Remote Euthanasia System

Final Design Report
Biomedical Engineering Design 200/300
Department of Biomedical Engineering
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Abstract

Decompression sickness is an illness that humans can get while under extreme external pressure like sailors trapped in sunken submarines under 5 atmospheres of pressure. The clients, Dr. Sobakin and Dr. Eldridge, were contracted by the Navy to determine how long humans could survive under this pressure while being rescued to evaluate the Navy's rescue protocol for sailors in a sunken submarine. The clients will be monitoring sheep in a hyperbaric chamber set to five atmospheres of pressure over the course of a 172 hour period. The sheep within the chamber have the possibility of getting decompression sickness which would cause great trauma and can ultimately lead to death. In order to prevent this traumatic end, the team has been tasked with producing a remote euthanasia system. There are commercially available syringe pumps that can serve this purpose; however, the pumps won't operate correctly under such high pressures. After careful consideration with the help of a design matrix, the team decided to use a lead screw/stepper motor design. The team's design utilizes a lead screw and stepper motor to generate linear motion to force the euthanasia solution from the syringe, which can be activated remotely from outside the chamber. The team plans to stress test the assembled system to ensure that it can maintain functionality throughout the duration of the experiment, the stepper motor will be tested to ensure a consistent speed, and that the euthanasia solution is completely forced out of the syringe when activated by the researcher.

Table of Contents

I. INTRODUCTION

A. Motivation

It takes around 172 hours or 7 days to rescue every sailor from a disabled submarine through the use of rescue submarines. This is a lengthy process and can take a serious toll on the health of the sailors' who are required to stay for extended periods in the sunken submarine until help arrives. At the bottom of the ocean, the sunken submarine is typically at almost 5 atmospheres of pressure, so sailors experience a wide variety of pressure and oxygen changes which often results in decompression sickness. Decompression sickness is also known as the "bends" when bubbles of air form in the blood vessels and cause immense pain in addition to other symptoms [1]. This is often a result of the uptake of nitrogen into the blood when air is breathed at increased ambient pressure [2]. Some symptoms of decompression sickness include: pain, neurological injury, cardiopulmonary collapse, and possibly death.

The Navy has tasked the clients of this project to test the Navy's standard operation to rescue sailors in a disabled submarine at the bottom of the ocean. To simulate the high pressure environment, the clients make use of a hyperbaric chamber. In typical clinical settings, hyperbaric chambers are often utilized to help fight infection or minimize injury [3]; however, too much exposure in a hyperbaric chamber may result in [4]:

- Lung collapse caused by air pressure changes (barotrauma)
- Seizures as a result of too much oxygen (oxygen toxicity)

The clients will be testing the Navy's protocols using sheep due to their physiological similarities to humans. Sheep have a similar cardiovascular system compared to humans, so testing the cardiovascular systems of sheep can help determine what would happen to humans under the same circumstance [1]. The clients will be using female sheep, as they have similar fat compositions to humans. Past research has utilized pigs, which has caused error due to the lack of psychological similarities between pigs and humans which has led to unreliable results according to the clients.

During these trials, some sheep are likely to get very sick while in the chamber. As a result, the IACUC have required the clients to have a manner to euthanize the sheep humanely prior to a rapid drop-out decompression if necessary. The clients do not have quick access to them in case of emergency, so a device that can remotely inject the solution in the vein is required.

B. <u>Existing Devices</u>

Hyperbaric chambers

Hyperbaric chambers are often utilized to help fight infection or minimize injury. They are typically set to induce a pressure of around 1.5 atm, which simulates what it would be like to be around 15-18 m of underwater [4]. In a hyperbaric oxygen therapy chamber, the air pressure is increased to three times higher than normal air pressure. Under these conditions, lungs can gather more oxygen than would be possible breathing pure oxygen at normal air pressure [4]. As a result, blood carries this oxygen throughout your body. This helps fight bacteria and stimulate the release of substances called growth factors and stem cells, which promote healing [4].

Depending on the chamber used, typical chambers are:

- A unit designed for 1 person. In an individual (monoplace) unit, the patient lies down on a table that slides into a clear plastic tube (Figure 1).

- A room designed to accommodate several people. In a multi person hyperbaric oxygen room, which typically looks like an open hospital room, a patient may sit or lie down.

Figure 1: An example of an individual (monoplace) hyperbaric chamber unit [4]

Infusion Pumps

Infusion pumps are pumps that are designed to inject fluid for prolonged periods of time, such as the Baxter Sigma Spectrum [5] (Figure 2). This device sells for around $1000, and is designed to be robust and last for decades. The pump draws fluid from a reservoir and then feeds that fluid through a tube into the patient's vein. The pump has the functionality that the rate and pressure with which it pumps the solution can be modified on the unit. However, pumps like the Baxter Sigma Spectrum are not rated for use in above 1.4 atmospheres of pressure. This poses a significant problem as the experiment where the device is to be used is being performed at up to 5 atmospheres of pressure.

While infusion pumps are designed to pump large amounts of fluid over long periods of time, syringe pumps are designed to pump fluid out of one or more syringes mounted inside the pump [6]. Although syringe pumps are typically used for research purposes, there are some commercially available units; however, these commercially available units are not usable in this project. Syringe pumps are usually operated via a keypad mounted directly on the unit, which would not work for this experiment as it would require the operator to be in the hyperbaric chamber. Furthermore, syringe pumps are not rated for anywhere near the pressure induced by the hyperbaric chamber which the device must withstand.

Figure 2: An image of the Baxter Sigma Spectrum Infusion Pump [5]

HOSPIRA Infusion Pumps

Hospira's Plum A+ hyperbaric infusion pump is the only FDA approved infusion pump for high pressure environments (Figure 3). Hospira manufactures various infusion pumps that are customizable for specific applications [7]. For IV infusions delivered to patients in monoplace chambers, the infusion pump is located adjacent to the chamber. The infusion pump administration set is connected to a specialized fitting in a port in the chamber hatch, which forms a seal. Inside the chamber, tubing from the specialized fitting is connected to the patient's IV catheter. The infusion pump's occlusion pressure is set to maximum. In order to deliver the IV solution into the pressurized environment, the pump must be able to generate 30 psi or more without alarming and stopping the infusion [7]. This device was the only FDA approved infusion pump on the market for hyperbaric environments; however, Hospira recently announced that it would be discontinuing the manufacture, sale, leasing, service, and support of the Plum A+ hyperbaric infusion pump.

Figure 3: An image of the Hospira's Plum A+ Hyperbaric Infusion Pump [7]

C. **Problem Statement**

Due to a new contract with the Navy, Dr. Aleksey Sobakin and Dr. Marlowe Eldridge are testing the Navy's standard operation to rescue sailors in a disabled submarine at the bottom of the ocean. In order to examine their standard operation, the team's clients will be using sheep and a hyperbaric chamber. This hyperbaric chamber will be putting the sheep through a variety of pressures that can be fatal. However, IACUC has asked the clients to institute a method to euthanize the sheep humanely prior to a rapid drop-out decompression if necessary. As the sheep are sealed away in a chamber, the client has asked the team to devise a method to remotely euthanize the sheep when they are inside the hyperbaric chamber. This euthanasia system will have three main subsystems. For the housing subsystem, there must be a way to secure the syringe within the device and to prevent it from moving or being accidentally discharged. For the injection subsystem, there must be a way to pump the euthanasia solution out of the syringe and into the vein in a timely, complete manner. Finally, there must be a remote control subsystem that enables the device to perform the injection protocol upon a button press by a researcher outside of the hyperbaric chamber.

II. BACKGROUND

A. Background research

The client will be injecting euthansia solution into a major vein of the sheep. The sheep will have a catheter inserted and sutured in order to allow direct access to this vein. Intravenous injections are often given through the jugular vein, but great caution needs to be taken when injecting in order to ensure that no other major arteries or veins are nicked, causing a more painful and less humane death [8]. In sheep, the jugular vein can be found lying in a line starting at the base of the ear running down the neck to the thoracic inlet. It is often necessary to part the wool to give adequate visualization of the vein. Adequate restraint is critical to avoid inadvertent puncture of other structures such as the trachea or esophagus. A 4-cm, 20-gauge needle can be used for venipuncture [9].

Pentobarbital is the most common medication to administer for animal euthanization [10]. It can be used in smaller doses as it is used as an anti seizure medication. Size of the animal being euthanized is a crucial part in how much they need to administer, and as a result, the client will be using similar sized female sheep in order to consistently use a similar dosage. Typically, a dosage of 100 mg per kilogram of body mass of the sheep is required to adequately dispatch a sheep [11]. Pentobarbital behaves as an incompressible fluid much like water. The shelf life of sodium pentobarbital is rated at 3 years when unopened, and 28 days after opening the package [11].

B. Research required to design and build your prototype

The device will use a lead-screw. This device will harness a form of a leadscrew coupled with a stepper motor that force feeds the leadscrew forward (the stepper motor "walks" in a direction away from the syringe) into the plunger of the syringe. This stepper motor is electrically controlled which would enable an interface with a microcontroller that can control its function (after some calibration) after a remote signal is sensed.

Choosing the correct motor relies on many factors. There are three main motor devices that the team is investigating, which include the DC Stepper Motor, DC Brush Servo Motor, and DC Brushless Servo Motor [12]. First, the DC Stepper Motor (Figure 4) has open loop positioning so no encoder is required. It utilizes a simple “pulse and direction” signal needed for rotation and has a high torque density at low speeds. However, there is no position correction in the event the load exceeds the output torque. It has a low power density meaning that the torque drops off dramatically at higher speed and the motor draws continuous current, even at standstill and experiences high iron losses above 3000 RPM [12].

Second, the DC Brush Servo Motor has linear speed/torque curve and low-cost drive electronics. In addition to having many different motor configurations available, it is highly customizable and is easy to control and integrate [12]. The DC Brush Servo Motor has a very smooth operating system which enables low speeds (depends on the number of slots and commutator bars) and a high power density. However, the motor will draw high current in an overload condition, and the angular velocity is more limited due to mechanical factors in the armature design and brush system [12].

Third, the DC Brushless Servo Motor has a high power density. This motor has the highest move response, acceleration, and smooth operation possible when compared to the other two motor options. That being said, the DC Brushless Servo Motor is also the most expensive of the three motors mentioned. The motor will draw high current in an overload condition and will use the method of feedback needed for closed-loop positioning. Furthermore, the DC Brushless Servo Motor has a high drive circuit complexity and cost.

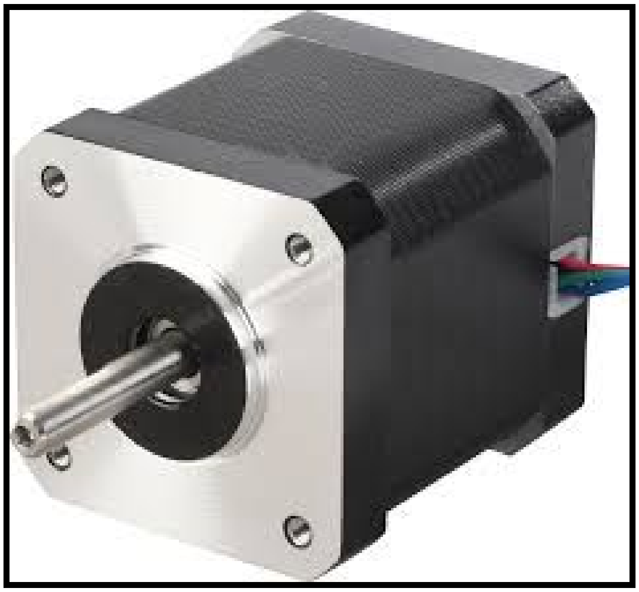

Figure 4: An example of a DC Stepper Motor that can be paired with a lead-screw [12]

In addition to choosing the motor based on functionality and cost, it must also meet the required load acceleration, overcome friction in the system, overcome the effect of gravity, and maintain a safe maximum operating temperature [12]. After selecting our motor and ensuring that it can work well for our application, a lead screw is to be chosen that can work in tandem with the chosen motor.

A lead screw uses a thread to convert the rotary motion of the stepper motor into linear motion. The performance of a lead screw depends on the coefficient of friction between the nut and the screw, which in turn depends on the material used for the nut and screw [13].

When utilizing a lead screw device, the correct nut must be chosen. To do this, one must look at the required load capacity. Plastic nuts are typically used for light loads of less than 100 lbs, although plastic nut designs for 300 lbs and beyond are possible [14]. Bronze nuts can be used for applications in excess of several thousand pounds. This project will most likely use a plastic nut, but a bronze nut may be considered if it's in the price range.

The pressure-velocity factor is also a determinant when choosing the correct lead screw device [14] (Figure 5). The pressure-velocity, or PV factor, is the product of the pressure and velocity between the nut and lead screw. It helps determine the load, speed and duty cycle that the nut can handle. Plastic materials have an intrinsic PV rating, the point at which frictional heat causes permanent deformation of the plastic. So the more load applied to a lead screw assembly, the slower it must be turned to avoid exceeding the nut’s PV limit.

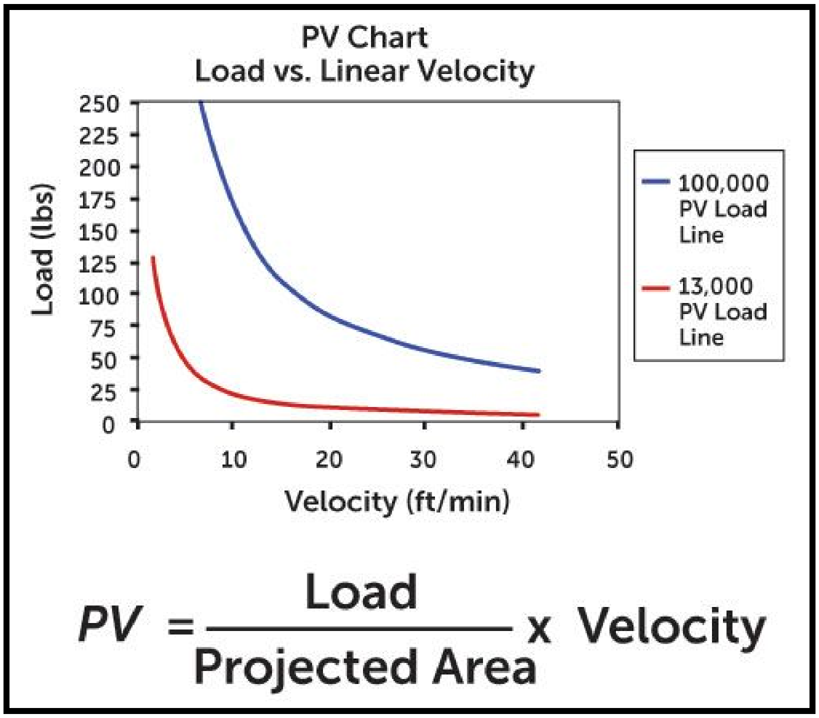

Figure 5: A graph expressing the pressure-velocity factor when choosing the correct lead-screw [14]

C. Client information

The clients for this project are Dr. Aleksey Sobakin and Dr. Marlowe Eldridge. Dr. Aleksey Sobakin is an associate scientist in the UW Department of Pediatrics. Dr. Aleksey does research in Orthopedic Surgery, Sports Medicine and Emergency Medicine. Dr. Marlowe Eldridge is a professor and chief of the Division of Pediatric Critical Care. Dr. Eldridge's research broadly involves cardiopulmonary interactions in congenital and acquired heart and lung diseases.

D. Design Specifications

This device's system needed to be able to operate in a system with a pressure of 5 atmospheres, it also needed to be able to withstand the pressure inside the hyperbaric chamber. Since there will be two sheep in the chamber at a time, the client requested two devices. The device was controlled by a switch wired in from the outside of the camber. The main goal was for the researcher on the outside to be able to press a button and cause the device to activate on the inside of the chamber. It needed to be a slow, controlled release of the solution in order to ensure a complete release of the euthanasia solution from the syringe

III. Preliminary Designs

Although three distinct designs were produced, they all possessed two distinct commonalities. First, the syringe was constant across all three designs, as this part was supplied by the client. The syringe is a 20cc Kendall Monoject Syringe with a Luer Lock Tip. Additionally, the devices each needed a control module to actuate the method by which they depress the syringe plunger. The team working on this project has decided to use a microcontroller to power the device, for its functionality, low cost and ease of use.

A. Rack and Pinion

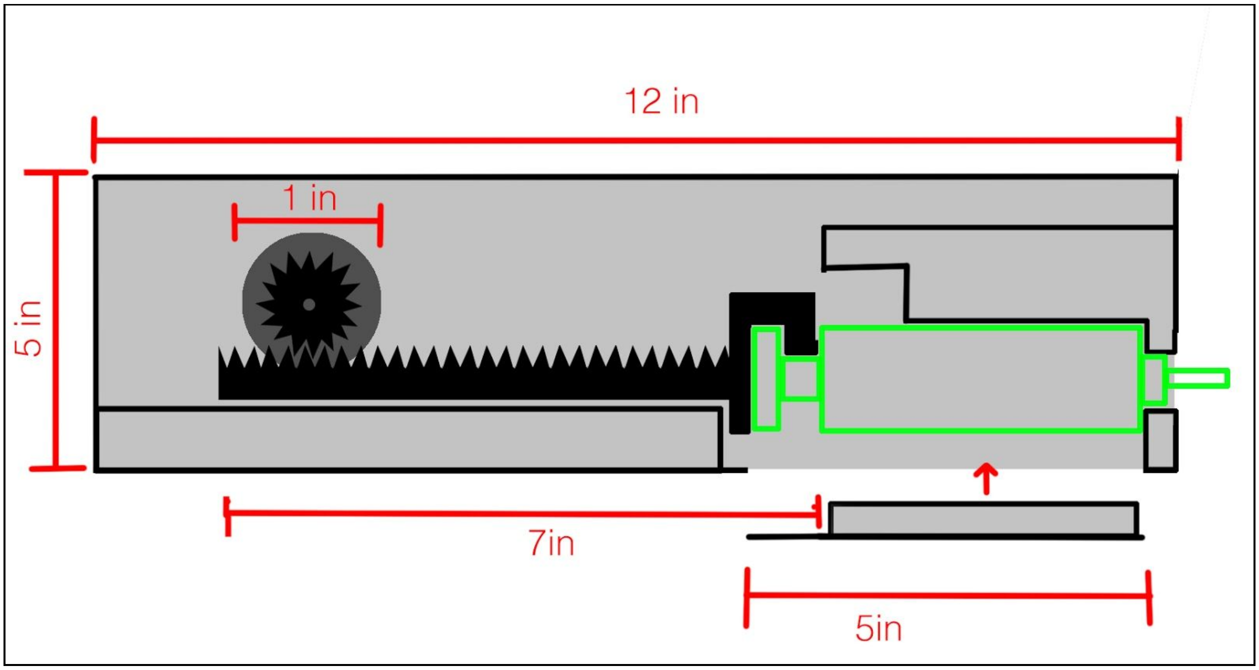

Figure 6: A side view of the Rack and Pinion design with dimensions labeled in inches

The Rack and Pinion design utilized a small direct current motor to drive a pinion gear which was fixed to the motor's output shaft (Figure 6). The pinion gear was in constant contact with a linear rack gear that was pinned against a smooth surface by the pinion gear. This gearing was able to translate the rotational motion of the motor into linear motion. The linear motion generated by this assembly was then used to depress the plunger of the syringe, since the syringe and rack gear were in constant contact. The rack gear was attached to the plunger of the syringe via a hook-like protrusion on the gear's end, which the end of the plunger slotted into (Figure 6). This protrusion's purpose was twofold: prevent accidental depression caused by the air pressure and prevent the syringe from shifting in its chamber. The high air pressure within the chamber could have depressed the plunger, since the liquid inside was filled at 1 ATM, and thus a pressure differential existed around the syringe. The protrusion on the rack gear locked the plunger in place, preventing this accidental discharge. Additionally, the protrusion kept the syringe in place by stabilizing it from the back. Other directional stabilization was provided by chocks molded into the device's housing, and the chock attached to the removable trapdoor (Figure 6). The syringe was to be loaded and removed from the device through this removable trapdoor located on the underside of the device housing. The syringe was loaded in a similar manner to a shotgun shell, in that the nose is pushed up and into the chamber, which then allows it to slide forward as the back slides up and in. Once in, it is completely encased by chocks, locking it in place.

This device had two advantages over the other designs, namely efficiency and cost. It would have been made primarily out of 3D printed carbon fiber reinforced PLA, which costs around $33 per kilogram [15], and approximately 700 grams would have been needed to print this design. This would have been cheaper than the other designs, which would have been made out of metal or wood. It also used a small DC motor which had a relatively low power draw, and the nature of the rack and pinion gear assembly would have allowed the motor to depress the syringe with relatively little energy.

B. Linear Actuator

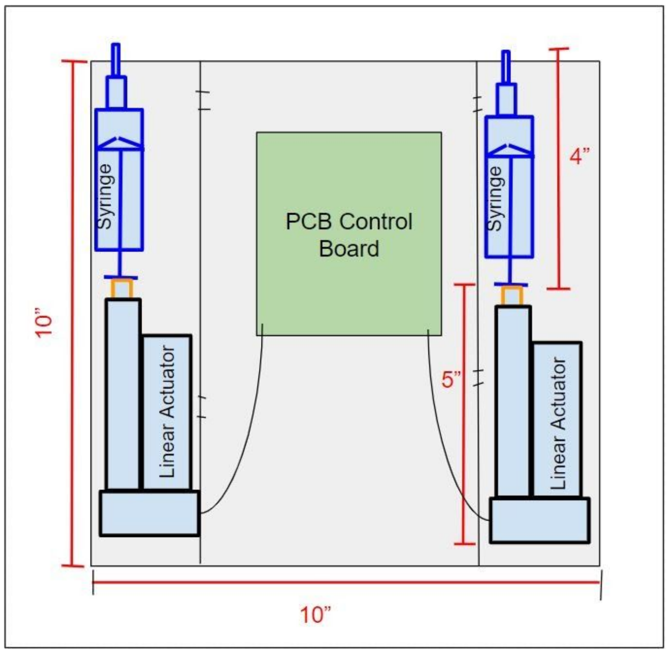

Figure 7: A top view of the Linear Actuator design with dimensions labeled in inches

The Linear Actuator design utilized two commercial linear actuator systems placed within a housing with their respective plunger arms interfacing with syringes (Figure 7). This design offers three key functionalities. First, the syringe would be able to be easily inserted into the box with the flat side of its plunger interfacing with the arm of the linear actuator where a holding apparatus keeps the syringe plunger from depressing prematurely due to the high pressures of the hyperbaric chamber. Subsequently, once used, the syringes are easily removable from the apparatus as to facilitate its use for the client. Second, the design made use of robust, consistent linear actuators to drive the plunging motion of the syringe when required by the user (Figure 7). These linear actuators are able to be purchased from commercial vendors with the specific function of translating an object linearly. As these are commercial systems, this would give confidence that the system would work consistently and without fail for many cycles. These linear actuators would be capable of being wired to a control board PCB that can interface and read the input of a receiver that can direct function. Once activated, linear actuators can generate high forces; however, they tend to act very slowly over their defined displacement. That being said, this function provided confidence that the linear actuator would be able to depress the plunger into the syringe without obstacle. Third, this design acts to incorporate two linear actuators within one housing that is controlled by a central control PCB (Figure 7). This PCB would read inputs from the user controller that could specify which linear actuator, and by extension, which syringe is required to be depressed. This would enable only one system to be built that includes selectivity for which syringe is to be activated depending on the sheeps' conditions within the chamber and to the discretion of the user.

Although this design offered consistency, selectivity, and robustness, the linear actuators are often very expensive in comparison to other linear motion motors. That being said, the pressure induced by the hyperbaric chamber also presents challenges in finding a linear actuator that can hold up to the pressures. As the linear actuators are often closed systems, the high pressure induced by the hyperbaric chamber may pose risks in disrupting function of the design over repeated use. Furthermore, linear actuators tend to be heavy, and large which would put undue strain on the housing and those that move the apparatus.

C. Lead Screw Plunge

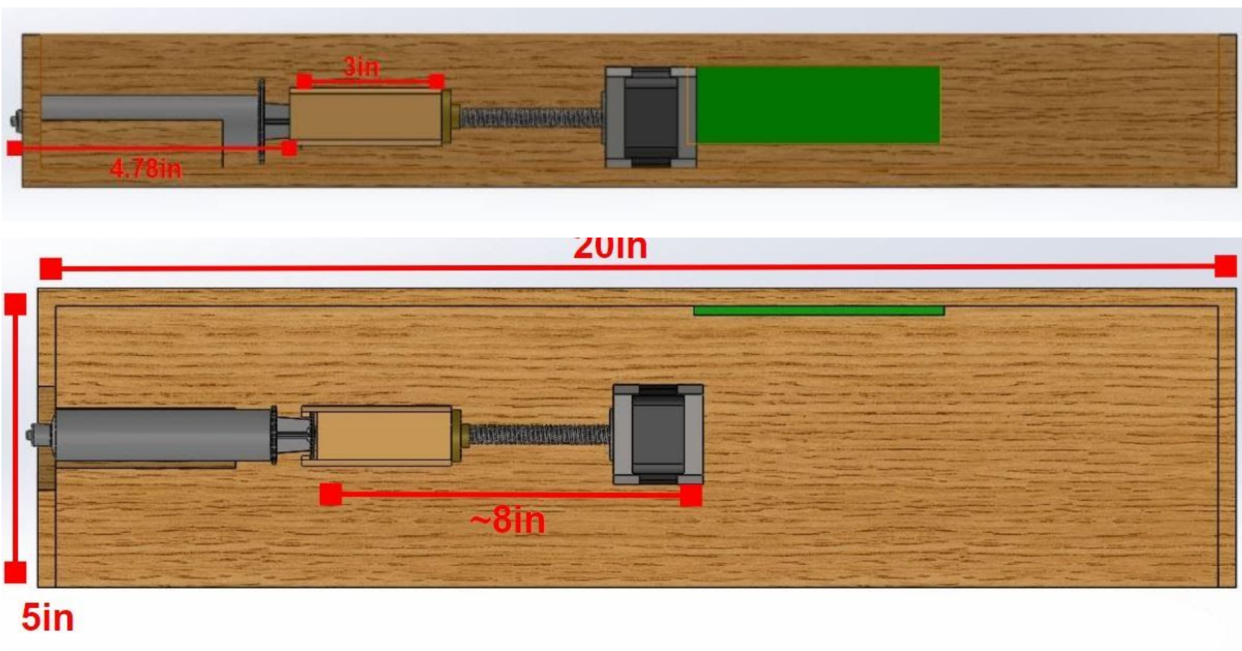

Figure 8: A side and top view of the Lead Screw Plunge design with dimensions labeled in inches

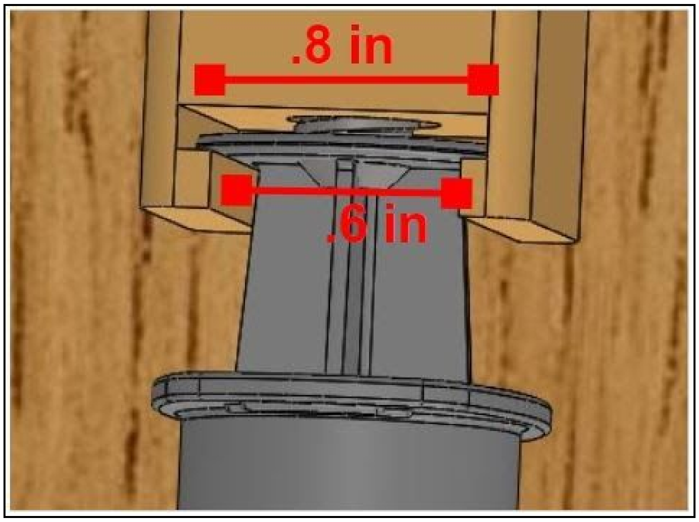

Figure 9: A closeup view of the interface between the plunger of the syringe and the slot in the holding cap with dimensions labeled in inches. The leadscrew is fed through the holding cap so it is still able to interface with the plunger to depress it upon controller activation

The Lead Screw Plunge utilized a lead screw coupled with a stepper motor in order to generate the linear motion required to depress the plunger of the syringe (Figure 8). The Lead Screw Plunge has three key parts that enable its function. First, the syringe was able to be easily slotted in the top of the apparatus such that the plunger of the syringe was able to interface with the holding cap (Figure 9) on the leadscrew and also be secured within the housing. The syringe rests on a guide built into the housing that would pin the syringe between the front opening of the housing (where the tubing feeds through) and the holding cap (Figure 8). By enabling this functionality, this would enable the user to easily insert the syringe into the box without worrying about accidental discharge or rupturing the tubing. This is key as the device is to be used many times which would require reloading of the syringe and accidental discharge of the syringe would be detrimental for the client's experiment. Second, there is a holding cap that is capable of being threaded onto the leadscrew such that it holds the plunger of the syringe in place (just in case the 5 atm pressure of the chamber causes the syringe to naturally depress) and will also allow for the forced plunging of the syringe as the leadscrew is in contact with the top of the syringe through the holding cap (Figure 9). As the top of plunger is held in place within the holding cap, the holding cap prevents the syringe from prematurely discharging euthanasia solution as the chamber is is pressurized. Finally, the main linear pushing mechanism comes in the form of a leadscrew coupled with a stepper motor that essentially force feeds the leadscrew forward (the stepper motor "walks" away in a direction away from the syringe) into the plunger of the syringe. This motion causes the release of the euthanasia solution from the syringe into the sheep. Luckily, the stepper motor and lead screw set is highly customizable to the design considerations at hand in terms of depression speed and strength; thus, this system can be made to fit under any depression speed requirements defined by the client. This stepper motor is electrically controlled via a PCB control board which would enable an interface with a microcontroller that can control its function (after some calibration) after a remote signal is sensed.

Although this design offers customizability, ease-of-use, and robustness, this design requires a fair amount of moving parts to work harmoniously which required careful, patient calibration. Next, the stepper motor chosen may be loud which could startle the sheep; however, this was taken into consideration when choosing the stepper motor to use.

IV. Preliminary Design Evaluation

Designs	Rack and Pinion		Linear Actuator		Lead Screw Plunge	
Reliability (30)	3	18	4	24	5	30
Efficiency (25)	5	25	3	15	4	20
Robustness (20)	4	16	3	12	5	20
Feasibility (15)	4	12	5	15	3	9
Ease of Use (10)	4	8	4	8	5	10
Cost (5)	5	5	1	1	3	3
Total (100)	84		75		92	

Table 1: Design matrix

The team defined 6 criteria to analyze the effectiveness of the proposed designs (Table 1). First, Reliability was defined as consistent delivery of expected results, such that all the solution is consistently forced from the syringe and speed of injection is consistent. In terms of Reliability, the team decided that the Lead Screw Plunge (with a score of 5/5) won the Reliability category due to its customizability in terms of force induced and speed as well as lead screw/stepper motor tandems being built to last. The Rack and Pinion design scored the lowest (with a score of 3/5) due to it having the least inherent customizability and that there may be issues with ensuring that the teeth of the pinion align with the rack over many uses.

Second, Efficiency was defined as how effectively and speedily the device can administer the euthanasia. The team chose the Rack and Pinion design to win the category (with a score of 5/5) because the design takes the least amount of time to depress the syringe, and also takes the least amount of power to do so. On the other hand, a lead screw/stepper motor and commercially available linear actuators tend to be slower with linear actuators being the slowest possible option (which is why it was scored 3/5 in this category).

Third, Robustness was defined as the ability for the design to be able to withstand repeated use and withstand the high pressure environment induced by the hyperbaric chamber. The team chose the Lead Screw plunge design to win the Robustness category (with a score of 5/5) due to it being manufactured out of metal components that can withstand repeated use and mechanical components that can withstand the high pressure environment. On the other hand, it was tough to find commercial linear actuators that can withstand the high pressure environment due to the nature of their closed system. The Rack and Pinion designed scored low in Robustness due to its components being made out of plastic which is inherently less strong and more prone to being destroyed over repeated use than metal.

Fourth, Feasibility was defined as how straight forward the design would be to complete in the given time frame of one semester. This category was won by the Linear Actuator (with a score of 5/5) because it can be just purchased and slotted into the design; however, the other designs will give the team a better engineering opportunity in the future. That being said, the Rack and Pinion designed scored higher (with a score of 4/5) than the Lead Screw Plunge (with a score of 3/5) in this category due to the main mechanisms being able to be 3D printed instead of order or manufactured from a third party like the components of the Lead Screw Plunge.

Fifth, Ease Of Use was defined as how easy the clients can interact with the design in order to activate it and reload syringes between experiments. The Lead Screw Plunge design won the category (with a score of 5/5) due to its slot-in method that makes it very easy and intuitive to replace the syringe between trials when compared to the other two designs, namely the shotgun loading method of the Rack and Pinion.

Sixth, the cost category was given a very low weight in the matrix because the team was not given a budget, but they still chose to keep spending at a minimum. The Rack and Pinion design won (with a score of 5/5) this category because it is made of plastic, and is therefore relatively inexpensive to produce. The Linear Actuator scored lowest in this category (with a score of 1/5) due to the high price tag associated with purchasing commercial systems.

Based on the criteria and the scores that the team gave the designs on the various criteria, the team decided to move forward with the Lead Screw Plunge design, and will begin production in the coming weeks.

V. Fabrication/Development Process

A. Materials

a. Bipolar Stepper Motor - Nema 17 Non-captive 34mm

A Stepper Motor Driver is a circuit or device that provides the necessary current and voltage to a Stepper Motor so that the motor has a smooth operation through the use of pulse signals produced from a controller and a driver that converts pulses into Stepper Motor Motion. A stepper motor works by rotating a large drum around a threaded rod (Figure 10). The two are polarized in opposite directions. The threaded rod is held in place by its threads, so rather than rotating, it moves through the magnetic field to "rotate" the threads while providing linear translation to the whole rod [16].

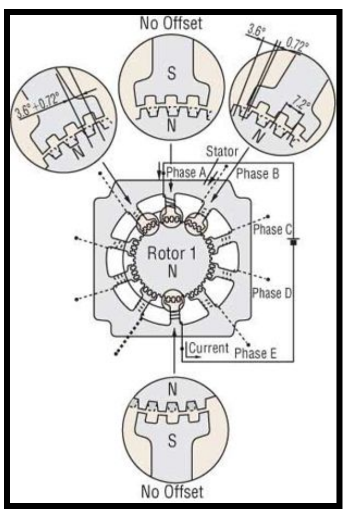

Figure 10: Excitation of threads in a stepper motor creating rotation and thus lateral movement [16]

The final stepper motor that the team chose was the Nema 17 Non-captive 34mm Stack 0.4A Lead 2mm/0.07874" Length 150mm (Figure 11). This stepper motor was chosen as it moved horizontally, and could expel the solution at our desired force of 1 N. This motor was 150 mm, meaning that it was capable of extending at least 7cm to fully plunge the plunger. It also was capable of traveling

35 revolutions in 10 second 210 RPM to obtain our desired velocity of .275 in/s. Based on the seemingly low force required to plunge the syringe and the seemingly low power requirement from the stepper motor to complete the task, this stepper motor was perfect for our project. This specific motor met the required load acceleration, overcome friction in the system, overcome the effect of gravity, and maintain a safe maximum operating temperature

Figure 11: The selected Nema 17 Non-captive 34mm Stack 0.4A Lead 2mm/0.07874" Length 150mm stepper motor [17]

b. Carbon Fiber PLA

Figure 12: Spool of Carbon Fiber Filament

Carbon fiber reinforced polylactic acid (PLA) 3D printer filament is made from a blend of carbon fibers and PLA (Figure 12). The carbon fibers serve to reinforce the PLA to increase its strength above that of normal PLA. Additionally, PLA is made from organic compounds, and releases trace amounts of nontoxic fumes when printed, which is not true for many filaments of similar strengths. It was necessary to choose a nontoxic filament since this device was printed on personal 3D printers inside a private residence. The main pitfall of PLA is its low resistance to heat, as it begins to deform around 60 degrees celsius. However, since this device was only to be used at room temperature, well within the stable temperature range for PLA, temperature was determined to not be an issue that would hamper the effectiveness of this device. This material was used to construct all of the structural components of the device. It was selected for this project because of its high strength, impact resistance, and ease of printing.

c. 20 cc Kendall monoject syringe with Luer lock tip

The Kendall syringe (Figure 13) is where the euthanasia solution will be kept while the sheep are undergoing experimentation. Tubing will be attached to the tip of the syringe, which holds a maximum of 20 ml of liquid. The Luer lock tip allows the tubing to be securely affixed to the syringe. The plunger will be attached to the stepper motor system so that it can be controlled on command.

Figure 13: Fully compressed 20cc Kendall monoject Syringe with Luer Lock tip shown

d. Heavy Duty Double Sided Mounting Tape

Figure 14*:* Double Sided Mounting Tape [18]

The Gorilla Glue Double Sided Tape was utilized to secure the device in the hyperbaric chamber (Figure 14). This tape was utilized to secure the device to the surface inside the chamber and to keep the device level. In addition to securing the device, the tape can be removed without leaving any residue behind or damaging the device.

e. AT89S52 Microcontroller

The AT89S52 is a low-power, high-performance CMOS 8-bit microcontroller with 8K bytes of in-system programmable memory that is produced by Atmel (Figure 15). The AT89S52 provides the following key features: 8K bytes of Flash, 256 bytes of RAM, three 16-bit timer/counters, on-chip oscillator, and clock circuitry [19]. These key features made the AT89S52 attractive to use for this project as it will be able to have more than enough memory for the program it needs to run and it is able to serve as its own timer which is key to controlling the speed of the stepper motor.

Figure 15: AT89S52 Microcontroller

f. L293D Driver IC

The L293D is a dual H-bridge driver (Figure 16). Specifically, the L293D is designed to provide bidirectional drive currents of up to 600-mA at voltages from 4.5 V to 36 V. The L293D's capacity for bidirectional current drive is more than sufficient to cover the 400mA current requirements of the 12V stepper motor used in this project [20].

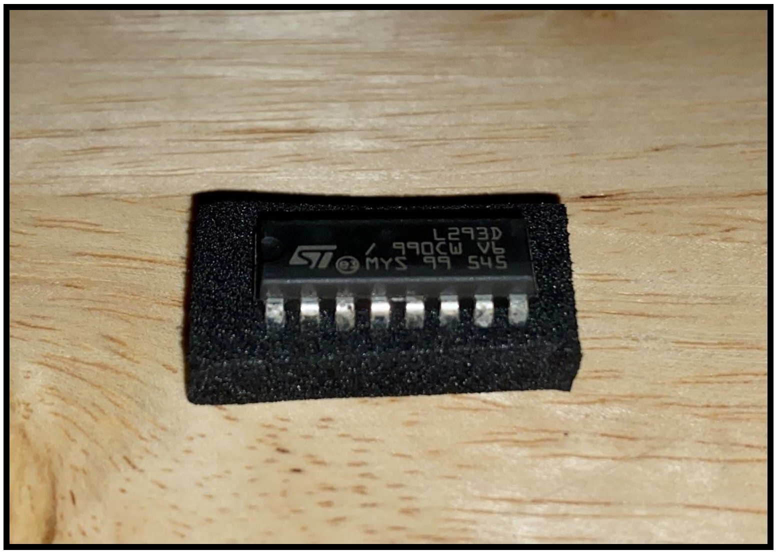

Figure 16*:* L293D Driver IC

g. MAX751CPA+

The MAX751CPA+ (Figure 17) is a through hole voltage regulator that allows the conversion of a Lithium ion battery from anywhere between 3.3V and 5.5V to be converted to a constant output voltage of 5V. This is used to power the AT89S52 microcontroller. In order to enable the function of this voltage regulator, a specific circuit was built around this chip based on its documentation (See Appendix B).

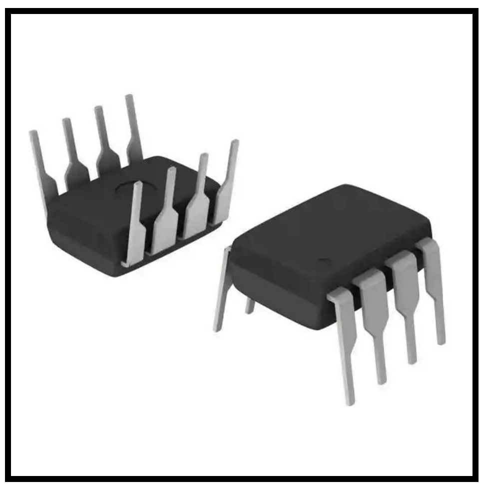

Figure 17: MAX751CPA+ Voltage Regulator

h. PRT-13855

The PRT-13855 (Figure 18) is a rechargeable lithium ion battery with a rated voltage output of 3.7V. It is chosen to be rechargeable so that the client does not have to purchase new batteries each time a test is run. This is within the rated input voltage range of the MAX751CPA+, so when the two are connected the MAX751CPA+ will output 5V as needed by the project.

Figure 18: PRT-13855 Lithium Ion Battery

i. HHR-150B01F10

The HHR-150B01F10 (Figure 19) is a battery pack that outputs 12V at a current rating of 1.5Ah for its total life. Additionally, it is rechargeable, so the client can use it repeatedly for many trials in a row. This battery will be used to power the motor when it is turned on, so it must have enough life to last the full 172 hours. This is why the battery was chosen to have 1.5Ah hour battery life, which is enough to fulfill the needs of the project based on our calculations due to the stepper motor only requiring 400 mA to run over a short period of time when activated.

Figure 19: HHR-150B01F10 12V Battery Pack

j. 6FC54-73

The 6FC54-73 (Figure 20) is a toggle switch with 3 functions (momentary on/off/momentary off). The switch allows the client to control the motor to go forwards/backwards as long as the switch is pushed to the desired position. This part was chosen because it gives the user complete control over motor function and allows the user to stop the motor whenever needed.

Figure 20: 6FC54-73 Toggle Switch [21]

k. 22 AWG Silicone Stranded Wire

Long wires were required to connect the remote control from outside of the hyperbaric chamber to the components of the motor controller/motor system in order to provide the researcher's control from outside of the chamber (Figure 21). This order comes with 6 different colors of insulated wires, which will help in differentiating wire purposes (momentary on/off/momentary off) when connected to the switch in the remote control.

Figure 21: Fermerry silicone stranded insulated wire spools [22]

B. Methods

a. Structural Component Development

i. Syringe Housing

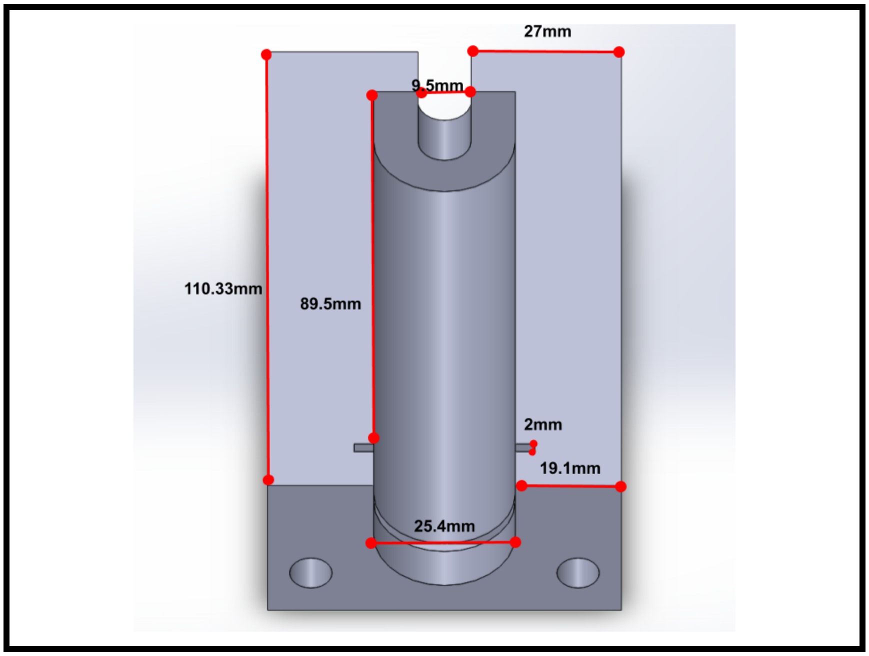

Figure 22: Syringe Housing with Dimensions

The syringe housing was created and modeled to specifically fit the 20 cc Kendall monoject syringe to be used by the client (Figure 22). The team worked to develop a part that the client could easily slot the syringe with euthanasia solution into and be structurally strong enough to function. The circular slot at the front of the device is open to allow for the tubing to fall into without excessive manipulation. When the client slots the syringe into the housing, the holding tabs on the syringe body are fit into the small 2mm slots at the back of the design. This acts to pin the syringe within the housing to prevent any forward or backward motion. Furthermore, the housing can be connected to other components using the two holes at the back which allows for the easy replacement of parts if needed. This piece was printed using a 3-D printer in Carbon Fiber PLA.

ii. Holding Cap

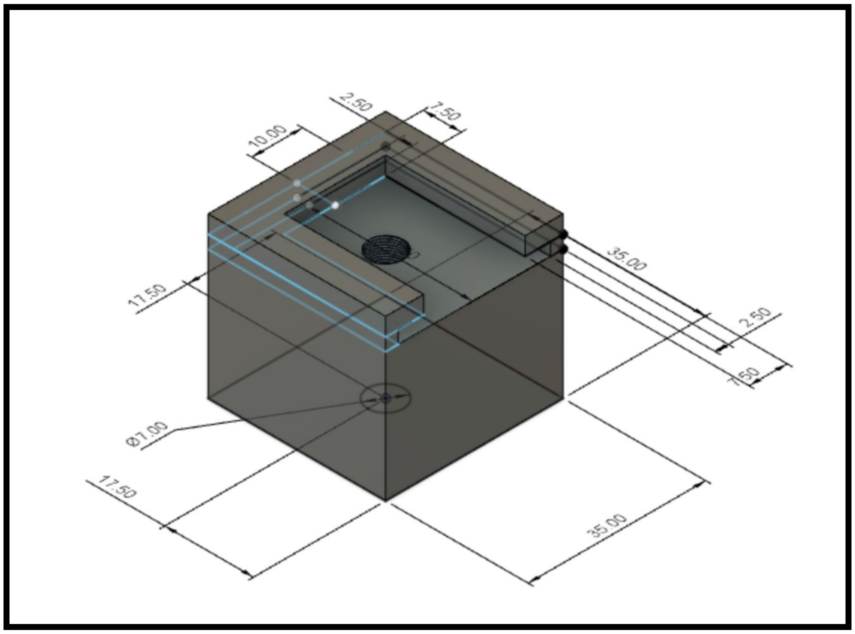

Figure 23: Holding Cap with Dimensions

The holding cap pins the plunger of the syringe to the lead screw so that they move together (Figure 23). There is a lip around 3 edges of the top of the component, with one open face that faces the syringe. The plunger slots into the open face to be held in place by gravity and the protruding lip. The lead screw is threaded into a hole that goes completely through this component. The syringe is prevented from compressing under the pressure of the hyperbaric chamber due to the resistance provided by the threaded connection between the holding cap and leadscrew. The holding cap was designed with a M7x0.5 threading in order to enable the threading of the holding cap onto the lead screw. This component was printed in carbon fiber PLA at the specifications in Appendix A.

iii. Motor Holder

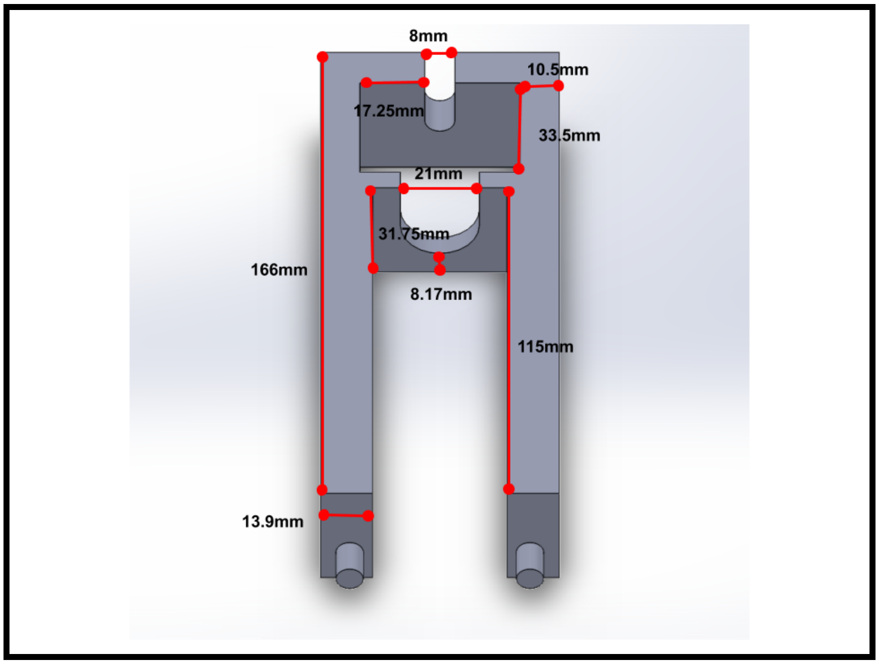

Figure 24*:* Motor Holder with Dimensions

The motor holder functioned to pin the stepper motor in place and to provide a strict track for the holding cap to move seamlessly through (Figure 24). The motor slotted into the back section and was held in place by friction and gravity. Adhesives were not utilized to secure the stepper motor in this structural piece in order to enable the reusability of the motor in a new structural piece if anything were to break. Thus, a tight friction fit was utilized to secure the stepper motor. The walls that surrounded the stepper motor chamber served to prevent the rotation of the motor, as well as to prevent longitudinal movement of the motor. The pegs on the near side of the piece slotted into the syringe housing, allowing for easy alignment and assembly of the pieces. This component was printed in carbon fiber PLA at the specifications in Appendix A.

iv. Electronics Base

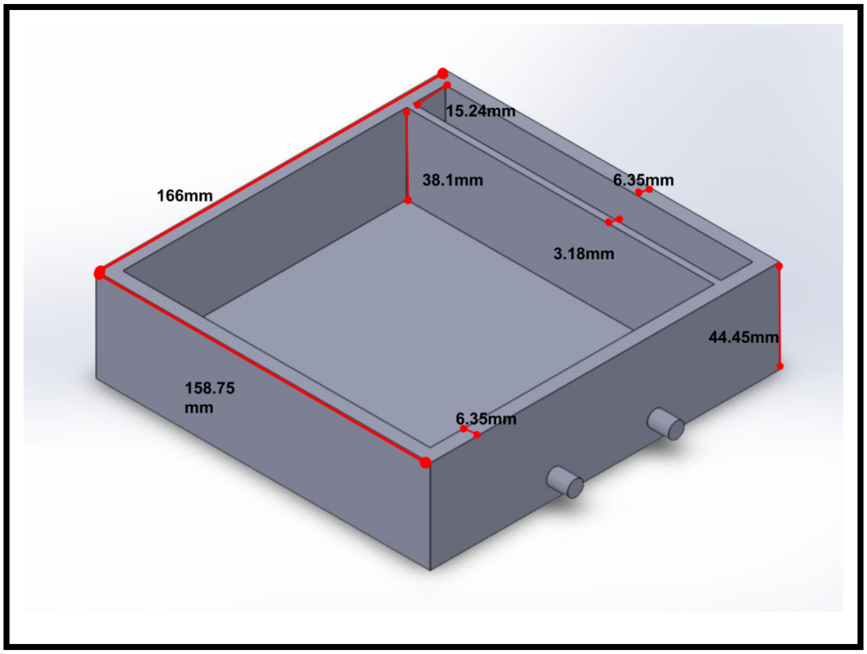

Figure 25: Electronics Base with Dimensions

The Electronics Base was created and modeled in Solidworks to hold the circuitry and power supply components (Figure 25). The base was the last piece that the team printed using a 3-D printer in Carbon Fiber PLA. The large open space is used for the circuitry components, and the smaller space is used to house the 12V battery required to power the stepper motor. Lastly, the base can be connected to the Motor Holder via the pegs on the design which allows for easy installation and replacement of the piece.

b. AT89S52 Microcontroller Programming

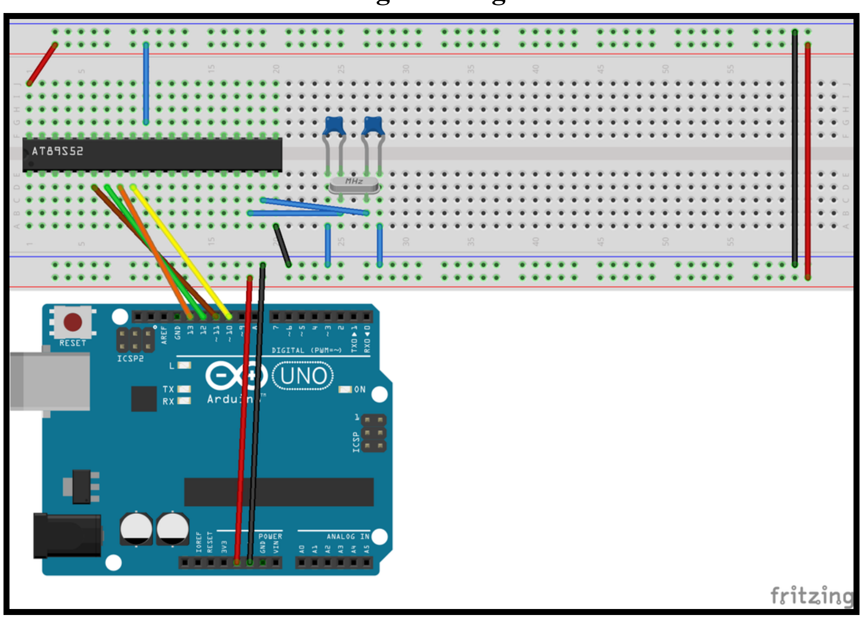

Figure 26: Diagram of the wiring needed when utilizing an AT89S52, crystal oscillators, and an Arduino device [23]

The AT89S52 was programmed through the use of an Arduino Uno. The first step in successfully programming the AT89S52 was correctly wiring the AT89S52. The wiring displayed in Figure 26 was utilized to interface the AT89S52 to the Arduino Uno. Specifically, outside of typical powering/grounding, the RST pin on the AT89S52 is wired to pin 10 on the Arduino, Pin 8 (P1.7) on the AT89S52 to pin 13 on the Arduino (SCK), Pin 7 (P1.6) on the AT89S52 to pin 12 on the Arduino (MISO), Pin 6 (P1.5) on the AT89S52 to pin 11 on the Arduino (MOSI). These wirings allow the AT89S52 to be programmed and are critical.

In order to program the AT89S52, the system also required the following components: a Crystal Oscillator (11.0592 mHz), two capacitors (33pF), a 10kOhm Resistor, and a 10μF Capacitor. A crystal oscillator was crucial to the programming as it allowed the Arduino and the AT89S52 to "talk" and allowed the uploading of code to be successful.

A crystal oscillator is an electronic oscillator circuit that uses a piezoelectric resonator, a crystal, as its frequency-determining element. To obtain a very high level of oscillator stability a Quartz Crystal is generally used as the frequency determining device to produce another type of oscillator circuit known generally as a Quartz Crystal Oscillator, (XO). When a voltage source is applied to a small thin piece of quartz crystal, it begins to change shape producing a characteristic known as the Piezo-electric effect. This Piezo-electric Effect is the property of a crystal by which an electrical charge produces a mechanical force by changing the shape of the crystal and vice versa, a mechanical force applied to the crystal produces an electrical charge [!!@].

The quartz crystal used in a Quartz Crystal Oscillator is a very small, thin piece or wafer of cut quartz with the two parallel surfaces metallised to make the required electrical connections. The physical size and thickness of a piece of quartz crystal is tightly controlled since it affects the final or fundamental frequency of oscillations. The fundamental frequency is generally called the crystal's "characteristic frequency" [24].

Basic wiring articles utilizing Arduino and crystal oscillators recommended using a 11.0592 MHz crystal oscillator. After selecting this crystal oscillator, we were then able to determine the capacitors. When choosing the two capacitors (C1 and C2) that you attach to the crystal in the programming setup, one needs to consider the load capacitance of the crystal oscillator chosen and the stray capacitance of the rest of the circuit (which was approximated to be between 3-5pF). One can utilize the (C1, C2 = 2*Cload – 2*Cstray) equation in order to determine the required capacitors to enable the appropriate oscillation of the crystal oscillator [25]. Using 11.0592 MHz crystal oscillator with a load capacitance of 20pF, we found that C1 and C2 need to be 30pf to 34pf. As a result, we decided to include two 33pF capacitors in the programming wiring.

Once the AT89S52 has been correctly wired to the Arduino and to the crystal oscillator, the program code (HEX program file) could be uploaded/burned onto the AT89S52. The AT89S52 was specifically programmed through the ArduinoISP and through commands on command prompt utilizing the "avrdude" module of Arduino. A HEX program was uploaded to the AT89S52 to coordinate the function of the device.

A C program was produced and exported in a HEX program format via the Keil uVision5 IDE (Figure 27). This program operates by first initializing an internal timer of the microcontroller so it produces its own PWM (pulse width modulation) timer in order to set the rhythm/timing of the following checks. This PWM timer dictates the speed of the motor as a result and can be adjusted accordingly. After initializing an internal timer, the system starts in the STOP position by setting the Forward and Backward pins of the microcontroller to HIGH. This effectively starts the system off at a clean slate, waiting for input. Next, the program enters a while loop that consistently checks if the forward OR the backward pins have been activated by the user via the remote. Once activated, the program will initialize the necessary powering of the Driver IC in order to drive the motor either forward or backward by altering which of the four pins attached to the driver IC are receiving power. As long as the Forward or Backward pins are activated, the forward and backward motion will ensue until the STOP pin is activated which will disengage the movement and bring the program back to the starting, clean state. One can see the full C program in Appendix D.

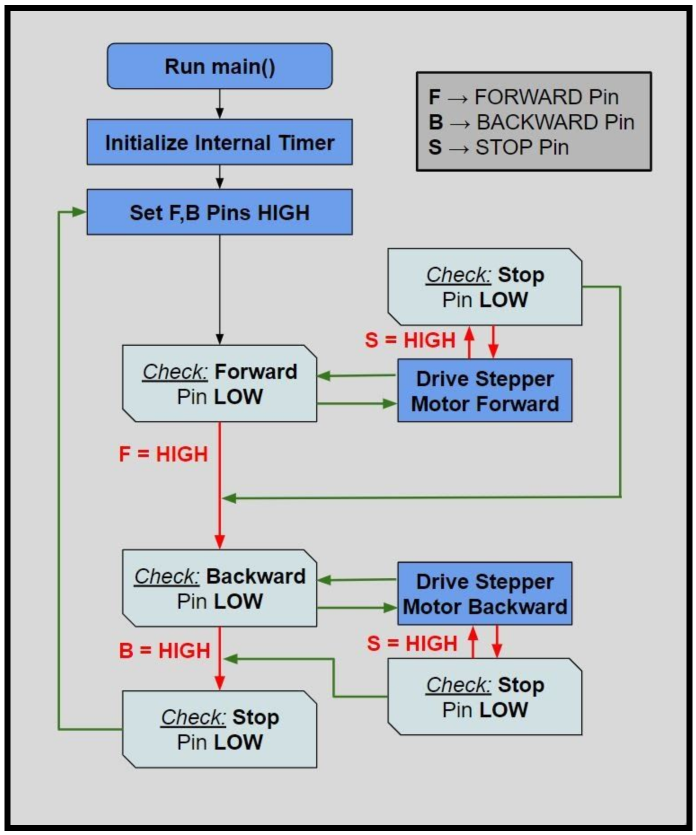

Figure 27: Software flow diagram of how the microcontroller operates.

c. AT89S52, L293D, and Stepper Motor Wiring

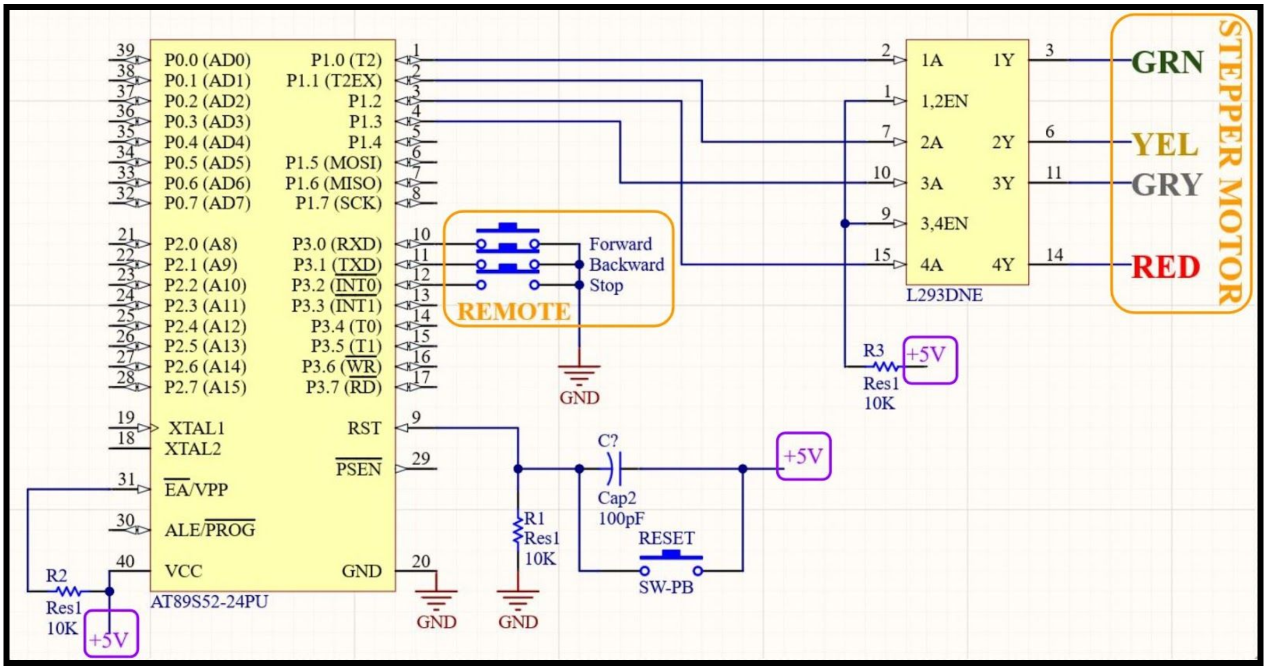

Figure 28: Altium schematic of the wiring of the AT89S52 microcontroller to the L293D driver IC which controls a stepper motor based on a user input from an external remote

The AT89S52 microcontroller (seen on the left side of Figure 28) is used to coordinate the forward or backward movement of the stepper motor based on input from the user. In order to satisfy the base wiring requirements as defined by the AT89S52 documentation, Pin 20 was wired to ground, Pin 40 to 5V, Pin 31 to 5V via a 10K resistor, and Pin 29 was wired in such a fashion to institute a reset switch (Figure 28). Next, three pins of the AT89S52 (Pin 10, Pin 11, and Pin 12) are dedicated to interfacing with a switch remote that is to be wired outside of the hyperbaric chamber and that will be in the hand of the researchers. This switch remote has three positions (FORWARD, BACKWARD, and STOP) which act to ground their corresponding pin (Pin 10, Pin 11, and Pin 12 respectively) when switched by the user (Figure 28). The grounding of these pins serves as user input to signal the microcontroller software to initiate or stop motor movement.

In terms of the connections between the microcontroller and the driver IC, there are four pins of the AT89S52 (Pin 1, Pin 2, Pin 3, and Pin 4) that are dedicated to interface with the L293D Driver IC (which can be seen on the right side of Figure 28). Pins 1, 2, 3, and 4 of the AT89S52 wire into four ports on the L293D (1A, 2A, 4A, and 3A respectively). When one of these four ports of the L293D are powered HIGH, the corresponding Y port (e.g. when A1 is powered HIGH, Y1 is activated) is opened to allow current through to drive the bipolar stepper motor. Depending on the order by which the A ports of the L293D are powered, the stepper motor will produce forward or backward linear motion of the leadscrew. Finally, Pin 1 and Pin 9 of the L293D are connected to 5V in order to enable the dual H-bridge functionality of the L293D unit.

C. Final Prototype

Figure 29: Assembled Remote Euthanasia Device

The device consists of four structural components: the holding cap, the syringe holder, the motor holder, and the electronics base (Figure 29). The holding cap holds the syringe plunger to the holding cap through the use of a 3 sided lip, which prevents the plunger from depressing or extending without input from the stepper motor. It slides back and forth with the lead screw, and is the only point of contact between the electronics and the syringe. The motor holder holds the stepper motor through the use of four walls with an open top and bottom. The motor is held snugly in the motor holder through friction. This was specifically included if the motor holder were to break, the stepper motor could be extracted and reused. The electronics base contains all of the circuitry and electrical components. This component attaches directly to the motor holder, permitting a short and direct connection between the motor and the electronics. Finally, the syringe holder cradles the syringe in a semicircular cavity. This piece makes use of the finger tabs on the syringe to lock it in place through the use of two grooves on either side of the cavity, which the tabs slot into. This component, combined with the tension or pressure put on the syringe by the stepper motor and holding cap keep the syringe firmly attached to the device. Overall, these components act to prevent the plunger of the syringe from moving prematurely and only when activated by the user. The dimensions for all these parts can be seen in figures 25, 24, 23, and 22.

The holding tape is a heavy duty double sided mounting tape. In order to keep the device secured to the surface in the chamber, the team decided to use this tape on the underside of the device. The tape can be easily removed after the experiment is finished.

In terms of the circuitry involved, the AT89S52 is used for its internal timer to coordinate the function of the stepper motor and to keep its velocity constant; however, the AT89S52 can not output the current required to drive the motor to motion. This was made up for by the L293D. The internal H-Bridges of the L293D are capable of providing the necessary current to drive the stepper motor and handling the higher voltages than the AT89S52. The usage of a dual H-Bridge system internally increases the current without drastically changing the voltage, which is useful because the output of the AT89S52 has enough voltage but not enough current to power the Stepper motor. The specific wiring between the AT89S52 and L293D can be seen in Figure b . The AT89S52 acts to coordinate the activation and current direction of the dual H-bridges within the L293D. Depending on which H-bridge is activated and the direction of current flows, this allows the cycle of magnets within the stepper motor to turn on and off in a way that rotates the lead screw in the desired forward/backward direction. To power all of these components, a voltage regulator is used to convert the output of a 3.3V lithium ion battery to a steady 5V output, which is how much voltage the driver IC and AT89S52 requires to function correctly. Furthermore, a 12V battery pack interfaces with the L293D to provide the current that travels the H-bridges in order to drive the stepper motor based on coordination from the AT89S52. Additionally, a wired external remote was used to control the movements of the stepper motor from outside the hyperbaric chamber. A remote was required to be wired outside of the hyperbaric chamber as the client does not have access to the inside of the hyperbaric chamber during the 172 hour experiment and a sheep could get sick at any point during the trial. The client's need to have rapid and easy access to kickstarting the machine.

D. Planned Testing

In order to meet the clients requests, the team would validate that the system could be activated after being on for 172 hours and validate that the speed of the lead screw is sufficient to fully plunge the syringe in roughly ten seconds. The clients have asked that the device last for 7 days because that is how long it takes a team to fully vacate a compromised submarine of its full crew. To validate the life of the batteries, the team would set up the full device and let it sit fully plugged into the power sources for 172 hours. After the device has been in this state for 172 hours, the device would be activated to ensure it works and this would constitute one trial. If the device did not function after 172 hours, a battery with a higher Ah rating would be necessary. The team would aim to run 10 trials. A proportion of success to failures would be constructed to communicate the success of this validation test. In order to validate the speed of the lead screw, the team would turn the switch to the "on" position for an interval, and would measure the time it takes to move 2.75 inches (or the total distance that the plunger needs to travel to fully expel all liquid in the syringe). This would constitute one trial, and the team would aim to run 50 trials. Next, the team would calculate the velocity for each trial. The velocities across all trials would then be averaged and then a 95% confidence interval would be created to characterize the velocity profile of the stepper motor. The client desired that the device take at most 10 seconds to fully dispense the liquid so the team would aim for a mean speed of .275 in/s across trials.

VI. Expected Results

Although the team was not able to directly test the data, future testing data can be analyzed using bootstrap t-tests. Bootstrap t-tests will be used to analyze the results found during testing the lead screw speed validation. For all of the tests run, an alpha value of 0.05 will be used. All testing will be done as described in the "Planned Testing" section.

The accuracy of the lead screw velocity will be determined by running a bootstrap t-test once the team is able to create a mirrored device. The t-test will be run on the measured velocity that the lead screw obtained and compared with the lead screw in the other device. The results will be used to determine if the differences between the paired device's velocities are statistically significant. After running the test, the team hoped to obtain a p-value < 0.05. If the p-value is larger than the alpha value, the null hypothesis that the velocities are considered equal is not rejected. If the p-value is less than the value of alpha the null hypothesis is rejected, which means the difference in velocity is not caused by chance. There is a significant difference between the measured velocity and the speed that our team calculated. In these tests, we expect to obtain a p-value of less than 0.05 which would support that the difference in velocity is not caused by chance, but by other factors that we can control.

Next, a 95% confidence interval will be created to characterize the expected movement of the device in order to ensure that the average speed of the stepper motor falls around .275 in/s as specified by the client (Figure 30). In order to analyze the battery life, a proportion of success to failures would be constructed to communicate the success of this validation test (Figure 31). We aim to have a 100% success rate of the batteries after the device ideas for 172 hours; however, the proportion of success to failures may illuminate a different result. This may cause us to search for other batteries that will work better for this application.

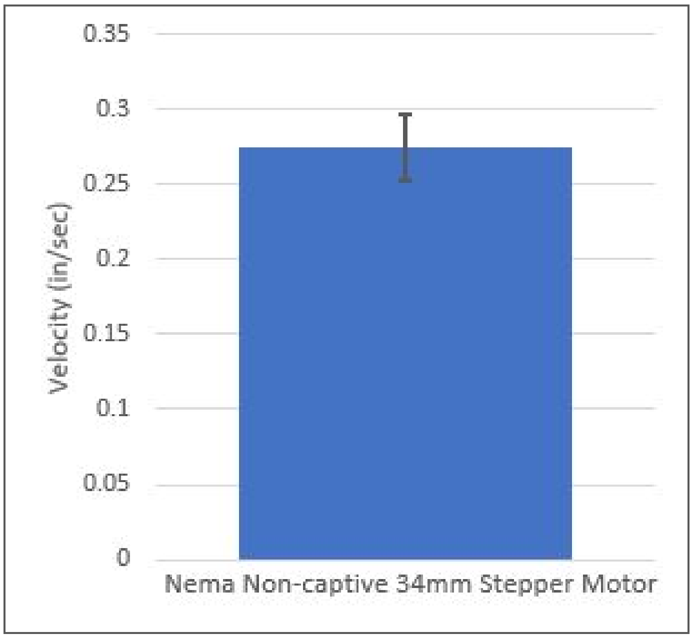

Figure 30: Expected results from the lead screw speed validation testing. The error bar represents the 95% confidence interval of the average speed of the stepper motor

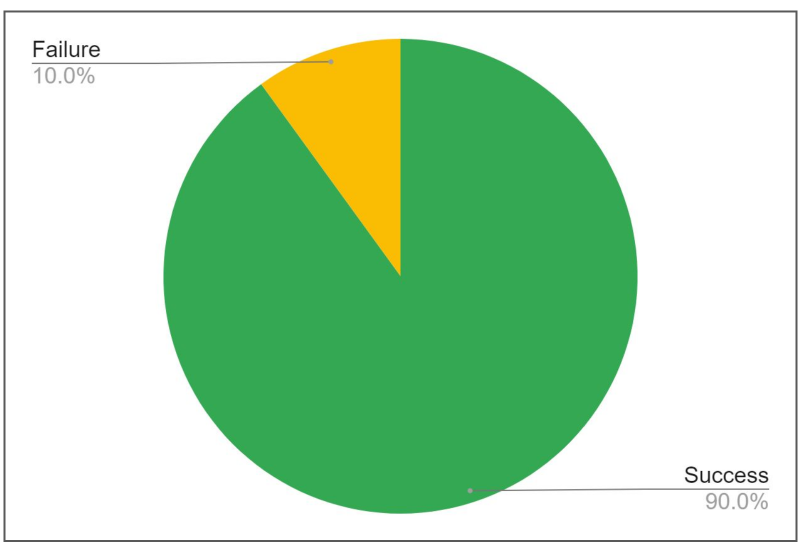

Figure 31: Minimum acceptable results from the battery life validation testing

VII. Discussion

It is important that the remote euthanasia device that we produce can deliver consistent results and can be relied on to last the duration of our client's experiment. Once COVID restrictions are lifted and more regular access to a testing lab is available, the team will aim to rigorously test the speed of the stepper motor and the battery life of the power source utilized in this project. By validating the speed of the stepper motor is around .275 in/s, this will ensure that the tubing connecting the syringe to the jugular vein of the sheep does not rupture. If the syringe was compressed too quickly, a buildup of pressure is thought to cause the failure of the tubing that the euthanasia solution will be pumped through as described by the client. If the tubing were to fail, this would lead to the unnecessary, unethical suffering of the sheep within the hyperbaric chamber. It is critical that the tubing remains undamaged throughout the duration of the experiment.

Next, by validating the battery life of the batteries utilized in this design, the team can provide confidence that the device can be activated after sitting idle for 172 hours. It is critical that the remote euthanasia device can be activated at any time during the 172 hour experimental trial becuase it is unknown if and when a sheep may exhibit early signs of decompression sickness. Based on the researcher's judgement, they will make the decision when to activate the device in order to prevent unnecessary, unethical suffering of the sheep due to decompression sickness.

In the future, there need to be various improvements to the systems that are in place. On the structural side, it is key that there is a cover for the electronics box in order to sequester the electronics away from potential tampering. On the software side, With all that being said, due to the poor visibility of the researchers to the inside of the hyperbaric chamber, the team aims to improve the programming by instituting a movement cap to force the system back to the stop state as soon as the plunger is fully retracted or depressed. This will prevent the holding cap from being pulled into the housing piece or being pushed against the housing piece which could either damage the threads of the holding cap or damage the housing piece itself. Finally, once these above improvements are made, a secondary device will need to be produced as per the clients request as two sheep are expected to be in the hyperbaric chamber during the duration of the client's experiment. Although the device has been designed to function in the high pressure environment, there are certain instances of error that may disrupt the function of the remote euthanasia device.

Throughout the duration of the sheep experiment, a potential source of error could be the variability of the pressure in the chamber. The team's calculations and design decisions were based around a certain pressure range, and if the pressure falls out of that range, the device has the possibility to fail. On the other hand, another small source of error could be human error from the researchers. There is a chance that the researchers missed the jugular vein when suturing, or the researchers accidentally put the wrong amount of Pentobarbital in the syringes. These small human errors could impact the performance of the team's device.

VIII. Conclusions

Our clients are experimenting with sheep in order to evaluate physiological changes that occur after being kept under submarine pressure conditions (5 atm) for 172 hours. With such pressure conditions, it is possible that the sheep would experience decompression sickness and/or traumatic symptoms. Thus, our clients tasked our team to develop a remote device that would be capable of euthanizing the sheep humanely in the event that pressure conditions bring about health complications to the test subjects. Our team's created device utilizes a wired remote control that communicates with a stepper motor controller to push and pull the plunger of a syringe filled with a euthanasia solution.

Over the course of this project, there were both things that did and did not work while the team performed specific tasks. On the structural side of the project, something that the team struggled with was modeling and 3-D printing threads. The threads of the lead screw had unusual dimensions which resulted in numerous attempts at 3-D printing threads on the holding cap. Another issue that the team worked through was keeping the lead screw parallel to the surface in the motor holder. The team resolved this by dropping the floor out of the motor holder and allowing another part of the motor to keep it in place. On the circuitry side of the project, the team had issues with getting all the components to work with each other. The team went through a lot of troubleshooting that included fixing the coding and making sure connections were in place and connected to the correct pins. As for things that worked, the team was able to successfully connect the structural aspects of the device to the circuitry side of the device. All the pieces were easily 3-D printed, and with the space left on the structural pieces, the circuitry components fit to complete the device. The team was able to create a device that the client can easily recreate if needed. Lastly, if given the chance to do this project again, the team would do a few things differently. The team would probably try to get more testing in before the end of the project to confirm that the device works. The team also would have tried to develop and incorporate a wireless option for the remote instead of using a wired remote.

There are a few goals that the team wishes to meet in the future to further improve the device and allow the client to begin their experiment. The first step the team will take is to thoroughly test the device under both normal and chamber pressures to make sure that it can consistently give the desired results without fail. The next step will be to print a second device to fulfill the client's request for two devices, so they could start their experiment. On the coding side of things, the team aims to improve the program by instituting a movement cap to force the system back to the STOP state as soon as the plunger is fully retracted or depressed. Finally, a way the team wishes to improve upon the device is to change out the wired remote to a wireless remote which will hopefully improve usability and the amount of wires going into and out of the chamber.

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NR1YwMDFERkxGVCZlbmNyeXB0ZWRBZElkPUEwODY0NDg0MkxYTklLNDFMVUY5ViZ3aWRnZXROYW1lPXNwX2F0ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU&th=1. [Accessed: 08-Dec-2020].

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X. Appendix

Appendix A - 3D Printing Protocol

There are 4 components to any 3D printed part: the ceiling, floor, infill, and shell. The shell consists of a set number of concentric and conjoined walls that runs along the vertical axis of the print. The ceiling and floor consist of a set number of completely solid layers of material, and sit on top of and below the shell. Together, the shell, ceiling, and floor form a complete and connected surface. This surface bounds the infill, which is a three dimensional grid with hollow cells. Infill is calculated as a percentage of interior volume. Since the components all needed to withstand 5 ATM of pressure, resistance to deformation from pressure was the key parameter that was optimized during the printing process.

Each part was printed with the following settings:

1. A 0.4 mm extruder nozzle was used because it offered a good balance between horizontal adhesion and precision.
2. A layer height of 0.12 mm was used because it promoted strong vertical adhesion and minimized layer lines on slanted top/bottom surfaces.
3. A shell width of 1.6 mm (4 passes) was used, since it provided a good balance between weight and resistance to deformation.
4. A ceiling and roof thickness of 1.08mm (9 layers) was used since it provided a top and bottom with a similar strength to the shell, to maintain uniformity.
5. An infill density of 40% was used. Although a much lower infill density, as low as 15%, would have sufficed, the design team felt it was important to “over-build” the components due to the catastrophic events that could have occurred if this device had failed.
6. A hotend temperature of 210℃ was used as per the filament manufacturer’s recommended settings.
7. A heated bed and enclosure were not used, as PLA does not require either.

APPENDIX B -- Voltage Regulator Circuit Diagram

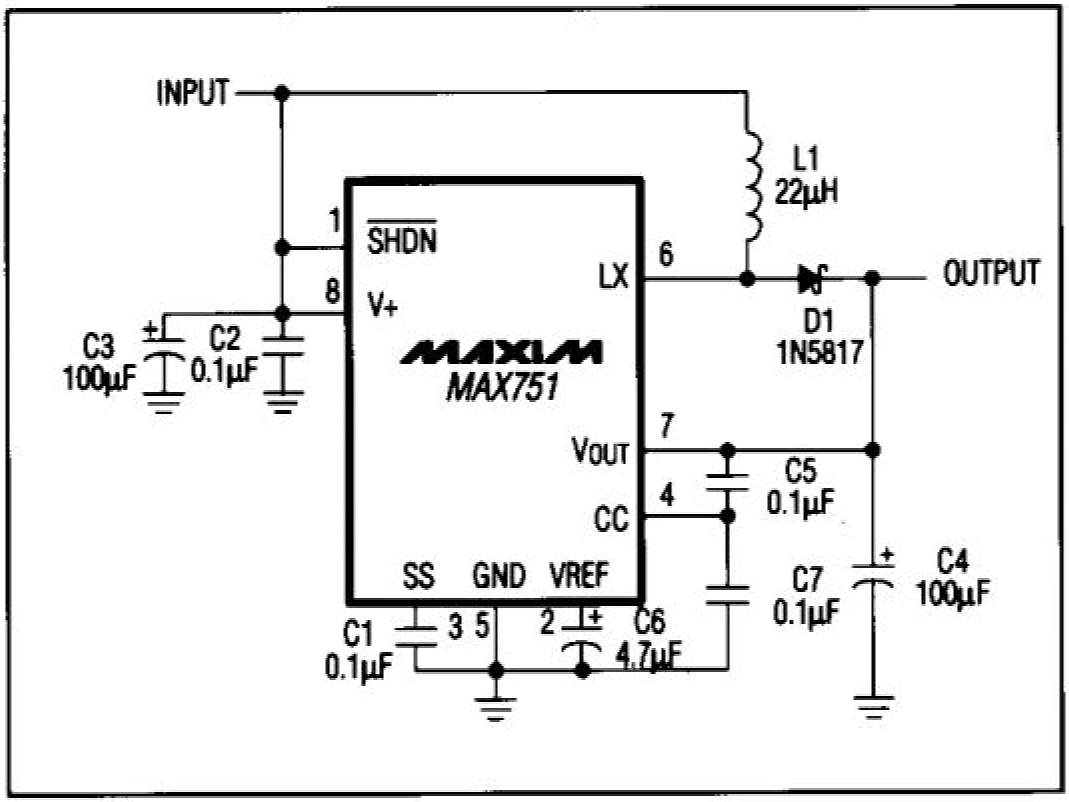

Figure 3. Standard-Boost Application Circuit (Non-Bootstrapped Mode)

Appendix C -- Expense Sheet

Dates	Product Name	Link to Part	Pricing/Item	Quantity	Receipt	Total Price
10/19/20	Carbon Fiber Filament	https://rb.gy/ntyeg0	$32.99	1	Amazon.com - Order 113-8238606-2479418[2395]	$32.99+Tax
10/19/20	Stepper Motor	https://www.omc-stepperonline.com/nema-17-non-captive-34mm-stack-04a-lead-2mm007874-length-150mm-17ls13-0404n-150d.html	$33.81	1	Stepperonline order confirmation[2396].docx	$33.81+Tax

11/16/20	Microcontroller	https://www.digikey.com/en/products/detail/microchip-technology/AT89S52-24PU/1008597?s=N4IgTCBcDaIIBUAcBOAygVjAWjAFgAUBVbAOQBEQBdAXyA	$2.48	10	11-16_INVOICE Digi-Key_77122324[2448].pdf	$24.80+Tax
11/16/20	33pF Capacitor	https://www.digikey.com/en/products/detail/tdk-corporation/FA28C0G1H330JNU00/7384520?s=N4IgTCBcDaICxwKwFoCMAOVGBsyBwyAIiALoC%2BQA	$0.19	10	11-16_INVOICE Digi-Key_77122324[2448].pdf	$1.92+Tax
11/16/20	Crystal Oscillator	https://www.digikey.com/en/products/detail/iqd-frequency-products/lfxtal003515bulk/8633684	$0.70	5	11-16_INVOICE Digi-Key_77122324[2448].pdf	$3.50+Tax
11/25/20	Voltage Regulator	https://www.digikey.com/en/products/detail/maxim-integrated/MAX751CPA/1240221?s=N4IgTCBcDaILIEEAaB2ArARgMIAUEGoBaAOQBEQBdAXyA	$4.51	1	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$4.51+Tax
11/25/20	3.7 V Battery	https://www.digikey.com/en/products/detail/sparkfun-electronics/PRT-13855/7559594?s=N4IgTCBcDaIIwFYBsAOAtH	$12.95	1	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$12.95+Tax

		VS0DkAiIAugL5A				
11/25/20	0.47µF Capacitor	https://www.digikey.com/en/products/detail/tdk-corporation/FA16X7R1H474KNU00/7384045?s=N4IgTCBcDaICxwKwFoCMAOVAGAnHZAcgCIgC6AvkA	$0.43	3	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$1.29+Tax
11/25/20	4.7µF Capacitor	https://www.digikey.com/en/products/detail/tdk-corporation/FG26X7R1H475KRT00/7326748?s=N4IgTCBcDaICxwKwFoCMB2RBmRZkDkAREAXQF8g	$0.83	3	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$2.49+Tax
11/25/20	22µH Inductor	https://www.digikey.com/en/products/detail/bourns-inc/5800-220-RC/774822?s=N4IgTCBcDaILIA4xILQDkAiIC6BfIA	$1.37	3	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$4.11+Tax
11/25/20	20V Diode	https://www.digikey.com/en/products/detail/stmicroelectronics/1N5817/770971?s=N4IgTCBcDaICwE4DsBaOBWOqCMKByAIiALoC%2BQA	$0.38	3	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$1.14+Tax
11/25/20	12V Battery	https://www.digikey.com/en/products/detail/panasonic-bsg/HHR-150AAB0	$39.28	1	11-25_INVOICE_Digi-Key 77315073[2449].pdf	$39.28+Tax

		1F10/271933?s=N4IgTCBcDaIAoAYCMBWAtAMSctA5AIiALoC%2BQA				
11/25/20	Double Sided Tape	https://www.amazon.com/Gorilla-Heavy-Double-Mounting-Inches/dp/B019HT1U9E/ref=sr_1_1?dchild=1&keywords=Gorilla+Heavy+Duty+Double+Sided+Mounting+Tape%2C+1%22+x+60%22%2C+Black%2C+%28Pack+of+1%29&qid=1607393857&sr=8-1	$6.74	1	Amazon.com - Order 112-9628774-9626620[2450].pdf	6.74+Tax
11/25/20	Wire Kit	https://www.amazon.com/Fermerry-Stranded-Electric-Tinned-Copper/dp/B089CQHRDT/ref=sr_1_1?dchild=1&keywords=Fermerry+22AWG+Stranded+Wire+Electric+Fence+Wire+Tinned+Copper+Hook+up+Wire+Kit+22+Gauge+6+Colors+10Ft+Each%2810+FT+6+Colors+Each%2C+22AWG%29..&qid=1607393889&sr=8-1	$9.99	1	Amazon.com - Order 112-9628774-9626620[2450].pdf	9.99+Tax

11/25/20	Toggle Switch	https://www.grainger.com/product/4X203?gclid=Cj0KCQiA-rj9BRCAARIsANB_4AC7IVLcH7VY3ExNEiZF8lyDr-xTy4-MNmsq3RlgQZ4kEdId10mnouYaAuDUEALw_wcB&cm_mmc=PPC:+Google+PLA&ef_id=Cj0KCQiA-rj9BRCAARIsANB_4AC7IVLcH7VY3ExNEiZF8lyDr-xTy4-MNmsq3RlgQZ4kEdId10mnouYaAuDUEALw_wcB:G:s&s_kwcid=AL!2966!3!281698275255!!!g!471571925921!&gucid=N:N:PS:Paid:GGL:CSM-2295:4P7A1P:20501231	$5.20	1	Not ordered	$5.20+Tax
						$184.72+Tax

Appendix D -- HEX Program Code

```
#include <reg52.h>
#include <intrins.h>

/* Define value to be loaded in timer for PWM period of 20 milli second */
#define PWM_Period 0xB7FE

  sbit sw1=P1^2;  /* Connected to 4A and drive 4Y */

  sbit sw2=P1^1; /* Connected to 2A and drive 2Y */

  sbit sw3=P1^3; /* Connected to 3A and drive 3Y */

  sbit sw4=P1^0; /* Connected to 1A and drive 1Y */

  sbit forward = P3^0;

  sbit backward = P3^1;
```

```
  sbit stop = P3^2;
unsigned int ON_Period, OFF_Period, DutyCycle;

/* Function to provide delay of 1ms at 11.0592 MHz */
void delay(unsigned int count)
{
    int i,j;
    for(i=0; i<count; i++)
        for(j=0; j<112; j++);
}

void Timer_init()
{
        TMOD = 0x01; /* Timer0 mode1 */
        TH0 = (PWM_Period >> 8);
        TL0 = PWM_Period;
        TR0 = 1; /* Start timer0 */
}

/* Timer0 interrupt service routine (ISR) */
void Timer0_ISR() interrupt 1
{
        PWM_Out_Pin = !PWM_Out_Pin;
        if(PWM_Out_Pin)
        {
                TH0 = (ON_Period >> 8);
                TL0 = ON_Period;
        }
        else
        {
                TH0 = (OFF_Period >> 8);
                TL0 = OFF_Period;
        }
}

/* Calculate ON & OFF period from PWM period */
void Set_DutyCycle()
{
        float period = 65535 - PWM_Period;
        ON_Period = period;
        OFF_Period = (period - ON_Period);
        ON_Period = 65535 - ON_Period;
        OFF_Period = 65535 - OFF_Period;
}
void main()
{
        int z=0;
        Timer_init();
        Set_DutyCycle();
        P3=0xff;
        P1=0x00;
        abc:
        while(stop==0)
        {
                forward=1;
```

```
        backward=1;
}

while(1)
{
         if(forward==0)
                                                  {
                                                  stop=1;
          while(forward==0);
                                        while(1)
                                        {
                                                z++;
                                                if(z==1)
                                                {
                                                 sw1=1;sw2=0;sw3=0;sw4=0;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==2)
                                                {
                                                 sw1=1;sw2=1;sw3=0;sw4=0;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==3)
                                                {
                                                 sw1=0;sw2=1;sw3=0;sw4=0;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==4)
                                                {
                                                 sw1=0;sw2=1;sw3=1;sw4=0;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==5)
                                                {
                                                 sw1=0;sw2=0;sw3=1;sw4=0;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==6)
                                                {
                                                 sw1=0;sw2=0;sw3=1;sw4=1;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==7)
                                                {
                                                 sw1=0;sw2=0;sw3=0;sw4=1;delay(30);
                                                 if(backward==0 || stop==0)
    break;
                                                }
                                                else if(z==8)
                                                {
```

```
                                        z=0;
                                        sw1=1;sw2=0;sw3=0;sw4=1;delay(30);
                                        if(backward==0 || stop==0)
  break;
                                       }
                              }
                             }

if(backward==0)
                             {
                             stop=1;
 while(backward==0);
                                 while(1)
                                 {
                                       z++;
                                       if(z==1)
                                       {
                                        sw1=1;sw2=0;sw3=0;sw4=1;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==2)
                                       {
                                        sw1=0;sw2=0;sw3=0;sw4=1;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==3)
                                       {
                                        sw1=0;sw2=0;sw3=1;sw4=1;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==4)
                                       {
                                        sw1=0;sw2=0;sw3=1;sw4=0;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==5)
                                       {
                                        sw1=0;sw2=1;sw3=1;sw4=0;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==6)
                                       {
                                        sw1=0;sw2=1;sw3=0;sw4=0;delay(30);
                                        if(forward==0 || stop==0)
  break;
                                       }
                                       else if(z==7)
                                       {
                                       sw1=1;sw2=1;sw3=0;sw4=0;delay(30);
                                       if(forward==0 || stop==0)
  break;
```

```
                                }
                                else if(z==8)
                                {
                                 z=0;
                                 sw1=1;sw2=0;sw3=0;sw4=0;delay(30);
                                 if(forward==0 || stop==0)
        break;
                                }
                        }
                       }
                       if(stop==0)
                           goto abc;
                   }
}
```

Appendix E -- PDS

Function:

Due to a new contract with the Navy, Dr. Aleksey Sobakin and Dr. Marlowe Eldridge are testing the Navy's standard operation to rescue sailors in a disabled submarine at the bottom of the ocean. In order to examine their standard operation, the clients will be using sheep and a hyperbaric chamber. This hyperbaric chamber will be putting the sheep through a variety of pressures that can lead to various health risks like pulmonary barotrauma or decompression sickness [1]. In fact, decompression sickness has the capacity to result in neurological injury or even death [1]. In order to avoid these traumatic health complications, IACUC has asked the clients to institute a method to euthanize the sheep humanely prior to a rapid drop-out decompression if necessary. As the sheep are sealed away in a chamber, the client has asked the team to devise a method to remotely euthanize the sheep when they are inside the hyperbaric chamber. This euthanasia system will have three main subsystems. For the housing subsystem, There must be a way to secure the syringe within the device and to prevent it from moving or being accidentally discharged. For the injection subsystem, there must be a way to pump the euthanasia solution out of the syringe and into the vein in a timely, complete manner. Finally, there must be a remote control subsystem that enables the device to perform the injection protocol upon a button press by a researcher outside of the hyperbaric chamber.

Client requirements:

- Housing materials, motor, and leadscrew must be capable of withstanding pressure differential caused by hyperbaric chamber
- Remote-controlled system to allow for activation of the system from outside the hyperbaric chamber based on the researcher's evaluation of the sheep's condition
- Method required to expel the euthanasia solution from the needle in a humane, timely manner

- It must be a slow, controlled release of the solution in order to ensure a complete release of the euthanasia solution from the syringe

<u>Design requirements:</u>

1. **Physical and Operational Characteristics**
   a. *Performance requirements:*

      The remote euthanasia system must be ready and usable each time a sheep is placed into the hyperbaric chamber for the experiment. In general, the remote euthanasia system is not expected to have to carry a load larger than the components that make it up; however, the system must be capable of withstanding and function within the pressure differentials induced by the hyperbaric chamber (5 atm). In terms of specifics, the remote euthanasia system that is to be developed will need to be able to perform three key tasks repeatedly and without fail.

      First, the system must be capable of expelling the euthanasia solution from the syringe through a sutured catheter inserted into the jugular vein of the sheep. This tubing must be short, allowing the solution to enter the sheep's bloodstream quickly after activation of the system. This expelling step must be timed properly in order to ensure the sheep is correctly euthanized. Second, the syringe must be able to be replaced and "reloaded" after use in order to ensure reusability of the remote euthanasia system. Third, the system must be able to be controlled remotely via a wireless signalling system (RF or Bluetooth) or through a wired signalling system depending on cost and feasibility. This will enable researchers to control the system outside of the hyperbaric chamber if any rapid sheep health degradation occurs. These three key capabilities will enable the remote euthanasia system to operate and to meet the client's requirements.

   b. *Safety:*

      This product is being made with the intention of humanely euthanizing animal test subjects, and the safety of those animals actually lies in assuring that their death is humane, because if they suffer, the device is no longer safe. It is important that the lead screw plunge system doesn't activate at unexpected times when handling. Although meant to dispatch animal test subjects, it is also important that this product euthanizes the animal test subjects in a timely manner in order to prevent them from succumbing to the medical issues of the hyperbaric chamber. This device needs to perform a humane euthanization, and it needs to be able to be activated when the researchers decide the time is right to reduce suffering of the animal.

c. *Accuracy and Reliability:*

Using a lead screw, the team needs to assure that it moves at a given speed to assure that the euthanization happens at the right rate. The syringe is approximately 9 cm long, and the client has requested that the injection happen in 10-20 seconds. Therefore the team needs the lead screw to move at anywhere between .5 and 1 cm/second. This can be achieved by calculating the teeth ratio of the gears used in the motor and using the appropriate thread size on the lead screw.

d. *Life in Service:*

The client requests that the device lasts as long as the hyperbaric sheep experiment lasts. This is roughly 172 hours. The experiments will be going all day and night, so the device must stay in service during this time. The client stated that the device must be able to function under 5 atm (73 psi) which has the possibility of impairing the function of the device[4].

e. *Shelf Life:*

Euthanasia will be performed using sodium pentobarbital. Typically, a dosage of 100 mg per kilogram of body mass of the sheep is required to adequately dispatch a sheep [5]. The shelf life of sodium pentobarbital is rated at 3 years when unopened, and 28 days after opening the package [5].

Batteries will need to be utilized in the project, as the device must be fully self-contained, and thus must rely on batteries within the device housing. Batteries are labeled with an expiration date on the packaging.

f. *Operating Environment:*

This device is going to be subjected to very high pressures (5 atm) due to the hyperbaric chamber environment [4]; thus, all components of the device, including the housing material and the containers of the medications will have to be able to withstand large pressures. The wireless signal will need to go through multiple inches of steel or glass in order to move the lead screw inside the chamber, so the team will need to test whether the signal can pass through those barriers.

g. *Ergonomics:*

The product will not interact directly with the sheep, as it will be positioned on the top of the housing that is securing the head of the sheep in the hyperbaric chamber. The syringe tubing will be the only aspect attached directly to the sheep. As a result, the device should not cause tangling of this tubing. No part of the device should induce any discomfort to the sheep.

h. *Size:*

The device must be compact, yet robust. The product must be large enough to fit a 20 cc Kendall monoject syringe with a luer lock tip and a lead screw/stepper motor to control the expelling rate of the sodium pentobarbital from the syringe [2]. This device will consist of electrical components, the injection system housing, and motorized components, which reach no more than 20 inches long. As a result, the device will be less than a cubic foot, measuring around 4 inches x 20 inches x 4 inches.

i. *Weight:*

Weight is not an integral factor in the design process due to the fact that the device will be attached to the top of the housing that is securing the head of the sheep in the hyperbaric chamber. However, the weight should not be too light so the device is not easily jostled from its resting position.

j. *Materials:*

It will be very important to choose materials that can withstand the pressure differentials induced by the hyperbaric chamber that is to be used in the experiment. Outside of the closed system of the syringe, the pressure changes will need to be considered in terms of the electrical components of the PCB, the injection system housing, and the motorized components. When possible, it will be important to avoid closed systems as this will mitigate the risk of having a closed system failing under pressure changes.

The materials utilized in this design should facilitate the creation of a lightweight, sturdy system that is capable of repeated use without disrupting the experimental design of the clients. When materials are chosen, it will be important to keep the pressure, the sheep's health, the overall structural integrity of the system, and the weight of the system in mind.

k. *Aesthetics, Appearance, and Finish:*

As the device's function is most important in the project, the device can have a very simple appearance. The client has not specified a color or type of finish; however, the device will be designed to be as professional and compact as possible while still functioning efficiently and effectively.

2. Production Characteristics

a. *Quantity:*

As the client is expecting that two sheep will be in the hyperbaric chamber at any given time, it is expected that two devices will need to be manufactured. It should be noted that the client expressed interest in integrating two injection systems in one box which would require only one device to be produced.

b. *Target Product Cost:*

The client has money built into their yearly budget for laboratory maintenance that they are using for this project. The client also does not have a specified amount, but the team has a goal of staying under $250.

3. Miscellaneous

a. *Standards and Specifications:*

For any application, the team will not need FDA approval or any governmental approval. The client conducting the experiment already has the necessary IACUC approval.

b. *Customer:*

The client would prefer for the device to be wirelessly actuated and dispense the euthanasia solution at a moderate pace in order to avoid rupturing a blood vessel and/or prolonging suffering. Additionally, the client would like the device to be able to euthanize two sheep either simultaneously or in rapid succession.

c. *Patient-related concerns:*

The most important part of a humane euthanasia is a quick and relatively painless death. Assuring death is very important, and if the animal doesn't die the decompression sickness, and the side effects of the injected medication cause the animal to suffer, which is contrary to the purpose of the project. Over the course of the experiment, the device will need to be removed from the chamber between trials, sterilized, reloaded with syringes filled with sodium pentobarbital, and then placed back in the hyperbaric chamber before the next test begins. Due to this expected use, old syringes need to be easily removable from the device and new syringes must be able to be reloaded with ease.

d. *Competition:*

There are similar items/patents that will compete with the design. A competing design for fluid injection in human patients was patented in the European Patent Office in 2016 [7][Appendix A]. This device injects insulin into the patient by leaving a permanent needle in the patient and using a pump to inject insulin into the patient.

Infusion pumps are pumps that are designed to inject fluid for prolonged periods of time, such as the Baxter Sigma Spectrum[9]. This device sells for north of $1000, and is designed to be extremely robust and last for decades. The pump draws fluid from a reservoir and then feeds that fluid through a tube into the patient's vein. It can vary the rate and pressure with which it pumps the solution. However, it is not rated for use in above 1.4 atmospheres of pressure, which would pose a significant problem, as this experiment is being performed at up to 5 atmospheres of pressure.

While infusion pumps are designed to pump large amounts of fluid over long periods of time, syringe pumps are designed to pump fluid out of one or more syringes mounted inside of the device. They are used primarily for research purposes, and while there are some commercially available, none meet the needs of this experiment. They are usually operated via a keypad mounted directly on the unit, which would not work for this experiment. However, the design of these would likely cause these syringe pumps to function better under the air pressure of this experiment than the infusion pump would.

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