Suction Cup System for Biologging Tags

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1. Introduction

1.1 Executive Summary

The practice of attaching electronic tags to animals for data acquisition, known as biologging, has been widely used to study the movements, behavior, and physiology of marine mammals and their environment. In recent years, considerable progress has been made in recording technologies used in the biologging tags as well as management, visualization, integration and analysis of biologging datasets [1]. But while advancements have occurred for the tags themselves, less attention has been focused on the attachment methods and possible ways of improving existing solutions making them less invasive and uncomfortable for the animal. Current methods for attaching these devices cover a wide range based on the animal's skin type, but for this project, we will solely study suction cups as an attachment method for bottlenose dolphins. We aim to not only understand the cups' attachment behavior but also improve their performance.

The focus of this project is on the local behavior of the suction cup. The main culprit of detachment for suction cups is natural leakage into the cup. Our design aims to address the issue of air leakage using an active monitoring system complemented with a vacuum pump to dispel unwanted air from the inner volume of the suction cup. Background engineering analysis is provided to investigate the important mechanisms of air leakage and how specific components can work together to address the issue. A set of requirements and specifications was created to address challenges and goals of the design. We also lay out the concept generation, evaluation, and selection phases to ultimately evaluate how well specific designs address the problem at hand.

Our final design concept was chosen and an active suction prototype was developed from the specific components. Code for the controls system was developed to actively monitor the pressure of the suction cup and determine when the vacuum pump needed to be used to re-establish a stronger connection to the surface medium. The overall design was accomplished through planning and testing of the system. Part of the verification process was done through observation of the system working along with additional testing of the pressure sensor giving insight into the leakage of the suction cup and the battery consumption.

We have successfully fulfilled the request by Professor Shorter for an active suction cup model. The report thoroughly details the entire design process from background information to the final design verification.

1.2 Problem Description

Model and design of local active suction cup system with ultimate goal of application for biologging tags for bottlenose dolphins.

2. Background & Problem Definition

2.1 Introduction to Biologging and Tag Attachment Methods

With recent advancements in sensor technology concerning size and data storage capacity, scientists and engineers around the world have begun to place wearable sensors onto animals with increasing levels of success. Biologging is the "use of animal borne devices to gather information on the behavior, movements, and physiology of the animals and/or the environment they use" [2]. The devices can be placed on both wild and managed animals for insight into migratory behaviors, foraging strategies, population dynamics, and health factors of individual animals [2,3].

While novel insights from the use of biologging tags can be helpful to both scientists and the chosen animal, there are other aspects of biologging that can be detrimental for the animal. Namely the capturing aspect of placing these tags on the animal can be extremely stressful [3]. In addition, the animals may change their behavior due to the tag placement which essentially makes the data useless [4]. Furthermore, if the tag is a certain color, shape, or size this might elicit a reaction from other animals and can negatively impact the social behavior of the tagged animal [4]. Also, there is significant variability amongst skin types of animals which therein affects the attachment method that can be used to place the sensors onto the animal. Amongst animals who are studied for biologging, the range of environments vary significantly as does the animal behavior, typical movements, and traveling distances. All these factors significantly complicate methods for tagging, deployment, and tag retrieval.

Figure 1. Seal with biologging tag [5]

While there are many options for biologging tags, this project will focus on the use of suction cups as the attachment method. We would like to understand the mechanism for suction and recognize the shortcomings in existing designs and try to improve upon them. However it is useful to look into other means of attachment to gain insight into motivations for certain technologies and what makes them successful or useful for biologging purposes.

Biologging is used to track data for a wide variety of animals. This includes anything from humpback whales to gray wolves. Therefore, different technologies need to be utilized for attaching sensors to different animals. It is impossible to design an attachment method that is successful for each animal, so it is useful to develop a good understanding of the state of the art in this field and why certain methods are used for specific animals.

Table 1. Biologging Tag Benchmarking

Method	Animal	Notes	Reference
Stainless steel locking wire	Stingray	Bruising and abrasions on tagging location	[6]
Bolt gun dart	Type C Killer Whale	No visible response to tag	[7]
Suction cup	Killer Whale	Attached via hand pole	[8]
Suction cup	Sperm Whale	Synthetic foam casing	[9]
Suction Cup	Dusky Dolphin	Silicon cups	[10]

Suction cups have been used in biologging studies before, but their attachment behavior has never been extensively studied specifically for biologging purposes. This is the main gap in the research we are hoping to cover, but it is essential to recognize the merits and pitfalls of other methods to further motivate improved technologies of suction cup attachments.

2.2 Suction Cup Behavior and Background

Suction cups have been used anywhere from elements in the locomotive mechanism of wall climbing robots [11] to attachments for GPS systems in vehicles. The material of suction cups is typically elastic and the geometry is usually circular and curved. The mechanism responsible for suction is when the cup is forcefully attached to a surface, air is expelled out of the inner cup area, which decreases the pressure inside the cup. The pressure difference between the inside and outside of the cup causes the cup to remain attached to a surface. There is a considerable amount of active research into modeling the behavior under various loads and adhesion mechanisms for locomotion [11-14]. These topics help to form a framework for understanding typical suction behavior and give insight into current issues with the technology.

Once suction cups are attached, one big issue is leakage into the suction cup, which leads to lower forces needed for detachment making the suction cup more likely to detach from a surface. One way to mitigate leakage is to design an active system with pressure sensing capabilities that can monitor the suction system and dispel fluid out of the system when the pressure goes over a certain threshold. This would mainly be useful for non-porous attachment media as porosity or roughness on a surface can easily let fluid flow into the suction cup [15].

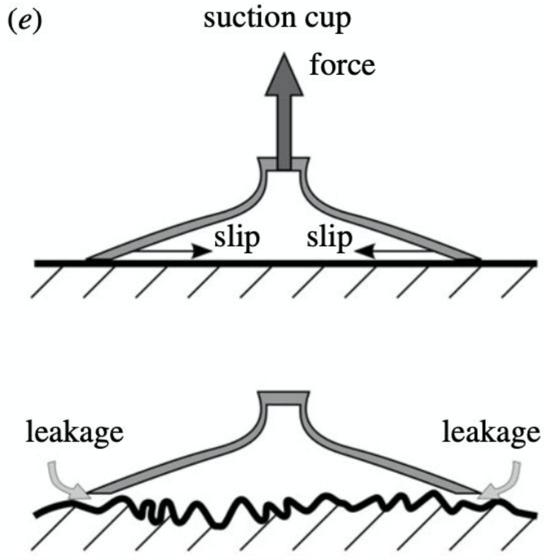


Figure 2. Suction cup behavior on smooth and rough/porous surfaces [15]

A significant research theme in the field of suction cups looks to improve the adhesion time for the cups. The primary cause of detachment occurs because of leakage at open channels at the interface between the cup and the substrate [16]. The factors that influence air leakage and ultimately the failure of suction cups is the volume, stiffness, and elastic moduli of the suction cup[16]. An ideal suction cup will have a lower elastic moduli if used on rough surfaces but it is difficult to model due to the time dependence of the elastic moduli for a viscoelastic suction cup. However, it is important to understand because it is ultimately the elastic moduli that is the most important factor of the suction cup behavior [16]. This is because the stiffness defines how well the cup will attach and stay attached to a surface. The challenges regarding leakage are the main concerns for the design of an active suction cup system. One method to mitigate leakage is to design an active system that monitors pressure and is capable of dispelling fluid when the pressure goes above a certain threshold.

2.3 Suction Cup Usage and Shortcomings for Biologging

Suction cups are utilized for biologging purposes due to their non-invasive nature. They are mainly used for short term (<24 hours) data gathering or monitoring[17]. To better understand suction cup behavior when attached to dolphins, it is important to understand basic mechanisms of suction. As stated above, the majority of suction cup research is focused on window cleaning or wall climbing robots [13,18]. The principles of suction are the same, but many of these applications are for mobile robots with a suction attachment. In these cases, the suction is used to detach and reattach in order to perform functions. With suction cups on dolphins, it is essential that the cups do not release prematurely. Beneficially, there have been observational studies that suggest dolphins have little or no response to the suction cup attachment, which is ideal for biologging purposes[10]. The physics of the attachment behavior of suction cups to dolphin's skin is not well understood due to the variable roughness and porosity of the skin. Therefore, it is necessary to simplify the project space to maintain feasibility and progression of the project.

The shortcomings of suction cups for biologging tags derive from the difficulty to remain attached to the animals for a given period of time. Given the overview of suction cups in the previous section, it is paramount to understand the phenomenon of leakage and focus on the leakage behavior of suction cups to ultimately improve the performance of a smart suction cup system.

2.4 Problem Definition

Model, design, and construct an active suction system that is capable of monitoring the pressure difference inside the suction cup to maintain a constant pressure difference between the interior and exterior of the suction cup under the effect of pressure changes and external forces of a bottlenose dolphin's environment for 24 hours.

3. Requirements and Specifications

The requirements for the suction system were derived from conversations and questions during meetings with our instructor, Professor Barton, and with our sponsor, Professor Shorter. The purpose of these meetings was to gain a better understanding of what is required of this suction device in order to improve current suction systems and resolve their issues. Once we developed requirements for the design, further research was conducted to translate the requirements into engineering specifications. All of the specifications can be tested, and a majority are quantifiable. These engineering specifications will determine if the device has successfully resolved the stipulated problem statement to our own standards. Each requirement has been determined and justified using relevant literature and stakeholder knowledge of the problem. The justifications for each requirement are necessary to describe the significance of each requirement to the entire project. The table below, Table 2, lists all of the requirements and specifications, along with the appropriate sources. Below the table, each requirement and specification is described in further detail, including a thorough explanation of why each is important to the solution.

Each requirement has been given a priority value from 1 to 5 where 1 means that the requirement is a high priority while 5 means it is a low priority. In general, priority is given to requirements that fundamentally affect the effectiveness of the basic functionalities of the suction system. On the other hand, a low priority is given to requirements that are not vital or essential to the basic functionality of the suction system but still useful in developing a solution. The low-priority requirements in this case pertain more to the environment that dolphins inhabit and will be examined following the initial focus of modeling, building, and testing an active suction cup.

Table 2: Requirements and Specifications

Requirement	Engineering Specification	Source	Priority
Ability to respond to pressure changes as a result of air leakage and maintain a constant pressure	Sustain a constant pressure of 0.15 bar in the suction cup Uses material with low elastic modulus	Professor Shorter, Tiwari, A., and B. N. J. Persson. "Physics of Suction Cups." *Soft Matter*, vol. 15, no. 46, 2019, pp. 9482–9499.	1
Strong enough to withstand drag/lift from dolphin swimming	Suction cup can withstand forces up to 150N and 600N in tangential (drag) and radial (lift) direction respectively	Shorter, K. Alex, et al. "Drag of Suction Cup Tags on Swimming Animals: Modeling and Measurement."	3
Waterproof packaging of electronic system	No water leakage into electronic system	Professor Shorter	5
System works properly for at least 24 hours	Battery life of the electronics lasts for at least 24 hours while the suction cup also reliably stays on the dolphin	Professor Shorter	1

Withstand the temperature range of the dolphin’s habitat	Suction cup and electronics must remain fully functional at any temperature in the range of 35-90 ℉	Barbieri, M. M., et al. “Using Infrared Thermography to Assess Seasonal Trends in Dorsal Fin Surface Temperatures of Free-Swimming Bottlenose Dolphins (Tursiops Truncatus) in Sarasota Bay, Florida.” *Marine Mammal Science*, vol. 26, no. 1, 2009, pp. 53–66.	4
Easy and quick installation	Less than 10 seconds to install on dolphin with less than 3 steps	N/A	3

The central requirement of the suction is to be able to monitor pressure and respond to internal air leakages that leads to a lower pressure differential to ultimately maintain a constant pressure inside the suction cup. A secondary concern of ours would be to take into account pressure differences arising from the dolphin’s travel through different environments. Bottlenose dolphins typically stay within 5 m of the surface, but are capable of diving up to 50 m deep. The pressure at this depth in saltwater is around 600 kPa [19], so the device should be designed to withstand pressures that high. Bottlenose dolphins can travel at up to 10 m/s, and often attain this speed while hunting, fighting, or fleeing from predators. While simulating the dolphin behavior can be useful, it is not the main concern for this design. Our sponsor, Professor Shorter, has made it clear to us that the suction cup should have a constant pressure of 0.15 bar regardless of the outside pressure. In order to successfully withstand these pressure differences, the material of the suction will also need to have a low elastic modulus. Nonetheless, the dolphin behavior is not a significant aspect of this project and the primary focus is developing a design to combat air leakage into the suction cup.

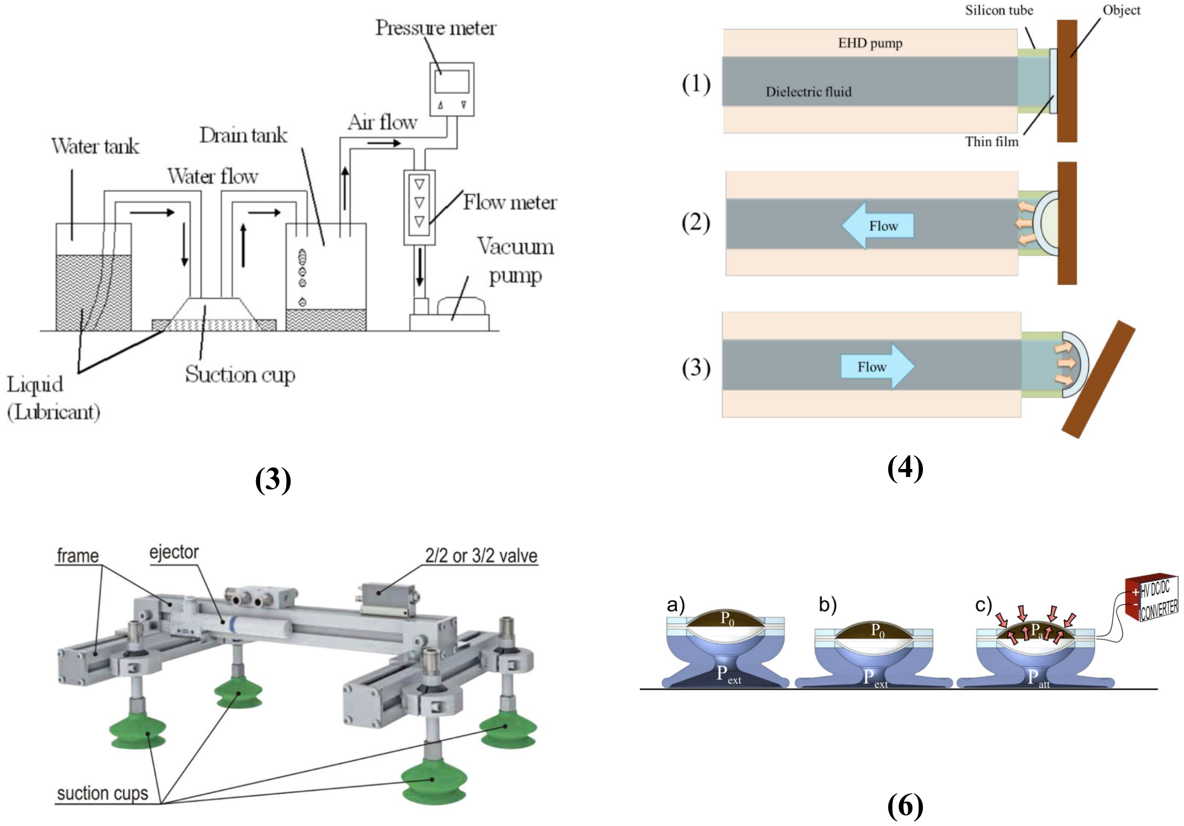
Another central issue is the power constraints of the components based on the capacity of a 1200 mAh battery. Given that the system should work for at least 24 hours, we cannot deploy sensors or pumps that drain the battery quickly. Therefore it is paramount that we perform proper engineering analysis on the components of the active system we design to insure that the monitoring and pumping could work for at least 24 hours. Along with the restricted battery life, there are size constraints to the components needed for operation. While all testing will be done in a controlled laboratory setting, the actual biologging tag would be deployed in a constrained environment so it is necessary to acknowledge this in our designs. If a system is successful under controlled lab conditions then it would be beneficial to expand testing to simulate the forces and pressures experienced in conditions a bottlenose dolphin would inhabit.

Another factor to consider is the drag and lift forces that will act on the suction cup as the dolphin moves through the water. These forces will act in the tangential and radial directions respectively. The lift and drag coefficients are dictated by $C_D = 2F_D/\rho u^2 A$ and $C_L = 2F_L/\rho u^2 S$ respectively [20]. Both are inversely proportional to the product of the density of the saltwater, the velocity of the dolphin relative to the saltwater, and the projected frontal area of the device. The suction should apply a strong enough force on the dolphin to prevent getting pulled off by the aforementioned forces. Broadly speaking, 600 N and 150 N have been determined as upper limits on the lift and drag forces respectively. However, we are primarily focused on developing a working prototype in a lab setting where the fluid surrounding the suction cup is air. The majority of testing will be directed towards maintaining this constant pressure differential in a static scenario. In an ideal world it would be good to test the suction cup under these forces lifted above but this is a secondary concern compared to executing a design that successfully mitigates air leakage.

The suction cup should cause as little discomfort and disturbance to the animal as possible because the ultimate application is for biologging purposes to accurately observe a dolphin's behavior. To facilitate this, it is important that the installation of the device is comfortable and quick for the animal. Furthermore a quick installation strategy is essential to successfully deploy the device. We have therefore chosen to ensure that the installation takes no longer than 10 seconds, and entails no more than 3 steps.

Other requirements that have been included but are of less importance are that the device is waterproof and fully functional in the anticipated temperature range. It is important that the electronic components of the device are packaged in a waterproof manner, since any moisture will jeopardize the functioning of the electronics. As far as temperature is concerned, bottlenose dolphins are typically seen to inhabit warm and temperate waters around the globe but the device must be fully functional between 35 and 90℉ because this is the temperature range that bottlenose dolphins have been found to swim in. This temperature range was chosen not only because of the water temperatures that the bottlenose dolphins swim in but also the temperatures that the bottlenose dolphins' skins remain at while at these temperatures [21].

Various suction cup designs from multiple different applications, depicted in *Figures 3-6* below, were explored to understand mechanisms for suction and how they address a specific problem. This exploration was focused on active suction systems that require a power source to maintain suction. Its benchmarking will assist during the concept exploration phase laid out in Section 5.



(3) **(4)**

(5) **(6)**

Figure 3-6. Four active suction cup systems are depicted: **(3)** Experimental setup of a vacuum-based wet adhesion system [22] **(4)** Active suction cup actuated by ElectroHydroDynamics (EHD) pump [23] **(5)** Gripping effector with active vacuum suction cups [24] **(6)** Proposed mechanism with dielectric elastomer actuator [25]

The images above highlight just a few examples of active suction cups we have researched in order to understand a wide range of potential solutions to our problem. Figure 3 depicts the wet adhesion system for application of a wall-climbing robot. This particular system allows for low friction performance of suction cup adherence to rough surfaces using a vacuum pump [22]. Figure 4 shows the actuation process of an EHD pump, which has been recently explored within the realm of soft robotics. This system would provide another way for us to maintain suction cup attachment by inducing pressure changes through the application of a high-intensity electric field [23]. This method of actuation would enhance the suction cups' ability to interact with their environment similar to that of an octopus. Figure 5 depicts a gripping effector used in automated plants for vacuum handling. This system uses a volume generator ejector, which results in the shortening of the channel to be routed under the suction cup membrane and therefore, would result in significant savings in energy consumption and operating costs (advantageous considering we would have a limited power supply) [24]. Finally, Figure 6 depicts a dielectric elastomer actuator for octopus inspired suction cups. This application of bio-robotics offers the option of a flexible membrane to help actuate our system in an underwater environment and a pressure sensor to monitor pressure differentials.

4. Concept Exploration

We broke down the concept exploration phase into three stages: concept generation, development, and evaluation/selection, all of which have been chronologically documented in our project timeline found in Appendix B. Initially, we followed the rules of brainstorming to generate divergent design ideas that reflected our research into different suction cup applications. We further developed these ideas by identifying key components of our system (e.g. valving and actuation) and using Morphological Analysis to produce even more solutions. We narrowed down these new solutions using basic screening requirements for our design and later grouped the remaining concepts based on what aspect of the design they aimed to address. Overlapping designs within each group were immediately evaluated, and after performing a Gut Check, the "best" designs were kept for final consideration. Finally, we selected our top three designs using a Pugh Chart (shown in Table 4 below).

4.1 Concept Generation

Having conducted the necessary background research and engineering analysis, we could clearly understand how to approach our problem and begin navigating our solution space. We brainstormed ideas that could address the two major functions of our system: continuous monitoring and maintenance of a constant pressure differential inside the vacuum area of the cup. To avoid fixation on a single solution to our problem, we drew inspiration from many different applications of active suctioning. Examples (Figures 3-6 above) include wall-climbing robots, suction grippers, and bio-robotic suction cups frequently inspired by octopuses.

During the initial brainstorming session, we promoted novel and creative ideas that could still solve the ultimate goal of maintaining suction cup attachment by counteracting natural leakage of the cup. These preliminary concepts, some depicted in Appendix A.1, center around the system's application onto hard and flat surfaces. Although our initial ideas stemmed from divergent thinking, we did recognize similar components across all our design concepts that were clearly essential to the basic functionality of our system. These components, labeled in Figure 7, formed the base design that will be referenced in our Pugh Chart (Table 4) for final concept selection. One component we deemed to be nonessential was a chamber or reservoir to store air dispeled from the system. Although this design element can be found in our preliminary drawings found in Appendix A.1, we realized that we could simplify our design by releasing air directly into the surroundings.

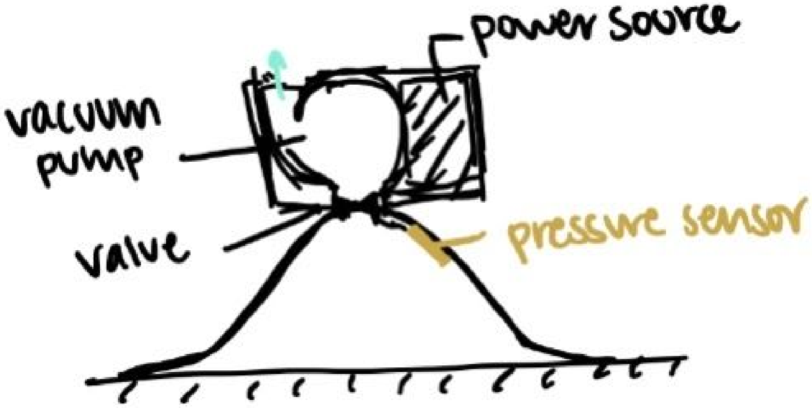


Figure 7. Basic conceptual design of the active suction cup system (Base Design #1)

Figure 7 above depicts the key components of a functioning suction system. First, we would require some type of pressure sensor to monitor the pressure inside the cup. We would need to design a valving system; in this case, a one-way valving system is sufficient because we are only focused on regulating airflow out of the cup. We would also require a power source and method of actuation to pull air out of the system. The suction cups will not be a component we need to design for, since we will be using the same ones Professor Shorter uses in his research, but we will still need to use our analysis of the cups, especially their dimensions and leakage rates, to inform the rest of our design decisions.

4.2 Concept Development

From our initial designs, we used Morphological Analysis (Table 3 below) to further generate concepts and later select down by using a number of screening requirements that we considered essential to our system.

Table 3. Morphological Chart for Active Suction Cup System

Sub-Functions	**Solutions →**			
1. Monitor Pressure Differential	Pressure sensor	Pressure transducer	Miniature barometer	Timed
2. Control Dynamics	Arduino	Raspberry Pi	Passive	---
3. Actuation	Spring	Vacuum Pump	Vertical Actuator	Vacuum ejectors
4. Regulate Fluid Flow	Passive valves	Control valves	Nozzles	Throttles
5. Waterproof Electronics	External Housing	Waterproof coating	Waterproof spray	Place inside suction cup

In Table 3 above, we broke down the many sub-functions required for our active suction cup system to maintain attachment to a surface. Subfunctions 1-4 were deemed crucial to the overall monitoring and response of the active system, while Subfunction 5 was later considered out-of-scope for our solution, considering we would not be testing underwater. From there, we came up with solutions (different components) that we could implement into more developed designs, in addition to the components already included in our preliminary concepts. These new ideas generated from Morphological Analysis were then screened using the following requirements:

1) *Uses a control system to monitor and respond to pressure changes in order to maintain a constant pressure differential of 0.15 bar*
    a) *Ability to pump air out of the suction cup as leakage occurs*
2) *Passive one-way valves*
3) *Includes 1200 mAh battery to power:*
    a) *Pressure sensor*
    b) *Vacuum Pump*

The first requirement ensures that each suction cup design can achieve the primary goal of continuous attachment to a surface for a 24 hour period. As for the second requirement, we decided that our design would use passive one-way valves to not only simplify our controller system but also avoid additional power consumption. And for the third, we required that our designs include a power source, which in this case would be a 1200 mAh battery (recommended by Professor Shorter). This battery would power two key elements of our system (must also be included in every design): pressure sensor and a vacuum pump, which we chose as our method of actuation after considering all components listed in Table 3. Design concepts that did not pass this basic screening were immediately discarded.

After screening this second round of ideas generated from Morphological Analysis, we were left with 11 viable designs (plus the base design in Figure 7) to be evaluated with a Pugh Chart, 9 of which are included in Appendix A.2.

4.3 Concept Evaluation & Selection

For the evaluation/selection stage of our concept exploration process, we assessed the base idea against the 11 additional ideas with the use of a Pugh chart. For our Pugh chart, we decided upon 6 main criteria on which the concepts would be evaluated:

1. *Practicality of design:* Perceived practicality was included as it has the potential to be a deal-breaking criterion, but is not a directly quantifiable measure of whether the design has met its requirements.
2. *Power consumption:* It is paramount that the device has low power consumption, because there are fixed limits on the power available to the device.
3. *Size and shape:* It is essential that the design has a streamlined structure, but all the proposed designs are somewhat flexible in terms of size and shape.
4. *Reliability and stability:* The device must be both stable and reliable if it is to fulfill its function of remaining on the animal's surface and collecting data for the required duration.
5. *Practicality of control system:* The control system in place must be as straightforward and simple as possible, so as to keep processing time and energy inefficiencies to a minimum.
6. *Ease of assembly:* The device should be easy to assemble, but this is largely detached from how well the device will perform its biologging duties.

Based on this reasoning, each of the six criteria were assigned a certain weightage, as per the typical proceedings of a Pugh Chart. *Power consumption* and *reliability and stability* were both assigned the maximum weightage of 5, *practicality of control system* was assigned 4, *practicality of design* and *size and shape* were both assigned 3, and *ease of assembly* was given the lowest weightage of 1. Following this split, each of the designs was given a -1, 0, or +1 in each category based on whether we felt it fared worse than, as well as, or better than the base design in each criterion. The scores were then totaled for each design, following the weightage distribution, and compared in *Table 4* below. Following standard Pugh chart protocol, scores for all categories were multiplied with the corresponding weights, and then added to provide total score for each design. For ease of comparison, the designs have been grouped by the aspect that each focuses on.

Table 4. Pugh chart for comparison of the base design against the 11 additional designs that were generated *(designs have been grouped by focus aspect, and color-coded by total score)*

Criterion	**Weight**	***Base***	***Valving***			***Methods of Actuation***			***Housing***				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Practicality of Design	3	0	0	-1	0	0	-1	-1	-1	0	-1	-1	-1
Power Consumption	5	0	0	-1	-1	-1	0	-1	0	-1	-1	0	0
Size and Shape	3	0	-1	-1	-1	-1	0	-1	+1	0	-1	-1	+1
Reliability and Stability	5	0	+1	+1	-1	+1	-1	-1	-1	+1	+1	-1	+1
Practicality of Control System	4	0	0	-1	-1	0	-1	-1	0	-1	-1	0	0
Ease of Assembly	1	0	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	0
Total		***0***	***+1***	***-11***	***-17***	***-4***	***-13***	***-21***	***-6***	***-5***	***-11***	***-12***	***+5***

How each design was scored in each category was based off of a group discussion with all 5 members of the team, so as to ensure that each member agreed with the assigned score. Design 1, naturally, was scored a 0 in each category, with all subsequent designs being scored on how they compared to Base Design 1. For example, Design 12 (the inverted structure) was marked a +1 for *size and shape* since its smooth, streamlined shape is a marked upgrade from the original. Likewise, Design 8 (the turtle-shell casing) was marked a 0 for *practicality of the control system* since its control system would be essentially identical to that of the base design. On the other hand, Design 7 (the self-pushing suction) was marked -1 for *practicality of design* because it is scientifically nonsensical to expect the suction to push upon itself without having a separate structure as a support from which to push from.

After arriving at total scores for each of the 12 designs, each design was color-coded based on how it fared in the evaluation process, with the highest-scoring designs being marked green, the lowest-scoring design being marked red, and those in the middle being marked yellow. These color codes were then used as a guide to sort the ideas into, respectively, those we would consider seriously moving forward, those we would scrap, and those we would not consider seriously, but take a second glance at to see if they contained any elements that could be incorporated into the final design.

Conducting this evaluation allowed us to successfully reduce a divergent pool of ideas into a convergent selection of designs to consider closely. Our top three concepts, Design 1 (Figure 7 above), Design 2 (Figure 8), and Design 12 (Figure 9) were all evaluated for final consideration, but we still took a look at Designs 5, 8, and 9 (all in Appendix A.2) to assess if any of their aspects could be incorporated into the final design.

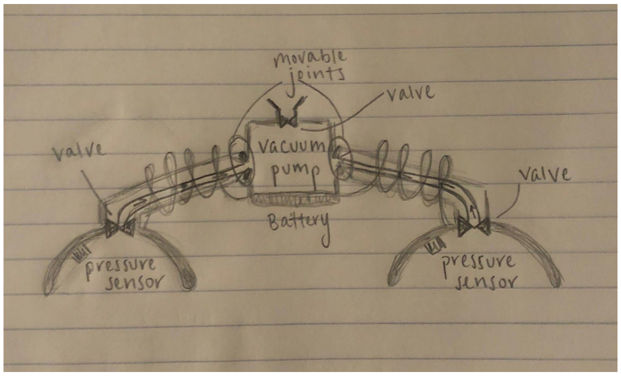


Figure 8. Movable joints for added flexibility and degrees of freedom of the mechanism where the tubes attach to the vacuum pump (Design #2)

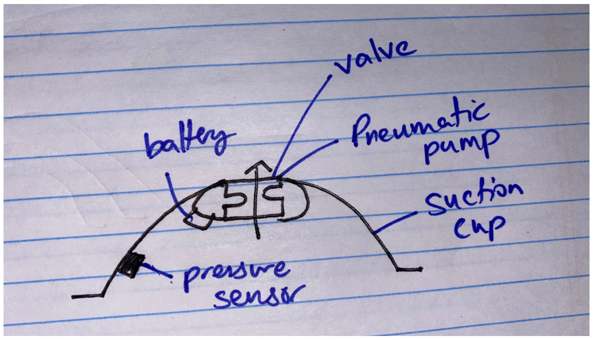


Figure 9. An “inverted” system where the pump is inside the suction cup and the suction cup acts as an outer casing (Design #12)

5. Final Design

After comparing the top designs from the Pugh chart, we decided to focus on a simple design. The design was broken down into the main subsystems: suction cup, piping, sensor, microcontroller, vacuum pump, and battery. Figure 10 below shows all of the major components in the final design. It features a single suction cup with piping that stems from the top which leads to the vacuum pump. The pressure sensor branches off from the main pipe using a T-splitter. The arduino microcontroller will be connected to the sensor, vacuum pump, and battery.

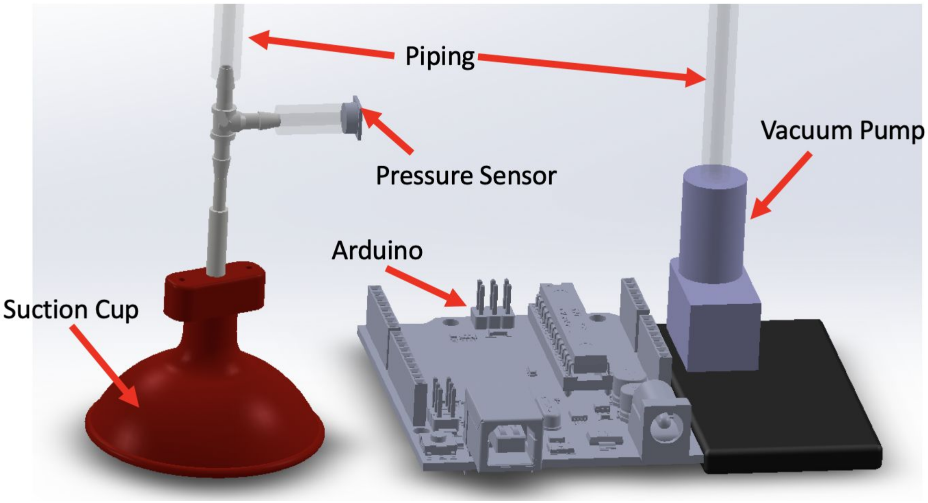


Figure 10. Final design including suction cup, piping, sensor, arduino, vacuum pump, and battery.

6. Engineering Analysis - Force/System Analysis Suction Cup

6.1 Suction Cup Force Balance

To address the engineering requirements outlined in the prior section, it is necessary to understand the local behavior of a suction cup when attached to a specific medium. As with many physics related problems, it is important to do a proper analysis of the forces at play. This is easiest to visualize in a free-body diagram as seen below in *Figure 11*.

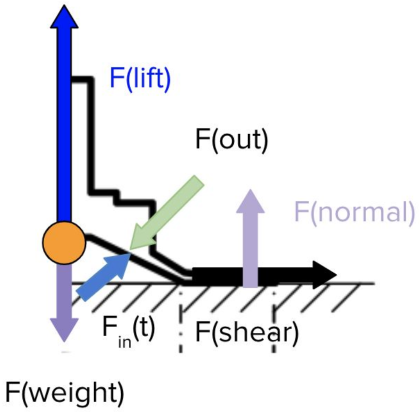


Figure 11. Free body diagram of suction cup cross section

The F(lift) is due to the fluid movement past the suction cup, F(out) is due to the external pressure on the suction cup, F(weight) is the force due to gravity, F(normal) is the force supplied by the attachment media preventing movement through the medium, and F(shear) relates to the elastic force of the suction cup but can be ignored in this specific case [Ge-Ma, 2015]. The most important force acting on the suction cup is $F_{in}(t)$, which is the pressure on the interior of the suction cup applied to a specific area. This force is related to the leakage of air into the suction cup and as more air leaks $F_{in}(t)$ increases which decreases the pressure differential ultimately leading to the detachment of the suction cup. We need to find a way to keep $F_{in}(t)$ at a constant value by monitoring the pressure and then using a vacuum pump to take air out which helps the cup remain attached. This is the main challenge of this design, to keep these forces in static equilibrium which assures that the suction cup will remain attached to the surface.

The mathematical force equilibrium is represented below.

$$Fx = 0 \tag{1}$$

$$Fin,x(t) + Fshear - Fout,x = 0 \tag{2}$$

$$Fy = 0 \tag{3}$$

$$Flift + Fnormal + Fin,y(t) - Fweight - Fout,y = 0 \tag{4}$$

Given this static force equilibrium scenario, it would be beneficial to be able to model the leakage into the suction to then know when to use the vacuum pump in order to change $F_{in}(t)$ to maintain equilibrium. However, present models are quite complex and rely on atomistic behavior of air flow and are thus beyond the scope of this project [16]. Therefore we will rely on empirical models developed by a graduate student, Ya-Yu (Dory) Yang, working in Professor Shorter's lab in addition to verifying the model based on the data shared with us. This empirical model will be discussed in a later section.

6.2 Leakage Behavior of Suction Cup

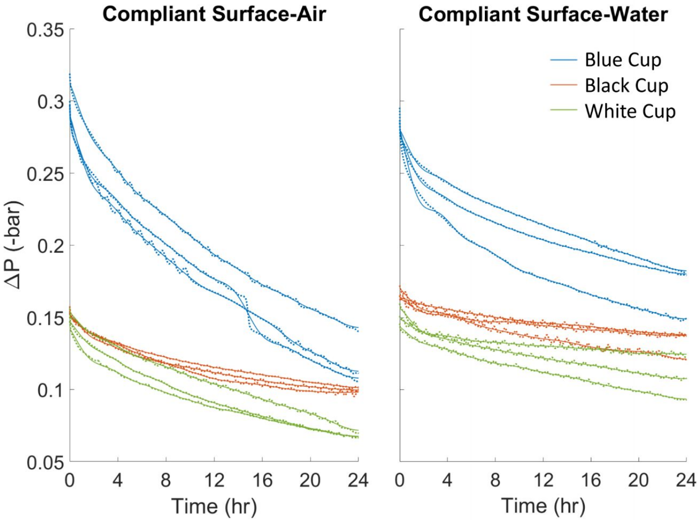
The plant dynamics are based on the dynamics of the suction cup leakage. The leakage is the main factor that contributes to the change in pressure in the suction cup. This means that it is important then to look at the change over time of the difference of pressure between the inside and outside of the suction cup. Due to air leakage into the suction cup from the environment, the change in pressure between the inside and outside of the suction cup exponentially decays because the pressures are trying to reach an equilibrium. If they do eventually reach this equilibrium, they are equal and then the suction is unstuck. Ideally, the pressure inside the suction should be very low in comparison to the pressure on the outside resulting in a high difference in pressure which keeps the suction tightly sealed onto the surface it is on. The change in pressure difference over time can be modeled using an exponential decay function.
The general formula for the exponential decay function used is the following:

$$\Delta P(t) = \Delta P_{int} e^{-t/\tau} \tag{5}$$

where P_{int} is the initial pressure difference, t is the time elapsed in hours ($0 \leq t \leq 24$), and τ is the time constant.

Data on three different kinds of suction cups was collected, compiled, and analyzed by a graduate student working on the topic of suction cups and biologging tags, Ya-Yu (Dory) Yang. The suction cups are classified according to their color, namely the white cup, black cup, and blue cup. Images of the three different kinds of suction cups are shown below in *Figure 12*. The data collected by Dory is shown below in *Figure 13*.

Figure 12. Suction cups used for the data collection. From left to right: white cup, black cup, blue cup.



Cup/ Air	Time constant (hours)	S.D.
Blue	26.86	3.39
Black	57.26	2.47
White	31.56	0.78

Cup/ Water	Time constant (hours)	S.D.
Blue	49.78	10.28
Black	116.95	39.90
White	84.57	42.84

Figure 13. Data on the decay of the three suction cup pressure differences over a 24 hour period. The data includes pressure difference graphs, time constants, and standard deviations.

As previously mentioned, the first and main step is to develop a suction cup system that works on a flat surface in air, so the data being considered is the data collected where air occupies the external fluid environment (graph on the far left in *Figure 13*). By looking at the graph on the far left we can see that the suction cup with the smallest decay over the 24 hour period is the black cup, greatest time constant. This means that the values of the pressure difference at the beginning (t = 0 hrs) and at the end (t = 24 hrs) have the smallest difference for the black cup in comparison to the blue and white cups. Therefore, any further consideration and analysis is only for the black cup because it's baseline performance is the best out of the three cups.

Going back to equation (5), we need to calculate the time constant τ. This was done by using the following equation:

$$\tau_{leak} = \frac{-24}{ln(\Delta P_{24} / \Delta P_{int})} \tag{6}$$

where ΔP_{24} is the pressure difference value after the 24 hours have elapsed (about 0.11 bar for the black cup) and ΔP_{int} is the initial pressure difference when zero hours have elapsed (about 0.15 bar for the black cup). By plugging in the corresponding values into equation (6) we calculated the value of τ to be about 57.26. Knowing the time constant value now, we can plug in all these values that we now know into equation (5) and the result is equation (7) below.

$$\Delta P(t) = (0.15)e^{-t/57.26} \tag{7}$$

Equation (7) describes the exponential decay of the pressure difference of the black suction cup over the 24 hour period. This model will be useful in order to help our system maintain a constant pressure difference of 0.15 bar. These types of dynamics involving the leakage of the suction cup and the pressure difference changes over time will be used for the plant dynamics within the suction cup system.

6.3 Initial Block Diagram Design for the Suction System

We created a block diagram in order to design and illustrate the system itself to perform further analysis of the controls system. For the suction system we designed a closed-loop control system. A closed-loop control system is a system that takes into account the current output and alters it accordingly in order to achieve the desired output. The closed-loop control system, also known as a feedback system, achieves this by making use of feedback loops. [26] The basic feedback control system for our project is shown below in Figure 14.

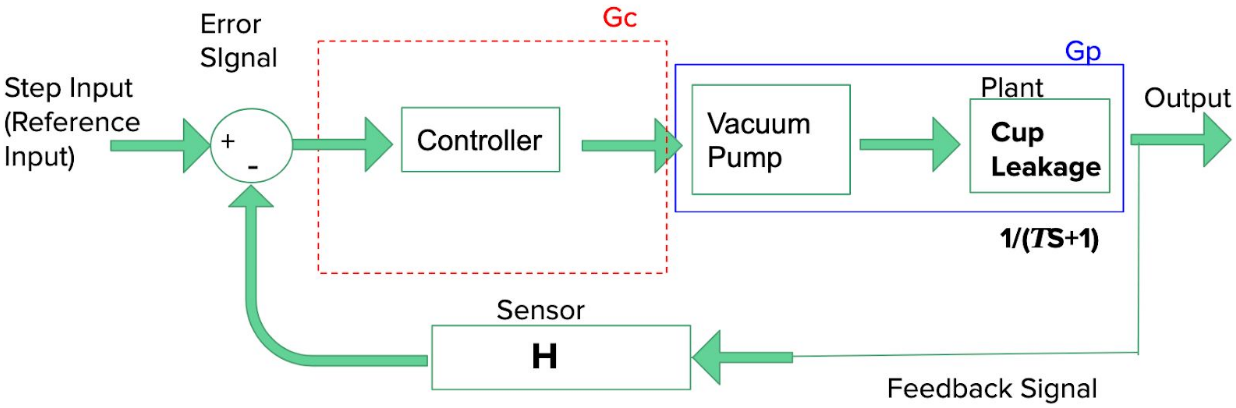


Figure 14. Illustration of the basic feedback control system block diagram

The original control system block diagram we designed is shown below in *Figure 15*. This block diagram made use of a PI controller. Our final system design does not make use of a PI controller for reasons explained later, rather we make use of an On-Off controller.

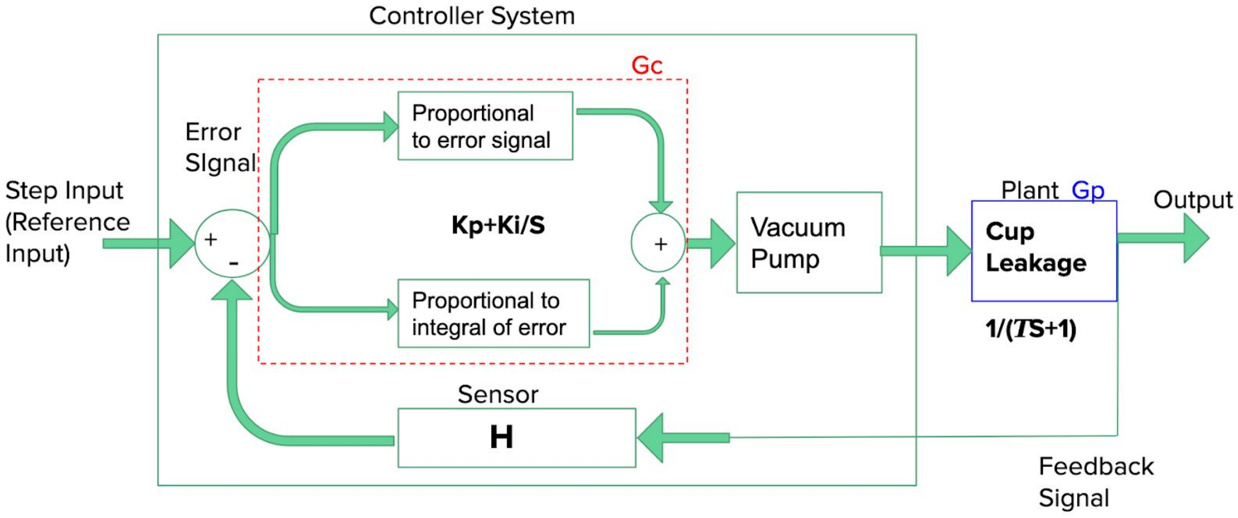


Figure 15. Block Diagram for Suction Cup System using a PI controller

The system above in *Figure 15* illustrates the feedback system using a PI controller which will be further explained in section 4.3. The PI controller would be responsible for taking into account the error between the output signal and the input reference signal in order to adjust the output signal accordingly until the output signal matches in the input reference signal. By analyzing this block diagram from left to right we can see that the far left sum block finds the difference between the reference input, which in our case is can be a constant or a step input (telling the system to keep a constant 0.15 bar), and the feedback signal which in our case is the output signal. This difference value is known as the error. The feedback signal in some cases must take into account the sensor dynamics, H. In most cases, including our case, the sensor dynamics are negligible and do not change the feedback signal enough to be considered significant. In this case the sensor transfer function can be modeled by a constant, 1, if the sensor dynamics are negligible, which is what we are considering in our block diagram. Alternatively, the sensor does not need to have a block, the output signal can go straight into the error sum (difference) block. After this far left sum block calculates the error, the error signal goes through the controller block which is the PI controller. As previously mentioned this system makes use of a PI controller meaning that there will be a Proportional block (transfer function = Kp) and an Integral block (transfer function = Ki/S). The error signal goes through both of these and then these two signals go through a sum block. The signal leaving this error sum block next goes into the plant, which should take into account the leakage dynamics and also the dynamics of the actuator. The actuator in this case is the vacuum pump whose dynamics are much faster than the leakage rate’s dynamics. This means that the vacuum pump’s dynamics can be considered negligible since the greatly slower leakage dynamics are much more dominant. The result is that the plant only takes into account the cup leakage dynamics, pressure difference changes over time. By taking the Laplace transform of Equation (7) above, the black suction cup’s pressure difference changes over a 24 hour period, we can obtain the plant's transfer function. The plant's transfer function is shown below in Equation (8).

$$\text{Plant Transfer Function } = L\{\, 0.15e^{-t/57.26} \,\} = \frac{8.589}{57.26s + 1} \tag{8}$$

The cup leakage dynamics are important to know because this will be the main cause of pressure difference decrease between the environment and the inside of the suction cup. The signal leaving the plant block is the output signal which in the case of a closed-loop system is also the feedback-loop signal. This feedback signal then goes back to the first sum block and the system continues to work as described. [26]

A condensed version of the block diagram can be seen below in *Figure 16* using the controller (G_C) and plant (G_P) transfer functions in *Figure 14*.

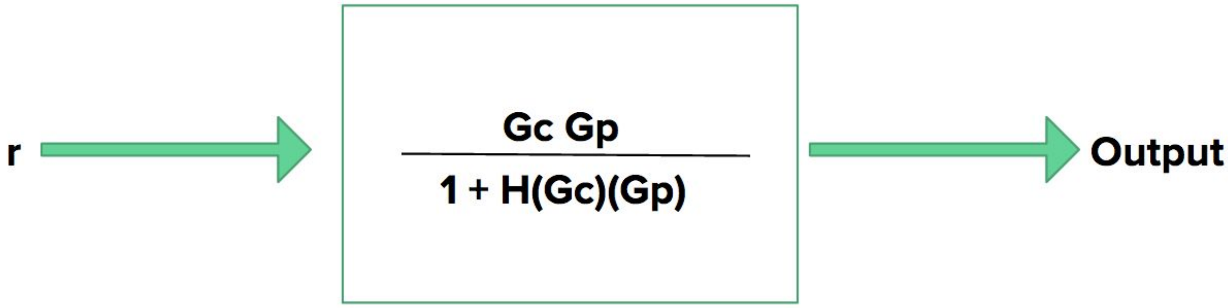


Figure 16. Condensed block diagram of *Figure 15* above where G_C is the controller transfer function, G_P is the plant transfer function, H is the sensor transfer function (constant 1), and r is the reference input (step input).

6.4 PI Controller Basics

A PI controller is a feedback control loop that calculates the error signal in the system by calculating the difference between the output signal and the reference input. In the case of the suction system, the input reference signal is a step input or constant telling the system that the pressure difference between the inside of the suction cup and the environment should be 0.15 bar. The PI controller is named the "PI" controller because of its two components. The "P" stands for the Proportional control component and the "I" stands for the Integral control component [26].

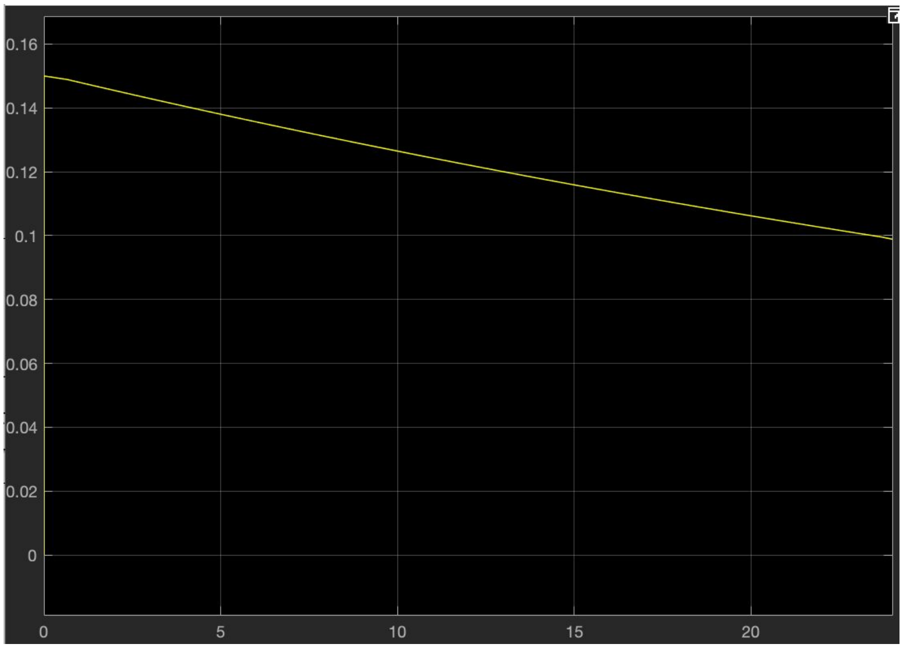
The proportional control sets the signal proportional to the error. If the proportional controller gain is too high then we get an unstable system and oscillation but if the proportional controller gain is too low then it will not properly respond to disturbances. Having only the proportional controller can be all that is needed in some cases, if the action required to fix the error is always the same. This action, however, can be different even if the error is the same in two different instances using the same system. Integral control is used to achieve zero steady-state error. Achieving zero steady-state error is otherwise not possible for a first order system with a step input. [26]

Integral control increases the system's action in relation to the error and the time that the error has persisted if the error has not reached zero. A large error causes the integral action to increase or decrease quickly while a small error causes the integral action to increase or decrease slowly. Essentially the system’s action will be applied according to the magnitude of the error and also the time that the error has persisted (not reached zero). [26]

The main disadvantage to using the PI controller is that the reaction to disturbances may be slow. In order to make the system’s reaction to disturbances faster we would need to use a PID controller. Besides the proportional and integral control that the PID controller uses, the PID controller also uses derivative control which is why a PID controller also looks at the rate of change of the error. By taking into account the rate of change of the error the system can more quickly and accurately adjust its action in order to bring the error to zero. Derivative control is not critical or necessary in many cases including this suction system because it adds complications to the trial and error tuning. Thus, a PI controller is all that we would need and is necessary for this suction cup system. [26]

6.5 Take-Aways from System Design with PI Controller

The decay of the pressure difference between the inside of the suction cup and environment can be seen below in Figure 17 (top) which is the scope of the block diagram also shown in Figure 17 (bottom).



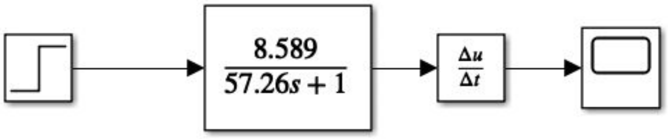


Figure 17. Scope showing the pressure difference decay over a 24 hour period for the selected black cup with a time constant of 57.26 hrs (Top). Block Diagram used to illustrate the pressure difference decay (Bottom).

By incorporating the PI controller and feedback loop into the system block diagram we expect to theoretically achieve a constant 0.15 bar value regardless of the elapsed time. This is what was observed once we incorporated the PI controller in the block diagram in Figure 18 below. The PI controller parameters were found using the Simulink PID Tuner App using Reference Tracking. The P parameter was 1.18229295794048 and the I parameter was 0.0206477987764668. The scope of the system with the PI controller can be seen below in Figure 19.

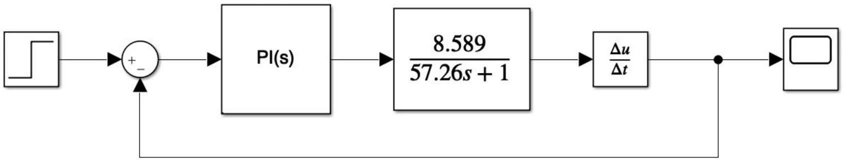


Figure 18. Block Diagram of system using a PI controller

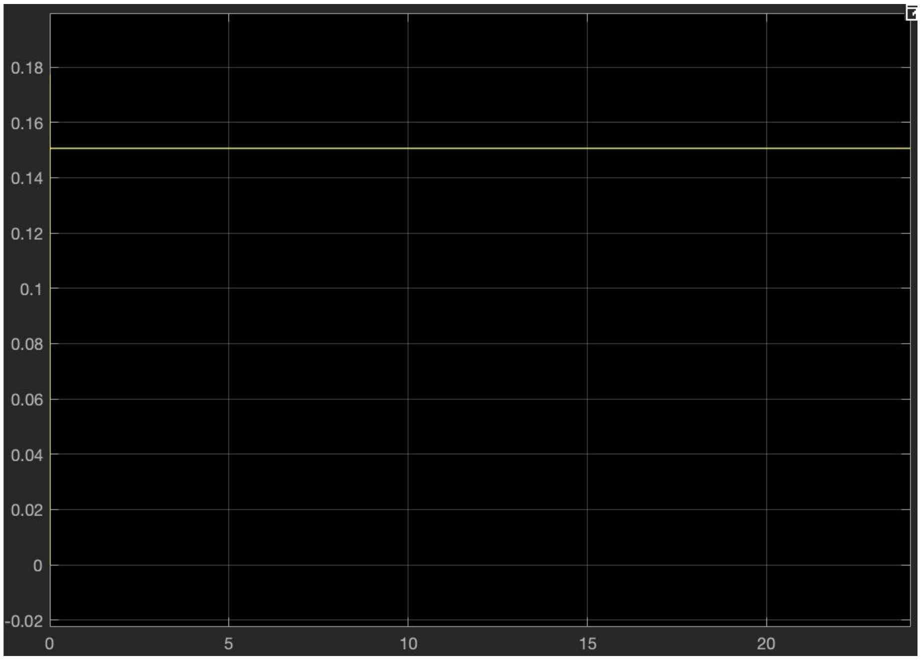


Figure 19. Scope output of block diagram system using a PI controller

As mentioned before, this was our initial take on using a controller for the system in order to maintain the constant 0.15 bar pressure difference. Looking further into the specs and abilities of the vacuum pump though, we realized that the vacuum pump was much too powerful in comparison to the amount of air that the pump would have to pull out of the suction cup. This means that the vacuum pump would not be able to handle the very small volumes of air that it would need to be pulling out constantly in order to maintain the constant pressure difference of 0.15 bar. This realization led to further discussion into how our control system should work, resulting in the idea of an On-Off Controller.

6.6 Final Block Diagram Design using an On-Off Controller

An On-Off Controller looks at the system and based on specified upper and lower bounds decides, in our case, whether to use the vacuum pump or not. This means that if the pressure difference goes below a specified lower bound value then the pump will work until the pressure difference reaches a specified higher bound value. Although the system will not be able to maintain a fully constant value of 0.15 bar throughout the 24 hour period, the system will still be able to remain around that 0.15 bar value given the pump's ability. The pressure difference bounds that we have decided are 0.09 bar as the lower bound and 0.16 bar as the higher bound. We decided on the high bound value because 0.16 bar is slightly greater than 0.15 bar, the value we are trying to maintain. We decided that having the pressure difference go up to a greater value than 0.15 bar was more beneficial than going to exactly 0.15 bar because this means the suction cup pressure difference will for sure be around the 0.15 bar value for longer even with leakage. A slightly higher pressure would not cause any problems because a higher pressure difference theoretically means the suction cup is more tightly sealed to the surface it is on. We decided on the 0.9 bar lower bound value based on the detachment pressure difference value of 0.5 bar. The suction cup detaches at a pressure difference value at or below 0.5 bar so in order to create a safety factor for our system, we have decided to make the lower bound pressure difference value 0.9 bar. This is not to say that we cannot change it further into testing if we determine that a higher or lower value can work better for the system and pump. Figure 20 below shows the block diagram used for this system using an On-Off Controller.

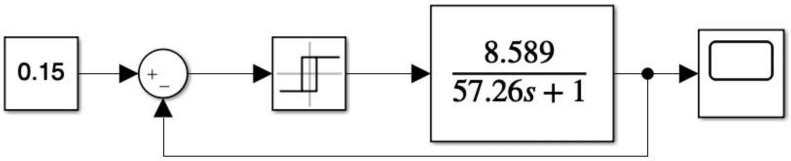


Figure 20. Block Diagram of the system using an On-Off Controller

The difference between the reference signal, 0.15 bar, and the feedback signal acts as the input for the ‘Relay’ block which determines whether the vacuum pump should be working or not. The relay block actually compares the error to an upper bound and lower bound error value to determine whether the pump should be working or not. These error bounds are determined based on the overall upper bound and lower bound pressure difference that we want to give the system by subtracting the reference value, 0.15 bar, by the system pressure difference bound that we want. For example, if we want the pressure difference lower bound to be 0.10 bar, then the lower bound value in the relay block will be 0.15 - 0.10 = 0.05. Using the same example, if we want the upper bound for the pressure difference to be 0.16 bar, then the upper bound in the relay block will be 0.15 - 0.16 = -0.01. Figure 21 below shows the scope of this system using the specified Relay block boundaries mentioned before, 0.16 bar upper bound and 0.09 bar lower bound.

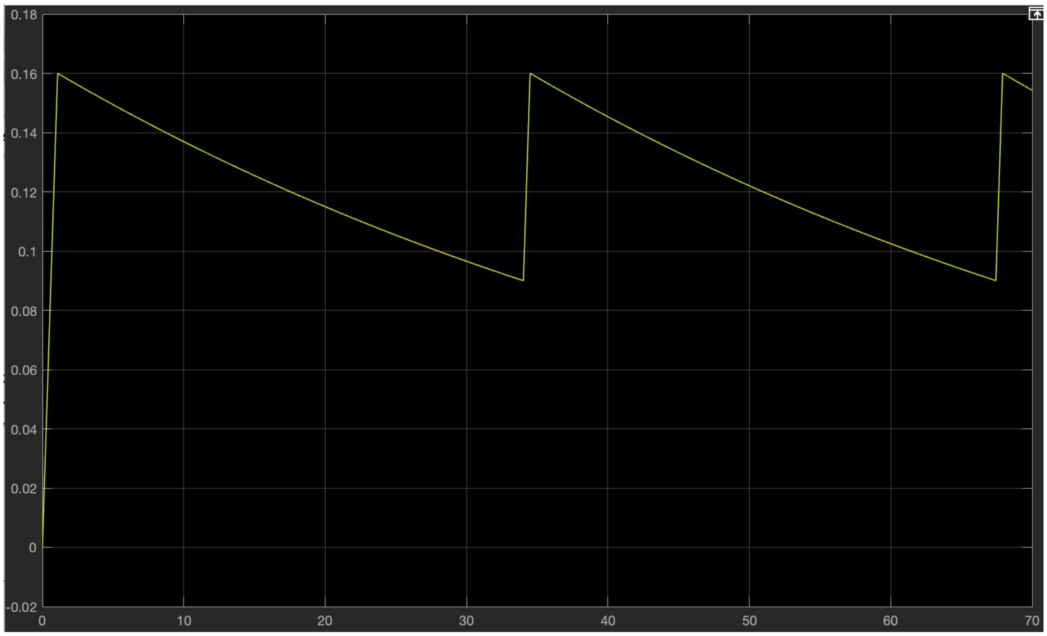


Figure 21. Scope of the block diagram of the system using an On-Off Controller with a 0.16 bar upper bound and 0.9 bar lower bound.

As an extra example, Figure 22 below shows the scope of the system if the lower bound were changed to 0.14 bar and if the upper bound were to remain the same, 0.16 bar. As mentioned before though, in order to make use of the vacuum pumps power we will keep the lower bound of 0.09 bar.

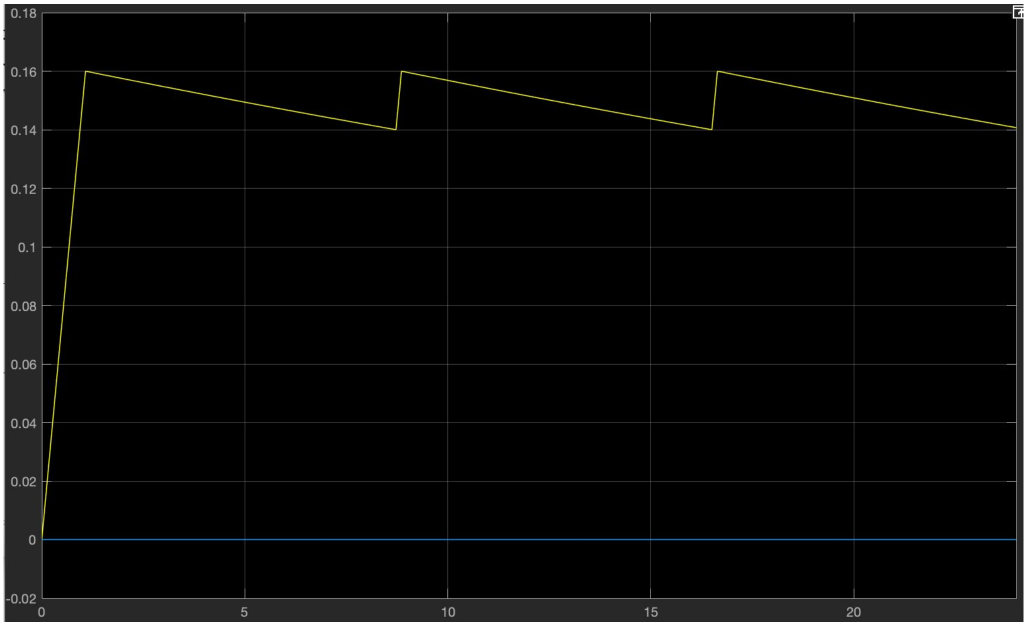


Figure 22. Scope of the block diagram of the system using an On-Off Controller with a 0.16 bar upper bound and 0.14 bar lower bound.

It is important to note that the scope outputs from these block diagrams are purely theoretical and considered as occurring in ideal scenarios. It is likely that the leakage and pressure difference change over time for the suction cups is higher than what was determined from data collection and calculations. This would mean that, in practice, the time constants for the exponential decay models of the leakage of the suction cups are smaller than calculated, meaning the decay occurs faster. This affects the system because this would mean that the pump is used more often. The On-Off Controller would be able to work effectively though, regardless of the possibly changing time constant because the controller works based on the set on/off limits that we specify.

When it comes to using the Arduino as our control method it will be simple to implement the On-Off Controller. Using the pressure sensor readings we will be able to determine the pressure difference and compare it to our reference value of 0.15 bar. This comparison will then determine whether the vacuum pump should be turned on or off.

7. Engineering Analysis: Vacuum Pump and Valving

The vacuum pump is an essential component of the design for an active suction system. The function is directly related to maintaining connection between the suction cup and surface. Therefore it is paramount to perform in depth analysis on the operation of the vacuum pump and what needs to be done to satisfy the design requirements. However, we do need to realize that this analysis is limited. While this analysis can produce relatively accurate values across a range, the actual operation of the pump and the interaction with the rest of the system will most definitely cause some sort of deviations in expected behavior. The goal of this analysis is to be thorough enough to justify the design choices. The rest of this section will be devoted to outlining assumptions and going through calculations relating to the leakage in the suction cup and how the pump will be used to address this issue.

7.1 Leakage

The main challenge the design needs to address is the air leakage and subsequent detachment of the suction cup. We are going to revisit the leakage data, shared by the graduate student Dory Yang, to better quantify the problem.

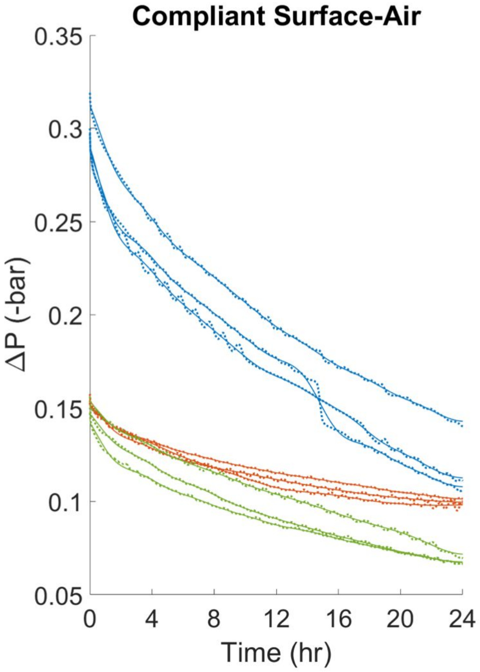


Figure 23. Leakage Data from Lab

This analysis will be focused on the orange curve because that is the data for the black cup which is the cup we are using in our actual system design. What can be seen in this plot is a decrease in the pressure differential between the interior and exterior of the suction cup over a period of 24 hours. The equation for ΔP will be shown below in Equation 9 where P_{in} is the pressure inside the suction cup and P_{out} is the pressure on the exterior of the suction cup which in this case is the atmospheric pressure, P_{atm} = 1.103 bar.

$$\Delta P = P_{in} - P_{out} \tag{9}$$

Using the data points from Figure 23 where the ΔP at time 0 is equal to -0.15 bar and the ΔP at 24 hours is equal to -0.1 bar. Rearranging Equation 9, it is possible to solve for $P_{in} = \Delta P + P_{out}$. So $P_{in,0}$ = -0.15 bar + 1.103 bar, $P_{in,0}$ = 0.863 bar and $P_{in,24}$ = -0.10 bar + 1.103 bar, $P_{in,0}$ = 0.913 bar. This data was gathered in ideal lab conditions and therefore represents a best case scenario. Later in this section, analysis with higher leakage rates will be performed.

7.2 Leakage Rate - Pressure to Volume Calculations

This pressure increase in the interior of the suction cup corresponds to physical air leakage. The lab experiments give a ΔP = 0.05 bar in a 24-hour period. To calculate the leakage rate, equation 10 is used below where V (mL) is the volume of air inside the suction cup, ΔP (bar) is the pressure difference during the time period, t (minutes) is the time in which ΔP is measured and P_{atm} (bar) is the atmospheric pressure.

$$Leakage\ Rate\ (ml/min)\ =\frac{V\cdot\Delta P}{t\cdot P_{atm}}\qquad(10)[27]$$

With a ΔP = 0.05 bar over 24 hours, V = 4 mL and the atmospheric pressure of 1.013 bar, a leakage rate of 0.000137 mL/min is calculated for this ideal lab setting. As seen above in Section 4.2, this leakage rate corresponds to a time constant of around 57 hours.

We know that detachment occurs at ΔP_{detach} = -0.05 bar and that when these suction cups are used outside the lab setting, the maximum time they stay on is roughly 9 hours. This means that there are some discrepancies between the lab data and what is going on when the suction cups are used on the dolphins. To take this into account we are going to examine cases for time constants of 0.5, 1, 5, and 10 hours as shown in Table 5 below. The exponential decay equation can be manipulated to solve for detachment time as shown below in Equation 11 with ΔP = -0.15 bar, ΔP_{detach} = -0.05 bar, and τ is the variable time constant

$$t_{detach} =-\tau\, ln\frac{\Delta P_{detach}}{\Delta P_0}\qquad(11)$$

Table 5. Examination of Different Time Constants

τ (hr)	**LR (mL/min)**	**Detachment Time (hr)**
0.5	0.01	0.55
1	0.005	1.1
5	0.001	5.5
10	0.0005	11

This table will provide some insight into how often the pump needs to be used (i.e. turn the vacuum pump on for a short period of time to increase the pressure differential) and how long the pump needs to be turned on to get back to ΔP_{diff} = -0.15 bar.

7.3 Valving

In order to keep the suction sealed, proper valving needs to be chosen. This section will go into calculations and analysis to ensure that the valve will act as we want it to. Essentially, the valve needs to keep air from flowing into the suction cup but simultaneously be able to open and let the vacuum pump suck air out of the suction cup. Therefore, the forces at this valve need to be modeled to ensure that the pump and valve will work well together. The chosen valve for analysis has a spring that holds the valve hinge in place. The forces involved will therefore be the spring force from the hinge, the weight of the valve, and the force produced by the air pressure from the vacuum pump. Figure 24 below provides a free-body diagram of the local valve area.

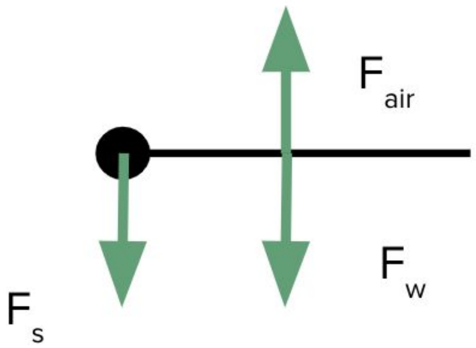


Figure 24. Free body diagram of valve hinge

A simple force balance is given below in Equation 12. In order for the vacuum pump to successfully manipulate the valve, the force produced from the vacuum pump must be greater than the spring force and the weight of the valve. The variables P_{air} is the pressure produced by the vacuum pump, A_{valve} is the area of the valve, m is the mass of the valve, k is the spring constant of a spring similar to the one used in the valve, and x is the compression length [28, 29].

$$F_{air} > F_W + F_s \tag{12}$$

$$F_{air} = P_{air} \cdot A_{valve} \tag{13}$$

$$F_W = mg \tag{14}$$

$$F_s = kx \tag{15}$$

$$P_{air} > \frac{mg+kx}{A_{valve}} \tag{16}$$

Solving for the variables listed above, P_{air} = 0.34 bar. This means that the pump will need to produce 0.34 bar of pressure in order to manipulate the valve. The chosen vacuum pump, T2-05 from Parker Hannifin is able to produce this value and this will be discussed in the next section [30].

7.4 Vacuum Pump Flow Rate and Power

All necessary information to calculate the volumetric flow rate of the vacuum pump and power consumption is known. The motor data sheet is utilized to assist with these calculations and is shown below in Figure 25.

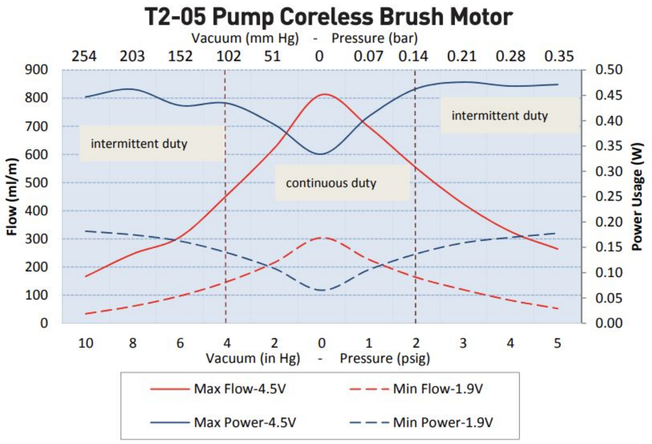


Figure 25. Motor power data sheet [30]

As found in the last section, the pressure the vacuum pump needs to produce is 0.34 bar. The battery being used has a voltage of 0.37 Volts. Doing linear interpolation between the intermittent duty curves of 1.9V and 4.5 V, the calculated flow rate is ~600 mL/min and the power consumption is about 0.4 W. This calculated flow rate is the ideal scenario with no impediments of the air flow. However, the valve will most definitely impede the flow of air so to navigate this, we assume we can get roughly ¼-½ of this ideal rate, so the air flow rate will be closer to 150-300 mL/min.

There is quite a large discrepancy between the air leakage rates and the flow rate produced by the vacuum pump. The maximum leakage rate found in the Leakage Rate section is about 0.01 mL/min while the minimum expected air flow rate produced by the pump is around 150 mL/min. This means that the vacuum pump will be turned on for a very short amount of time when being used, most likely in a pattern of pulses or blips.

The suction cup will become detached from the surface at a pressure difference of around -0.05 bar, but we do not want to get close to that so the vacuum pump will be activated when the pressure difference is -0.09 bar for about a 2x safety factor. This pressure increase in the interior corresponds to about 0.2 mL of air and if the flowrate of air is around 2.5 mL/sec, the vacuum pump would need to be turned on for around 0.1 seconds. This is a very short period of time for a motor to turn on. The motor specification sheet does not offer information about the reaction time of these motors so more extensive analysis will have to be performed in a lab setting to ensure that the vacuum pump can operate like this.

The goal of this system is to be able to maintain suction for at least 24 hours. Therefore, analysis needs to be performed to see how often the pump will need to be used to ensure consistent suction.

We will now look back to Table 5 and the various time constants and corresponding leakage rates. Given that the vacuum pump will be turned on whenever the pressure difference gets to -0.09 bar, we can calculate how long this takes and how many times the pump would need to be turned on for a variety of these leakage rates and time constants. Table 6. provides information about

Table 6. Pump Usage and Leakage Rate Relationship

τ (hr)	**LR (mL/min)**	**Time to ΔP = -0.09 bar (hr)**	**# of Pump Uses in 24-hour Period**
0.5	0.01	0.255	94
1	0.005	0.511	47
5	0.001	2.55	10
10	0.0005	5.1	5

This analysis on the motor will ultimately give us a head start during testing. Performing additional analysis on higher leakage rates will give us a more realistic framework for the problem at hand. While the motor is an essential aspect of the system, it cannot work in isolation and other aspects of the system design must be thoroughly researched to ensure that enough preparation is done to justify the design. Thus far, the analysis has been done with data from the T2-05 Vacuum Pump from Parker Hannifin. Given the findings, we are confident that this vacuum pump is the correct choice given the design problem.

8. Engineering Analysis - Suction Cup, Tubing, and Pressure Sensor

8.1 Suction Cup

To minimize leakage within our system, we decided on the black suction cup in Figure 12 for our physical mockup because it has the largest time constant (57.26 hours) compared to the white and blue cups. We took approximate major dimensions of our chosen cup, specifically its port hole diameter, base diameter, and inner height. We found the port hole diameter (found at the top of the suction cup) to be ~1.5 mm. In its resting position, the inner diameter of the base is ~42 mm and the inner height is ~10 mm. In its attached position, the vacuum area diameter and height are ~40 and ~5 mm, respectively. We initially decided to place the pressure sensor inside the cup (without impeding the cup's surface contact in its flattened state) for accurate readings of internal pressure, but considering the vacuum area's small dimensions, we no longer saw that as a viable option. We ultimately decided to change the placement of our sensor, which will be discussed later on in Section 8.3.

8.2 Tubing/Connectors

To connect all our key components together, we used silicone rubber tubing (shown in Figure 26 below), which has high flexibility, excellent electrical insulation, and tight seal assurance.

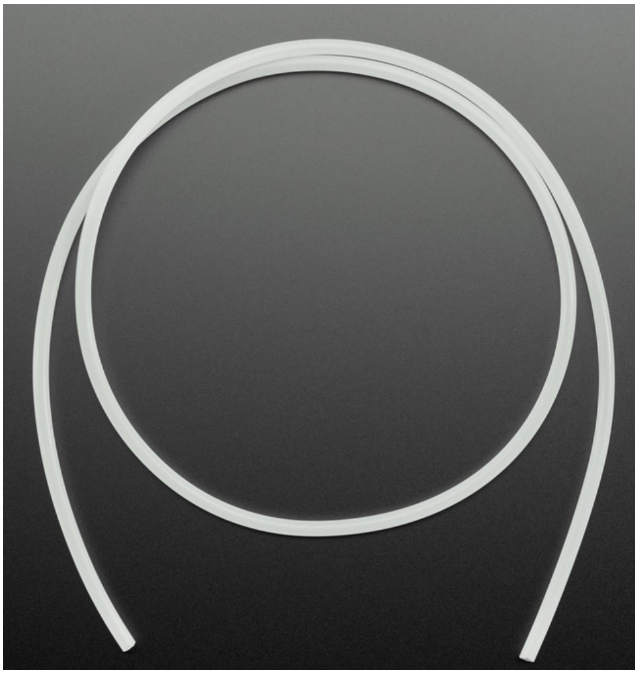


Figure 26. High Temperature Rubber Tubing for Air and Water [31]

We chose tubing with ID 3/32” [31] to fit the ports of our T2-05 Micro Diaphragm Pump, but to connect the tubing to our suction cup, we used a plastic reducer [32] for Tube ID **(A)** 3/32” or 2.4 mm **(B)** 1/16” or 1.6 mm. This tube fitting, pictured in Figure 27 below, converts the cup’s port hole diameter of ~1.5 mm to the silicone tubing ID of 2.4 mm.

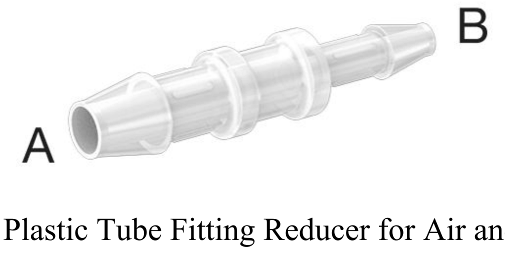


Figure 27. Plastic Tube Fitting Reducer for Air and Water [32]

We then used the tee splitter in Figure 28 [33] below to divide our 3/32” ID tubing into two directions: one leading directly to the vacuum pump and the other leading to the pressure sensor. The pressure sensor line, however, required a larger tube diameter to fit the sensor within the system, so we also purchased silicone tubing with ID 1/4” [31] and a plastic tube fitting reducer [32] for Tube ID **(A)** 1/8” or 3.2 mm **(B)** 1/4” or 6.4 mm. No connectors could be found that converted 3/32” directly to 1/4”, but we found that the 1/8” end of the reducer fit well within the Tube ID 3/32”.

Figure 28. Plastic Tube Tee Fitting for Tube ID 3/32” [33]

All fittings have a single barb to ensure extra tight connections throughout our line and overall, eliminate any additional leakage of air within our system.

8.3 Pressure Sensor

In choosing the pressure sensor of our system, we considered several sensors from a variety of providers. Key factors in our selection process involved size, temperature tolerance, voltage tolerance, the range of pressure that the sensor is able to read, and the resolution with which it reads them. With respect to size, we sought to look for a sensor that could be placed inside the tubing being used for the rest of our system, and thus searched for a unit that could fit into the 2.4 mm diameter of the 3/32” tubing.

Unfortunately, we found that sensors that small were not readily available off the shelf, and were only in use and development in private research facilities. This presented a major challenge to us from a design perspective, and forced us to re-engineer our plan to have the sensor seated inside the main tubing. We therefore decided to encase our sensor inside a separate chamber, which would have a larger cavity in order to accommodate the larger sensors we had access to from the market.

Adding a converter would enable us to use larger tubing in the section containing the pressure sensor, and allowed us some more flexibility, since using 1/4" tubing would mean an internal diameter of around 6.35. It was still difficult to find a sensor that would fit completely and comfortably inside this space, but the MEAS MS35803-01BA [34] from TE Connectivity (shown below in Figure 29) contained a circular sensor attached onto a square backing piece, with the circular part of the unit being small enough to fit inside the tubing. We decided that it was sufficient for only this part to be inside the tubing, leaving the square backing outside the tubing, closing off its opening. This would also make it easier to wire the sensor to the control system, without compromising the pressure-reading capabilities of the sensor. In order to ensure that the vacuum is fully sealed, we would use Loctite as an adhesive with which to close any gaps left at the opening of the tube.

Figure 29. MEAS MS35803-01BA from TE Connectivity

The chosen sensor also fulfills the stipulated functionality requirements. It operates reliably in a temperature range of -40 to 85 ℃, which comfortably accommodates the temperature range of bottlenose dolphins' habitats. It can handle voltages of up to 3.7 V, thus matching the voltage supply in the circuit. The unit also reads pressures of up to 30 bar, with a resolution of 12 μbar, also fulfilling the needs set by the system.

9. Risk Assessment

9.1 Overall Risk

Each added component in a design can add to the risk of failure of the entire system. It is therefore important to maintain simplicity while still meeting the design requirements. Each component of the design carries some form of risk given the task asked of the specific system. If a design is too reliant on one critical component then failure of this component would be completely detrimental to the performance. Ideally, a design would take into account the inherent risks and have methods for mitigating risk and dealing with potential failures. The entire premise of an active suction system for biologging tags is based on the failure of the suction cups. If suction cups worked well enough as tag attachments then there would be little need for an active system. Nonetheless, an active system has been designed to deal with this inherent failure of the suction cups.

9.2 FMEA Table

This section contains a very basic FMEA table analyzing the individual components of the active system design and identifying failure methods and ways to reduce the probability of failure.

Table 7. FMEA Table to Outline Failure Modes of Key Components

Component	Failure Mode	Likelihood	Control Method
Suction Cup	Leakage leading to detachment	Primary cause of failure, genesis of active system design	Focus of active system design
Tubing	Poor connection and additional leakage	Not very likely, good connection can be assured with proper testing	Pressure testing with and without tubing to determine any weak points
Valve	Does not open/close	Possibly but not likely, perform multiple tests beforehand to ensure consistent behavior	More testing, potentially use multiple valves for a safety factor
Pressure Sensor	Miscalibrated or broken	Definitely possible, it is essential aspect for active control	Implement multiple sensors with a backup in case one malfunctions or is miscalibrated
Vacuum Pump	Too weak/too strong pulls of air from cup	Works well and should last for these shorter data acquisition periods	Add to controls system/code to certify that vacuum pump will not over or under pull air from the cup
Control System	Incorrectly coded Can't adapt to non-lab environment	Low, extensive testing and debugging can ensure a resilient controls system	Look at any edge cases and test controls system to assure that it works for any unique scenarios that may occur during deployment
Battery	Depletes before data acquisition period is finished	Potential for failure, low battery capacity couple with high usage of vacuum pump leads to no more active system	Multiple batteries Decreases pump use which decreases safety factor

The main components are analyzed above while looking at what their respective failure modes could be as well as the likelihood of this type of failure and what could be done to decrease the probability of failure. All aspects are important in their own right but the entire system is designed so that the suction cup does not detach for a given period of time. However because suction cup is the focus of the design another component will be considered for further analysis of the potential highest risk component.

9.3 Highest Risk Aspect

The highest risk aspect in the current active suction cup system is the pressure sensor. Testing can be done to alleviate issues with the tubing, valving, and vacuum pump. In addition the controls system can be extensively tested and multiple batteries could be used if size permits. However, the pressure sensor is tied to all functioning aspects of the design. The pressure sensor is the one that sends the signal through a microcontroller in order to notify the vacuum pump to turn on. If something goes wrong with the pressure sensor then the vacuum pump will not work properly and all other components are essentially useless at that point. Nonetheless, there are potential mitigation strategies that really decrease the likelihood of total failure if the pressure sensor fails.

9.4 Risk Mitigation

A clever controls system can be devised to work around these issues. For example, it could potentially be made that if no signal came from the sensor after X minutes, then the vacuum pump would turn on at regular intervals and keep working. While there is no longer monitoring and on demand use of the vacuum pump this would ensure that the suction cup would remain attached, which is the core of the design problem. Extensive testing could be performed with the system to find how long detachment occurs on the dolphin with a passive suction system. This could be worked into the controls system by giving this backup code a large safety factor so that the vacuum pump would be used often enough to remain attached to the surface. Overall, all relevant failure methods need to be taken into consideration in order to create a resilient design. Given all the potential modes of failure, the pressure sensor was identified as the one with the highest likelihood due to it’s integral role in communicating to the vacuum pump when to turn on. Many of these potential failure modes can be with extensive testing while others can be reduced with clever backups in the controls system if something goes wrong during deployment. Risk is something inherent in all designs but it is a matter of identifying the risk and trying to mitigate it in order to design as resilient a system as possible.

10. Detailed Design Solution

Figure 30 below shows the final prototype and all of its components.

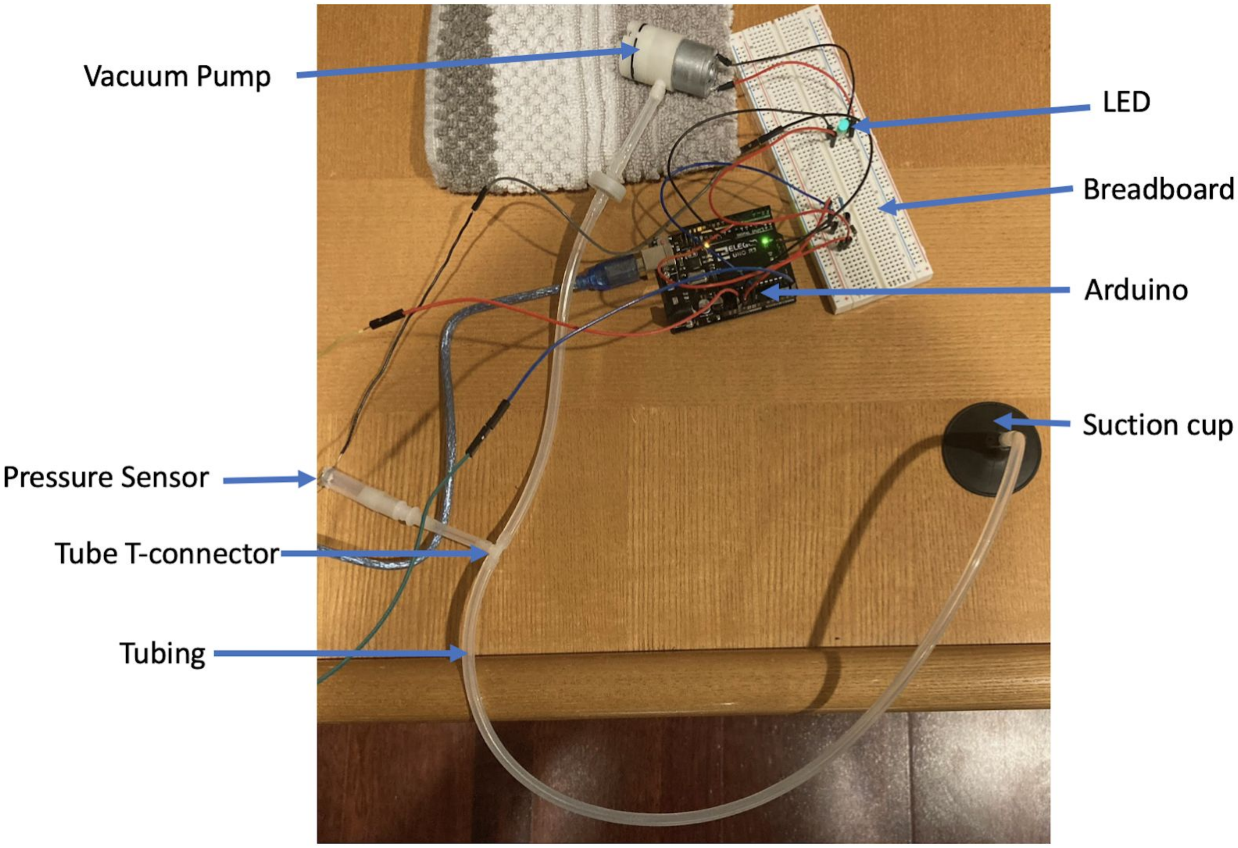


Figure 30. Final Prototype

Each of these components played a significant role in the design's success. The components include the suction cup, the pressure sensor, the vacuum pump, the tubing between components, the valving, the Arduino Uno, a laptop to run the Arduino and monitor data from the system, and all of the wiring between the Arduino, the components, and the breadboard. Our final prototype design was very true to our final design choice. The final prototype also included an LED light on the breadboard that would light up brighter whenever the vacuum pump was working.

The tubing was attached between the suction cup, pressure sensor, and vacuum pump as decided by our final design choice. To make sure the pressure sensor monitored the pressure properly without disrupting any other aspect of the design we continued forward with our design choice of using a T-shaped connector for the tubes. Using this T-shaped connector we were able to place the pressure sensor within the same volume of space that the inside of the suction cup was in without disrupting the suction cup. This connection is shown below in Figure 31.

Figure 31. T-shaped connector connecting the pressure sensor, suction cup, and vacuum pump

The only activity associated with setting up the suction cup was connecting the suction cup to the tubing mentioned above. The pressure sensor was small enough to fit inside of the tubing. In order to collect that information from the pressure sensor we had to use information provided from its spec sheet. The spec sheet informed us which three out of the 8 pins on the back were useful to us. The useful pins used on the back of the pressure sensor were the voltage in pin, ground pin, and data out pin. Wires were soldered on to these pins in order to then properly connect the pressure sensor to our Arduino Uno. In order to ensure that the sensor would not fall off but also, most importantly, was tightly sealed into the tubing in order to avoid extra air leakage, we applied super glue on the back of the sensor for two reasons. The first reason was to secure the sensor to the tubing and cover up any extra space around the sensor that would cause extra leakage. The second reason was to secure the wires on the sensor since the soldering was not very strong and was causing issues with the wires where they would break off from the sensor. So to fix this problem we applied the super glue on top of the soldering connections made between the wires and the sensor which successfully secured these wires. The sensor is shown below in Figure 32, showing the wiring, soldering, and connection to the tubing.

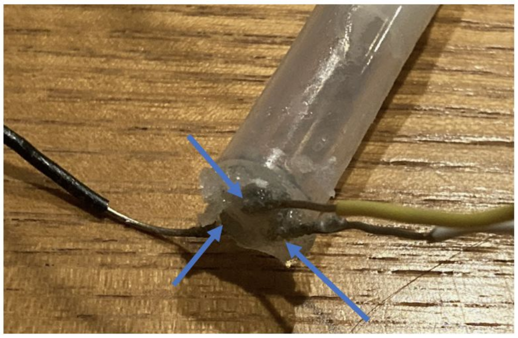


Figure 32. Image of the back side of the pressure sensor showing the soldering plus layer of super glue for extra support between the sensor and the wires going out to the Arduino.

The vacuum pump was attached to the third and final end of the tubing. The vacuum pump was a much easier connection to make with the tubing since it already had an appendage that fit tightly inside of the tubing. The tight fit allowed for no significant/noticeable extra leakage and for the vacuum pump to proper pull air out of the suction cup volume. The only other connections made with the vacuum pump were the wires associated with giving the pump power. The vacuum pump can be seen below in Figure 33.

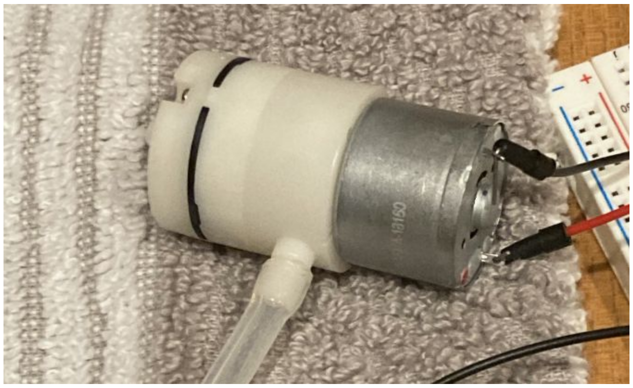


Figure 33. Image of the vacuum pump used with its power wires connected

An Arduino Uno controller was used as the control method along with the breadboard in order to manage all of the wire connections that were necessary. The Arduino Uno, the wiring, and the breadboard are shown below in Figure 34.

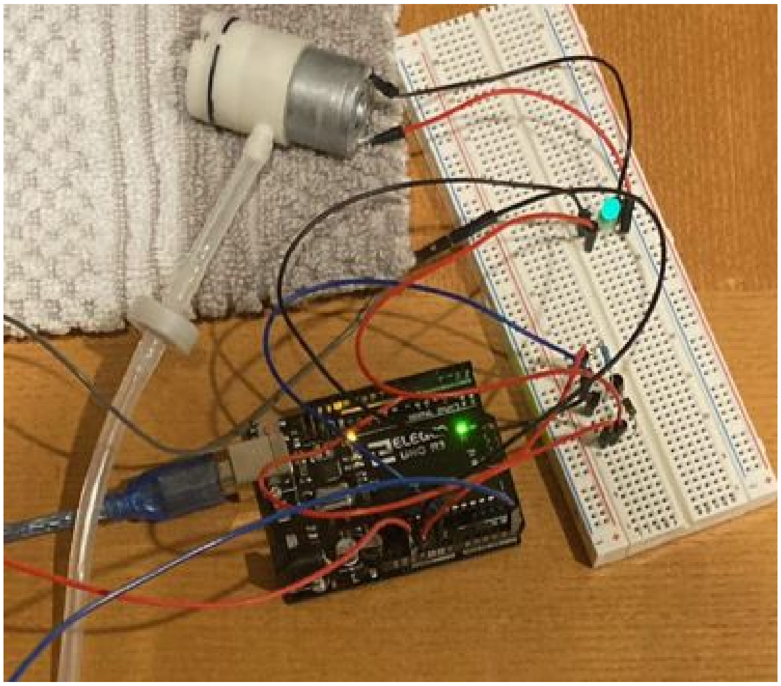


Figure 34. Image of the Arduino Uno, wiring, and breadboard

The wiring follows a structure such that the pressure sensor and the vacuum pump are both connected to the Arduino Uno in order to have power and be able to communicate between the two. This is essential for the system to work so that the vacuum pump can work based on information that the pressure sensor is providing. The breadboard is used to provide extra room for connections. The vacuum pump is connected through the breadboard to the 5V output and ground on the Arduino Uno, after going through connections with a 270 Ω resistor, 1N4001 diode, and PN2222 transistor. The back of the pressure sensor has the structure and pins shown in Figure 35 below.

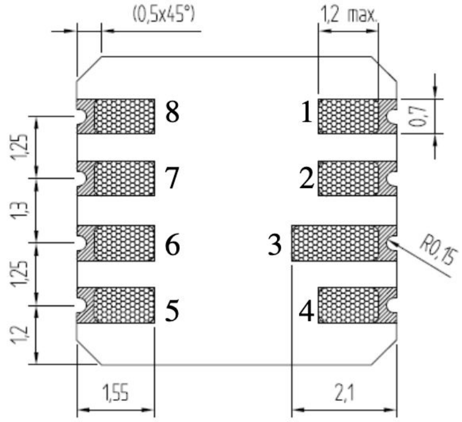


Figure 35. Structure and pins on the back of the pressure sensor

The pins that were used on the pressure sensor were pins 8, 5, and 2. Pin 8 is the serial data output, Pin 5 is the positive voltage supply, Pin 2 goes to the ground. Pin 8 was connected to the A1 pin in the Arduino Uno in order to read the pressure sensor's data. Pin 5 was connected to the power supply 3V from the Arduino Uno, and Pin 2 was connected to a ground pin on the Arduino Uno. A circuit diagram of the all of the system wiring is shown below in Figure 36. A larger and unmarked version of this circuit diagram can be seen in Appendix C.

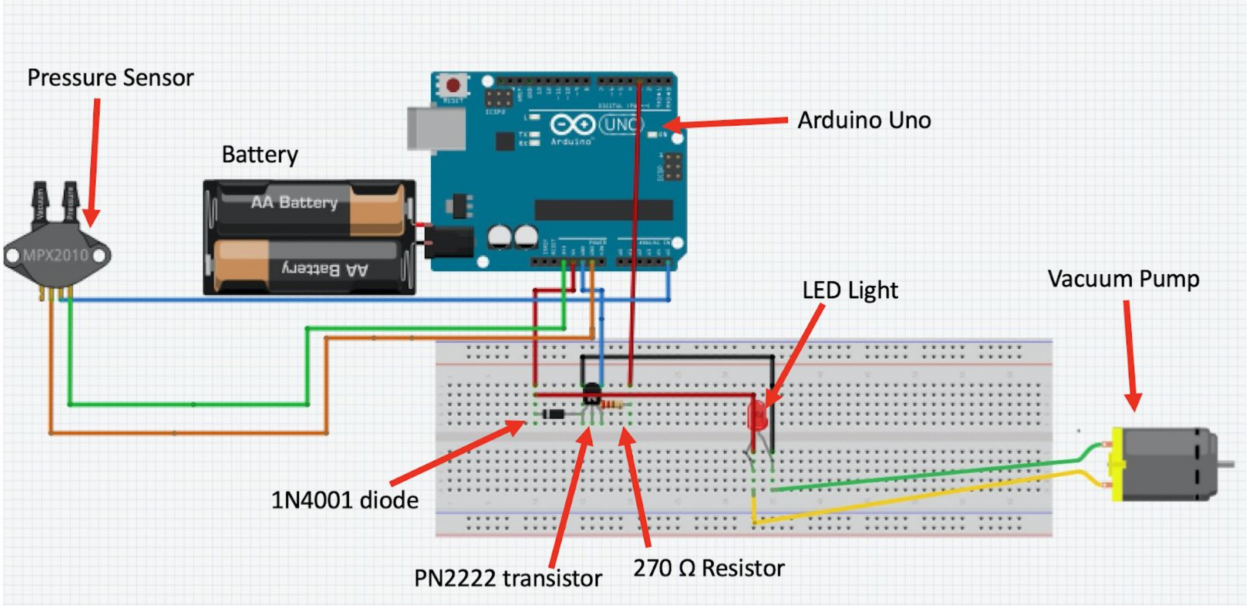


Figure 36. Circuit diagram of the suction cup system using Fritzing

Since we used an Arduino Uno controller we had to write code that appropriately managed the communication between the pressure sensor and vacuum pump. The code is shown in Appendix D. In the Arduino code we have a constant loop going where the pressure sensor is continuously reading the pressure value. Within the code's loop we put in pressure thresholds, upper and lower bound pressure values. In the code loop we made it so that if the pressure sensor reads a value higher than the specified upper limit pressure value then the vacuum pump is turned on. The loop keeps going and once the pressure sensor reads a value lower than the lower limit the vacuum pump is turned off. Using this method is how our system is able to keep within a specified pressure range.

It is important to look at how our final prototype design aligns with the aforementioned requirements and specifications. The requirement "Ability to respond to pressure changes as a result of air leakage and maintain a constant pressure", can be achieved with the successful use of all of the design's components including pressure sensor, vacuum pump, tubing, suction cup, Arduino Uno microcontroller. Appropriate and successful communication between the pressure sensor and the vacuum pump will allow the system, if put together appropriately, to respond to pressure changes via the vacuum pump. The specification for this requirement was to "Sustain a constant pressure of 0.15 bar in the suction cup" and "Uses material with low elastic modulus". The final design's components, like when talking about the requirement, are all able to work together to achieve this 0.15 bar if tuned appropriately and if communication between the pressure sensor and the vacuum pump via the microcontroller is successful. Whether this was achieved will be elaborated in Section 11. The second requirement was that the system should be "Strong enough to withstand drag/lift from dolphin swimming". Since our final design is a simplified design that is only meant to test the system's ability to maintain a constant pressure (keeping the suction cup secure), this requirement is overlooked by this simplified final design and would be looked into further into the development of this device. The third requirement was to make the system have "Waterproof packaging of electronic system". Similar to the second requirement, due to the nature of the simplified final design this requirement is one that would be looked into further into the development of this device and is currently not taken into account. The fourth requirement is that the "System works properly for at least 24 hours". Our system makes use of a 1200 mAh battery in order to make sure the 24 hour mark is met by the system. The success of this type of batter is discussed in Section 11. The specification for this requirement is that the "Battery life of the electronics lasts for at least 24 hours while the suction cup also reliably stays on the dolphin". As previously stated, the chosen batter of 1200 mAh has the ability to successfully last for 24 hours while powering the vacuum pump and pressure sensor. As for the part of the specification that states that the battery and suction cup should successfully stay on the dolphin for the 24 hours, again due to the nature of the final design this cannot be determined at the current stage of the device. The fifth requirement is for the system to "Withstand the temperature range of the dolphin's habitat". Similar to previously mentioned requirements, this is outside of the scope of the final design due to its simplified nature and use only at room temperature. The final requirement was for the "Easy and quick installation" of the device on the dolphin. The final design's scope again does not look into this and consequently this is a requirement that would be discussed further into the development of the device.

The main difference between the final prototype and the final design is that the final prototype uses the power source coming from the Arduino Uno rather than using a separate battery. The reason for this choice is that the Arduino's power pins were readily available to use with the breadboard and with other circuit components in order for the pressure sensor to provide pressure readings by giving different voltage values via the other circuit components. The voltage from the Arduino and the battery that would have been used are the same.

11. Verification

In general, our active suction system solution was successful with respect to the main design requirements possible with the final simplified design. The requirement and specifications are shown in Section 3, Table 2. Due to our simplified final design, the main requirements that were applicable were the system having the "Ability to respond to pressure changes as a result of air leakage and maintain a constant pressure" and that the "System works properly for at least 24 hours". Therefore in order to verify that our system works successfully, abiding by these requirements, we will be looking at the system's ability to monitor pressure accurately, the system's ultimate response to pressure changes in order to keep a constant system pressure, and the system's ability to work off of the chosen battery for 24 hours.

11.1 Constant Pressure Monitoring

To ensure that our active system could continuously monitor pressure values inside our suction cup, we needed to verify that our pressure sensor could accurately output pressure readings. We decided on a simple test to verify if our sensor could constantly track and provide proper values as pressure inside the cup changed. This allowed us to check if our wiring connections were correct and stable, and whether we had successfully sealed off our pressure chamber. We first used the sensor's spec sheet to determine which pins (shown in Figure 35 above) were useful for our data collection and proceeded to make wiring connections between our pressure sensor and the Arduino Uno. A short script, included in Appendix D, was then written to read internal pressure values and output them to the serial monitor.

We repeatedly attached and detached the suction cup from a hard wooden surface to see if the Arduino could recognize pressure changes inside the cup. After performing several tests, the code successfully yielded appropriate output values, thus verifying that the wiring connections were stable and that the vacuum chamber had been sealed as intended. Output readings, which can be seen in Sections 11.2 and 11.3, were continuous and highly responsive, considering the high resolution of our pressure sensor.

11.2 System Response/Pressure Maintenance

Our chosen microcontroller, the Arduino Uno, and method of actuation, the T2-05 Micro Diaphragm Pump, were key in verifying our main design requirement: keeping a constant pressure within the suction cup and maintaining attachment to a surface. Specifically, our system was required to hold a constant internal pressure value of 0.15 bar by pulling air out of the suction cup when necessary, since the natural leakage into the cup would decrease the pressure difference between the inside of the suction cup and the outside environment until the resulting detachment of the cup. By achieving this, our system would successfully secure the cup to a surface.

We ultimately needed to test whether our system would function as intended. To ensure that the system is 'working properly', it should respond to pressure changes so that the vacuum pump turns on when an upper pressure threshold is exceeded inside the cup, and turns off when a lower threshold is reached. When the pump is on, the system should be pulling air out of the suction cup, decreasing the pressure inside the cup and thus increasing the pressure difference between the inside and outside of the cup.

To validate the system's performance, we tested our physical prototype on a hard, flat surface. Empirical methods allowed us to not only track the response of our system via changes in pressure readings but actually observe the pump pulling air out of the suction cup to counteract leakage. We first wrote an Arduino script, included in Appendix D, to specify the upper and lower pressure limits of our system. When the upper threshold is reached, the Arduino sends an input (voltage) signal to the vacuum pump, a constant value that corresponds to the vacuum speed set by the user. The pump turns on and pulls air out of the suction cup until the lower pressure limit is reached, after which the input signal switches to zero and the vacuum pump turns off. For the purpose of visual demonstration, we increased the vacuum response within the Arduino code to not only see, but also hear the pump working. As an additional visual aid, we placed an LED light in parallel with the vacuum pump, which gets brighter when the pump is actively pulling in air. Then applying the suction cup to a flat surface, we monitored the pressure sensor output over the attachment period, which can be seen in Figure 37 below. The pressure readings tracked the pump's overall activity, denoted by major drops in pressure, and indicated whether the pump could continuously maintain a desired pressure value inside the cup.

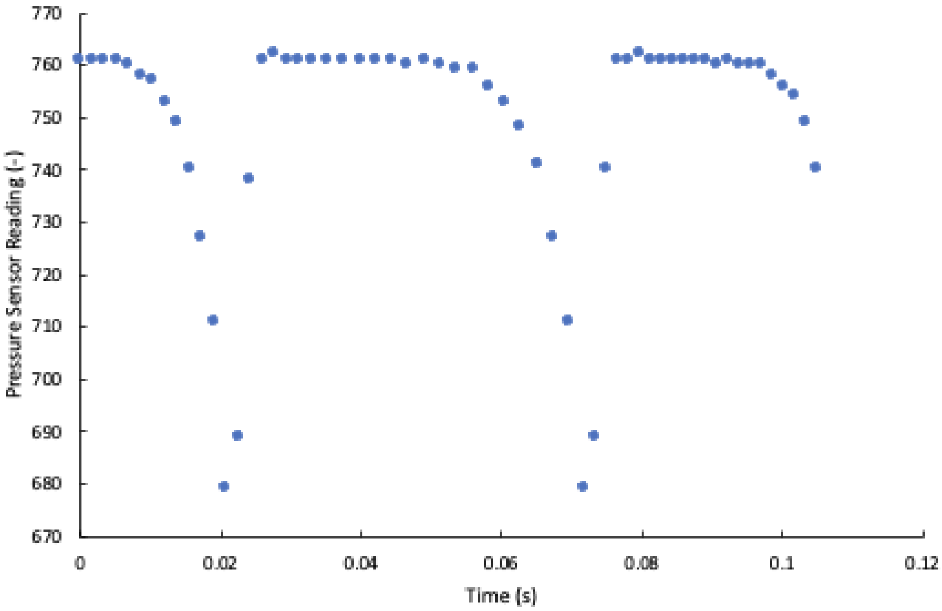


Figure 37. Pressure sensor output readings over time for suction cup testing on a hard, flat surface.

We ultimately found that our system was successful both in maintaining a constant internal pressure and in preventing detachment from the flat surface. The graph shows that pressure readings remain fairly constant, except for slight decreases caused by natural leakage into the cup. These decreases exceeded the pressure limit and triggered a response from the vacuum pump, as shown by the sharp increases in pressure. The pump continuously pulled air out of the cup until the internal pressure value was restored to ~760. However, further calculations are needed to convert the sensor readings to absolute pressure values and verify that the pressure inside the suction cup can truly be maintained at a value of 0.15 bar for the stipulated 24-hour duration.

11.3 Battery Life Over 24 Hours

Our original specification required our system remain attached to the surface for a minimum of 24 hours. To verify this design requirement, we decided to use the battery from the Arduino because it was easily integrated into our system and was found to function similarly to a 1200 mAh battery. For the purpose of testing battery life, we attached the suction cup to a yoga ball, which more closely mimics the skin of a dolphin as opposed to a flat wooden surface. We originally chose to analyze the battery's operation by running our system for 24 hours, but later decided that it would be more efficient to simply examine the pressure sensor readings plotted against time. Figure 38 below shows this graph, and demonstrates cyclic fluctuations in the pressure input. We could then estimate what percentage of the time our pump was actually running and then use the load current to calculate our total battery consumption in mAh.

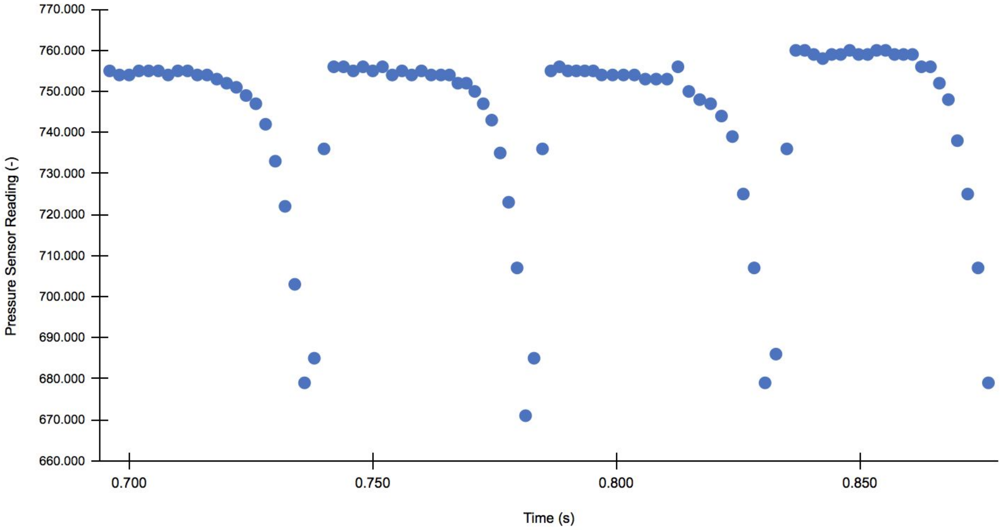


Figure 38. Pressure sensor output readings over time for suction cup testing on elastic yoga ball.

The pressure plotted above is seen gradually decreasing, then rapidly increasing again to a nominal value, and then beginning the cycle again. The gradually decreasing portions of the pressure data reflect the natural leakage, and the rapidly increasing portions indicate the time during which the pump is actively pulling in air. Since the power consumption of the pressure sensor is negligible, and the pump accounts for most of the power used, the percentage of time during which the pump is operating can be used to provide a safe approximation of the power consumption across 24 hours. The pump is seen to be operational for around 9.5% of the time in the graph, during which it is operating at 500 mAh. Extended to the 24-hour period, this means that around 1140 mAh is consumed in total, meaning that the system comes fairly close to depleting the 1200 mAh stored in the battery. Thus, it is reasonable to extrapolate that the battery used in our system will last for 24 hours as intended. Attaching the suction cup to the yoga ball yielded a smaller leakage rate compared to testing on a flat surface. Since its isometric elastomer material more closely resembles the skin of a dolphin, as opposed to a hard wooden surface, the power consumption calculated here may be more representative of the actual battery usage when installed on the actual animal. However, the drag and lift forces incurred from the dolphin's swimming may encourage detachment, meaning that further tests on the battery consumption will need to be conducted once the underwater environment can be simulated.

11. Discussion and Recommendations

The final model has been fundamentally successful in accomplishing what the project set out to do. Many methods of attaching biologging tags to animals are unreliable, or instead resort to invasive or uneconomical ways of keeping the tag on the animal for the required amount of time. Bottlenose dolphins have a skin that can be characterized as an isometric elastomer, so suction cups would appear to be the most straightforward way to create an attachment, but this option is often hindered by the natural emergence of leakage, which puts the device at risk of detachment.

Our model takes a head-on approach to tackling this issue, and employs active control to provide a solution that is neither uncomfortable for the animal nor inefficient in its resource consumption. The various components of the model have been set up so that the pump is only triggered if leakage is detected, and so that it stops working again as soon as the attachment has been re-established. This ensures that the pull of the suction is never stronger than necessary, thereby circumventing the risk of disturbing the dolphin. Furthermore, this means that the system conserves energy by working only when necessary, which will be of particular advantage when the system is deployed with a limited power source.

The scope of our project is limited in that it primarily serves to demonstrate that this is a model that has the potential to work in a real-world application. In view of this, various modifications will need to be implemented before this design is developed into one that can successfully be installed on a live dolphin.

Since the current model has been constructed as a tabletop demonstration, the components have been selected and integrated in a manner that handles air, rather than water, as the fluid in question. Before the device is submerged in the dolphins' habitat, every component would need to be re-evaluated and potentially updated to be water-resistant and to successfully manipulate the water to regulate the pressure as required by the system. Water has distinctly different properties from air, such as a higher density and viscosity, as well as a fixed volume since it is a liquid. Corresponding changes will need to be made in order for the device to show the same success manipulating water as it has shown with air, and further testing will likely be necessary at this stage.

Furthermore, the electronic components must be kept completely dry to avoid any possibility of short-circuiting, which would severely impede the functioning of both the control system and the tag. Chemical considerations will also need to be taken into account, and the design must be adapted so that no components are at risk of corroding or otherwise negatively interacting with the seawater as well as being able to withstand surrounding pressure changes.

Since the current model has been built with demonstration in mind, the constants in the control system have been tweaked to elicit a more visible physical response from the system. We sought to make it clear that the motor was working when necessary, so the response speeds of the pump were exaggerated to make the pump louder. These values will need to be re-calibrated prior to deployment, in order to establish a more precise balance between the input and the output. This may perhaps be implemented through trial and error modification of the controls, or, more accurately, through a mathematical analysis of the fluid dynamics.

The structural aspects of the attachment also fall outside of the scope of our work, and will need to be brought into consideration as the model is developed into a workable design. Many components of our model have not been rigidly secured to one another, being connected only by flexible wires and tubes. This would be unfeasible for real-world application, and housing and support will need to be established for the entire device. In doing so, it is important to ensure that the structure is sturdy enough to withstand the physical ordeal of being dragged through seawater at high speeds. Bearing this in mind, the shape must also be made as streamlined as possible in order to minimize water resistance.

Our demonstration also does not account for the actual biologging tag that the suction will be holding onto the dolphin. This device will have properties of its own, and will bring with it various physical concerns that must be addressed. Most immediately visible is the fact that our model has the tubing emerging directly out of the center of the suction cup, leaving little room to mount a biologging device on the top of the cup. This means that mounting the biologging tag will not be as straightforward as perhaps anticipated. The tag will need to be integrated into the housing and support of the design along with the other components, rather than added afterwards.

One limitation of our current model is that it has only been tested for short durations. It may have been more insightful to let the device run for the stipulated 24 hours to ensure that it is able to sustain the attachment for that period of time as well. As it stands, the attachment shows no signs of weakening during the short periods for which it has been tested, but it is impossible to know for certain until the device is tested for the required duration. A secondary battery or battery with a larger capacitance could be added or substituted at a minimal volume addition, if additional power is necessary. This would be a helpful next step to look into.

Furthermore, we experienced various issues with connecting the sensor to our circuit. The sensor model was chosen with the initial intention of attaching it to the inside of the cup, so there were no pins attached to the sensor. However, our model was later revised to move the sensor outside the cup, so this aspect was ultimately unnecessary. It was very difficult to solder the wires onto the small surface area of the sensor backing, and multiple attempts were needed. This likely damaged the connection to some extent and added unnecessary resistances. This means that there is a risk of unreliable or inconsistent readings from the sensor, which would disrupt the input signal. A useful revision to our current design would be to replace the sensor model with one that comes with attached pins for ease of connection, better accuracy, and more efficient use of space.

We also experienced trouble with the adhesives we used in the structure. While we initially sought to use flexible epoxy, this took far too long to set, causing our components to fall apart repeatedly and become slippery and gluey, rather than firmly set. Superglue was later used to patch up these attachments, and was found to be extremely effective, so it would have perhaps been more efficient to exclusively use superglue from the beginning for all attachments, rather than leaving unnecessary traces of epoxy in the model. It may also be helpful to extend the use of superglue to the tubing attachments of the design as well, in order to seal the attachments more securely.

Ultimately, however, our model shows that this is an approach with much promise to work. Testing our device on a yoga ball indicated that it is well suited to handle isometric elastomers, but our attachment also showed success on a number of other surfaces, such as book covers and glass. This indicates that our active suction system could perhaps, in the future, be extended to a wider range of species in addition to dolphins, such as whales, porpoises, manatees, dugongs, or sea turtles, all of which have surfaces akin to those our model worked successfully on.

12. Conclusion

This report contains motivation for the defined problem, list of engineering requirements and specifications, an exploration into the design process and potential concepts we considered for the development of the suction system, our final design, engineering analysis looking into the methods chosen for the problem solution, risk assessment, detailed design solution, and verification of the final design. Considerable progress has been made in recording technologies used in biologging tags and less attention has been put into the attachment methods. The use of a suction cup on the animal at hand, like a dolphin, is an easy and less invasive method of attachment. Our solution was to create an active suction system that keeps a constant 0.15 bar pressure difference between the inside and outside of the suction cup and keeps the suction cup tightly secured to the surface it is on. After completing our concept exploration phase, our final design is a simplified design that looks only into maintaining the constant pressure difference in order to keep the suction cup tightly secured and making sure that the system can work for 24 hours straight. In order to finalize the different technical components and aspects of the final design we conducted a variety of engineering analyses for the control system, vacuum pump, and suction cup. Our final solution is able to maintain a constant pressure based on set parameters and threshold values via the control method, Arduino. Our final solution is also able to work for 24 hours straight given the Arduino and chosen battery of 1200 mAh. The verification of these successes was discussed and completed via observation and data collection. This report holds the full details of the design along with a discussion and recommendations for future improvement.

Authors

Patrick Girard is graduating with a bachelor's degree in Mechanical Engineering in May 2021. He is from Ann Arbor, Michigan and enjoys playing basketball and volleyball, hiking, golfing, and reading in his free time. He also has a minor in the History of Art. He has spent time working as a research assistant for Professor Siegel in the Energy Storage and Materials Simulation Lab working on thermal energy storage materials and systems. This has facilitated his interest in renewable energy technologies and novel energy storage methods.

Santhosh Karthikeyan is graduating from the University of Michigan in May 2021 with a bachelor's degree in Mechanical Engineering. He is from Austin, Texas and enjoys traveling, writing, and keeping fit in his spare time. Academically, he is passionate about mathematics, physics, and technology, and has worked and studied in a variety of connected areas. He has been enthusiastic about animals his whole life, and spent much of his childhood learning about wildlife, thereby facilitating his decision to undertake a biologging-centric research project.

Dylan Rodriguez is a Mechanical Engineering Major at the University of Michigan, Class of 2021, also minoring in Computer Science. He is from Houston, Texas and grew up in an international environment to Peruvian parents. He began having an interest in mechanical engineering after realizing that math and physics were his prefered subjects in school. He is interested in energy systems and the energy industry. He enjoys playing soccer, playing instruments, and working out. He has gained industry experience in the automotive industry and hopes to gain experience in the energy industry now.

Melinda Li is studying Mechanical Engineering at the University of Michigan and is graduating in May 2021. She is from Houston, Texas and enjoys playing computer games, watching shows, baking, and cooking. She grew up surrounded by the automotive industry and was especially interested in her math and physics classes. She is interested in design but also wants to gain more experience in systems and controls. She has experience in the oil and gas industry.

Emily Isip is a senior at the University of Michigan, graduating in May 2021 with a Bachelor's Degree in Mechanical Engineering. She is from San Francisco, California and enjoys traveling, eating/cooking, and swimming. She first became interested in engineering after realizing she could combine her passion for hands-on design projects with her interest in the physical sciences. She grew up admiring and learning about cars, and with most of her technical experience involving vehicle design, she plans to pursue a career in the automotive industry.

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This project was completed with help of faculty members at the University of Michigan, our instructors, and our peers. We would like to thank Joanna Thielen, the librarian and research assistant for the ME department, for her guidance in conducting research at the beginning stages of our project helping us to have a better understanding on the subject and have a solid foundation moving forward. We would also like to acknowledge Professor Kira Barton for helping us throughout the semester by always providing constructive feedback in order to improve our project and to view our problem from different perspectives. Professor Kira Barton's help, advice, and perspective throughout the semester allowed us to move forward whenever we reached an obstacle. We would like to thank our sponsor Professor Alex Shorter and Ya-Yu Yang (Dory), a graduate student working closely with Professor Shorter. Dory's help is greatly appreciated for providing us with her knowledge and data of testing she had done on the leakage rates of some suction cups. Professor Shorter's guidance helped us to narrow down the scope of our problem at hand. His advice and feedback throughout the design process helped us to focus on what was truly important in our project and what was out of the scope. His guidance for components/supplies needed greatly moved us forward in the design process. Overall Professor Shorter helped us to steer the direction of our project in a successful direction.

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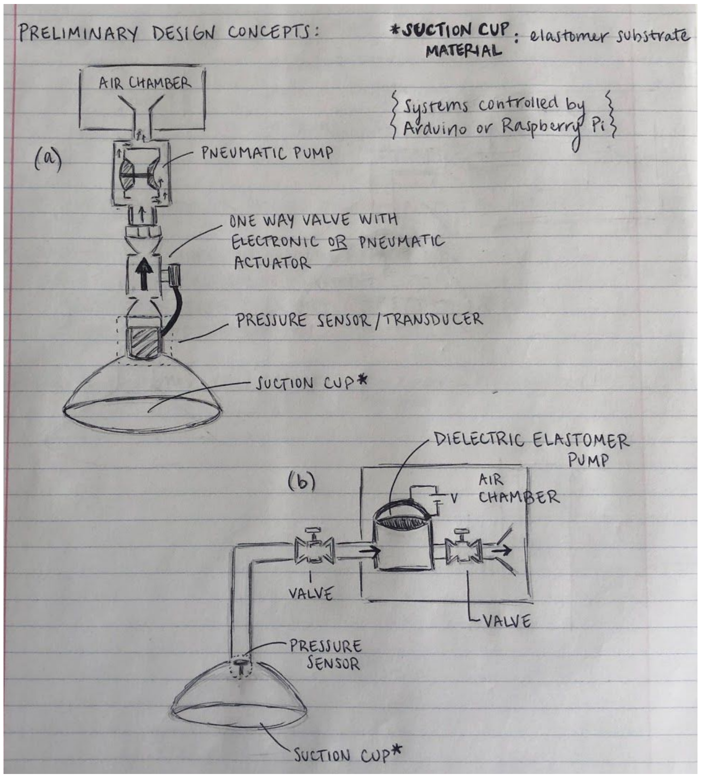
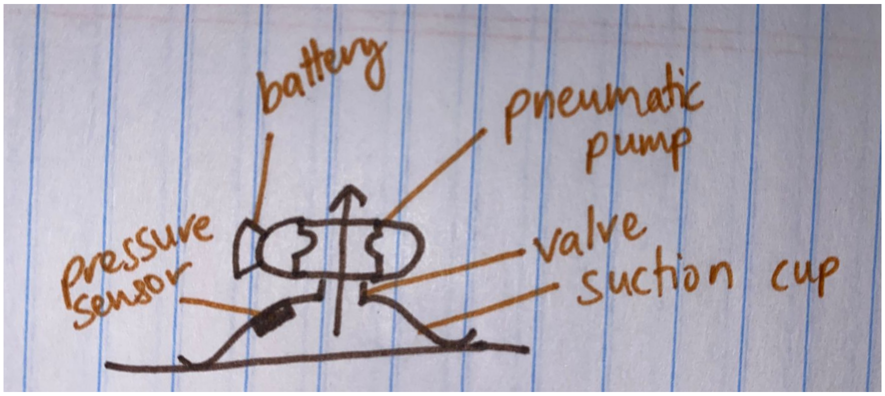
Appendix A - Concept Drawings

Appendix A.1 - Preliminary Designs

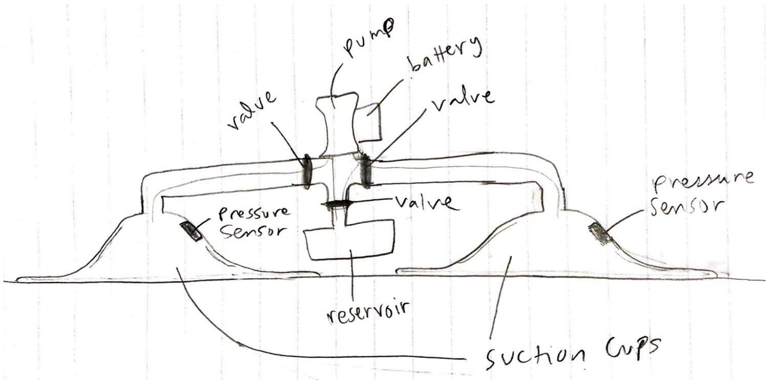
The following concept drawings for an active suction cup system are marked with key components essential to the system's functionality:



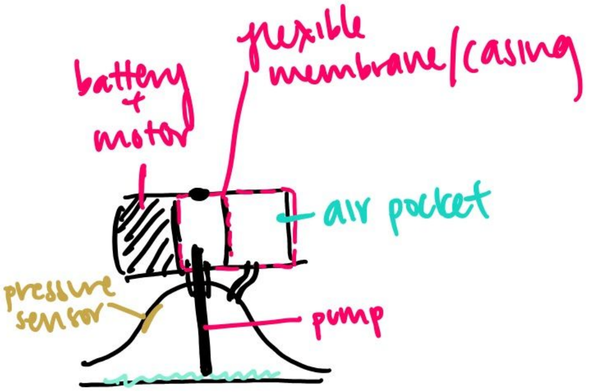
(A.1.1a) One basic system with one-way valving and external pump **(A.1.1b)** A second system with a dielectric elastomer (DE) actuator to drive a pneumatic diaphragm pump [X]



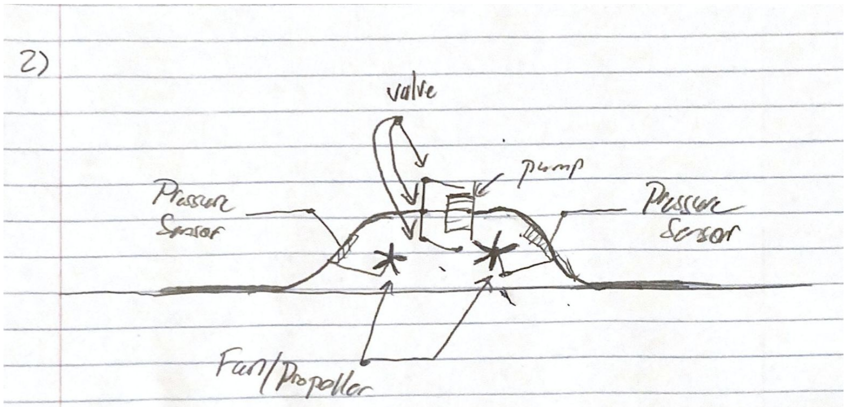
(A.1.2) Pneumatic pump to dispel extra fluid without a reservoir



(A.1.3) Multi-valve design to connect a single pump to 2-4 suction cups



(A.1.4) Pump placed directly inside the suction cup with a flexible air pocket to store dispeled air



(A.1.5) Fluid propellers designed as a method of actuation to expel fluid from the suction cup

Appendix A.2 - Evaluated Design Concepts

We organized our concepts into three categories: valving, methods of actuation, and housing. These categories were created based on the three elements of our design that clearly differentiated each concept from the other.

Valving

Each of the designs in this category has multiple suction cups which correspond with unique ways of incorporating valving compared to the basic conceptual design.

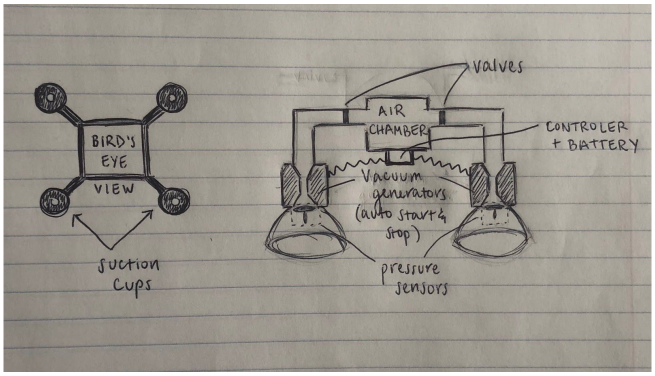


Figure A.2.1 A four cup system with a vacuum for each of the suction cups (Design #3)

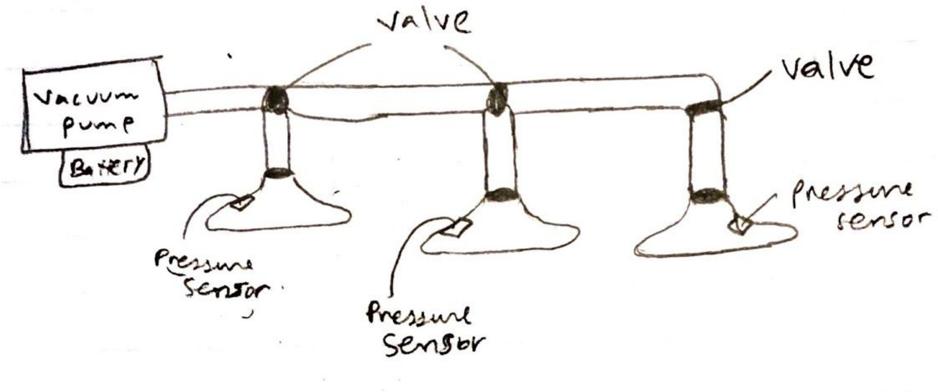


Figure A.2.2 A system of three suction cups that are connected in series via a single tube, each having a valve that opens separately (Design #4)

Methods of Actuation

Each of the designs has a different method to maintain and adjust pressure.

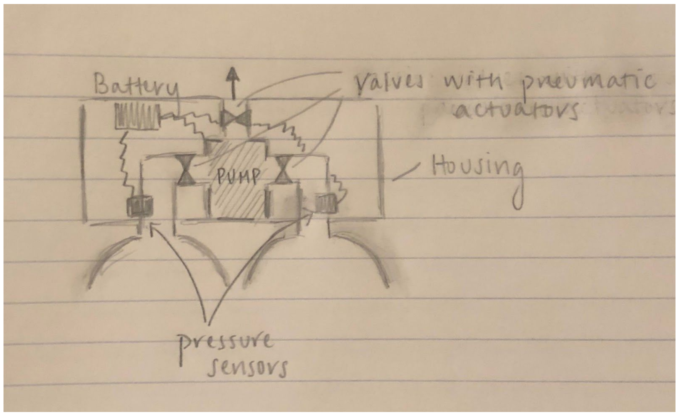


Figure A.2.3 A vacuum pump is used to remove fluids and release them into the atmosphere (Design #5)

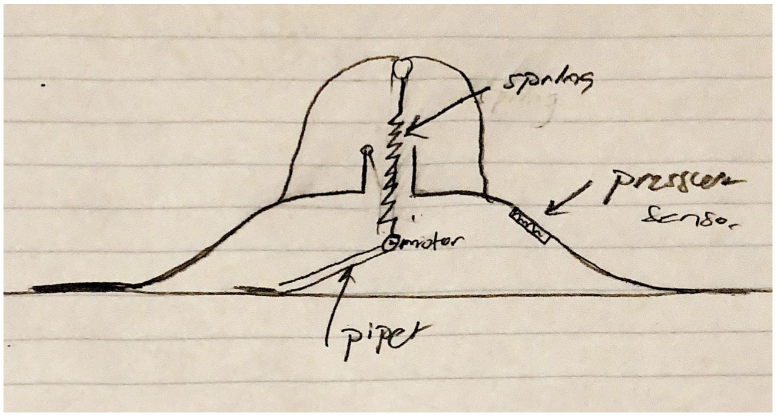


Figure A.2.4 Uses a spring and pipet to control fluids within the suction cup (Design #6)

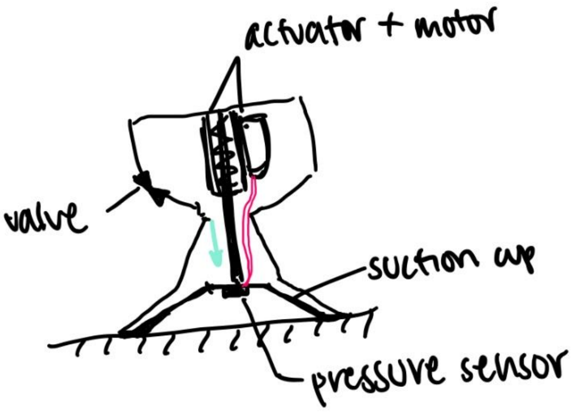


Figure A.2.5 A vertical linear actuator pushes and holds the suction cup down (Design #7)

Housing

All designs have a housing that encases the vacuum, pipe, and suction cup system.

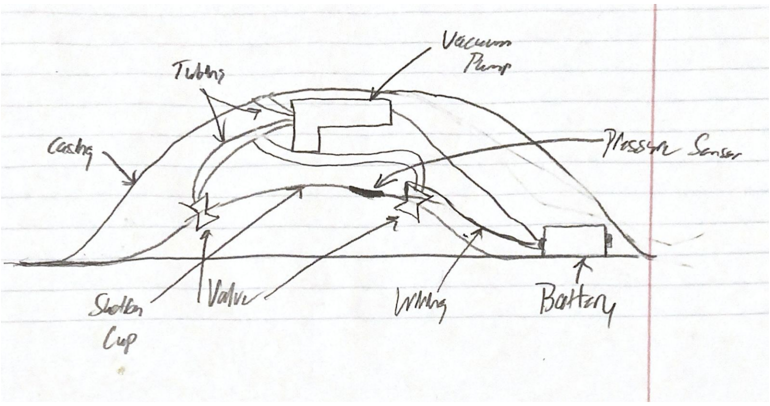


Figure A.2.6 Large enough suction cup to cover the entire system (Design #8)

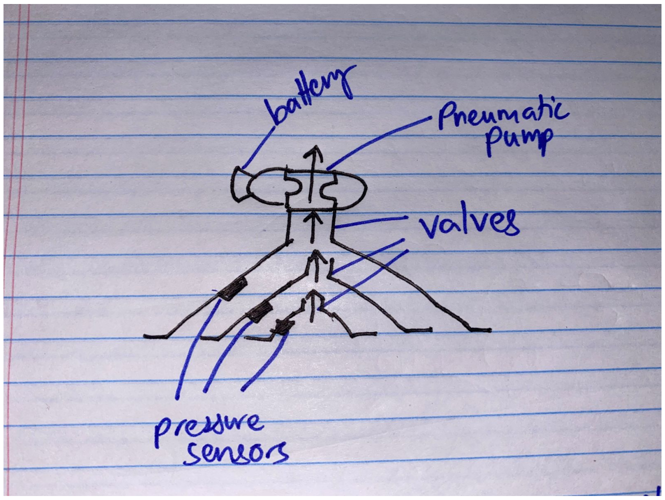


Figure A.2.7 A layered, triple suction cup system where all three suction cups are connected by a central pipe leading to a pump.(Design #9)

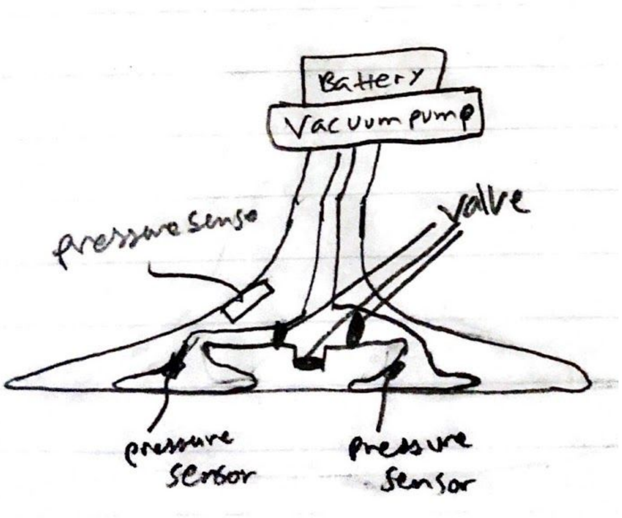


Figure A.2.8 A system of two suction cups that are connected to a central pump and enclosed in a space (Design #10)

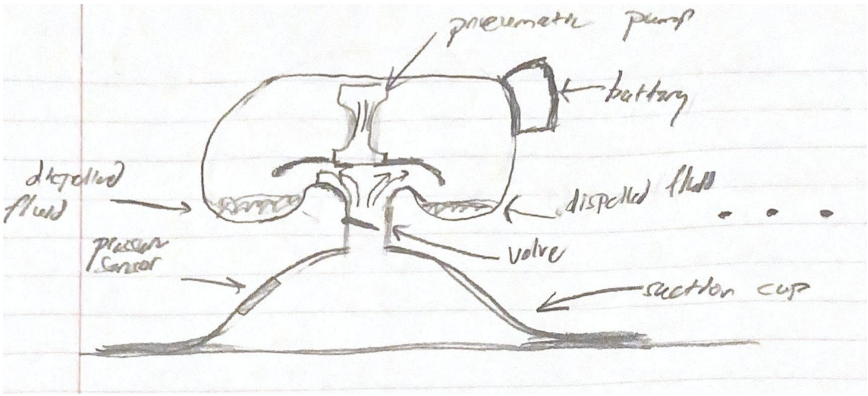
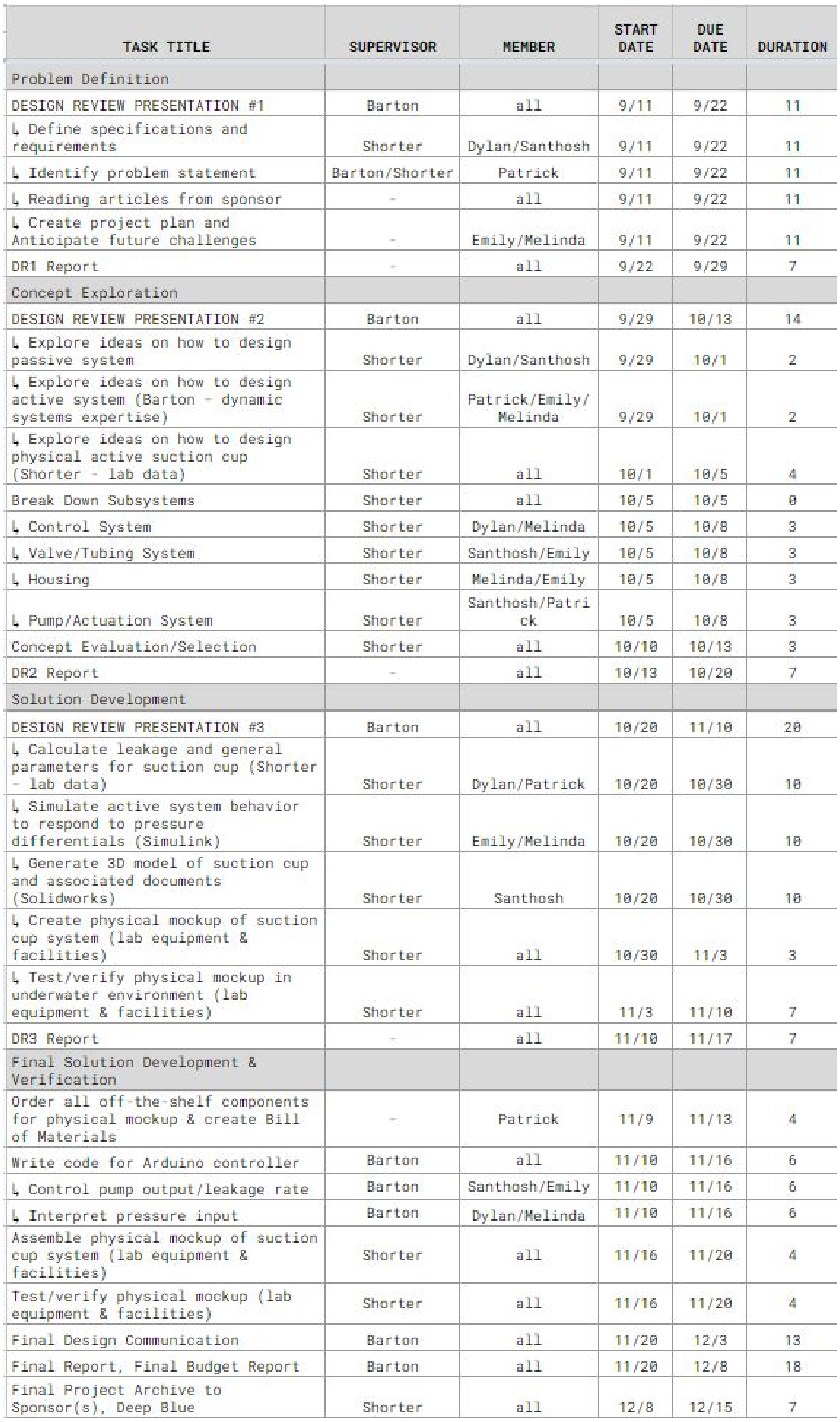


Figure A.2.9 Similar to the Base Design #1 but has a reservoir within the housing to contain excess fluid (Design #11)

Appendix B - Project Plan



TASK TITLE	SUPERVISOR	MEMBER	START DATE	DUE DATE	DURATION
Problem Definition					
DESIGN REVIEW PRESENTATION #1	Barton	all	9/11	9/22	11
↳ Define specifications and requirements	Shorter	Dylan/Santhosh	9/11	9/22	11
↳ Identify problem statement	Barton/Shorter	Patrick	9/11	9/22	11
↳ Reading articles from sponsor	-	all	9/11	9/22	11
↳ Create project plan and Anticipate future challenges	-	Emily/Melinda	9/11	9/22	11
DR1 Report	-	all	9/22	9/29	7
Concept Exploration					
DESIGN REVIEW PRESENTATION #2	Barton	all	9/29	10/13	14
↳ Explore ideas on how to design passive system	Shorter	Dylan/Santhosh	9/29	10/1	2
↳ Explore ideas on how to design active system (Barton - dynamic systems expertise)	Shorter	Patrick/Emily/ Melinda	9/29	10/1	2
↳ Explore ideas on how to design physical active suction cup (Shorter - lab data)	Shorter	all	10/1	10/5	4
Break Down Subsystems	Shorter	all	10/5	10/5	0
↳ Control System	Shorter	Dylan/Melinda	10/5	10/8	3
↳ Valve/Tubing System	Shorter	Santhosh/Emily	10/5	10/8	3
↳ Housing	Shorter	Melinda/Emily	10/5	10/8	3
↳ Pump/Actuation System	Shorter	Santhosh/Patrick	10/5	10/8	3
Concept Evaluation/Selection	Shorter	all	10/10	10/13	3
DR2 Report	-	all	10/13	10/20	7
Solution Development					
DESIGN REVIEW PRESENTATION #3	Barton	all	10/20	11/10	20
↳ Calculate leakage and general parameters for suction cup (Shorter - lab data)	Shorter	Dylan/Patrick	10/20	10/30	10
↳ Simulate active system behavior to respond to pressure differentials (Simulink)	Shorter	Emily/Melinda	10/20	10/30	10
↳ Generate 3D model of suction cup and associated documents (Solidworks)	Shorter	Santhosh	10/20	10/30	10
↳ Create physical mockup of suction cup system (lab equipment & facilities)	Shorter	all	10/30	11/3	3
↳ Test/verify physical mockup in underwater environment (lab equipment & facilities)	Shorter	all	11/3	11/10	7
DR3 Report	-	all	11/10	11/17	7
Final Solution Development & Verification					
Order all off-the-shelf components for physical mockup & create Bill of Materials	-	Patrick	11/9	11/13	4
Write code for Arduino controller	Barton	all	11/10	11/16	6
↳ Control pump output/leakage rate	Barton	Santhosh/Emily	11/10	11/16	6
↳ Interpret pressure input	Barton	Dylan/Melinda	11/10	11/16	6
Assemble physical mockup of suction cup system (lab equipment & facilities)	Shorter	all	11/16	11/20	4
Test/verify physical mockup (lab equipment & facilities)	Shorter	all	11/16	11/20	4
Final Design Communication	Barton	all	11/20	12/3	13
Final Report, Final Budget Report	Barton	all	11/20	12/8	18
Final Project Archive to Sponsor(s), Deep Blue	Shorter	all	12/8	12/15	7

Figure B.1 Project plan that was followed throughout the semester

Appendix C - Circuit Diagram (Unmarked)

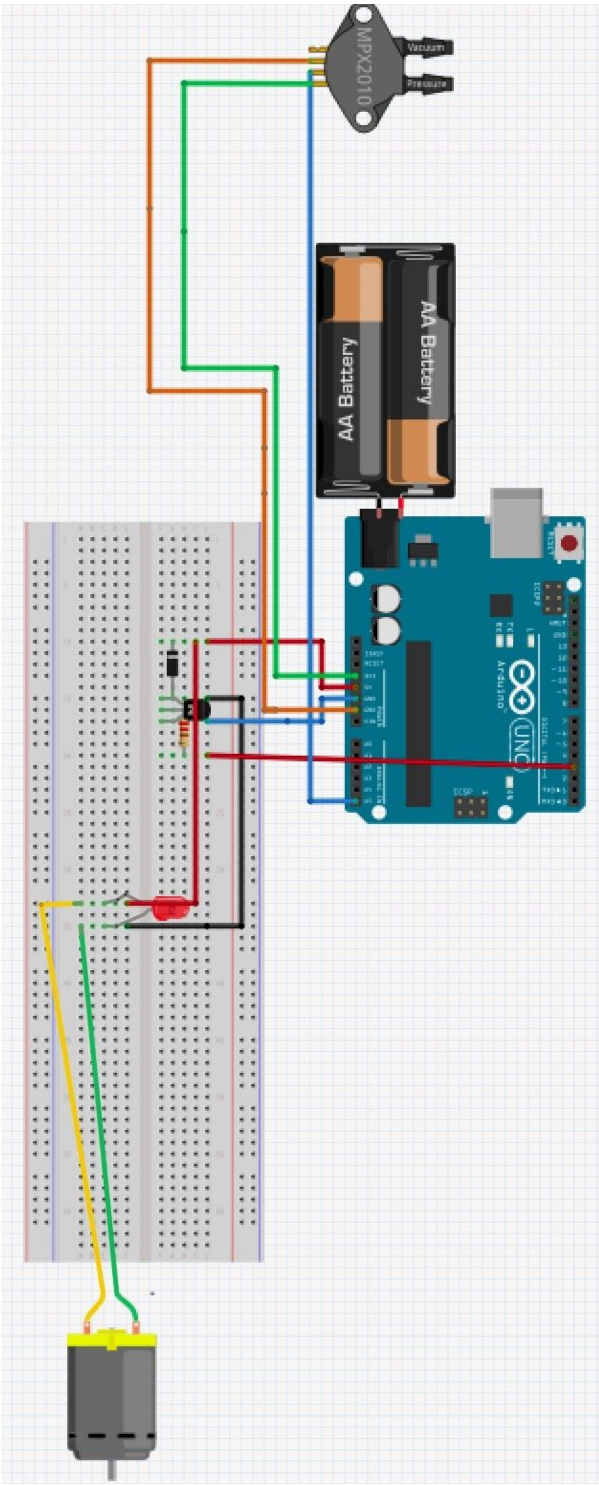
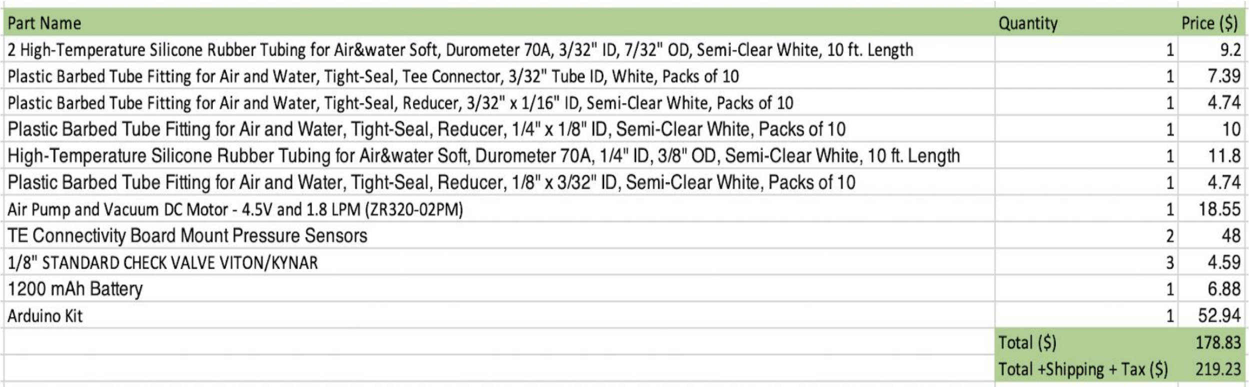


Figure C.1 Circuit diagram reflects set-up for physical prototype.

Appendix D - Arduino Code

```
//motor
int motorPin = 3;
//sensor
const int pressuresensor = A5;
int pressuresensor1 = 0;
void setup() {
  //motor stuff
  pinMode(motorPin, OUTPUT);
  Serial.begin(115200);

  //sensor stuff
  Serial.begin(115200);
  Serial.println("Start");
  pinMode(pressuresensor, INPUT);
}

void loop() {

  //motor stuff
  int speed = 1000;
  int off = 0;

  pressuresensor1 = analogRead(pressuresensor);

  if (pressuresensor1 > 400 ){
      analogWrite(motorPin, speed);
  }
  if (pressuresensor1 < 0 ) {
      analogWrite(motorPin, off);
  }

  Serial.print("Pressure Sensor: ");
  Serial.print(pressuresensor1);
  Serial.print("\t \n");

}
```

Appendix E - Bill of Materials



Part Name	Quantity	Price ($)
2 High-Temperature Silicone Rubber Tubing for Air&water Soft, Durometer 70A, 3/32" ID, 7/32" OD, Semi-Clear White, 10 ft. Length	1	9.2
Plastic Barbed Tube Fitting for Air and Water, Tight-Seal, Tee Connector, 3/32" Tube ID, White, Packs of 10	1	7.39
Plastic Barbed Tube Fitting for Air and Water, Tight-Seal, Reducer, 3/32" x 1/16" ID, Semi-Clear White, Packs of 10	1	4.74
Plastic Barbed Tube Fitting for Air and Water, Tight-Seal, Reducer, 1/4" x 1/8" ID, Semi-Clear White, Packs of 10	1	10
High-Temperature Silicone Rubber Tubing for Air&water Soft, Durometer 70A, 1/4" ID, 3/8" OD, Semi-Clear White, 10 ft. Length	1	11.8
Plastic Barbed Tube Fitting for Air and Water, Tight-Seal, Reducer, 1/8" x 3/32" ID, Semi-Clear White, Packs of 10	1	4.74
Air Pump and Vacuum DC Motor - 4.5V and 1.8 LPM (ZR320-02PM)	1	18.55
TE Connectivity Board Mount Pressure Sensors	2	48
1/8" STANDARD CHECK VALVE VITON/KYNAR	3	4.59
1200 mAh Battery	1	6.88
Arduino Kit	1	52.94
	Total ($)	178.83
	Total +Shipping + Tax ($)	219.23

Figure E.1 Final bill of materials for the entire benchtop system.

Appendix F - Supplemental Appendix

Engineering Standards

We ultimately did not need to incorporate engineering standards in our project. After simplifying the scope of our design, any considerations that would have warranted verification against appropriate standards were disregarded. Our system's application onto a hard and flat surface rather than a live dolphin eliminated any safety standards during our design development or verification process. In addition, our testing in a stationary lab setting (air) removed any consideration of standards for secure wiring and sufficient electrical insulation in an underwater environment. The assembly of our physical prototype was fairly simple; only a small soldering job was necessary to attach wiring to a pressure sensor, which by no means required the level of quality outlined by industry standard (IPC Standard). Finally, all connections within our system were made easy using tubing and plastic tube fittings, but since no harmful or corrosive fluids would pass through them, no quality standard needed to be met.

Engineering Inclusivity

We sought to practice inclusive decision making at every stage of the design process, and kept accessible stakeholders in the loop as much as possible. This included regular communication and updates with all parties, and complete transparency. We sought to adopt a beginner's mindset and refrained from jumping to conclusions ourselves, instead turning to stakeholders for input so that we could make the most informed decisions possible. Our first point of contact was often our sponsor, since our model intended to fulfill their requests, and they would therefore provide the clearest image of what he expected from us as engineers. We also regularly consulted with academic authorities depending on the nature of the challenge at hand and avoided invisible forms of power.

One notable example of power imbalance came due to the fact that the bottlenose dolphins were primary stakeholders in our project. Because they are non-human animals, it was impossible for us to request their input, and they therefore had little to no power in the design process. It was therefore our responsibility to compensate for their lack of power, and empathize with their experience whilst making all of our decision choices. This meant that we rejected several methods of attachment on the dolphins' behalf, since they would be painful, invasive, or otherwise unpleasant. Furthermore, we were careful to ensure that our pump never employed excessive force, since this could cause the superficial blood vessels in the dolphins' skin to burst, and potentially create a bruise. While dealing with non-human animals presented unfortunate hurdles to inclusivity, we sought to use our power as engineers to make decisions with their best interests in mind.

We have learned that practicing inclusivity is the best possible way to make successful design choices and avoid dissatisfaction and difficulties further down the line. This has enabled us to put ourselves in the shoes of the stakeholders and ensure that our decisions are in line with their demands as well, and maximize our chances of succeeding in our work.

Environmental Context Assessment

It is essential to view a design from an environmental context point of view. Given the monumental impact that engineering has on the earth, both positive and negative, sustainability is an important goal to strive for. Multiple questions need to be answered to amplify any environmental issues that a design may bring. Some examples are "Does the system make significant progress towards an unmet and important environmental or social challenge" or "Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits" just to name a few. While the design of an active suction system for biologging applications is a very early stage prototype, it is still crucial to develop a framework that allows us to answer these bigger picture questions.

The research area that this active suction attachment is for biologging. Typically, biologging is a more environmentally conscious discipline. Much of the work done is to either look after the health of animals or track migratory behaviors over long periods of time. This project was more focused on shorter term deployment for these tags, around the order of 1 day or so. While this does not provide any insight into migration of bottlenose dolphins, it would allow for extended analysis of the health of the animal. Given that one can track animals that can go places humans cannot, biologging tags can provide great insight into the geography of the ocean in addition to information about climate change. These are just some of the important arenas that biologging research is done in. While the motivation for much of this research is quite pure, there would still be an environmental impact if our design was implemented. This has to do with the manufacturing of suction cups, use of a motor, tubing, valving, and a microcontroller all placed on a wild animal. However, given that this is a niche research topic, there is nothing of serious concern with this. This also answers the second question posed about the costs of the design outweighing the benefits. In the case of an active suction system for biologging, the benefits can be extremely useful, namely knowledge about the health of animals, migratory behaviors, or even unique insights into the changing environment that these animals inhabit. While the costs are still existent, they do not pose a serious threat to impinging upon the benefits that information from biologging tags can provide.

Social Context Assessment

While the active suction system is just a singular prototype, it is important to assess the social landscape that this engineering design could be a part of. This involves taking a deeper look into who might be affected by the technology. There would be many stakeholders in this field, namely the designers and manufacturers of the active system, the scientists and engineers who work in the field of biologging, other researchers in adjacent fields, the animal trainers, environmental activists, or potentially animal rights activists.

This technology would be potentially beneficial to many of the stakeholders. The designers would want their product to be successful and the manufacturers would want this product to be financially viable. The scientists and engineers in the field are always looking for improvements in data gathering techniques and would be even more so interested in biologging attachments that are non-invasive. The field of biologging is not terribly well known amongst the general populous so there it is relatively unlikely for there to be large swaths of people who are wholeheartedly against the idea of implementing an active suction cup system onto a dolphin. Some animal rights activists may point out ethical issues involved with biologging. However, as suction cups are relatively harmless when compared to barbs or epoxy as an attachment method, the attention would not be focused on the use of suction cups. There would most likely not be a serious economic benefit to this product unless it were to be so much better than all other alternatives so there would probably not be many detractors of this technology.

Comparatively to passive suction systems, these active systems have more components and higher costs in general for the material, acquisition, transport, and inventory. This is a big downside to the active system. This can be countered by an improvement in the performance of these cups which leads to less replacements needed which would be more environmentally viable. Overall, there are many costs and benefits to this design that need to be weighed appropriately. While the additional material purchased for an active suction system compared to a passive system is close to $180, there would be many ways to move this cost down with appropriate manufacturing and optimization of the design. The scale of biologging tag research is quite miniscule compared to industrial technologies so this improved design would not have an impact that would lead to serious social or environmental issues. It is important to contextualize this design in a larger framework because it must be realized that all designs have a much larger effect than initially realized.

Ethical Decision Making

It was important to us to be mindful of engineering ethics throughout our design process, and for us to make careful, informed decisions whenever confronted with an ethical dilemma. Although our system is only a singular prototypical model, we needed to approach our tasks as though we were designing the final model to be deployed in the real world. Ethical violations made during the prototypical stage could easily manifest in the final product and result in an engineering disaster or scandal. As engineers, we are responsible for ensuring that the final product is backed by a foundation of ethical, carefully considered design choices.

The device is intended to be installed on a live, non-human animal, and it is important for us to remember that ethics are not limited only to the human parties involved. In our case, we treated the bottlenose dolphin as a stakeholder and empathized with its experience at every stage of our process. We were presented with a specific ethical dilemma in attempting to decide on a method of attachment with which to keep the biologging tag on the dolphin. Using a passive suction would not be invasive to the dolphin, but is at a high risk of detaching due to natural leakage. We were presented with a wide range of alternative methods of keeping the tag attached to the dolphin, such as using strong glue or a locking wire, but these would all be unpleasant and painful to the dolphin. Therefore, this option failed the Reversibility Test, since none of us wanted this experience for ourselves. Therefore, we chose to use a pump-assisted suction device, since this would be non-invasive and therefore ethical.

A further ethical dilemma was encountered as we considered the energy consumption of our device. If the pump were to be running continuously, it would resolve the risk of leakage, but would be wasteful and uneconomical in terms of power use. This option failed the Universality Test, since we all agreed that we would not want to live in a world where everyone consumed energy resources excessively, beyond what was required. We therefore opted to use an active control system that only triggered the pump when leakage was detected, and switching it off otherwise. This was the more ethical option since it allowed our device to conserve power and therefore be more resource-efficient.

Lastly, our prototype needed to deliver on its promise and provide a truly workable model that demonstrated that an active suction cup system can be used to attach a biologging tag to a bottlenose dolphin. We worked carefully to fulfill the tasks we were given, and strove for complete transparency with the other stakeholders throughout the process. It was important for us to provide a clear picture of the work we were doing, and the products we were delivering, both to gain the most accurate feedback possible, and to avoid any kind of dishonesty or ambiguity. Falsifying information or otherwise misrepresenting our work would constitute deceit, and therefore fail the Universality, Reversibility, and Publicity Tests, so we steered clear of these options at all times.

By examining both microethics and macroethics, and using reliable processes and tools whenever presented with an ethical dilemma, we made decisions in line with established codes of engineering ethics. We have been fully aware that we are personally liable for any ethical violations that occurred, and have done our best to fulfill our responsibility to do what is right.