoyancy to the vehicle**.** One way is by making the vehicle a pressure vessel and allowing the trapped air to provide the required buoyancy. This adds unnecessary structural and manufacturing difficulties and limits the types of materials that can be used.

Because the casing is constructed of low density Nycast 12, it was determined that the entire vehicle should be flooded. Consequently foam must be added to increase buoyancy of the vehicle. There is a great variety of commercial off-the-shelf (COTS) foam available, but there are several limiting factors that narrow the choices. The main factor is that the foam must survive depths of 1,000 ft plus a small safety factor. Also, this foam must provide sufficient buoyancy while submerged. After performing a rough weight estimate of the vehicle submerged (Section 2.3.2), it was determined that foam with a density of 24 lb/ft^3 would be sufficient. The foam chosen is manufactured by Engineered Syntactic Systems. Their MZ-24 series foam has a density of 24 lb/ft^3 and can with stand pressures up to over 3,000 ft. Engineered Syntactic Systems stated that the MZ-24 foam would compress around 0.22% (rendering the change in buoyancy negligible) of its volume, thus the foam should be cleaned once every year depending on usage [7]. The replacement time may be determined by the quality of fit of the foam inside the vehicle. This foam not only provides buoyancy for the vehicle but it also acts as a protective barrier between the internal electronics and the inside wall of the vehicle structure. The foam will be custom machined to hold the internal electronics securely in place.

Hydrostatic Analysis

The design criteria requires the vehicle remain neutrally buoyant when fully populated with the payload, as well as maintain a static pitch trim of 0° or slightly nose down. This called for a study of the effects of buoyancy and vehicle weight. The force exerted by the seawater on the bottom of the vehicle acts through the center of buoyancy, while the force exerted by gravity on the boat acts through its own center of gravity. The study showed the centers of weight to be 14.28 in from the bow and buoyancy to be 13.63 in. This 0.65 in difference results in the vehicle to trim slightly nose up. It was determined that approximately a ¼ lb weight should be added in the nose cone on the keel in order to restore zero trim.

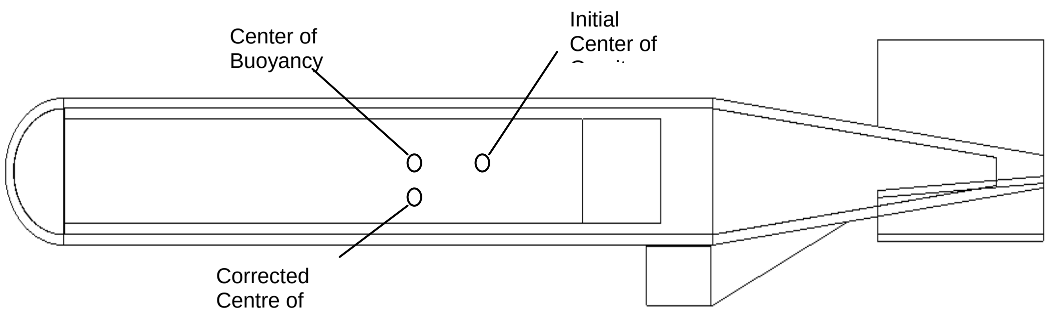

Figure 3: Centers of Mass and Buoyancy

The weight of the vehicle is 39.42 lbs while buoyancy is 23.8 lbs. In order to reduce the discrepancy between weight and buoyancy, a lead sheet of dimensions 6.14 in x 5.57 in x 0.25 was added to the vehicle directly below the center of buoyancy, around the inside of the hull, on the keel (Appendix A2). These additions keep the vehicle neutrally buoyant and at zero trim and also generate a righting moment to stabilize the recorder.

Hydrodynamic Analysis

To calculate the loads that would be applied on the towing cable by the vehicle (and also the stress in the vehicle towing line) it was necessary to use the drag coefficients for the different features of the unit. Drag force was calculated using Equation 1.

Equation 1: $$D = \frac{2C_D}{\rho A V^2}$$

The following coefficients were obtained from Hoerner [8] for a 30-knot tow speed.

Table 3: Drag Coefficients and Forces at 30 knots

Component	C_D	Frontal Area (in^2)	Drag Force (lb)
Myring Hull	0.1000	9.920	17.609
Fins x 3	0.0200	1.240	1.3203
Pressure Transducer	1.2000	1.085	23.479
Total Drag			**42.409**

The design case for the vehicle towing line is related to total drag through the water and occurs when the vehicle becomes snagged on a rock or seaweed and when there is a rapid change in direction causing a snatch load. This was modeled as the application of an impulse load equal to twice the maximum speed applied over a period of 0.1 seconds. Using Equation 2, the total impulse in this scenario is 163 lbs. A safety factor of 3 was then applied, which provides a figure of 489 lb force to be endured by the towing line. The selection of the towing line is discussed in more detail in the Equipment Selection section.

$$\text{Equation 2: } I = \frac{mV}{t}$$

Computational Fluid Dynamics should be performed to analyze the effect of the towing cable on the flow field around the speed/depth recorder. This will allow the correct length of towing line to be used between the towing cable and the vehicle.

During operation of the recorder it is likely that the end of the towing cable will become horizontal. When this occurs, the data logger and the cable will be in close proximity and contact between the two is inevitable. To stop this from occurring and causing damage to both the recorder and the cable, further work is required. One possible solution is to include a depressor in the recorder towing line such as a lead weight, which will offset the position of the recorder from the cable to avoid contact.

When the recorder is moving through the water, the fins are acting to stabilize its motion. However, at different speeds, the fins will act to cause lift of varying magnitudes, generating a dynamic trim. This trim will cause disturbances in the flow field around the recorder, which in turn will lead to distortions in the pressure readings. It is essential that the effect of the fins is considered so that the pressure readings can either be corrected or calibrated. It may be the case that the effects of the fins are negligible, in which case a simple pressure sensor calibration will suffice. If however, the effects of the fins are significant, it may be necessary to alter their size and type or introduce some stabilization system. Whatever the case, further analysis must be conducted to ascertain the fin's effects on dynamic stability of the recorder.

Equipment Selection

In order to accurately measure depth and speed, different methods of gathering data were reviewed. Depth and speed data can be obtained directly from pressure and speed transducers, but can also be indirectly measured or calculated from other sources.

Depth can directly be measured via pressure transducers, which convert the local pressure to an equivalent height of water. Alternatively, depth can be measured by the strain applied to a watertight compartment via a Wheatstone bridge strain gauge. At various depths, the hull would be compressed by differing amounts, causing a strain. After calibration, the gauge output could be set to output a corresponding depth of seawater.

Speed can be measured directly, although unlike depth it is easier to measure indirectly. Paddlewheel or propeller measurements use the movement of the paddle or propeller, which is proportional to the speed of the recorder through the water. The subsequent rotary motion is measured and converted to a velocity.

Laser Doppler Anemometers measure the time for particles in fluid to pass through a pair of laser beams, and are known to be accurate although are very expensive. Indirect methods of speed measurement are based on the pressure differential between static and stagnation pressure. The difference between the two is the dynamic pressure and from this, the vehicle's velocity can be calculated. To achieve this, a manometer or two pressure sensors are required.

Both work on the same principle and in a similar manner to measure static pressure, and stagnation pressure in the flow stream. Speed can also be measured via a load cell, located at the interface between the towing cable and the recorder. The towing force increases with speed and the output from the cell can be calibrated to calculate speed when the drag coefficient of the recorder is known.

Another technique to determine the velocity of the vehicle is to use a load cell to directly measure the drag of the body. Using Equation 1, where D is the measured drag force, the velocity of the vehicle can be determined.

In order to use this technique the drag coefficient of the vehicle must be determined prior to deployment. The process of determining the drag coefficient adds unnecessary monetary and time expenditures to the design process as well as added complexity in the structural design of the vehicle itself. Several commercially available load cells were reviewed. The load cell technique would also require a separate data logger and power, although available data loggers are expensive and do not sample at a sufficient rate.

A number of commercially available depth gauges were reviewed, although the majority required a separate recording system, which would significantly add weight, volume and complexity to the system. Most of those that were found to be self contained were expensive and had a sampling rate, which was too low for the required use. One combined depth transducer and recorder was found which is self contained and powered, and has a sampling rate of 6 Hz which is sufficient for the purposes of the recorder. The unit will be described further below.

The fully integrated XR-620 data logger and sensor package that was chosen is designed and manufactured by Richard Brancker Research (RBR Ltd.). The XR-620 system is capable of making all of the measurements required as well as the optional temperature and salinity measurements if the budget allows it. The logger package (Table 4) contains a plastic housing rated to over 2,400 ft as well as temperature, depth, and an additional pressure sensor to indirectly determine velocity (using the above method) as stated above. The estimated cost of this integrated package is approximately $6,250. If salinity measurements are desired this will cost an estimated additional $1,400. This logger is capable of taking samples at 6 Hz on all four channels for 20+ hours, depending on which memory option is chosen. This allows multiple eight hour testing sessions without the need to remove the logger from the vehicle to download the data. Standard rechargeable camera batteries power the XR-620 logger. The software provided with the data logger is compatible with MATLAB. This software allows the user to specify data collection rate and sampling start and stop times. It is also possible to set a threshold for when the logger will begin to collect data, so the logger would be in a power-conserving mode until it reaches a prescribed depth. An estimate of the battery and memory consumption is also provided. Using the software, it is also possible to calibrate the instrumentation and logger as well as synchronize the logger's clock with the computer to which it is attached. The XR-620 synchronizes with any computer running Windows 98, NT, 2000, XP or Vista via a USB connection. The software has an intuitive graphical user interface that displays the retrieved data as tables and color-coded graphs. The logger specifications, as provided by the manufacturer, are proved in Table 4. The accuracy of the instrumentation used by the XR-620 logger are provided in Table 8 [9].

Table 4: RBR XR-620 Logger Specifications

Base Logger	Specifications
Internal Power	4 - 3V CR123A cells (camera batteries)
Communications	RS-232/485 cable, telemetry-USB
Download Speed	~115,000 samples/minute
Clock Accuracy	±32 seconds/year
Size	400mm x 64mm
Memory	8 Mb flash variable up to 2 Gb option
Weight	1.2 kg in air (389 g in water)
Calibration	NIST traceable standards
Sampling Rate	Variable up to 6 Hz
Depth Rating	740m

The design criteria state that the vehicle must mount to multiple cable diameters and types and needs a universal clamp design. The team located a towing cable clamp manufactured by Shark Marine. Their product currently adapts to cables up to ½ in. diameters. Shark Marine stated that they could produce a clamp that will meet the design team's design specification of cables up to 1.5 in. diameter [10]. This clamp was found to be the best option and is shown in Figure 4. This clamp is simple but effective and provides a means to quickly adjust to the cable diameter. It securely holds the cable by a specially designed jaw, with no damage to the cable. It is assumed this cable clamp design will be sufficient, however further information on the yield strength of the various tow cables is needed to validate this assumption.

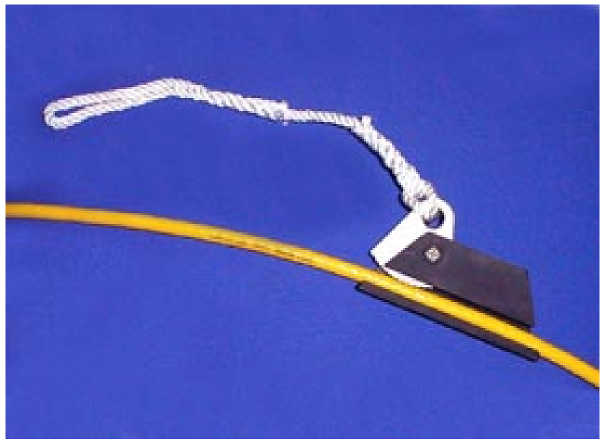

Figure 4: Towing Cable Clamp

After evaluating various ropes and wires, the design team determined that the best method of attaching the vehicle to the towing cable clamp is through the use of 500 lb test nylon fishing line. The strength of the fishing line exceeds the maximum calculated impulse load. In addition to the fishing line, a swivel will be used as the link between the towing cable clamp and the vehicle. The purpose of the swivel is to reduce the amount of coiling in the towline.

Systems Integration

The assembly of the vehicle was kept as simple as possible. The vehicle separates into two halves where the tail cone begins, as shown in Figure 5. These two halves will be bolted together using standard bolts and heli-coil screw thread inserts. The number of attachment points has yet to be determined. The fins and nose cone will be jointed using pins and epoxy. Holes will be drilled in a yet to be determined number and pattern and aluminum rod will be used as pins to add structural integrity to the epoxy bond. The foam will be simply inserted and held in place by friction and the vehicle itself. This allows the foam to be removed for easy cleaning, replacement and logger retrieval.

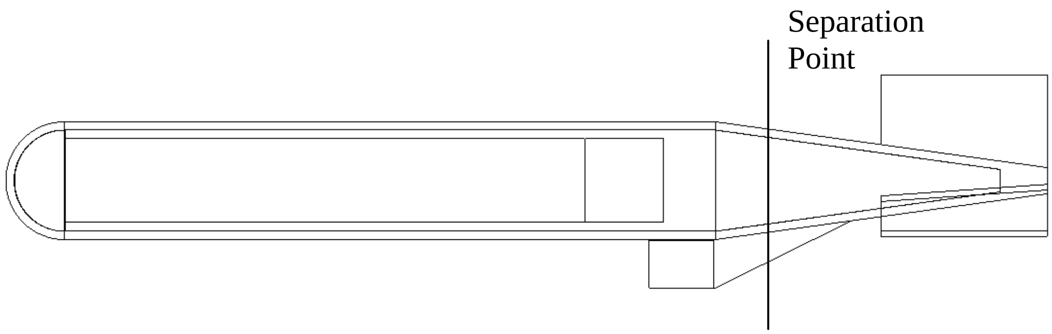

Figure 5: Location of Separation Point

To provide a location for the static pressure sensor, a flooded compartment was required, and it was decided that this compartment would be as small as possible to minimize any loss in buoyancy. The area adjacent to the data logger was chosen as the location for flooding as it also allows easy access to the end of the data logger for data transfer. The compartment has a diameter of 2.52 in. and extends 2.36 in. aft. Multiple holes are needed throughout the vehicle to allow water and air to quickly escape. This will allow uniform flooding with minimal air pockets.

As stated above, in order to determine the velocity of the vehicle total pressure as well as the static pressure of the flow must be measured. Then, using Equation 3, the velocity can be determined.

Equation 3: $$V^2 = \frac{2(P_o - P_s)}{\rho}$$

The static pressure, P_s, is provided by the depth sensor while the stagnation pressure, P_o, needs to be measured by an externally mounted pressure sensor that is exposed to the free stream flow around the vehicle. This external sensor will be mounted towards the aft of the vehicle as show in Figure 4. The placement of the sensor is such that it does not interfere with the rear stabilization fins. The sensor is also mounted on the bottom of the vehicle thus providing roll stability via the pendulum effect. The longitudinal positioning of the sensor is due to the fact that the instruments connect to the RBR Ltd. XR-620 only at one end, which is positioned facing aft. The pressure sensor location may be moved forward depending on cable and connector management needs.

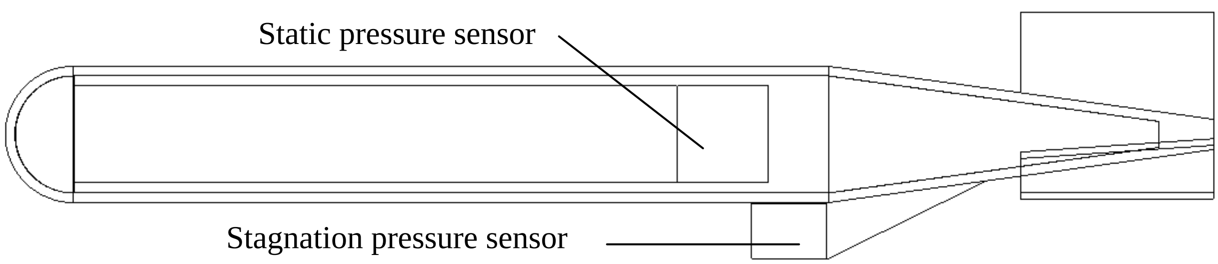

Figure 6: Location of Pressure Sensors

Section 3 – Conclusion

Project Summary

The vehicle contains an integrated stand-alone data logger and uses a combination of foam and free-flooded compartments to remain neutrally buoyant. To improve flexibility, significant attempts to reduce systems complexity were made. The feasibility of this final design is demonstrated in the critical areas of depth and speed sensors, power, cable clamp, and data collection. The fabrication cost estimate shows a cost of $8,200 per unit (Appendix B: Cost Engineering).

Recommendations for Future Work

The design team concluded that the concept is feasible. Although several risk areas have been identified, additional efforts in the following areas should provide a successful design:

- Computational Fluid Dynamics Analysis,
- Optimize Centers of Buoyancy and Weight,
- Detail Casing Fastener Design,
- Material Trade-Offs,
- Foam Placement,
- Dimensions and Placement of Fins,
- Placement of Dynamic Pressure Sensor,
- Yield Strength of Tow Cable,
- Stop Cable/Recorder Contact, and
- Dynamic Effect of Fins.

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Appendix A: Calculations

A-1 Material Weight Breakdown

Table 5: Weight Calculations

Property	Value
hemisphere OD	3.5000 in
wall thickness	0.2500 in
hemisphere ID	3.0000 in
hemisphere volume	**4.156 in^3**
tube OD	3.5000 in
wall thickness	0.2500 in
tube ID	3.0000 in
tube length	20.0000 in
tube volume	**51.051 in^3**
logger volume	78.5254 in^3
flooded volume	16.6974 in^3
cone OD	3.5000 in
wall thickness	0.2500 in
cone ID	3.0000 in
cone length	10.0000 in
cone volume	**8.5085 in^3**
fin length	3.1500 in
fin height	2.0000 in
fin thickness	0.2000 in
total fin volume	**3.7800 in^3**
cover length	2.4000 in
cover height	4.7500 in
cover thickness	0.1000 in
cover volume	**1.1400 in^3**
Logger Weight	0.8378 lbs
Total Enclosed Volume	168.096 in^3
Total Nycast Volume	68.6354 in^3
Foam Volume Available	83.4068 in^3
Foam Weight Available	1.14504 lb
Total Nycast 12 Weight	3.4940 lb

A-2 Hydrostatic Analysis

All centers of force are taken from the most forward point of the nose cone.

Table 6: Weight and Buoyancy Calculations

Element	Center of Volume (in.)	Buoyancy (lbs)	Buoyancy Moment (ft lbs)	Center of Mass (in.)	Weight (lbs)	Weight Moment (ft lbs)
Casing	15.591	2.89554	33.2930	15.8779	3.17782	37.21217
Logger	9.646	2.82277	20.0802	9.646	0.85786	6.10251
Foam	15.394	3.13151	35.5515	12.795	1.20250	11.34738
Sensor	20.472	0.01184	0.1788	20.472	0.11026	1.66482
Misc. + Ballast*					3.513	
Overall	**15.276**	**8.86166**	**89.1035**	**14.698**	**8.86166**	**56.32687**

*This category is intended to balance the vehicle's pitch and buoyancy and was added after the calculation below.

Table 7: Mass Balance Calculations

Center of Buoyancy	10.05494
Center of Mass	10.53146
Centers Difference	0.47651
Difference in Forces	3.51322
Difference in Moments	32.77664
Required Force	2.5404
Required Mass	**0.2590**

A-3 Instrumentation Specifications

Table 8: XR-620 Specifications [9]

Temperaure	
Range	-5 °C to 35 °C
Accuracy	±0.002 °C
Resolution	< 0.00005 °C
Time Constant	~3 s (standard), optional ~0.1 sec
Drift	< 0.002 °C/year
Depth/Pressure	
Range	Variable from 10 – 8,500 m
Accuracy	± 0.05% full scale
Resolution	< 0.001% full scale
Time Constant	< 10 ms
Conductivity	
Range	User specified
Accuracy	±0.003 mS/cm at 35psu 15°
Resolution	Up to 0.0001 mS/cm0~0.001 mS/cm/°
Time Constant	~0.1 sec depending on flow rate

A-4 Vehicle Dimensions

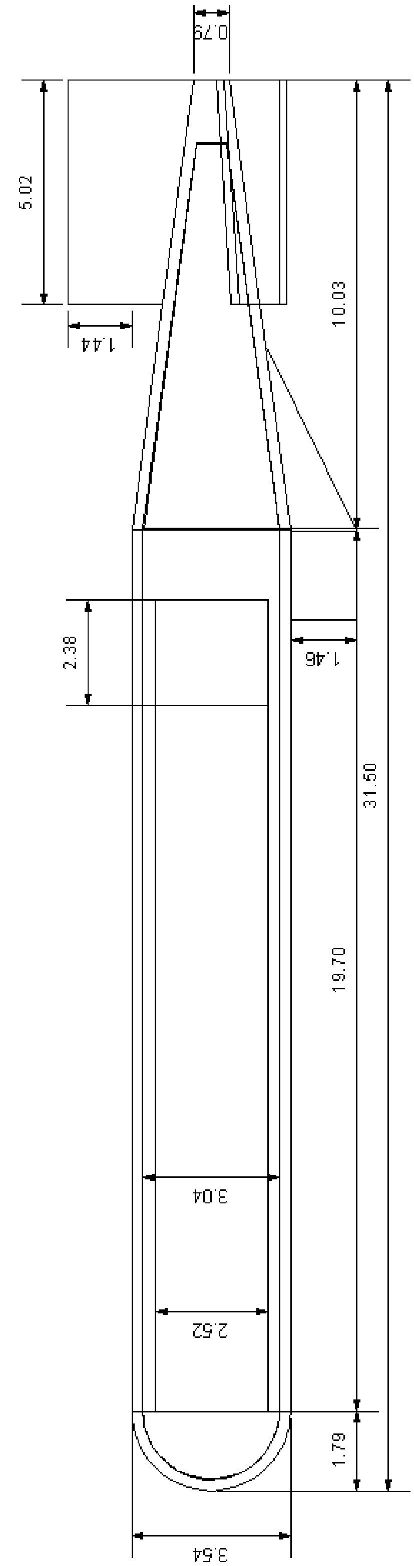

Figure 7: Vehicle Dimensions

Appendix B: Cost Engineering

Table 9: Cost Estimate

Description	Part No.	Company	Price	Notes
Data Logger	XR-620	RBR	$6,260.00	3% discount if 10 or more are ordered
Nycast 12 rod		Aetna Plastics	$197.68	1 ft or 2 ft lengths; four-week lead time
Nycast 12 round tube		Aetna Plastics	$329.50	$197.68 per ft
Foam	MZ-24	Engineered Syntactic Systems	$30.00	$600 per cubic ft
Cable Clamp		Shark Marine	$95.00	Will customize per our specifications
SPRO Heavy Swivels	IJ-117349	Cabela's	$1.74	560 lb test; $8.69 per 5
Jerry Brown 500lb Hollow Spectra	HS075Y500	BHP Tackle	$.37	75 yds for $27.50
Hardware			$20.00	Heli-Coils and Fasteners
Labor Estimate			$1,280.00	16 hours at $80 per hour
Total price			$8,214.29	