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# BYOE: Soft Robotic Fish Project

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# BYOE: Soft Robotic Fish Project

***Abstract.*** This paper presents a college-level project to develop a simplified soft robotic fish with the end goal of creating an engaging toy for children. The project uses 3D-printed components and molded silicone to create a hydraulically actuated fish. The motivation for developing this project was to introduce students to soft robotics with an emphasis on learning the concepts of soft materials fabrication, 3D printing, hydraulics, buoyancy, and actuation and control. The proposed activity was created by undergraduate engineering students to be used as teaching materials for other undergraduate students and to expose them to soft robotic concepts. The project was developed based on the idea that the development of learning activities by students and for students might increase engagement and interest. Implementation can include hands-on laboratory exercises or small group learning activities. Students are tasked with producing a functional and enjoyable toy product for the target audience emphasizing practical applications of soft robotics. The fish toy is non-autonomous and powered externally through tubes and two hand pumps or syringes to generate a hydraulic pressure differential to move the tail and propel the fish toy. This design provides an opportunity for students to explore non-traditional materials and actuation methods. Instead of using typical rigid link mechanisms, this project uses soft materials for actuation, which brings a unique perspective to engineering. The project contains more than movement or locomotion by including various metrics of success. The metrics include reliability, durability, simplicity of assembly, and potential incorporation of extended features and experiences into classrooms. An example of this would be onboard actuation and control which will be discussed as an alternative. The project enables a comprehensive learning experience that exposes students to many different aspects of soft robotics, ideally allowing them to improve their knowledge retention. This paper presents comprehensive documentation of how the student-designed prototype was constructed and could be adapted for a classroom, an itemized list of requisite materials, and explores potential design permutations. It serves as a valuable reference for the potential integration of the project into the mechanical engineering curriculum at Rowan University through courses like Machine Design and Mechatronics, or at other institutions that offer similar courses.

## Motivation

This BYOE paper was developed by three undergraduate mechanical engineering students at Rowan University, who were new and unfamiliar with the soft robotics field. The team expressed an interest in acquiring expertise in the field while endeavoring to craft an original project utilizing soft robotics. The objective was centered around creating compelling projects tailored for educational purposes, aimed at enhancing undergraduate learning experiences in mechanical engineering through soft robotics. As soft robotics is a relatively new field [1], many undergraduate students are unaware of its existence or unfamiliar with the opportunities in this field. As a result, there is an urgent need to increase students' awareness of this emerging engineering field. There are many valuable engineering skills students can be exposed to through the field of soft robotics, including mechanical design, soft material behavior, physics principles, and creative thinking during design. Utilizing soft materials for such a project offers the advantage of facilitating smooth movement without necessitating the incorporation of rigid links. This flexibility not only enhances the overall fluidity of motion but also contributes to a more adaptable and responsive design, particularly in dynamic environments where flexibility is paramount [2]. Traditional course-based robotics projects include a single actuation principle, mostly using electric motors [3]. In contrast to conventional system designs characterized by servo motors, rigid linkages, and gears, the envisioned robotic fish project provides students with the chance to delve into two alternative principles: hydraulic and pneumatic actuation. This approach represents a departure from the extensive mechanical work associated with traditional designs. Hydraulic and pneumatic actuation methods can be seamlessly integrated into a classroom environment utilizing readily available resources which we detail in this paper. Hands-on experiences and projects-based learning as proposed in this activity represent some of the best ways for students to learn new knowledge and develop a deeper understanding of the underlying actuation principles, material properties, and behaviors [4]. Furthermore, the project tasks students with designing a soft fish toy tailored for children, setting up an opportunity to foster an entrepreneurial mindset among students. Our project endeavors to ignite interest among students in the realms of soft robotics and innovative design.

**Design Intent**

There are many ways one can actuate soft robots which include hydraulic, pneumatic, combustion, and magnetic actuation [5]. This paper examines the application of hydraulic actuation, a less frequently employed principle, in energizing a soft robotic mechanism. Hydraulic actuation is the method of using liquid properties to perform mechanical functions in a system as demonstrated with the robotic fish [6]. The advantage of hydraulic actuation is its high power generation compared to pneumatic or other similar actuation principles [7]. The project's appeal lies in its straightforward materials and design, which facilitate the effective demonstration of these concepts in classroom settings through low cost, hands-on activities.

Throughout the project, students should be encouraged to brainstorm and design their fish toy, exploring a variety of design options that reflect how their creations will look and function. The expansive design scope of this project not only cultivates students' creativity but also presents them with challenges to overcome as they navigate through the open-ended design process. By introducing elements such as varying design constraints or randomized features specific to each project, students are encouraged to think outside the box, ensuring a diversity of ideas. This approach not only fosters innovation but also enriches learning as students draw inspiration from the wide array of solutions and perspectives presented by their peers' projects and existing soft robotic fish designs [3].

**Educational Context**

The presented robotic fish project would be a great implementation of soft robotics concepts for college-level engineering students due to its unique actuation principle and creative, open-ended design process. For instance, this project provides an opportunity for second-year engineering students to engage in practical engineering design exercises and acquaint themselves with the domain of soft robotics. Students would be exposed to parametric design, fabrication, and basic fluid mechanics theory applied to soft materials, which, in the long run, will improve students' abilities to learn and link together other theoretical concepts. Pre-existing expertise conducive to this project would encompass proficiency in utilizing 3D modeling software such as SolidWorks, coupled with foundational experience in 3D printing techniques. Other skills could include an understanding of various actuation principles (e.g., hydraulics or pneumatics) and silicone fabrication processes. While an in-depth familiarity of the silicone curing process and prior hands-on experience in silicone mixing and degassing would be beneficial, these skills could be taught through the project activities. Students should also be prepared to troubleshoot issues, as theories may not always directly translate to functional physical prototypes, which is an important lesson for aspiring engineers to learn. In addition, the project can be tailored or even simplified to target different audiences, depending on the duration and difficulty level of the learning activities. For the simplified project, pre-made 3D-printed molds and ready-to-assemble parts can be made available for students.

Materials used to accommodate the hydraulic system included Ecoflex silicone rubber (that allows large deformations and motions), thermoplastic polyurethane (TPU), and polylactic acid (PLA) filaments. For instructors and classroom preparation, it is essential to have a 3D printer, a vacuum chamber, and a power drill set with bits. Designing the molds for the body and tail of the fish required 3D modeling skills using computer-aided design (CAD) software, such as SolidWorks which was used in our project prototype. Designing an appropriate body with chambers (see Figure 1), where the water flows through and builds a pressure to cause material deformation, is directly related to various physics concepts. Creating chambers of the proposed size and thickness to withstand increased pressure will allow the fish to bend the tail and exert force through the tail when it is actuated, resulting in a forward propulsion. Meticulous design and fabrication of chambers via the molding process facilitate the production of sufficiently spacious and appropriately configured chambers, ensuring controlled water flow conducive to regulating the fish's movement. With this consideration in mind, the body shape used in our prototype was crafted into a triangular form with rounded edges to minimize the resistance during water traversal. To enable additional design flexibility, students will be encouraged to experiment with the shapes of their tails and interior chambers to maximize propulsion in future project implementations.

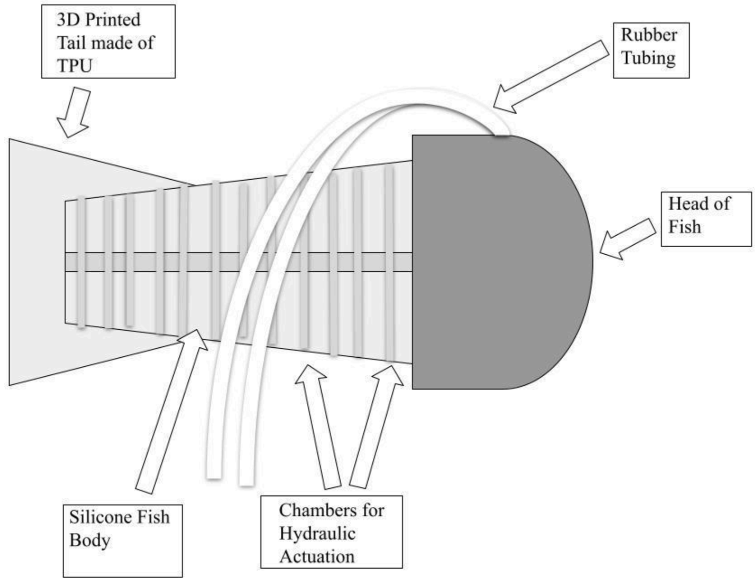



**Figure 1:** Illustration of soft robotic fish schematics.

Based on our experience designing the prototype, we recommend organizing students into small groups to conceive 3D-printed models of the fish body incorporating hydraulic actuation. Utilizing 3D-printed components and silicone, students can then undertake the challenge of crafting a functional prototype, with each group delivering a presentation on their respective designs. Emphasizing simplicity, the project facilitates a straightforward molding process and encourages experimentation with fluid chamber dimensions. Alternative iterations of the project could involve the design of diverse body or fin configurations, offering students further valuable insights into fluid dynamics and actuation principles. Ideas for potential design variations could include fins that are considered "active" and fins that are considered "passive", where "active" fins would help propel the fish. A major but possibly important variation would be the size of the chambers. A smaller chamber would result in smaller flow rates, whereas a larger chamber size would increase the flow rate. At the same time, the chamber size would also affect the overall weight of the fish toy and the drag force when it moves through water. Therefore, broadening students' understanding of applied concepts and challenging them to consider contradicting design parameters through this soft robotic project are essential.

The ultimate objective of this project is to integrate it into a classroom setting for student engagement, although this implementation has not yet occurred due to time constraints. Consequently, there was no opportunity to gather feedback or results from potential students who would complete the project that we, the student authors, designed. However, the student design team found the project highly engaging, as it allowed us to innovate and progress from ideation to a tangible prototype. We incorporated concepts such as soft materials and fluid dynamics into the design work, extensively experimenting with silicone variations and mold shapes. Additionally, we applied fundamental fluid dynamics principles to estimate the required force for proper actuation of the fish. Throughout the project, the team encountered and learned from challenges, contributing to a deeper understanding of the soft robotic fish's functionality and iterative model enhancement.

## Learning Outcomes of the Project

There are several learning outcomes that we anticipate students will gain from completing this project, some of which target skills traditionally covered in mechanical engineering courses while others may be more broadly interesting in the general engineering field. Students will learn to create various parts from non-traditional engineering materials, demonstrating an understanding of unique engineering design and fabrication principles. Due to a specific requirement that the product is designed for a target audience, students will have to think about how their customers (i.e., children) would interact with this toy and how to make it accessible for a certain age range, which will stimulate them to engage their entrepreneurial mindset. Students will learn about the concepts related to soft robotics and actuation principles and learn effective techniques in CAD and parametric design. Throughout the process, students will be able to learn from the challenges of the project as well as their experiences and observations. This allows students to cultivate critical thinking and problem-solving skills essential to the project. We have separated the learning outcomes by topics that are closely related to mechanical engineering and topics that are more broadly applicable.

Mechanical Engineering Learning Outcomes

- Design and fabricate a hydraulic actuation system using soft components and assembly
- Explain how hydraulic actuation can be used to propel a soft robotic fish

General Engineering Outcomes

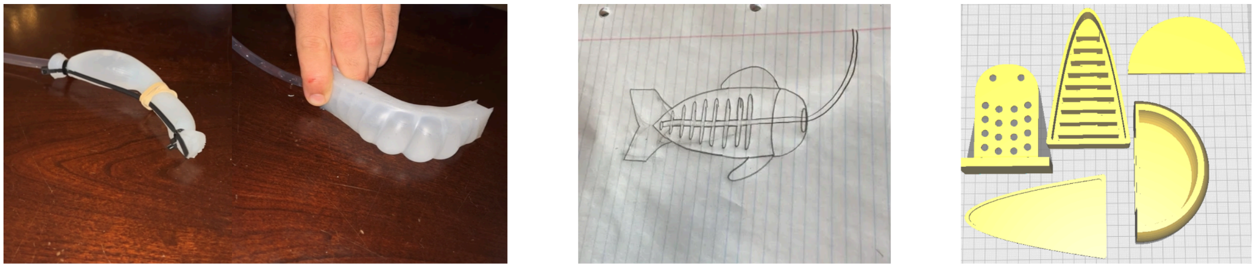
- Create a design that implements entrepreneurial practices to meet an audience's needs
- Apply parametric design and engineering troubleshooting
- Design and iterate on prototypes using CAD and 3D printing of molds

Students' achievements will be assessed based on their attainment of the aforementioned learning objectives, successful completion of the soft robotic fish within specified time constraints, and evaluation of the swimming capability of their fish toy.

## Activity Execution

This section provides a sample of how such an activity could progress in a typical classroom. The sample of progression was based on the design process of our team, which includes three junior undergraduate students from mechanical engineering, in creating the project from scratch. This attempt also documents the lessons learned and captures key insights on the activity executions.

Once the project has been assigned, students should be encouraged to come up with their design for the fish and to add their defining features to enhance the fish's capabilities to swim. The following steps can be used to run this activity in a classroom within 6-7 weeks to help students complete the activity (steps can be rearranged to fit the student's design). We provide details about our prototype design process to add additional insights into how the project could be incorporated into a course.



a) b) c)

**Figure 2.** a) Demonstration of hydraulic actuation principle (fluid being pumped through tubing) by providing a bending motion within the silicone tube. b) The original hand drawing of the final prototype. c) Mold and body components for the final design.

1) Instructors can demonstrate a simple actuation using a hydraulic system. A sample is shared in Figure 2a, showing the hydraulic actuation principle with a bending motion. Instructors must discuss how the chamber size and material structures can affect the capability of actuation and bending motion through the silicone mold.

2) Next, instructors can ask students to brainstorm ideas and sketch their designs for their fish. Students should consider how the actuation chambers are integrated into the fish.

   ○ Figure 2b shows a hand sketch of the fishtail.

3) An initial prototyping process can include the fabrication of simple rectangular shapes that focus on understanding the basics of hydraulic actuation as demonstrated in the initial prototypes (see Figures 2a and 3).

   ○ The goal of these prototypes for our own process was to learn and understand how silicone behaves and expands when water or another fluid is pumped into the internal chambers. As seen in Figure 2a, the original fishtail prototype is attached using zip ties to inflate or pump the fluid to create bending. In the first, more basic prototype (Figure 2a), one zip tie was also attached along the body of the tube-shaped fishtail to provide rigidity and allow it to bend in only one direction.

**Figure 3:** Silicone mold in the shape of the body of the fish.

4) The next step could include the preparation of molds for fabricating the body components based on students' hand drawings to visualize how their fish will function in water.

Students can use SolidWorks or other CAD modeling packages to design the molds or modify the models prepared ahead of time by the instructor for demonstration purposes. Students will also need to make sure to design the head of the fish around the body components to allow for proper assembly. The fish should be constructed of three main components, including the 3D-printed head, the silicone body which will need to have 3D modeled molds, and the 3D-printed rear fin which can be seen in Figure 4.

- The goal of our final prototype was to attach two silicone body molds that the team had experimented with in the third stage. To start, we made a new mold that was similar to the shape of the fish's body seen in Figures 3 and 4. The fish head (shown in Figures 1 and 4) was then designed around the shape of the body to allow for the attachment of the two components. Once these components were completed, the team used TPU filament to make a tail that would mainly be used to connect the two main silicone body parts. Its second use was to provide slight stiffness and act as a backbone to aid the body in pushing the water and helping the fish swim smoothly.

5) Next, these molds and components should be 3D printed by the students.

- Our group started with relatively small chambers for the printed molds, after troubleshooting, we concluded the chamber size needed to be larger to provide a smoother and more accurate flow. Therefore, it is important to note that the chamber size is a critical design parameter when considering the tail's bending motion and the flow of water.

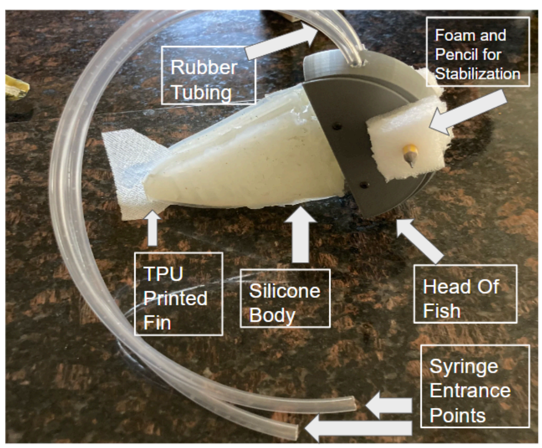



**Figure 4:** Final design with labels.

6) To start with the fabrication process, students would first need to learn how to mix both components (i.e., base polymer and curing agent) of the silicone rubber and use vacuum chambers to remove trapped air bubbles. Ecoflex 00-20 silicone, which was used in our prototyping, comes with a molding protocol that instructors can provide to the students for them to learn about the process. After degassing, students will pour the silicone into their molds and allow it to cure until firm and dry. The duration varies based on the

selected product (minutes to hours). A suggested alternative solution for simplification is to use silicone rubber material that may not need a degassing process.

  - We used multiple prototype iterations to familiarize ourselves with the process (e.g., Figure 2a). This may be useful for instructors to do with their students.

7) The tubes would then need to be attached to the body pieces through the head which will complete the actuation of students' fish. Attachments will need to be made between the silicone pieces and the 3D-printed body components to complete the construction of the fish. Screws, nuts, and silicone can be used to secure these components together. In addition, 3D-printed TPU pieces can be used to aid the components that need to be attached due to the flexibility of TPU and its ability to adhere to other 3D-printed pieces. If students fail to have the actuation principle work, they must repeat steps 4-6 in order to have a functional prototype at the end.

  - Based on our design, we had two tubes, one that would go into each mold, allowing one mold to bend one way and the other mold to bend in the opposite direction. Next, we drilled holes through the head to allow access to the tubes. These pieces were connected using extra silicone for a stronger attachment, along with a few screws and nuts to secure the body of the fish to its head.

8) The final designs can then be tested by first measuring the bending angle of the tail and later tested in large bins full of water where students can see how their fish performs in the water. Designs can be evaluated based on whether students' designs have forward movement in the water as well as if the actuation of the design moves the same way a real fish would.

  - We encountered challenges with our prototype being balanced in the water. Based on our design, we recommend that if students have issues with the fish not being balanced in the water, holes can be drilled through the fish head and a pencil or dowel can be placed through these holes along with styrofoam placed at the ends of the pencil/dowel. This is how we fixed the balancing issues we encountered. We will further discuss how our prototype performed in the next section.

9) While simple, the development of soft robotic fish toys necessitates an entrepreneurial mindset, pivotal for the market trend analysis in the toy industry as well as for the optimization of design and manufacturing processes. This entrepreneurial approach is fundamental to the project's design phase, ensuring the creation of a viable and impactful product. We recommend highlighting this element of the project by encouraging students to present their deliverables as potential commercial products, highlighting the key elements that they think will make their products good toys.

**Sample Prototype Performance**

To demonstrate the feasibility of the project for ourselves, we tested our prototype in water. Two different environments were utilized to test the fish including a tub filled with water (Figure 5) and a pond (Figure 6). In the small tub, a pencil was drilled through the head of the fish to stabilize the head and only allow movement to the body and tail. Once the stationary actuation was validated, the fish was placed into a pond to test its movement. Testing the soft robotic fish in a pond helped gain information on how fast and how far the fish swam, and whether or not the fish could stay afloat. After testing, it was found that the fish swam at a speed of approximately 0.09 m/s. Using syringes to control hydraulic actuation led to slowing down the fish's movement and making it difficult for the fish's tail to swing back and forth rapidly. The fish was able to swim over 0.60 meters but was limited in distance due to the length of the tubes connected to the syringes. Finally, the fish was successful in staying afloat due to the pencil acting as a balancing agent using styrofoam squares. The long tubes and syringes caused the actuation of the fish by pumping water in and out of the body letting the fish swim with forward movement in the pond, ultimately proving that hydraulic actuation could make the fish toy function.

**Figure 5:** The final prototype demonstrating stationary movement using water pumped from syringes and plastic tubes.

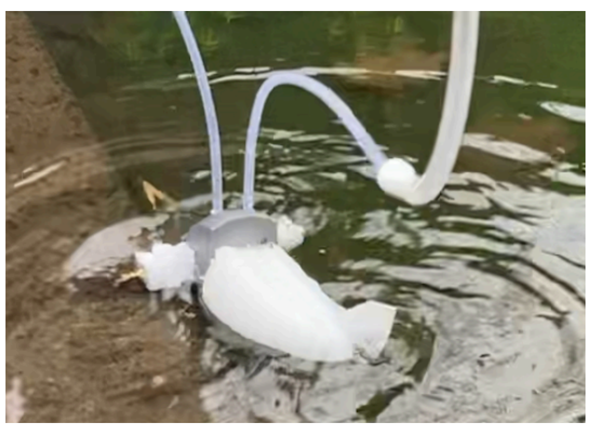


**Figure 6:** The final prototype is swimming and mimicking the movement of a real-life fish in a pond.

## Closing Summary

In summary, the integration of this project into a classroom setting has the potential to yield multiple educational advantages for students. These include the acquisition of skills in generating diverse 3D-printed body components from unconventional engineering materials, showcasing comprehension of distinctive engineering design and fabrication concepts, and employing an entrepreneurial approach to develop a product tailored to a specific audience. To achieve this, students will have to think about how their targeted customers, i.e., children in this case, would interact with this toy and how to make it accessible for a certain age range. Finally, they will identify issues related to soft robotics and actuation principles as well as gain experience in a new and expanding field of soft robotics.

We explored several ways to make this activity more complex and interesting, including making the fish autonomous. While different methods were explored, the main focus was to make the project engaging and target specific learning objectives without being overly complicated. Keeping this in mind, we used syringes to manually power the fish since it was the easiest way to implement hydraulic actuation in a classroom environment and could be replaced with pumps for more advanced courses. Another alternative that could increase the complexity of this project would be having students perform calculations on speed and force before construction and testing for accuracy.

By completing this project, we anticipate that students will learn more about the soft robotics field, or possibly pursue this field for their career. Based on our own experiences as student designers, we think this project will enable students to use engineering training and their creative thinking to design their soft robotic fish as well as incorporate other objectives such as having various fin designs, measuring the forces required to propel the fish, and flow visualization. By acquiring a small list of materials, this project can be easily replicated and adapted by instructors in a classroom setting. This would be a great project for undergraduate engineering students to expand their knowledge of basic design principles, soft materials, and fabrication.

**Acknowledgments**

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**Appendix A - Materials List**
**(Vendor - Amazon)**

| Material | Cost | Quantity |
|---|---|---|
| Smooth-On Ecoflex 00-20 Super Soft Silicone Rubber | $34 | Pint Unit |
| OVERTURE PLA Filament 1.75 mm PLA 3D Printer Filament, 1 kg Cardboard Spool , Dimensional Accuracy +/- 0.02mm | $14 | 1kg Spool (2.2lbs) |
| OVERTURE TPU Filament 1.75 mm Flexible TPU Roll, 95A Soft 3D Printer Filament, Dimensional Accuracy +/- 0.02 mm (TPU Black) | $21 | 1kg Spool (2.2 lbs) |
| 3D printer | 150$-$1000 | One printer minimum |
| 2 Gallon Vacuum Chamber, Upgraded Multipurpose Acrylic Vacuum Degassing Chamber, Transparent Vacuum Chamber, for Resin Degassing, Silica Gel Degassing | $120 | One minimum with a vacuum |
| Clear Tubing Assortment, 2 mm 3 mm 4 mm 5 mm ID, Flexible Plastic Tube Hose Set For Home Repair Water Oil Transfer Aquarium, BPA Free and non-toxic | $10 | 12 Meters in length and 1 mm in Thickness |
| 20 mL Syringe Catheter Tip with Covers, Large Plastic Syringes for Jello Shots Syringe Party, Liquid, Oral, Feeding Pet, Food, Dispensing- Individually Sterilized Sealed | $21 | 50 Pack |

| | | |
|---|---|---|
| Cable Zip Ties, Black Assorted Sizes 12+8+6+4 Inch, Multi-Purpose | $5-$10 | 400 Pack |
| MBC Mat Board Center, 11x14 inch White Foam Boards, 1/8" Thick | $14 | Pack of 10 Acid-Free Foam Boards |
| LUPANTER 180 pcs SAE Stainless Steel Nuts and Bolts Assortment Kit, Including 6 Sizes 1/4-20 Hex Bolts, Flat Washers, Lock Washers. | $17 | 50 Pack |
| Dewalt Drill Set | $99 | 1 set |

## Appendix B - Technical Drawing