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Abstract

The following report details the basis of design for a submarine prototype that simulates an automated evacuation vehicle for offshore structures. This report will outline the progress that has been made since Phase 1 of the Capstone Project. This will include motion and stress simulation results, analytical findings, coding changes, testing procedures, material changes, and deployment modification. LifeSub Engineering is developing this project to prove that submarines can be used for offshore evacuation systems. The final section of this report provides information about the third phase of the project where the prototype will be tested and bring the project to its conclusion.
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1. Introduction

In response to a request by Dr. Michael Hinchey from Memorial University of Newfoundland, LifeSub Engineering has decided to assess the viability of a submersible evacuation system used in offshore platforms. This project was developed to validate the idea that automated underwater vehicles (AUVs) are safer than lifeboats on offshore platforms where they can avoid uncontrolled risks that can arise at the water surface.

In Phase 1 of this project the current evacuation solutions were assessed, a submarine prototype was designed and methodologies were developed for potential deployment strategies, prototype testing procedures, and coding requirements for prototype automation were developed. Future considerations were put into place at the conclusion of this phase to continue design verification with Dr. Hinchey and commence fabrication.

In Phase 2 of this project, optimization of the prototype design was completed and fabrication of the prototype was initiated. During this process, the design has undergone significant evolution in terms of the geometry. The overall dimensions of the hull have been increased and a propeller shroud has been incorporated in the aft for protection. The prototype optimization process was accompanied with analytical lifting calculations and a quarter-model structural design analysis. Upon completion of this design, the fabrication phase of the project was initiated; the status of which is currently ongoing. In conjunction with the structural design of the prototype, work has been ongoing to analyze the motion of the prototype during deployment using Flow3D Computational Fluid Dynamic Software with a focus on vertical deployment analysis. To implement the deployment strategies being refined by this analysis, continued development of the automated system control has been undertaken. This includes the development of control codes for each control component as well as the selection, acquisition, and integration of sensors and control components into a single control system.

This report outlines all of the progress that has been made since Phase 1 and will provide insight into the future work, which will be executed during the third and final phase of this project.

2. Prototype Design and Evolution

Initially this prototype was to be manufactured from 150 millimeter (mm) (6 inch) Aluminum round stock with an overall hull length of approximately 550 mm (21.65 inch). After a discussion of the intended future use of this prototype with Dr Michael Hinchey – prior to the start of fabrication – it was concluded that more internal space was
required to allow for the addition of directional control. To accommodate this additional space requirement, the prototype dimensions were increased to 700 mm (27.56 inch) in length and 175 mm (6.89 inch) in diameter. The revised design makes use of 150 mm (6 inch) internal diameter Polyvinylchloride tube with a wall thickness of 12.5 mm (0.5 inch) with two solid stock Acrylonitrile butadiene styrene (ABS) plastic end caps. In addition, the fasteners connecting the end caps have been modified from Stainless Steel to Nylon M5 socket head cap screws to reduce cost and mitigate the potential for corrosion. At the stern of the prototype, a propeller shroud has been added to the design. This component has been designed to mount onto a modified version of the existing tail, which consists of six equally-spaced Nylon M5 Socket head cap screws, increased from the four-bolt pattern previously selected. Inherent in this design is the ability to stand the prototype vertically in order to easily lift and store the prototype between tests. An eye bolt has been incorporated in the nose of the prototype, which will allow for lifting the submarine for vertical deployment. A visual comparison of these changes can be found in Figure 1 below.

Phase 1

Phase 2

Figure 1 - Prototype Evolution
3. Prototype Analysis

3.1. Lifting Analysis

To ensure safe lifting of the prototype during mobilization and testing, an analytical lifting analysis was completed. In order to deploy the submersible prototype, it must be lifted into position and lowered into the deployment tube before the deployment sequence is initiated. This will be done by connecting a cable or hook rod to the eye bolt on the nose of the submarine. In order to ensure success during this procedure, a failure analysis was conducted to define the constraints for lifting (Appendix A). The maximum lifting force was calculated based on the maximum wet weight of the prototype with an allowable lifting acceleration of 1 \(\text{m/s}^2\). This resulted in a conservatively-estimated applied load of 125N. This load was used to analyze the lifting hook and the critical bolted connections between the end cap and the hull, which occurs between the nose and the hull section.

The eye bolt was first analyzed for bolt tension, tear-out failure, bearing failure, and bending. From the results, the bending stress was found to be higher than the yield strength under full loading in the horizontal direction. To define safe lifting requirements under this loading condition, a safety factor of two was applied to the yield strength and used in the bending stress calculation to determine the limiting force that will cause yielding. With this force representing the maximum horizontal component of the applied lifting force, the allowable lifting angle was constrained to \(\pm 10^\circ\) from vertical (Figure 2). This constraint will be incorporated into the procedure for lifting which will be implemented during testing.

The load condition used for the lifting analysis represents the worst case lifting requirements of the prototype, which will occur in atmospheric conditions during mobilization, deployment, or post-test retrieval for all ranges of prototype orientation. As a result, no further lifting calculations are required for this analysis.

The bolts, which connect the nose to the hull of the submarine, were analyzed next. This was based on the lifting limitations defined from the eye bolt calculations. Axial bolt tension of the four-bolt connection was calculated with the result of 2\% material utilization; thus the design will maintain structural integrity during lifting operations. The torque requirements for the socket head cap screws and eye bolt were limited to 1 N-m, which is below that of the maximum torque limitation allowed for a \(\frac{1}{4}\) -20 UNC Nylon threaded connector.
3.2. Finite Element Analysis (FEA)

A quarter-model hydrostatic pressure analysis was used to validate the structural integrity of the hull. This analysis was completed by cutting the SolidWorks hull assembly longitudinally through the centerline in a horizontal and vertical plane to reveal a quarter of the model. This model was then bounded along the cut planes using a Roller/Slider fixture and fixed in space with a fixed mate at the nose of the model. Due to the thickness of the nose, an assumption was made that a fixture in this location would not affect the results of this analysis. A 60 kilopascal (kPa) pressure was applied to all external surfaces of the hull up to and including the inner surface of each o-ring gland. This load was chosen as a conservative estimate of the maximum differential pressure this prototype will encounter based on an operating depth of 6 meters in fresh water. Beyond this point, no further load was applied. The model was then divided into finite elements using a six millimeter curvature mesh and the analysis was performed.

The analysis yielded a maximum stress of 2.03 megapascals (MPa), this resulted in a limiting factor of safety of 11.47, which occurred along the radial contact between the body of the hull and the tail section in the ABS material of the tail as depicted in Figure 3.
Under these conditions, the maximum deflection of the hull was found to be 35.2 micrometers (μm). This value was deemed to be well below any value that would cause structural yielding within the prototype or affect the accuracy of internally mounted pressure sensors. Figure 4 represents a side profile of the deflection plot with a deformation exaggeration of 500 times that of the actual model deformation.

The results achieved through this analysis validate the structural integrity of the prototype design. With the validation of this design complete, construction of the prototype housing has been initiated. Further insight into the setup and results of this analysis may be found in Appendix B.

3.3. Motion Analysis

3.3.1. Flow3D

Flow3D is Computational Fluid Dynamics (CFD) software that allows users to model fluid flows and determine information such as, anticipated forces, velocities, and pressures. LifeSub Engineering required the utilization of Flow3D for the purpose of modeling the deployment of the submarine. Information which was required involved
obtaining the distance to achieve horizontal-orientation and visual confirmation of the motion of the submarine.

Due to limitations of the Student Flow3D License, it was not possible to develop a fully-refined model. This is because the number of grid cells that could be used was limited at 200,000, resulting in dimensions not being true to size. Some of the dimensions that presented problems in the software included: 1) the tolerance between the inner diameter of the tube and the outer diameter of the submarine (Figure 5), 2) the submarine body thickness (Figure 6), and 3) the point mass diameter - representing the center of mass (Figure 6). Each of these dimensions had to be large enough for Flow3D to capture in the mesh, resulting in errors being introduced into the model.

![Figure 5 - Large Simulated Tolerance between Submarine and Tube](image1.png)

![Figure 6 - Submarine Shell Thickness and Point Mass](image2.png)
The errors that were introduced into the model include:

- Potential submarine rotation within the tube due to large gap dimension, resulting in an accidental preference for rotational direction upon exiting the tube; and,

- Inability to successfully test an increased number of center of gravity locations due to required sizes of the submarine shell and the point mass, resulting in potentially inaccurate motion of the submarine.

The impact of these errors will be reduced significantly with the use of an upgraded Flow3D license, provided by the Client. The actions required to refine the model are discussed in the Future Work section of the report.

### 3.3.2. Flow3D Setup

#### 3.3.2.1. General Pane

To determine the optimal simulation time, LifeSub Engineering ran the model using various simulation durations. The single fluid was assumed to be incompressible, with free surface or sharp interface tracking, and using single precision computational accuracy.

#### 3.3.2.2. Physics Pane

The physics that were implemented into the model included gravity (9.81 m/s\(^2\) downwards), moving and simple deforming objects using the collision model, and viscosity and turbulence using the two-equation model with no-slip or partial slip.

#### 3.3.2.3. Fluid Pane

The single fluid used for the model was water at 15°C with a density of 1000 kg/m\(^3\). This is because the fluid in the wave tank is assumed as fresh water.

#### 3.3.2.4. Mesh & Geometry Pane

The tube and the submarine components were inserted and then assembled in Flow3D. The submarine, after being assembled, was oriented into the tube such that the propeller was facing downwards. The submarine was allowed to move while the tube was fixed in
place. A point mass sphere was introduced into the submarine hollow body to represent the submarine’s center of mass and the total mass of the submarine. The configuration of the tube, the submarine, and the point mass are shown in Figure 7.

![Figure 7 - Tube, Submarine, and Point Mass Configuration](image)

The mesh was set up such that there was a 50x50 cell mesh-plane along the X-Y cross-section of the submarine and the tube, as shown in Figure 8. The Z-direction was given a 65 cell mesh-plane, as shown in Figure 9. This 50x50x65 mesh resulted in a total of 162,500 computational cells being utilized.
In addition, the fluid elevation was chosen such that it was above the submarine and the tube, so both components could be fully submerged. This is shown in Figure 10.

Figure 10 - Fluid Elevation with Submarine and Tube

3.3.2.5. Boundary Conditions

To simplify the model, the boundary conditions were assumed to be opened walls (meaning fluid and objects can pass through the boundaries), with an atmospheric hydrostatic pressure applied in the downward Z-direction. The bottom of the mesh was given a wall boundary condition, simulating the bottom of the deep water tank. In addition, there were no other forces, velocities, or pressures imparted into the mesh, resulting in still water, with no waves or currents. The boundary conditions are shown in Figure 11.
3.3.3. Results

The information that LifeSub Engineering wanted to obtain from this simulation model was to prove that, due to the center of gravity being below the center of buoyancy, the submarine would have a natural tendency to rotate to obtain a horizontal-orientation. This is shown in Figure 12, which is a breakdown of the submarine motion upon exiting the tube.
In addition, it was required to obtain the distance at which the submarine obtained a horizontal-orientation. It was determined that the distance the submarine reaches at this point in the simulation is 1.58 metres (5.2 feet) below the exit of the tube, approximately 2.80 metres (9.2 feet) from the water surface. This position gives the submarine sufficient clearance so that it will not collide with the tube as the submarine propels forward, and allows sufficient ground clearance of 0.80 metres (2.8 feet) such that the submarine will not collide with the bottom of the tank. A summary of these dimensions imposed onto the Flow3D model are shown in Figure 13.

![Diagram showing submarine distances]

Figure 13 - Submarine Distances Summary

4. Fabrication

The construction of the prototype is being carried out in three phases. The first phase of this process will include the fabrication and assembly of the nose, hull, and tail of the prototype, including installation of the o-ring seals and assembly of the components. The completion of this phase consists of CNC lathe and milling operations, which are currently underway, within the machine shop of Technical Services. It is anticipated that the completion of these parts will be within the upcoming week. This operation is shown in Figure 14.
The second phase of fabrication will involve the Rapid Prototyping of the ring guide, tail shroud, and internal mounting sleds, which will be used to situate the internal components of the prototype. The completion of this phase has been estimated at one work week from the time the part files are received by the technicians. This task will be carried out upon verification of the deployment tube dimensions. Purchase and verification of the deployment tube will be completed in the upcoming week. Once these construction phases are underway, the final stage of prototype construction will begin. This phase will cover the remaining fabrication requirements for the submarine, including the fabrication and mounting of the mechanical pre-ballast, wire routing, hose routing, and prototype assembly. This fabrication phase will be completed in conjunction with the commissioning of the prototype.

5. Controls

5.1. Speed Control Code

In Phase 2, code was developed to allow testing of the speed of the Tecnadyne thruster. To achieve this, the code was designed to increment the voltage going to the thruster to +5 Volts (V) and decrement the voltage to -5 V in a continuous loop. This would continuously move the submarine in forward and reverse directions, respectively.
To accomplish this, the experimental circuit setup was used with the sample thruster. In this setup, the sample thruster used two wires and only saw a voltage drop of ±2.5 V as opposed to ±5 V. To get the voltage drop for the thruster, one wire was set to base of +2.5 V while the other had a voltage that varied between +5 V and ground (0 V), which gave the ±2.5 V voltage drop range. For the sample thruster, the digital output for +2.5 V was 127. This meant that one wire could be set to 127 in the code while the other incremented by one up to 254 (+5V) and decremented by one to ground (0 V) in a loop.

The code was established and executed through the experimental circuit setup. The code started the thruster at rest (0 V drop) and accelerated the thruster as it went from 0 V to +2.5 V. At a +2.5 V to 0 V drop, the thruster began decelerating as it continued to rotate in the same direction. At 0 V, it went to rest again. After that, the thruster began accelerating in the opposite direction as the voltage drop ranged from 0 V to -2.5V. When the thruster reached -2.5 V, it began decelerating as the drop changed from -2.5V to 0 V. From here, the process repeats.

This code allowed a looping process that showed acceleration and deceleration of the thruster in both the forward and reverse directions. It provided a basis upon which the Tecnadyne thruster code can be applied to test relative speed of the thruster.

### 5.2. Depth Control Code

The depth control for the submarine was developed using a 3-staging system where each stage is for a specific band or range of depth. The desired depth band is set at the middle stage. In the Depth Control code, the pressure sensor reads the pressure data and stores it in a variable. A slight delay is then initiated and a second reading of pressure is taken, which is then stored in a different variable. The difference of these two variables is taken to provide a change. This change can then be compared to a set change-allowance variable, which will dictate whether the stepper motor adds or subtracts ballast.

At the first stage, the stepper motor continually adds water to bring the submarine down into the next stage. If too much ballast is added and causes the submarine to move too quickly (the change in pressure of the data readings is greater than the allowance limit), then the submarine is prepared for the next stage and a two second delay is set. This stage is the in-between band, or desired depth range, which is governed by a predetermined value. The current submarine depth data is taken from a set target value, and an absolute value is given to provide an offset. This offset is then compared to the change allowance value, and if the offset is less than the allowance limit, the stepper motor removes ballast and goes to the next stage or depth range and a count variable is incremented. If the count is greater than a predetermined limit or the error values is less than the negative of the
change allowance value, the stepper motor removes ballast. This is then put into a continuous loop. See Appendix C for more information.

Although the code can relatively control the depth of the submarine, the aim is to avoid risk of continuous overshooting; to provide relative stability of the submarine in the desired depth band. In Phase 3, this code will be refined to ensure that an efficient proportional-derivative (PD) control loop governs the depth of the submarine.

Also, the goal is to incorporate additional coding for a ballast tank sensor. This would provide a method to escape the main control loop if an error occurs that sends the submarine toward the bottom of the tank. While considering the other sensor readings, if the ballast tank reached a critical pressure, the thruster could shutdown and the ballast could release all water to raise the submarine.

5.2.1. Roll and Pitch Control Code

Additional code will be implemented to control a two-axis accelerometer, which will be used to monitor the pitch and roll of the submarine. Similar to the Depth Control code, an acceptable range will be given for roll and pitch with an upper and lower limit for each respective axis as shown in Figure 22 (Appendix D). Even so, this code will not implement corrective measures that will reset the submarine to its neutral position in the water. This will naturally be done through the lower center of gravity that is vertically close to the center of buoyancy. Over time, the submarine should inherently correct itself, even with mild changes to the ballast tank. The objective of monitoring the roll and pitch is to ensure that the submarine has relatively settled into a neutral position when at the desired depth dictated from the Depth Control code. Once this is done, the thruster can be activated to allow the submarine to evacuate from the structure (Figure 22).

6. Commissioning

Verification of the submarine will be done by testing the coding, evaluating the structural integrity of the submarine under pressure, seeing the responsiveness to ballasting, and assessing the motion after deployment.

Once all test codes are completed using the experimental circuit setup, the codes will be implemented into the completed circuitry for the prototype. After the system and related equipment are working, it will be incorporated into the submarine structure, but not before it passes pressure testing.
When the structure of the submarine is built, it will be tested to verify its sealing capability under pressure. Weights will be placed inside the submarine structure, and the submarine will be placed at the bottom of the deep water tank for one-hour for observation.

If there are no leaks, the internal equipment will be added and ballasting tests will be performed. This will be done through observation of the propeller. As the submarine is lowered into the deep water tank, the propeller will be coded to activate in the desired range of depth for the submarine, which will be set by the pressure sensor and coding. The propeller will be coded to rotate slowly as to not cause significant movement of the submarine as it is lowered. This will be done through dry tests with the thruster. Testing will be done until a desired range for submarine depth is determined.

After ballasting is completed, the submarine will be tested to go through the desired motion and leveling that will be exhibited in the refined Flow3D simulation for Phase 3 (see Future Work section of report). This will be done by adjusting weights if necessary to ensure proper location of the center of gravity. Code will be implemented to remove ballast once the submarine reaches a low depth in the tank, which is a permanent safety measure that is explained in the Depth Control Code section of the report.

When the depth control and launch motion are satisfactory, the submarine will be monitored as it continues to control depth. This will allow observation of the settling time required for the submarine to achieve a neutral position in the desired depth band, as well as the angle range for which the neutral position can be classified. This will be based on how the roll and pitch of the submarine are affected by the ballast system when it attempts to correct the submarine depth.

After this is complete, the full code will be implemented. The code will allow the submarine to activate the thruster and move away from the structure when depth, roll positioning, and pitch positioning are satisfied. This is shown in Figure 22.

7. **Deployment Methodology**

In Phase 1, it was decided that the submarine would be vertically deployed, both nose first and propeller first. In order to orient the submarine from a vertical to a horizontal position, it was decided that the center of gravity would be coincident with the center of buoyancy in the vertical axis, but located below the center of buoyancy longitudinally. This would create a couple moment that would allow the submarine to transition into the neutral position. This technique was proven through the Flow3D simulation using the SolidWorks model, and showed the viability of testing vertical deployment for the
prototype. Even so, the addition of horizontal deployment was added in Phase 2 with a list of possible launch methods for a full-scale submarine on an offshore structure.

In Phase 2, the original deployment strategies presented were modified to reflect propeller-down vertical launching and to include horizontal deployment. The prototype will be tested in both ways and help prove the validity of the full-scale deployment strategies shown in Figure 23 (Appendix E). These processes were developed to present the possible techniques that could be used in a full-scale submarine on an offshore structure. By proving that the prototype can be launched in both the vertical and horizontal positions, it validates the motions involved for these full-scale deployment strategies.

7.1. Prototype Deployment Strategies

7.1.1. Vertical Deployment

The prototype will be vertically deployed in the wave tank through a vertical pipe attached to the carriage above the wave tank. The pipe will have a portion that is submerged, which will be large enough to fully encapsulate the submarine and allow the submarine to be at an appreciable depth where the pressure sensor draws a reading to activate the code. The pipe exit in the water will be at a depth within the bounds for the submarine to rotate into the neutral position. This is outlined in the Flow3D section.

The submarine will be lifted down into the pipe through the use of a cable or hook rod that connects by the attached bolt. The submarine will be released once it is underwater in the pipe. At this point, the coding will initiate due to the pressure reading, and the submarine will draw ballast, (as discussed in the Depth Control Code section of the report).

Once the submarine draws enough ballast, it will sink and settle into the desired depth range. From here, if it is in the relative neutral position, the thrusters will activate and the submarine will move away from the deployment area.

7.1.2. Horizontal Deployment

The prototype will be horizontally deployed in the wave tank through a horizontal pipe attached to the carriage above the wave tank. The pipe will be fully submerged, and will be large enough to fully encapsulate the submarine and allow the submarine to be at an
appreciable depth where the pressure sensor draws a reading to activate the code. For the horizontal launch, this should be well after the point at which the pipe and submarine are fully submerged. The pipe exit in the water will be at a depth within the bounds for the submarine to settle into the neutral position.

The submarine will be within the pipe as it is placed in the water. As the pipe is lowered, the pressure sensor will draw a large enough reading to activate the code. This code will have a delay to ensure the horizontal pipe is situated at the given depth. After this time, the thruster will turn on at a specific speed and time to launch the submarine out of the pipe. These parameters will be determined through testing.

Once the submarine is out of the pipe, it will draw ballast and sink into the desired depth range. From here, if it is in the relative neutral position, the thrusters will activate and the submarine will continue to move away from the deployment area.

7.2. Full-scale Deployment Strategies

In Phase 2, the prototype deployment strategies were changed to reflect the motions that could be exhibited in the potential, full-scale deployment strategies outlined in Figure 23.

For the first strategy in Figure 23, the submarine undergoes a vertical deployment similar to the prototype. A submarine can be lowered off the topsides of an offshore structure through a pipe and into the water where it can acquire ballast. This is similar to the prototype being lowered through the pipe and into the water from the carriage above the wave tank.

For the second and third strategy in Figure 23, the submarine undergoes a horizontal deployment similar to the prototype. In the second strategy, the submarine is in a bay area in the gravity base of the offshore structure. Personnel could enter the bay area from the topsides and go into the submarine. Once everyone is inside, the bay area could be flooded and the submarine can exit into the ocean. The third strategy would be similar, but more closely reflect the method of docking for shuttles at the International Space Station. Personnel could enter the submarine directly from the topsides, and once everyone is inside, the submarine can detach from the structure and drive out of the tube covering.

The idea behind developing these full-scale strategies was to show that submarine motion involved can be validated through the horizontal and vertical launch methods for the prototype. In-depth analysis of these potential, full-scale strategies fall outside the scope of this project; however, general recommendations can be drawn from the prototype testing. This will be done in Phase 3.
8. Future Work

Over the next coming weeks, LifeSub Engineering plans to perform the following tasks:

- Refine Flow3D Model using an upgraded software version;
- Complete construction and fabrication;
- Continue to optimize control codes;
- Perform testing and analysis; and,
- Develop a list of general recommendations for full-scale implementation.

The Flow3D model requires refining due to inaccuracies caused by the coarse mesh (200,000 cells) that was available in the Student License. The Research License of Flow3D will allow for a finer mesh (1 million cells) to achieve greater precision and accuracy. The refining process will involve updating the current submarine model in Flow3D to the refined working SolidWorks model, allowing for more space within the submarine for the placement of the center of gravity. In addition, the spherical point mass will be reduced in size to allow for further space to adjust the placement of the center of gravity. Lastly, using the Research License of Flow3D, forces will be inserted at desired points in time to model the buoyancy forces and thrust forces as the submarine reaches the desired depth and orientation.

Currently, the different parts and components for the submarine are being delivered and are being inspected by LifeSub Engineering team members. As each component passes inspection (dimensions are correct, finish is clean, etc.) they will be assembled to form the submarine. The submarine will be assembled with all internal workings to ensure there is sufficient space within the submarine. Once this is complete, the submarine will be disassembled and the different components will be prepared for the required tests outlined in the Commissioning section of the report.

While this is ongoing, LifeSub Engineering will continue to refine and optimize the submarine control codes.

The testing and analysis phase will be completed concurrently with the optimization of the control codes. As each test is completed, the results will be analyzed to determine the requirements for optimizing the different parts of the control code and the methods by which the submarine and components are being tested.

Lastly, LifeSub Engineering has decided to develop a list of general recommendations for full-scale implementation based on results acquired from testing. This will be outlined in Phase 3.
Appendix A:
Lifting Analysis
Bolt Tension

The maximum weight that the submarine can be is when the tank is full (11.21142 kg).

\[ F = mg \]

\[ F = (11.200 + 11.42 \times 10^{-3}) \times g \]

\[ F = 11.21142 \times 9.81 \]

\[ F = 109.98 \text{ N} \]

\[ F \approx 110 \text{ N} \]

Our desired acceleration for lifting is 1 m/s²

\[ F_{\text{net}} = F_{\text{lift}} + F_{\text{weight}} \]

\[ F_{\text{net}} = (11.2 \times 1) + 110 \]

\[ F_{\text{net}} = 121.2 \text{ N} \approx 125 \text{ N} \]
Area = \pi r^2

A = 1.2903 \times 10^{-5} \text{ m}^2

\sigma_{\text{actual}} = \frac{F}{A}

\sigma_{\text{actual}} = \frac{125}{1.29032 \times 10^{-5}} = 9.68 \text{ MPa} \approx 10 \text{ MPa}

Elastic properties of the eye bearing (Nylon):

Young's Modulus (Modulus of Elasticity) E = 2-4 GPa

Ultimate Tensile Strength \( S_u = 45 - 90 \text{ MPa} \)

Yield Strength \( S_y = 45 \text{ MPa} \)

Maximum strain that bearing can have:

\[ E = \frac{\sigma}{\varepsilon} \]

\[ \varepsilon = 4.26 \times 10^{-3} \]

As long the \( \sigma_y > \sigma_{\text{actual}} \) and also it is just 20% of the yield strength this eye bearing will work perfect and also the material of this bearing will prevent the corrosion.


Tear Out

Area of the shearing plane \( \bigcirc \times 2 \)

\[
A = \pi r^2 \times 2
\]

\[
A = \pi (0.25)^2
\]

\[
A = 0.0491 \text{ inch}^2
\]

\[
A = 3.11677 \times 10^{-5} \text{ m}^2
\]

\[
\sigma_{\text{actual}} = \frac{F}{A}
\]

\[
\sigma_{\text{actual}} = \frac{125}{3.11677 \times 10^{-5}}
\]

\[
\sigma_{\text{actual}} = 4.0106 \text{ MPa}
\]

Bearing Failure

*Area of the bearing = \( \pi r \times \text{thickness} \)*

\[
A = \pi \times \frac{0.25}{2} \times 0.25
\]

\[
A = 0.09817 \text{ inch}^2
\]

\[
A = 6.3338 \times 10^{-5} \text{ m}^2
\]

\[
\sigma_{\text{actual}} = \frac{F}{A}
\]

\[
\sigma_{\text{actual}} = \frac{125}{6.3338 \times 10^{-5}}
\]

\[
\sigma_{\text{actual}} = 2.0 \text{ MPa}
\]
Bending Stress

Bending will occur at the end of the submarine where the bolt is.

\[ M_d = F \cdot d \]

\[ M_d = 125 \times 0.02032 \]

\[ M_d = 2.54 \text{ Nm} \]

Bending Stress on the bearing:

\[ \sigma_{Bending} = \frac{M_y}{I} \]

\[ \sigma_{Bending} = \frac{M_y}{\frac{1}{4} \pi r^4} \]

\[ \sigma_{Bending} = \frac{2.54 \times 0.00635}{\frac{1}{4} \pi (0.00635/2)^4} \]

\[ \sigma_{Bending} = 101 \text{ MPa} \]

As long as the bending stress is greater than Yield Strength \( S_y \) calculation need to be done for the maximum force that can be allowed by the nylon.

The lifting requirements of the submarine have been designed to accommodate a maximum allowable bending stress of \( 0.5S_y \).
Allowable angle of lift is the interval between the longitudinal axis and ±10°
Bolt Tension

\[ A_t = \frac{\pi}{4} \left( \frac{d_r + d_p}{2} \right)^2 \]

Where the \( d_r \) and \( d_p \) is pitch diameter and the minimum of the major diameter of the bolt.

\( d_r = 0.2425 \text{ inch} = 0.0061595 \text{ m} \)

\( d_p = 0.2225 \text{ inch} = 0.0056515 \text{ m} \)

\[ A_t = \frac{\pi}{4} \left( \frac{0.0061595 + 0.0056515}{2} \right)^2 \]

\[ A_t = \frac{\pi}{4} \times 3.4875 \times 10^{-5} \]

\[ A_t = 2.739 \times 10^{-5} \, \text{m}^2 \]

\[ \sigma_{actual} = \frac{F}{A} \]
\[ \sigma_{\text{actual}} = \frac{110 \, N}{4 \times A_t} \]
\[ \sigma_{\text{actual}} = \frac{110}{1.096 \times 10^{-4}} \]
\[ \sigma_{\text{actual}} = 1.003 \, MPa \]

Maximum Torque of the Bolt and the Eye Bolt

\[ F_{\text{preload}} = 0.66 \times \sigma_{\text{Yield}} \times A \]
\[ F_{\text{preload}} = 0.66 \times 45 \times 10^6 \times \pi r^2 \]

Bolt:

\[ F_{\text{preload}} = 871.73 \, N \]
\[ T_{\max} = K \times D \times F_{\text{preload}} \]
\[ T_{\max} = 0.2 \times 0.00635 \times 871.73 \]
\[ T_{\max} = 1.11 \, Nm \approx 1 \, Nm \]
Eye Bearing:

\[ F_{\text{preload}} = 885 \, N \]

\[ T_{\text{max}} = K \times D \times F_{\text{preload}} \]

\[ T_{\text{max}} = 0.2 \times 0.00635 \times 885 \]

\[ T_{\text{max}} = 1.12 \, Nm \approx 1 \, Nm \]
Appendix B:

FEA Analysis
Figure 15 - Roller/Slider Fixture

Figure 16 - Fixed Geometry location on nose cone
Figure 17 - Applied Load - 60kPa

Figure 18 - 6 millimeter curvature mesh
Figure 19 - Von Mises Stress Plot

Figure 20 - Strain Plot
Figure 21 - Factor of Safety Plot
Appendix C:
Codes for Submarine Control
/********************************************
**********
SUB SPEED CONTROL
*********************************************/

/* header files */
#include <16f876.h>
#define FUSES HS,NOWDT,NOPROTECT
#define FUSES NOBROWNOUT,NOPUT,NOLVP
#define DEVICE ADC=10  // 10 BIT
#define I2C(master, sda=PIN_C4, scl=PIN_C3, slow)
#define DELAY(clock=20000000)
#define ORG 0x1F00,0x1FFF{}

/* declare variables */
float data;
long count;
int power;
int base;

void n(int out);
void m(int out);

/* main code */
void main()
{

  // setup ports //
  setup_adc_ports(ALL_ANALOG);
  setup_adc(ADC_CLOCK_INTERNAL);
  setup_timer_2(T2_DIV_BY_16,254,1);
  set_adc_channel(2);
  delay_us(21);
  n(127); m(127);

  /* start mission */
  while(TRUE) {
    data=read_adc();
    delay_ms(2);
    if(data>44.0)
      {break;}
  
  // data //
  delay_ms(1000); 

  base=127;
  power=base;
  count=0;

  /* control loop */
while(TRUE)
{
    count++;
    delay_ms(10);
    if(count<127 || count>381)
    {
        power=power+1;
        n(base); m(power);
    }
    if(count>127 && count<381)
    {
        power=power-1;
        n(base); m(power);
    }
    if(count>508)
    {
        count=0;
    }
}

void n(int out)
{
    i2c_start();
    delay_ms(1);
    i2c_write(0x5e);
    delay_ms(1);
    i2c_write(0);
    delay_ms(1);
    i2c_write(out);
    delay_ms(1);
    i2c_stop();
}

void m(int out)
{
    i2c_start();
    delay_ms(1);
    i2c_write(0x5e);
    delay_ms(1);
    i2c_write(1);
    delay_ms(1);
    i2c_write(out);
    delay_ms(1);
    i2c_stop();
}
SUB DEPTH CONTROL

/* header files */
#include <16f876.h>
#include <fuses.h>
#include <device.h>
#include <i2c.h>
#include <delay.h>

#include <16f876.h>
#include <fuses.h>
#include <device.h>
#include <i2c.h>
#include <delay.h>

/* declare variables */
int it,times;
float target,error;
float band,stop;
float new,old;
float offset;
float change;
float data;
long count;
long limit;
int stage;
int lag;

void add(int one, int two);
void sub(int one, int two);

/* main code */

void main()
{

  // setup ports //
  setup_adc_ports(ALL_ANALOG);
  setup_adc(ADC_CLOCK_INTERNAL);
  setup_timer_2(T2_DIV_BY_16,254,1);
  set_adc_channel(2);
  delay_us(21);

  /* start mission */
  while(TRUE) {
    data=read_adc();
    delay_ms(2);
    if(data>11.0)
    {break;}}

delay_ms(10000);
data=read_adc();
delay_ms(2);
old=data;

// data //
delay_ms(1000);
limit=10000;
target=512.0;
band=250.0;
stop=50.0;
times=1;
stage=0;
count=0;

/* control loop */

while(TRUE)
{
  /* ballast tank */
  set_adc_channel(2);
delay_us(21);
data=read_adc();
delay_ms(2);
new=data;

error=target-data;
offset=abs(error);
change=new-old;
old=new;

if(stage==0 && change<+stop)
  {add(lag,times);delay_ms(2000);}
if(stage==0 && change>+stop)
  {stage=1;delay_ms(2000);}
if(stage==1 && offset<stop)
  {sub(lag,times);delay_ms(2000);}
if(stage==1 && offset<stop)
  {stage=2;delay_ms(1000);count++;}
if(count>limit || error<-stop)
  {sub(lag,times);}
}

void add(int one, int two)
{
  it=0;  while(it<times){it++;
  output_high(PIN_B3); output_low(PIN_B2);
  output_high(PIN_B1); output_low(PIN_B0);
delay_ms(lag);
  output_low(PIN_B3); output_high(PIN_B2);
  output_high(PIN_B1); output_low(PIN_B0);
delay_ms(lag);
  output_low(PIN_B3); output_high(PIN_B2);
}
output_low(PIN_B1); output_high(PIN_B0);
delay_ms(lag);
output_high(PIN_B3); output_low(PIN_B2);
output_low(PIN_B1); output_high(PIN_B0);
delay_ms(lag);} }

void sub(int one, int two) {
    it=0; while(it<times){it++;
    output_high(PIN_B3); output_low(PIN_B2);
    output_low(PIN_B1); output_high(PIN_B0);
delay_ms(lag);_
    output_low(PIN_B3); output_high(PIN_B2);
    output_low(PIN_B1); output_high(PIN_B0);
delay_ms(lag);
    output_low(PIN_B3); output_high(PIN_B2);
    output_high(PIN_B1); output_low(PIN_B0);
delay_ms(lag);
    output_high(PIN_B3); output_low(PIN_B2);
    output_high(PIN_B1); output_low(PIN_B0);
delay_ms(lag);_
    output_high(PIN_B3); output_low(PIN_B2);
    output_high(PIN_B1); output_low(PIN_B0);
delay_ms(lag);
Appendix D:

Code Sequence Diagram
Appendix E:

Full-Scale Deployment Strategies
Figure 23 - Full-Scale Deployment Strategies
Appendix F:

Part Drawings
**Support Ring**

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**Dimensions:**
- Ø 0.5315
- Ø 0.683
- Ø 0.250

**Notes:**
- Deburr and break sharp edges
- Surface finish: unless otherwise specified
- Tolerances: linear, angular

**Scale:** 1:2

**Drawing Information:**
- Do not scale drawing
- Revison: A1

**Weights:**
- See P.O.

**Material:**
- See P.O.
Appendix G:

Project Schedule
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**Project Management Schedule**  
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