ME 450: Design and Manufacturing III

Team 32: My Breathing Buddy

Final Report

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EXECUTIVE SUMMARY

A strong understanding and execution of breathwork is critical for wind musicians in achieving proper musical tone, volume, and expression. Currently, the process to teach musicians accurate techniques such as diaphragmatic breathing is done with physical touch, promoting unhealthy boundaries between student and teacher, and vague descriptions of how to breathe while playing instruments such as “blow” and “support.” Many musicians also have no understanding of what their lungs are physically doing when they take in a breath. The My Breathing Buddy (MBB) is a lung, rib cage, and diaphragm simulator that demonstrates breathwork to help musicians visualize and understand these necessary breathing mechanics from an anatomical perspective.

Currently, the My Breathing Buddy is manually inflated with a bulb, requiring the user’s full attention and expertise to portray certain breathing techniques. To reduce the need for users to manually inflate the MBB, we aim to design, manufacture, and evaluate an electro-mechanical actuation system to inflate and deflate the MBB to represent four different breathing techniques relevant to musicians.

Considering stakeholder interests, our team developed a list of functional requirements and engineering specifications for the MBB 3.1, as well as verification plans for each using our team’s knowledge of engineering principles and standards. We investigated prior benchmarking models, including the last iteration of this project, MBB 3.0, to determine the goal of producing one unit of the MBB 3.1, designed for small-scale production of ten to fifteen units per year, focusing on decreasing complexity, noise, and form factor.

Our team has conducted a comprehensive design generation stage, first focusing on exploring the entire design space to generate 80+ solutions. We then converged upon 5 potential designs using functional decomposition, morphological charts, and general engineering knowledge. A deeper analysis was conducted on these solutions through the use of first principles and Pugh matrices before ultimately selecting an Alpha design and modeling it in CAD.

After conducting a design review of the Alpha design with project sponsors, we developed a more detailed design focusing on our functional requirements and DFMA. We built a prototype of the design that went through a rigorous testing procedure to inform us of design changes that must be made before ultimately manufacturing the Final Build, or the MBB 3.1. This testing procedure also aimed to verify that all functional requirements have been met. A validation plan has also been developed to determine if MBB 3.1 solves the problem statement.

Following the completion of this validation plan, the Final Build has been manufactured, assembled, and presented to the stakeholders as well as a comprehensive presentation of the processes that were completed in order to make the final MBB 3.1 design possible.

ABSTRACT

The My Breathing Buddy (MBB 2.0) is a manually pumped lung, rib cage, and diaphragm simulator that demonstrates breathwork to help musicians visualize and understand breathing mechanics from an anatomical perspective. With the MBB 3.1, we aim to design, manufacture, and evaluate an electro-mechanical actuation system to inflate and deflate the MBB to represent four different breathing techniques relevant to musicians. We will produce one unit, designed for small-scale production of ten to fifteen units per year, focusing on decreasing complexity, noise, and form factor.

PROJECT INTRODUCTION AND BACKGROUND

Wind musicians require specialized breathwork to achieve proper musical tone, volume, and expression. Understanding the anatomy and mechanics of the breath is thus a crucial piece of knowledge for these musicians. The My Breathing Buddy can serve as a useful tool for teaching techniques necessary for these purposes.

Anatomy of the Lungs

Breathing is one of the most essential tasks that a human being will do in life and is the first action taken upon birth with the inhalation of air and the expansion of the lungs. The average human takes about 20,000 breaths per day and, as a result, it cannot be understated how crucial breathing is in the lives of human beings [23].

The primary function of the respiratory system is to move fresh air into the lungs while removing wasteful gasses [24]. Once in the lungs, the oxygen from the inhaled air is absorbed by alveoli into the bloodstream and carried throughout the body [8]. At the same time, carbon dioxide is removed from the blood by the alveoli and removed from the body by exhalation [8]. The diaphragm is a dome-shaped muscle that sits below your lungs and heart and is largely in part seen as the main breathing muscle of the body shown below in Figure 1 [4].

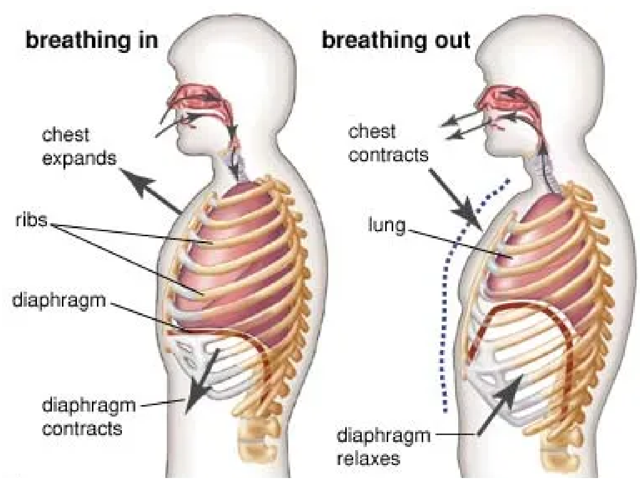


Figure 1: Depiction of diaphragm movement during inhalation and exhalation. [4]

Upon inhalation, the diaphragm will contract and flatten while, simultaneously, the chest cavity enlarges [10]. This diaphragmatic contraction creates a makeshift vacuum in which air is pulled into the lungs [25]. Upon exhalation, the diaphragm will relax and return to its natural dome-like shape as air is forced out of the lungs as shown in Figure 1. Controlling the diaphragm is an important skill to master for wind musicians and singers.

Breathwork for Musicians

Controlled breathing and proper utilization of the diaphragm are instrumental for wind musicians to achieve accurate musical tone and expression. Diaphragmatic breathing is a technique where the user consciously uses the diaphragm to take a deep breath, reaching 100% lung capacity [26]. Diaphragmatic breathing can also increase lung capacity and control over extended practice, which allows for the amount of air entering and exiting the lungs to be better regulated [26]. Regulating air flow is extremely important for wind musicians to ensure they can get a full breath quickly, exhale at a variety of rates, and conserve air capacity over the length of many verses.

Diaphragmatic breathing is generally taught through physical contact where the instructor will place their hand on the location in which the student should expand their diaphragm to show where to focus the air when inhaling [27]. This physical contact can create unhealthy boundaries where the teacher, student, or both, feel uncomfortable. From the student's perspective, they may not wish to be touched to learn to play an instrument, and from the teacher's perspective, they may be overly cautious and "self-conscious" to the point where it becomes a distraction in teaching. Also, this teaching method creates opportunities for teachers to abuse this physical contact at the expense of the student. Safe environments for both students and teachers are extremely important in the educational system so everyone can focus on their respective goals. Diaphragmatic teaching methods are also accompanied by vague terms such as "support" and "feel" which do little for students to understand how to improve, especially when most do not have a strong understanding of the anatomy of the respiratory system.

It is these gaps in traditional diaphragmatic instruction that the My Breathing Buddy (MBB) hopes to fill. Developed by Professor Amy Porter, our sponsor for this project, the My Breathing Buddy is a 3-D printed rib cage surrounding a latex lung that acts as a diaphragm simulator. Professor Porter is a Professor of Flute at the School of Music, Theatre, and Dance at the University of Michigan. She developed the MBB to educate musicians about the anatomical perspective of breathing and how to increase lung capacity and draw a full breath. She hopes to shift the status quo of music instruction from physical contact to the MBB, supporting both the education and safety of students. The second iteration, the MBB 2.0, is shown below in Figure 3.

Figure 2: My Breathing Buddy 2.0 with a front view (left) and a bottom view (right) [1].

The MBB solves the issues of physical contact between the student and instructor by allowing instructors to show how the body works without physically touching the student, promoting healthy boundaries. The MBB also provides the student with an accurate anatomical demonstration of how the diaphragm reacts under certain inhalation and exhalation stresses. The MBB 2.0 expands and contracts when manually inflated with a hand bulb, mirroring the inhalation and exhalation of a musician, which is shown below in Figure 4.

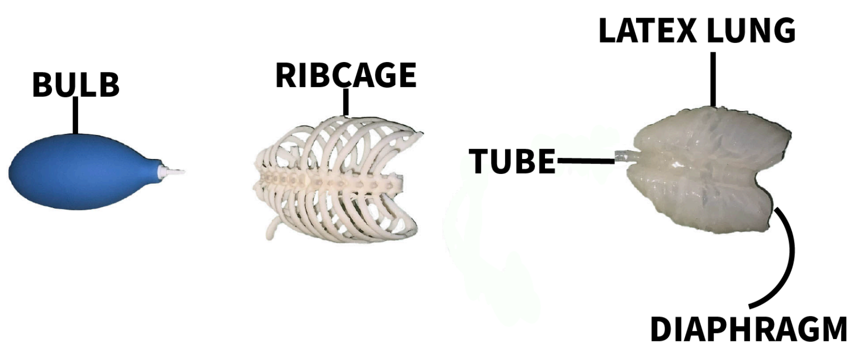


Figure 3: Breakdown of MBB 2.0 components [2].

The user can inflate and deflate the MBB at different rates by controlling the air bulb to model different breathing techniques. The need for manual input from the user to operate the MBB 2.0 means that to effectively demonstrate diaphragmatic breathing, both hands must be used: one hand must hold the product and the other must squeeze the bulb to perform the simulated breathing motion.

After MBB 2.0, version 3.0 was created to try and rectify some of the shortcomings of the previous iteration. The main goal of MBB 3.0 was to be hands-free, so instead of using the air bulb requiring manual user input, the lungs were to be inflated and deflated through an automated system. MBB 3.0 was developed by a previous ME 450 team and they chose to inflate it by a motor and air valve as shown in Figure 5.

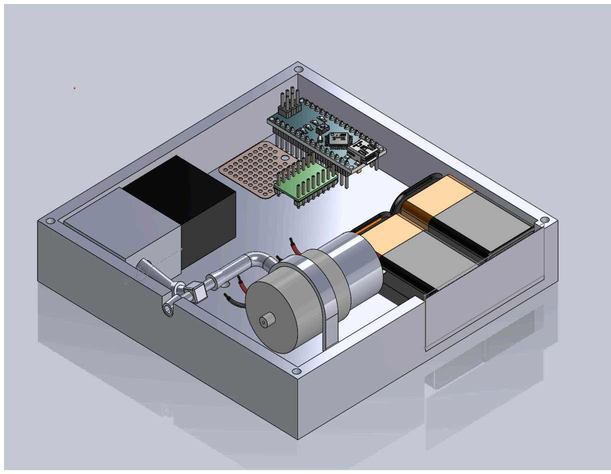


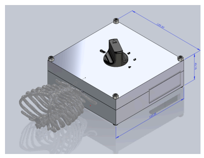
Figure 4: MBB 3.0 developed by a previous ME 450 team. The lungs were inflated using an air pump and a controllable valve [19].

While they succeeded in making the MBB hands-free, there were additional shortcomings that were overlooked when creating this iteration. The air pump system and valve system they chose to use were extremely noisy, which distracted from the teaching lessons. The MBB 3.0 was powered using a wall socket, which greatly reduced the spaces in which it could be used. Furthermore, the previous team chose to create breathing modes based on breathing rates. Breathing volume is a more important factor in playing wind instruments than the breathing rate, so the MBB 3.0 struggled to provide adequate lessons. Therefore, our sponsor Professor Porter has asked us to create MBB 3.1, a complete redesign of MBB 3.0. A successful version will be an electro-mechanically actuated system to inflate and deflate the MBB to represent four different breathing techniques relevant to musicians.

Benchmarking

To further understand the scope of our project, we compared the previous iteration of the automated My Breathing Buddy, MBB 3.0, two spirometers, an electric air pump for inflatable objects, and a manual bike pump. Spirometers are devices that measure exhalation force to estimate the amount of air in the lungs [5]. Although not directly used as a teaching device for musicians, spirometers do provide insight into lung capacity and given there are no devices similar to the MBB, spirometers can be used as a comparison. Similarly, air pumps and bike pumps are clearly not teaching devices for musicians, but they serve as a comparison as other devices that can inflate objects at different rates using different mechanisms. This comparison will be beneficial in understanding the variety of methods we could use to inflate the latex lungs of the MBB. The evaluation is shown below in Table 1.

Table 1: Benchmarking of five devices [6][12][45][46]

Device					
Cost	$60	$19.99	$2175	$20.99	$44.99
Functionality	Teaches breathwork through demonstration	Teaches breathwork through measurement	Teaches breathwork through measurement	Inflates and deflates objects	Inflates bike tires
Noise	65 dB	55 dB	50 dB	80 dB	30 dB
Portability	13.72cm x 13.10cm x 4.45cm	39.62cm x 36.32cm x 19.05cm	15.8cm x 8.3cm x 4.3cm	33.78cm x 27.94cm x 30.48cm	72.39cm x 26.67cm x 10.16cm
Fluid Movement	Air pump	Blows air via mouth	Blows air via mouth	Air pump	Volume change

The first device used in benchmarking was the MBB 3.0. The MBB 3.0 was developed by a previous ME 450 team for Professor Porter, but was deemed too noisy, not portable because it was powered using a wall socket, and of poor build quality. The MBB 3.0 is made out of a 3D-printed case fastened in the corners with a large dial on its top surface to control the specific breathing mode. 65 dB is about the noise level of a busy coffee shop, which is a distracting level when teaching music. This noise came from the air pump, which inflated and deflated the latex lungs, taking in air from the atmosphere and controlling the inflation and deflation rates using a valve. An air pump is an extremely efficient and fast method to inflate the lungs, and the inflation method is a consideration we will have to make when developing requirements and generating concepts. After discussions with our sponsor, it was deemed that a manufacturing cost of $60 is too expensive for mass production when it comes to commercialization. The main cost came from the air pump and solenoid valve, so avoiding these components in our design would reduce cost. Our sponsor also mentioned that the dimensions of the MBB 3.0 were too large, reducing its portability. However, the function of the device is to teach breathwork through demonstration, which is still the goal of MBB 3.1 and will be implemented in our design.

The second device used in this comparison was an incentive spirometer shown in the second column of Table 1 [12]. Incentive spirometry involves blowing into a tube and using a visual incentive to exhale your "best" breath, in this case by keeping the balls raised for as long as possible [6]. Our sponsor wishes for the MBB 3.1 to require no additional user input after turning the device on and selecting the operating mode, so blowing air into the latex lungs is not a viable fluid movement. This device teaches lung capacity through measurement, which is not the goal of MBB 3.1. Incentive spirometers are simple plastic devices with manual timing and calculation of lung capacity required based on the model [12]. This is reflected in the price, with it costing $19.99. It also is quieter than the MBB 3.0, with a noise level of 55 dB. This device is one of the largest ones benchmarked, and would not meet the dimensional standards described to us by our sponsor.

The next device is an electromechanical spirometer, located in the middle column, which measures the exhalation force and provides an estimated lung capacity [5]. Because it performs the calculations automatically, it is a much more expensive device, costing $2175. Like the incentive spirometer, its functionality is to teach breathwork through measurement, which does not meet the problem definition of this project. Furthermore, the user blows into the device to operate it, which does not meet the usability standards described to us by our sponsor. However, it is a quieter device at 50 dB, the same as a quiet conversation [7], which would not be a distraction while teaching. This electromechanical spirometer has similar dimensions to the MBB 3.0, which was previously mentioned to be too large.

The fourth device compared in this benchmarking is an air pump for inflating objects such as air mattresses and pool floats. Air pumps consist of a motorized fan that pulls air from the atmosphere into the object it is inflating [49]. Air pumps for this application are relatively cheap, at $20.99. Like the air pump used in MBB 3.0, it is extremely loud at 80 dB, which is comparable to the noise of a garbage disposal and is a distracting level in a teaching environment. Once again, an air pump is a workable solution to inflate the latex lungs, but further testing will need to be done to determine if it is the optimal solution for the MBB 3.1. Finally, this device is one of the largest ones benchmarked, and would not meet the dimensional standards described to us by our sponsor.

The final device benchmarked is a manual bike pump. Manual bike pumps work by taking in air when a plunger is pulled upwards and forcing it into the tire when the plunger is pushed downwards [50]. This process can be viewed as a change in volume to inflate an object which tends to be a slower but quieter method to inflate an object compared to an electric air pump. The noise level for a typical bike pump is 30 dB, which is less than that of a quiet conversation and is therefore not a distraction in a teaching environment. Bike pumps are in the middle range of prices for objects compared in this benchmarking exercise and are significantly larger than the rest of the devices, not meeting the dimensional standards of our sponsor.

This benchmarking process helped us to explore functional requirements that will be explained further in the report. We hope to have the MBB 3.1 portray the same demonstrative functionality as the MBB 3.0 to be an effective tool for teaching breathwork. The different fluid movements helped us to think about how we plan to define inflation rates and volumes in regards to the operating modes of the MBB 3.1. Ideally, we will be able to create a prototype for this device at a similar price to the incentive spirometer such that the MBB is commercially viable. We aim to create a device that is at the same noise level, if not lower, as the manual bike pump so the MBB does not take away from a music lesson. Finally, we have many examples of devices that are too large and can work to develop a case smaller in size.

DESIGN PROCESS

After familiarizing ourselves with the project, we evaluated multiple design processes before ultimately adopting one best suited to our anticipated challenges. We opted to follow a design process described below in Figure 5.

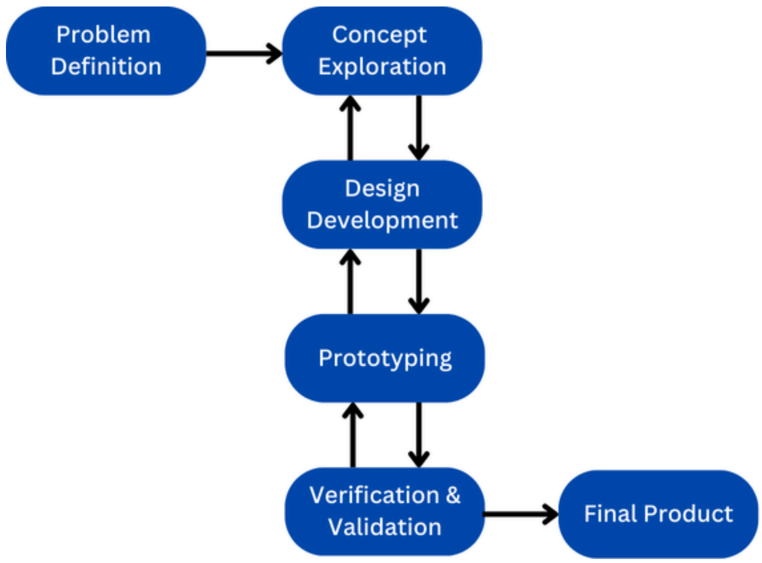


Figure 5: Planned design model for ME 450 Team 32.

This design process emphasizes iteration, which we place high value on for this project. We have built in significant time through the design process for iteration, specifically in the "prototyping" block because we anticipate multiple rounds of prototyping for optimizing our electrical hardware, software, and noise reduction plan.

When developing this design process, we referenced Models of designing, by Wynn and Clarkson [28]. We drew inspiration from problem-oriented models as a strong understanding of the problem allows us to structure requirements and specifications systematically. Specifically, we modeled our design process after the one developed by Ehrlenspeil shown in Figure 6.

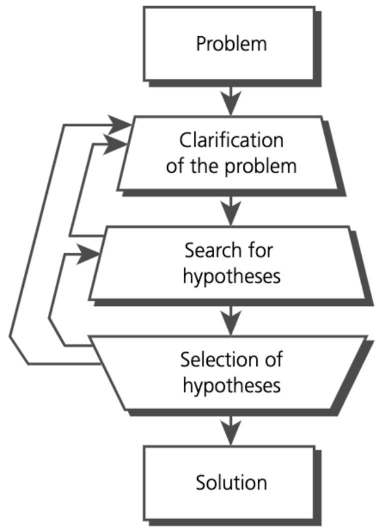


Figure 6: Problem-oriented procedural cycle for systems analysis [28].

This model highlights iteration, specifically iterating amongst generated concepts developed in the "Search for hypotheses" phase based on analysis conducted in the "Selection of hypotheses" phase. We also considered the iterative model developed by Evans, which combines stage and activity models shown in Figure 7.

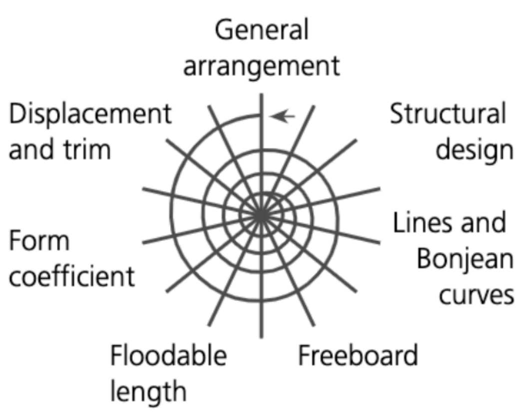


Figure 7: Evan's design spiral in reference to building a ship [28].

Although this model aligns with our interest in iteration, we believe a linear model is better suited for our project because we do not plan to update our problem definition once it has been developed.

The design model we opted to use is also different from the ME 450 design model shown in Figure 8.

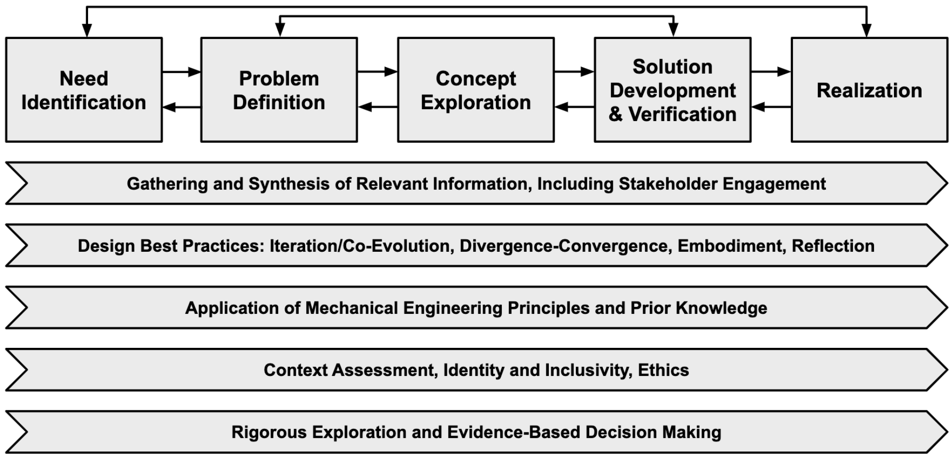


Figure 8: ME 450 design process framework [29].

Our model places more emphasis on the iteration between "Concept Generation" and "Solution Development & Verification". We specifically have a block for prototyping where the majority of the process will be iterative to find the optimal solution. Because this is a complete redesign from the previous semester's solution, we want to consider and test all viable solutions to prevent our sponsor from having yet another prototype that will be redesigned the following year.

DESIGN CONTEXT

Throughout the duration of this project, it is important to realize that our biases, stakeholders, power dynamics, and contextual factors impact our decisions. There is always a broader context that influences the design process and engineers' choices, so being aware of it in our ME 450 project will help us to practice inclusive design.

Stakeholder Analysis

To determine the key individuals, stakeholder groups, and organizations who may be impacted by our project, we developed a stakeholder and ecosystem map. The stakeholders were categorized into primary, secondary, and tertiary levels depending on their influence and were further grouped according to the role they play within our project as shown in Figure 9.

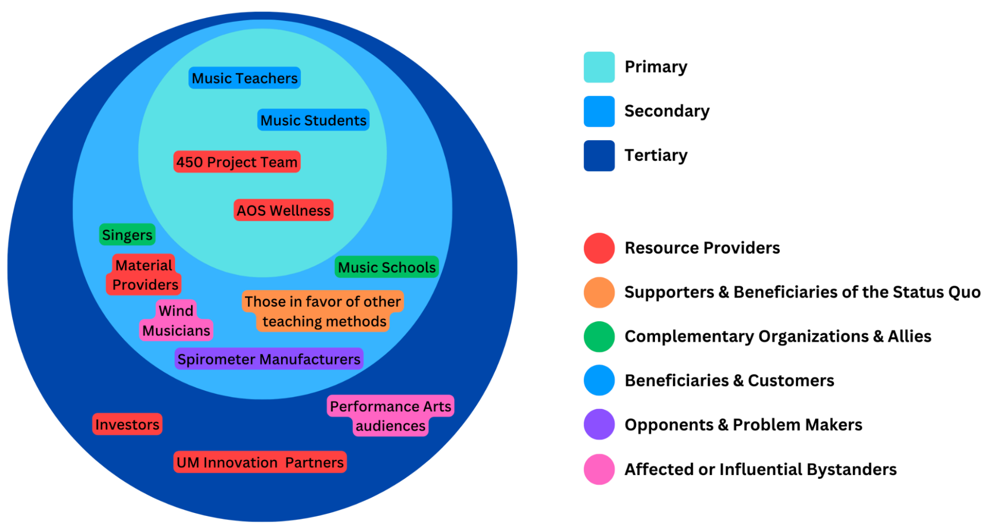


Figure 9: Blended Stakeholder and Ecosystem Map.

Primary stakeholders refer to those whose lives or work are directly impacted by the problem and or the development of a solution which includes AOS Wellness, our ME 450 team, music teachers, and music students. AOS Wellness is the company that our sponsor, Professor Amy Porter, created to develop and sell the MBB, so the success of this project directly impacts the success of AOS Wellness. AOS Wellness is also the main resource provider for this project as they provided the problem statement and a list of requirements for us to meet. The main beneficiaries and customers of this project are music teachers and music students. Music teachers are the main users as they are the ones who utilize the MBB as a teaching device and music students are the main beneficiary as they are the ones who will be learning from the MBB. Music breathwork is generally taught using physical contact where teachers place their hands on the students to show where and how their breath is stored, creating a potentially dangerous power dynamic between students and teachers. The main social impact driving this project is that the

MBB provides touchless teaching by showing where and how the breath is stored by demonstration instead of physical contact, promoting healthy boundaries between teachers and students. Our sponsor believes this social impact goes hand in hand with the educational impact of the MBB as she hopes to redefine all aspects of teaching breathwork, not just the educational gains of the student. The priorities of these impacts align with the list of functional requirements and engineering specifications our team has developed and therefore will positively support the social implications of this project.

Secondary stakeholders refer to those who are part of the problem context but may not experience the problem themselves and or may not be directly impacted by a solution. For this project, the secondary stakeholders consist of material providers, singers, music schools, wind musicians, those in favor of other teaching methods, and spirometer manufacturers. Material providers will ultimately help create the solution, but are not impacted by it, and are therefore secondary stakeholders. They are also categorized as a resource provider because they represent those who will supply us with the actuation, transmission, and electrical systems and other components for our final design. Singers represent a complimentary ally to the MBB because although the current scope of our project has the end user being those learning to play a wind instrument, singers also require a strong understanding of breathwork and can benefit from the teachings of the MBB. Music schools also represent a complimentary organization because music schools can supplement their curriculums with teaching programs built around the MBB. Those in favor of other teaching methods were categorized as supporters of the status quo because they may be music professionals who believe that physical contact is an important part of the teaching process or are teachers who wish to abuse the aforementioned power dynamic with their students. This group would be negatively impacted by the success of the MBB because their preferred method of teaching would no longer be the status quo. Another group that may be negatively affected by the success of the MBB is spirometer manufacturers. Spirometers are another device that teaches breathwork and lung capacity but through measurement instead of demonstration. The success of the MBB would pull market shares away from them, which is why they were categorized as opponents of the MBB. They also are a secondary stakeholder because they were used in the benchmarking process as they are an indirect competitor to the MBB.

The final stakeholder category is tertiary, which are those who are outside of the immediate problem context but may have the ability to influence the success or failure of a potential solution. They consist of investors, the UM Innovation Partners, and performance art audiences. Investors are generally not impacted by the solution of the design process, but their capital can impact its success, which is why they are tertiary stakeholders and categorized as resource providers. Professor Porter has partnered with UM Innovation Partners who are a specialized investor providing not only capital but also access to entrepreneurial advice and events for startups. They are also categorized as resource providers because they are providing our sponsor with access to customers and other investors. Finally, performance arts audiences are the last tertiary stakeholder because they influence the success of musicians and if they support musicians who use the MBB, then they can also influence the success of the MBB. For this same reason, they were further categorized as influential bystanders; they have the ability to influence the success of the MBB by supporting the musicians who use it.

Contextual Considerations

We aim to design with sustainability in mind. During the prototyping phase, all 3D printing will be done in PLA, which is considered a sustainable material because it is renewable and biodegradable. We will also make use of all previously purchased materials and hardware from last semester's iteration of the project before purchasing and consuming more materials. However, we do plan to include a printed circuit board (PCB) within our design to control the volume inflation of the MBB. The disposal of PCBs comes with risks because they can release harmful pollutants into the soil and atmosphere and are not recyclable. Another less sustainable aspect of our design is the use of batteries to power the actuation system of the MBB 3.1. We could use rechargeable batteries or lithium batteries instead of disposable batteries to increase the sustainability of our design. However, this would increase the cost of manufacturing as these batteries tend to be more expensive.

As mentioned above, the MBB has the opportunity to create healthy boundaries between teachers and students by shifting the teaching process away from physical contact. Creating a safe environment for students to learn music has massive social implications and one that ethically we as the design team should focus on. Therefore, an accurate representation of the lungs during different breathing techniques is imperative not only to meet that functional requirement but also to ensure a teacher does not need to use physical contact to display that method. Considering the ethical consequences of your design choices is an important component of the engineering design process, so we plan to review our work internally and with our sponsors to ensure we meet these standards.

The main power dynamic we face is with our project sponsor. As the design team, we choose how often we meet with our sponsor and ultimately make the final design decisions. This is a form of visible power. It can be reduced by keeping an open line of communication with our sponsor, meeting with them biweekly, and acknowledging that our identities impact our design choices. One invisible form of power we have over the end users is our background as engineers. None of us have a musical background, so we are treating the solution to this problem as an engineering one, not as a musical one. Therefore, we could potentially be skewing the views of the end-users to see the MBB more as a technological tool than a musical one. To mitigate this, creating a focus group with students and music teachers could provide insight into how they view the MBB and its functionality, making the design process more inclusive.

USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Considering this is the second iteration of a previous ME 450 project, we first talked with Professor Porter about issues she had with the previous solution to influence any requirements our design has. The main changes she wanted were a decrease in the noise created by the design, the size of the design, and its cost [18]. We also discussed that the modes of operation should be changed as the previous idea of various breathing rates wasn't beneficial to the application of the MBB. We used the previous list of requirements and specifications as our baseline and checked with our sponsor to ensure that these other requirements were still aligned with what she desired. We also looked at the previous team's research to verify their specifications matched the requirements effectively. The requirements were categorized as "High", "Medium", or "Low", to distinguish the priority in meeting these requirements. Requirements categorized as "High" must be met because they are critical to the functionality of the MBB 3.1, or are heavily requested by our sponsors. Requirements categorized as "Medium" must be met, but the device's functionality does not depend on these requirements. Finally, if a requirement is categorized as "Low", it is a requirement that is nice to have, but not meeting these requirements would not cause the project to be considered unsuccessful. Table 2 below shows the current list of requirements and their associated specifications.

Table 2: List of design requirements and their associated specifications.

Priority	Design Requirement	Design Specification
High	Operate at Multiple Breathing Modes	4 Simulated Respiration Settings: Deep Breathing - Full inflation in ≤ 2 seconds, deflate in 3-4 seconds Piggyback Breaths - Full inflation in ≤ 3 seconds in 4 partial inflations, deflate in ≤ 2 seconds Articulation Mode - Full inflation in ≤ 2 seconds, with 4-5 rapid deflations lasting ≤ 1 second Regular Breathing - Fill to 1/2 max capacity, breathing at a rate of 12-16 breaths per minute
High	Operate at an Appropriate Noise Level	≤ 50 dB at all operating conditions
High	Be Portable	Fits in a case with a volume ≤ 1400 cm^3 Weighs ≤ 1 kg with case
High	Be Internally Powered	Have the power source be contained within the component box.
High	Be Non-Invasive to MBB 2.0	No design changes to MBB 2.0 MBB 3.1 integrates seamlessly
High	Be Safe for Users	Meets relevant requirements under BS EN 62368-1 for electrical safety
High	Automatically Operated	Operates at a breathing mode selected by the user without the need for a manual pump
Medium	Be Affordable	≤ $40 for commercial product
Medium	Be Robust	Fully functional after 3 consecutive 76 cm drop tests, each landing on different faces
Medium	Convenient Profile Interface	Baseline: ≤ 25mm wide and 15mm tall mechanical interface Ideal: Remote interface on a device such as a smartphone
Medium	Designed for Manufacturability	Design for production of 10 units a year. Minimize complexity, and amount of parts, and use off-the-shelf components as much as possible.
Low	Be Presentable	Scores > 3.5 on sponsor-determined presentability Likert scale.
Low	Volume Inflation Indication	An indicator on the MBB that shows shallow (0-14.75 mL), medium (14.75-29.5 mL), and full (29.5 - 44.25 mL) breaths with 3 distinct colors.

Operate at Multiple Breathing Modes

This requirement deals with the multiple operating modes of the MBB. After watching videos that Professor Porter has uploaded of her teaching music students with the MBB and her recommendations to teachers on what they can teach with the MBB, we determined four main modes that would be beneficial to this teaching style [2]. The main purpose of the MBB is to show music students who may not have the best anatomical understanding of the respiratory system the diaphragm movement during breathing, without physical contact [1]. Considering this, it would be beneficial to show different breathing techniques that are commonly used in music or that effectively show a relation between the diaphragm and the breath taken. This requirement was listed as a high priority because it represents the main functionality of the MBB 3.1. From these considerations, we came up with four breathing modes, Deep Breathing, Staggered Breaths, Articulation, and Regular Breathing.

Deep Breaths are extremely important to musicians as they need to be able to take a full breath and play long measures of music. This model serves as a way to show students what a deep breath looks like in terms of the diaphragm to help them visualize this in their bodies.

The Piggyback breaths come directly from a method of teaching that Professor Porter recommends [2]. The purpose of this mode is to help teach students that the amount the diaphragm has dropped is directly dependent on how much breath has been taken [10]. The diaphragm partially drops each breath when taking a series of shallow breaths, dropping further as long as no breath is exhaled.

The third mode is Articulation, which is a technique that musicians commonly use to control how notes connect [17]. This mode shows how your diaphragm would move in a case of articulation, or rapid puffs of breath. During these rapid puffs, the diaphragm drops fast with each interval. The specific breath timings were chosen after discussing with Professor Porter what each interval might look like and our attempts to recreate them using MBB 2.0. The difference in exhalation time for Piggyback Breaths and Deep Breathing come from wanting to show a slow exhalation and fast exhalation.

The final breathing mode is Regular Breathing, which relates to everyone, not just musicians. This serves to show students what normal breathing may look like and how that can differ to the breaths taken when playing music. The rate of breathing was chosen to model the average respiratory rate of an adult, which is 12-16 breaths per minute [8]. In the context of inhalation volume, during regular breathing, the average adult inhales about 450 milliliters of air [13], while the max lung capacity on average is about 6 liters [14]. Using this relation would mean that our model's regular breathing is 1/12 of the max capacity of the lung. However, this would barely cause any movement in the MBB and wouldn't serve to show anything to students, so we decided to exaggerate this volume and fill it to 1/2 the max capacity of the lung.

To test whether this specification is met, we will use a stopwatch to time the inhalation and exhalation times for the first 3 breathing modes. For the final mode, we plan to use our automation device to inflate a balloon with air and submerge it in water to measure the volume by displacement. Using a balloon is preferred to the MBB to not risk ripping the latex lung or exposing it to water. We also plan to use a timer and count the number of breaths that occur in one minute to ensure we have the appropriate respiratory rate.

Operate at an Appropriate Noise Level

One of the major issues of MBB 3.0 was how loud it was when operating. Our sponsor listed this as one of her most important requirements to improve upon in MBB 3.1, therefore it is considered high priority. The previous team had set a maximum noise limit of 65 decibels, but it proved to be too loud. We researched different sound levels associated with the decibel limit and found that 50 dB is similar to the sound of a quiet conversation [7]. This would be an adequate noise level for a teaching environment as it would be quieter than conversations between a student and teacher and wouldn't be too distracting. Professor Porter agreed that this is an acceptable noise limit.

To verify this requirement, we will use a decibel meter to measure the maximum decibels reached by each operating mode and confirm it is less than 50 decibels.

Be Portable

Our sponsor also revealed that she desired the automated portion of MBB 3.1 to have a smaller form factor than the one presented in MBB 3.0, making this a high priority requirement. At the end of the semester, the previous team 3D printed an additional smaller case that Professor Porter found suitable [18]. The dimensions of this case were 10.16cm x 10.16cm x 3.5cm. This design assumed the components that MBB 3.0 utilized, specifically an air pump, valve, and no internal batteries. Given this is a redesign, we do not plan to implement this exact design and the dimensions of the case for the MBB 3.1 changed. We showed the dimensions of the new case to our sponsor, who deemed it acceptable. Furthermore, we changed the dimensional requirement to be volume based instead of three length dimensions, to increase our freedom in determining the dimensions. This new requirement is a case with a total volume less than or equal to 800 cm^3. We left the weight limit of 1 kg the same as this is still aligned with our sponsor's requirements.

To verify that we have met this requirement we will use calipers to measure the final case dimensions and a scale to weigh the device.

Be Internally Powered

MBB 3.0 was powered by a wall socket, which limited the environments in which it could be used. To overcome this problem, we aim for the power source to be contained within the components box. This phrasing was chosen to not limit our selection of a power source but still achieve Professor Porter's desire to remove an external power source connection. Because our sponsor specifically mentioned their desire for this requirement and that it would change the environmental usability of the MBB 3.1, this requirement was deemed high priority.

To verify that we meet this requirement we must make sure there is no connection to an external power source while it's operating and we can operate the device in all four modes.

Be Non-Invasive to MBB 2.0

Since the initial latex lung and rib cage have been designed and a manufacturer has already been selected to develop it, our sponsor would like for the MBB 3.1 to not impact its design. She also wishes for a simple transition between using MBB 3.1 with a hand bulb if desired. For these two reasons, we opted to make this a high priority requirement.

Verification of this requirement is trivial, because as long as we do not alter the initial design of the latex lung we have achieved this requirement. Our design will take place solely adding onto the latex lung.

Be Safe for Users

This product will have some electrical components and wiring and therefore it is imperative to ensure it will not be a danger to consumers. The previous design team listed IEC 60065 clauses 8 and 9 as their safety specification, but upon researching this standard we found it has been superseded by IEC 62368-1. Through the University of Michigan we had access to BSOL standards and found the equivalent standard BS EN IEC 62368-1. We must adhere to clause 5 which gives standards for the prevention of electrically-caused injury. This includes the use of insulation to prevent contact depending on the level of power source that is used in an electrical device such as this, to mitigate the danger of electrical shock [20]. Given that user safety is stated within the first canon of the ASME Code of Ethics, being safe for users is a high priority requirement [51].

As per the standard, to verify this requirement, we must ensure that there is insulating material preventing bare contact from a regular person and parts at ES2 energy levels except for pins of the connectors, and any bare parts at ES3 [20]. We will also perform a grounding test with a multimeter to ensure that there is a solid connection to ground.

Automatically Operated

To achieve the aforementioned modes, it can be difficult to stay consistent when relying on human input to achieve them. It is also desired to have a design that doesn't require constant manual operation so students can use their hands to hold their instruments but still activate the MBB. This leads to a specification stating that the MBB should operate at the breathing mode chosen by the user with zero additional input required after setup, making it of high priority because this relates to its functionality.

If the design requires more input to function other than the initial choice of setting and then the shutting off of the design this requirement has not been met, otherwise we have met this requirement.

Be Affordable

Our sponsor conducted focus groups amongst potential customers and determined a price reduction from $200 to $80 was necessary to make the product commercially viable. She requested that the prototype be under $40 to provide an adequate profit margin [18]. Because our sponsor asked for this requirement, but it does not impact the functionality of the design, it was given a medium priority.

Since we are given a set limit for the price of our prototype as long as the parts of our prototype are under the set limit then we have achieved this requirement.

Be Robust

During the use of the product, it is likely to be placed on a desk or table. Therefore our design should be able to remain functional after a drop from such a height, as this could be a common load case that the MBB faces. The average height of a desk is 76 cm [21], so we decided that our device should stay functional after 3 consecutive drops from this height, on each face. This way we can ensure that our design will not cease functionality from a probable accident in its use case. Designing a robust case does not specifically change the functionality of the case, but dropping it could, so we made this a medium priority requirement.

The specification indicates the type of test we would conduct to ensure the robustness of our design, being a drop from 76 cm on each face. We can also further verify this before the drop using stress calculations on the different parts within our design, this may be more complex however, this could help ensure the likelihood of our design passing this test.

Convenient Profile Interface

Our sponsor found the interface on MBB 3.0 to be too large. Based on the dimensions of the dial used in MBB 3.0, we set the specification for our interface to be less than or equal to 2.5 cm wide and 1.5 cm tall. Professor Porter also showed interest in a remote interface on a device such as a smartphone, however, she indicated this wasn’t something that she desired for right now. Therefore we set having a mechanical interface following those dimensions as a baseline that we must achieve, but if possible we would try to have a remote interface on a smartphone. Because this requirement does not directly impact the functionality of the design and the deliverable for is still undetermined, it was listed as a medium priority.

The verification of this requirement is a measurement of the dimensions of the mechanical interface. However, in the case that we are able to implement the remote interface, the existence of a connection method from a device such as a smartphone to the MBB must be present. This entails having a software-based user interface on the device with options to start each operating mode and stop the MBB.

Designed for Manufacturability

While we are only producing one unit prototype for this project, we are aiming for our design to be manufactured at a scale of 10 units per year. This means we will aim to maximize the use of off-the-shelf products, minimize the complexity of novel components, and minimize the number of parts used in the design. This requirement must be met, but the device's functionality does not depend on it, so it is a medium priority.

We will discuss with Professor Porter and manufacturers to ensure that this device can be manufactured within the cost specified in requirement 7 at the scale of 10 units per year. We will collaborate with an IOE student that Professor Porter has hired through the Undergraduate Research Opportunity Program (UROP) to help determine effective sourcing of our materials.

Be Presentable

To help market the product to future customers, our sponsor would like the design to be presentable. How something looks can be very subjective, so quantifying aesthetics is difficult. After conducting research, we determined that a Likert scale is commonly used by researchers and educators to measure less concrete variables [22]. Therefore, we opted to use a sponsor-determined 5-point Likert scale on presentability with a target score of 3.5 or higher. Although we aim to create a presentable product in this semester, it does not impact the functionality of the MBB 3.1 and could be easily fixed, so this requirement was listed as a low priority.

After determining a Likert scale with sponsor-approved questions, we will send this out to our sponsors to judge themselves, as well as several music students to gauge the consumer base. If the average score is above our set score of 3.5, we have met this requirement.

Volume Inflation Indication

The final functional requirement asked for by our sponsor was a visual indication of the volume inflation of the lungs. This would show 3 different colors representing shallow, medium, and full breaths done during use of the MBB 3.0. The previous team had done tests with a syringe to determine the volume of air that corresponds to a full breath. From their data we saw that the max inflation corresponded to 44.25 mL of air [19]. Dividing the max capacity of the lung by 3 we can achieve ranges for the volume of air for each of these breath levels, of 0-14.75 mL, 14.75-29.5 mL, and 29.5 - 44.25 mL, for shallow, medium, and full breaths respectively. Although our sponsor asked for this, they made it clear that it is something that it is nice to have instead of a requirement.

To verify this requirement a temporary testing mode will be made, where the MBB is inflated to each of these levels. We will test that the indicator correctly portrays the volume within the MBB for a known amount of air by utilizing a syringe.

CONCEPT GENERATION & SELECTION PROCESS

We began our concept generation process by having each team member complete the ME 450 Concept Exploration Learning Block, where we each generated 20 unique concepts on our own. During this process, many of us used the tools gathered from the learning block, such as design heuristics and morphological charts, to aid in divergent thinking and generate novel ideas. Some of our earliest concepts are shown below in Figure 10.

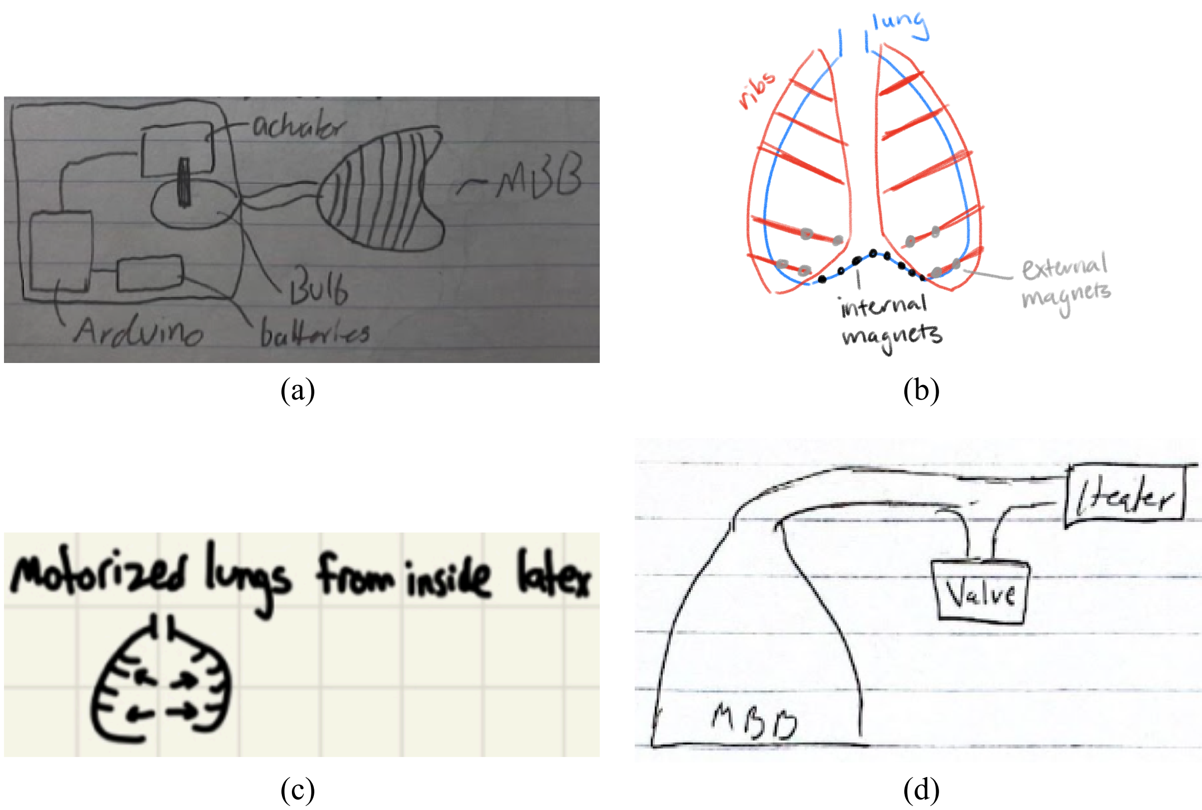


Figure 10: Examples of initial concepts developed by the team. (a) Actuator pushes on bulb to inflate the MBB. (b) Magnets are used to control the position of the diaphragm of the MBB. (c) Motor actuates retractable pushers on the inside of the lung. (d) Heater is used to expand air and inflate the lung.

Having completed the learning block, we then came together with our collective 80 concepts and began sorting and organizing them into identifiable categories. We realized that our concepts could generally be decomposed into four subfunctions: air storage, fluid movement, actuation, and transmission. Air storage refers to where the air that will inflate the lung comes from. Fluid movement refers to how air will be moved in and out of the lung. Actuation refers to the method in which the fluid movement will be actuated. Transmission refers to the smaller components necessary to translate the actuation into movement. Essentially, the actuation and transmission power the fluid movement, which draws air from the air storage. Figure 11 below illustrates how these subfunctions operate together to inflate and deflate the lung of the MBB.

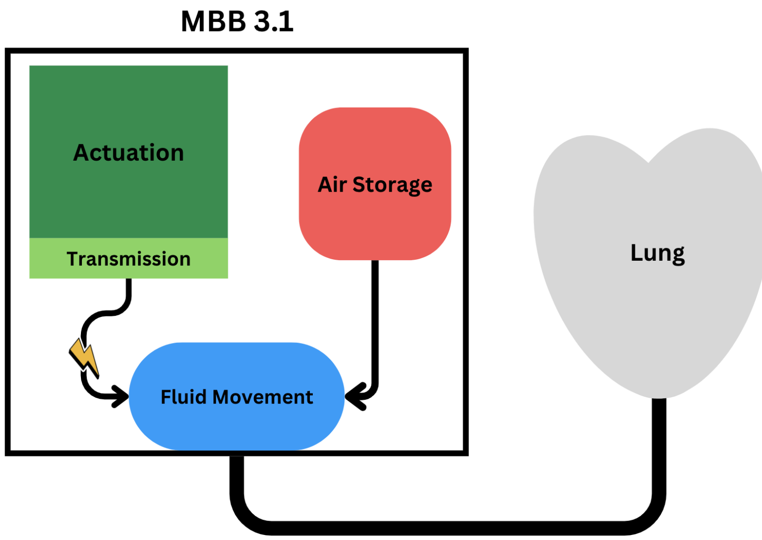


Figure 11: Functional decomposition diagram of MBB 3.1.

Now understanding the different subfunctions involved in the project, we gathered together and used brainwriting to come up with a list of ideas to accomplish each subfunction, building off of each other's ideas in the process to come up with new ones. The long lists of ideas for each subfunction are shown below in Figure 12. However, with so many ideas generated, we needed to reduce the number of ideas to be able to narrow our focus onto a smaller set of concepts. To do this, we considered the main requirements of achieving the breathing modes, size, and cost, and used our engineering intuition that we have developed to quickly eliminate ideas that were deemed not practical or feasible. For example, pressurized canisters were eliminated from air storage because we would not want to have a limited supply of air that would have to be replaced, and hydrogen gas generators were eliminated from fluid movement because it is simply not feasible. Some ideas were very similar, and in these cases the one we suspected would perform worse was removed. In the end, we narrowed the options down to the top three for each sub function, which are highlighted in red in Figure 12.

Air Storage	Fluid Movement	Actuation System	Transmission System
Balloon	Electric fan	DC motor	Rack and pinion
Plastic bag	Air Pump	Stepper motor	Belt and pulley
Pressurized canister	Water gun but for air	Hydraulics	Chain and Sprocket
Air compressor	Chemical reaction	Piezoelectric motor	Lead Screw
Bellows/Accordion	Vacuum	Electromagnetism	Planetary gears
Air cylinder	Leaf blower	Linear	Radial gears
Air bladder	Hydrogen gas generator	Pneumatics	4-bar linkage
Rigid container	Jet engine exhaust	Thermal	Crank-Shaft
Bulb	Volume & pressure changes	Chemical	
Atmosphere	Heat to expand/contract air	Piston/Cylinder	
Coiled tube			
Origami system			
Syringe			

Figure 12: Table of the different ideas generated and the 3 ideas in each function sub-system that were chosen, highlighted in red.

Using the top three options for each subfunction, we created a morphological chart to make the process of generating new concepts more efficient, shown in Figure 13 below.

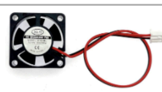
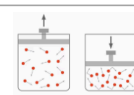
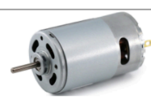
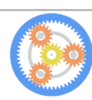
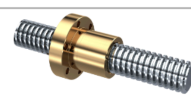
Air Storage	 Bellow [30]	 Syringe [31]	 Atmosphere [32]
Fluid Movement	 Electric Fan [33]	 Air Pump [34]	 Volume/Pressure Change [35]
Actuation System	 DC Motor [36]	 Linear Actuator [43]	 Pneumatics [38]
Transmission System	 Planetary Gears [39]	 Lead Screw [40]	 Rack and Pinion [41]

Figure 13: Morphological chart.

If one option from each sub-function within the morphological chart were selected to be put into a single concept, there would be 81 potential concepts from all of the different combinations. Knowing that 81 was too high a number for the team to be able to evaluate properly, we decided to eliminate some options in order to prune branches and dwindle down the total number of potential concepts. Specifically, Electric Fan, Pneumatics, and Planetary Gears were deemed reasonable to eliminate. Electric Fan was eliminated because an example that fit our form factor could only move air at 2.83 m/s which is not enough to create the pressure required to inflate the lung (see Appendix for calculations). Planetary Gears were eliminated because they struggle to apply linear motion, which the Bellow and Syringe require. Pneumatics are too expensive and will not fit our form factor, so they were eliminated as well.

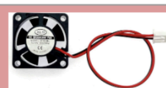
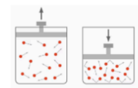
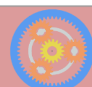
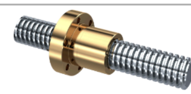
Air Storage	 Bellow [30]	 Syringe [31]	 Atmosphere [32]
Fluid Movement	 Electric Fan [33]	 Air Pump [34]	 Volume/Pressure Change [35]
Actuation System	 DC Motor [36]	 Linear Actuator [43]	 Pneumatics [38]
Transmission System	 Planetary Gears [39]	 Lead Screw [40]	 Rack and Pinion [41]

Figure 14: Pruned morphological chart.

The pruned morphological chart shown above in Figure 14 now lends itself to 24 potential concepts, which is much more feasible than the previous 81. However, not all options from one sub function are compatible with all options from another. For example, Bellows and Syringe are not compatible with Air Pump, and Atmosphere is not compatible with Volume/Pressure Change. Also, we noted that some of the Air Storage options, specifically Bellow and Syringe could also count for Fluid Movement depending on the configuration of the concept. Understanding these relationships and using our engineering intuition, we moved forward by creating five viable and evaluable concepts, shown below in Figure 15 and Table 3.

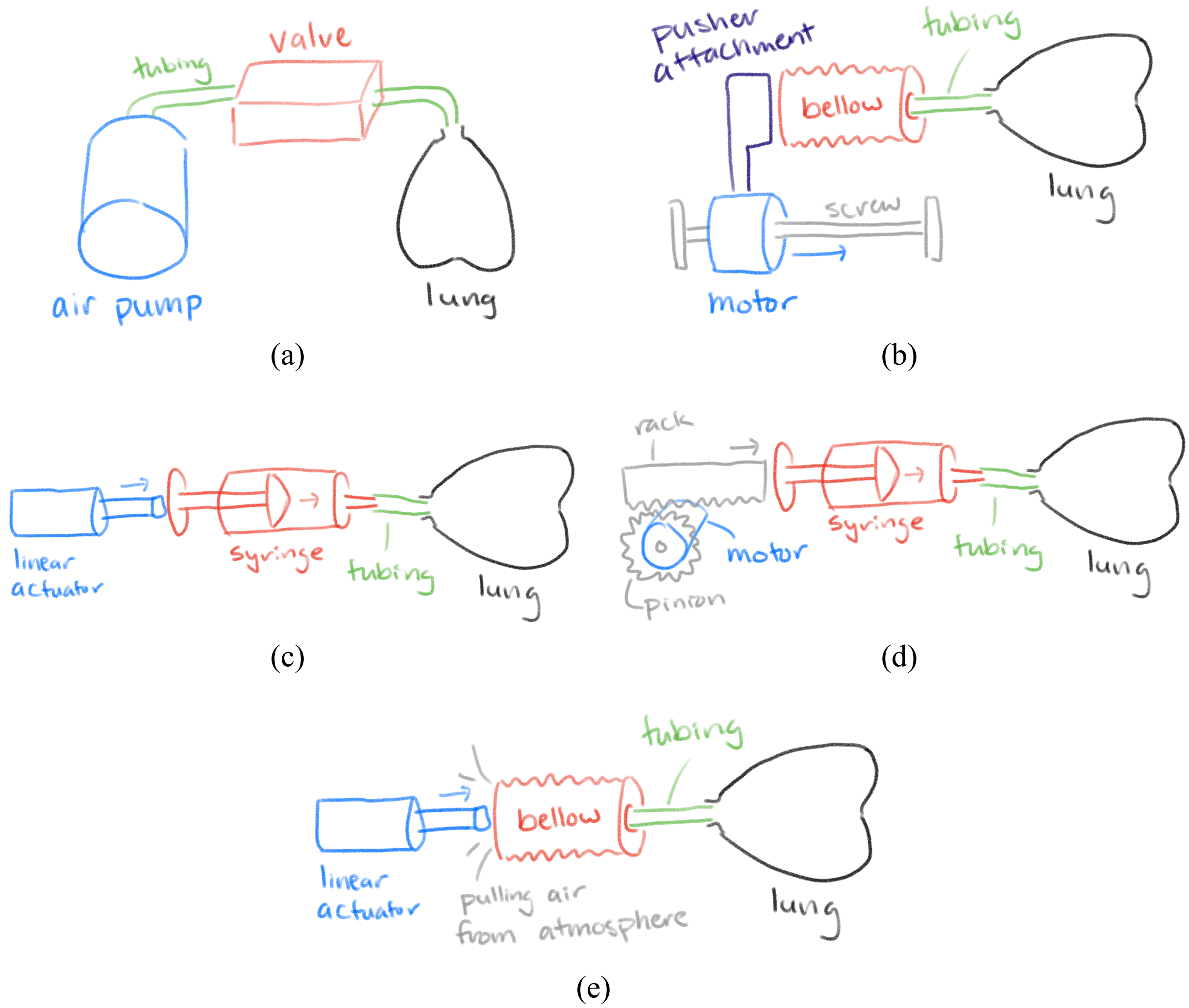


Figure 15: Sketches of Concepts 1-5 (a-e in the Figure, respectively).

Table 3: Concepts 1-5 using the options from the morphological chart.

	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Air Storage	Atmosphere	Bellow	Syringe	Syringe	Atmosphere
Fluid Movement	Air Pump	Vol/Pres Change	Vol/Pres Change	Vol/Pres Change	Bellow
Actuation System	N/A	DC Motor	Linear Actuator	DC Motor	Linear Actuator
Transmission System	N/A	Lead Screw	N/A	Rack & Pinion	N/A

The five concepts were then evaluated using a Pugh Chart that considered noise, size, price, and complexity. Noise was given the highest weight of 4 because it was a major complaint by our sponsor about the MBB 3.0 that we need to address in the MBB 3.1. Size and price were given lower weights of 2 because while they are listed in our requirements as high priority, they are a bit more lenient when it comes to the function of our product. Complexity was given the lowest weight of 1 because it relates to our medium-weighted design for manufacturability requirement, which is not essential to the overall function of our product. Concept 1 was used as the baseline in the Pugh Chart because it would be similar to the MBB 3.0's design; our concept was to use the same components but create better housing and noise insulation. The results of our Pugh Chart analysis are shown below in Table 4.

Table 4: Pugh Chart for Concepts 1-5.

	Weight	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Noise	4	0	1	1	1	1
Size	2	0	-1	-1	-1	-1
Price	2	0	0	-1	0	-1
Complexity	1	0	-1	-1	-1	-1
Total		**0**	**1**	**-1**	**1**	**-1**

Looking at the results of our Pugh Chart analysis, because Concepts 2-5 did not utilize an air pump, they all improved on noise but lost in terms of size because the components are quieter but bulkier. For price, Concepts 3 and 5 lost points because linear actuators are more expensive than an air pump or DC motor. For complexity, Concepts 2-5 lost points because they involve more components than Concept 1. Overall, the results indicated that Concepts 2 and 4, that used some sort of volume/pressure changing system actuated by a DC motor, would be the most promising moving forward.

Looking at Concept 2, we liked the idea of using a lead screw because it seemed simple to set up and operate successfully. However, we were concerned by the idea of using a bellow because none of the team members have experience with bellows and how controllable they are. Moreover, we were concerned about finding a bellow that would hold enough volume of air to inflate the lung. Looking at Concept 4, we liked the idea of using a syringe because we had already conducted empirical testing with syringes on the MBB in-person and felt comfortable about its capabilities to control air flow. We were concerned, though, about potentially using a rack and pinion because of the need to have proper tooth engagement; this seemed more difficult to manufacture and assemble properly. Thus, taking what we liked from both concepts and eliminating what might cause problems, we decided to use a syringe with a lead screw in our alpha design.

ALPHA DESIGN

Examined below is our Alpha design, or the solution we currently believe is optimal. It was chosen as objectively as possible by using a variety of concept generation and selection processes. This design was developed by the ME 450 design team, without major influence from sponsors, to ensure novelty. Shown below in Figure 16. is the Alpha design for the MBB 3.1 consisting of a syringe representing the Air Storage System, a stepper motor representing the Actuation System, and a lead screw representing the Transmission System.

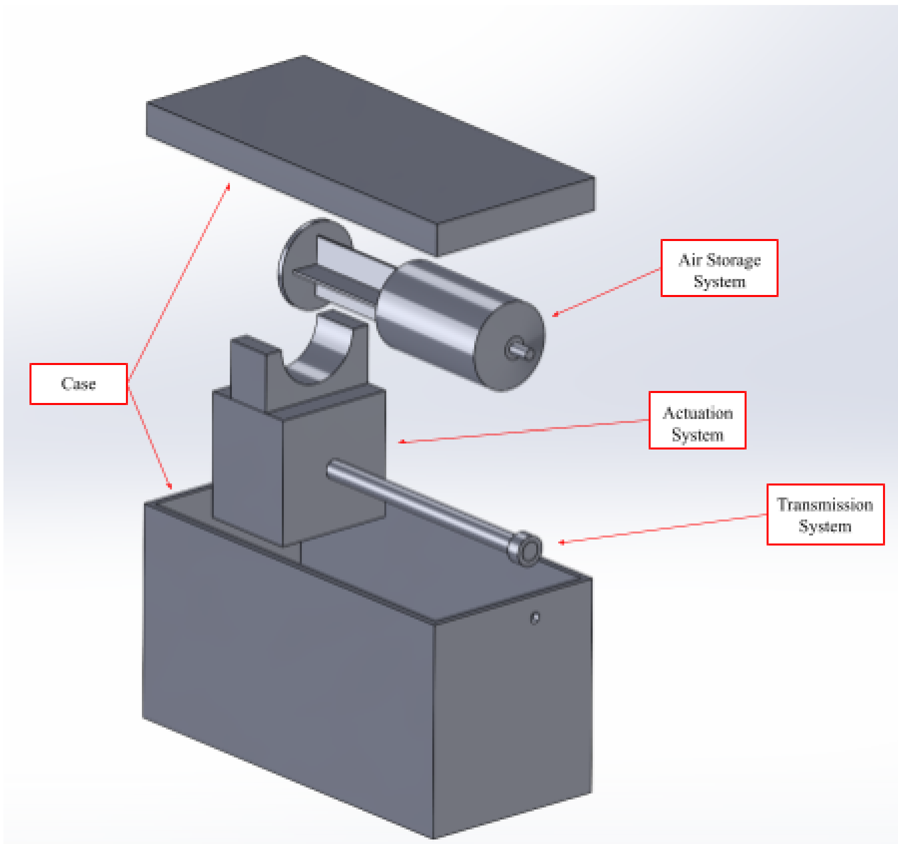


Figure 16: The image shows our Alpha design broken into its main subsystems, the Air Storage System, Actuation System, and Transmission System, as determined using functional decomposition described above. These components are all stored within a case with dimensions meeting our functional requirements.

Our Alpha design focuses on the interactions between each subsystem while fitting within the given form factor. The Fluid Movement subsystem for this concept is a change in the volume of the syringe, which causes air to be pumped into or expelled from the latex lung. Because this fluid movement depends on the syringe, it will be further discussed when detailing the air storage system. The actuation and transmission subsystems rely on one another to develop linear motion, therefore in the following text, they will be explained together as the Linear Actuation System.

The dimensions of the case are 14 cm, by 6.5 cm, by 8.26 cm, which meet those outlined in our functional requirements. The case will consist of two parts, a top and a bottom, that are 3D-printed and secured using fasteners. The bottom part of the case contains a hole where the latex tubing connecting the syringe to the lung will travel. There will also be a mechanical interface on the exterior of the case, but its exact placement will be determined once the electrical components of the Alpha design are finalized.

Air Storage System

The air storage subsystem consists of a syringe. The syringe will be connected to the latex lung through latex tubing, creating a closed system. A closed system is a practical choice for this context given our form factor and low noise level functional requirements because an open system would rely on the use of electronically controlled valves which are large, or air pumps which are noisy. Currently, we plan to modify a 150 mL syringe by cutting it to only store 60 mL of air. It was determined through testing that the maximum volume of air needed to inflate the lungs to the levels outlined in our functional requirements is 45 mL. We opted to include a safety factor of 1.33 to account for the air within the tubing. Syringes with larger volumes tend to have larger diameters rather than longer barrels, which means a syringe with a maximum volume of 150 mL can store 60 mL of air in a more linearly compacted manner compared to a syringe with a maximum volume of 60 mL. Syringes are also actuated linearly by the expansion and contraction of a plunger, adding to its dimension in one axis. Given our dimensional requirements, a syringe with a larger diameter and shorter height is a more space-efficient way to store 45 mL of air while applying linear motion to it. The dimensions of the syringe we plan to use are 43.2 mm in diameter and length 58.86 mm, which means if the plunger is the same height as the barrel, the total height of the syringe is 117.12 mm, which fits within our dimensional requirements, as seen in Figure 16.

Linear Actuation System

The Linear Actuation System combines the Actuation and Transmission Subsystems and can be seen in further detail in Figure 17.

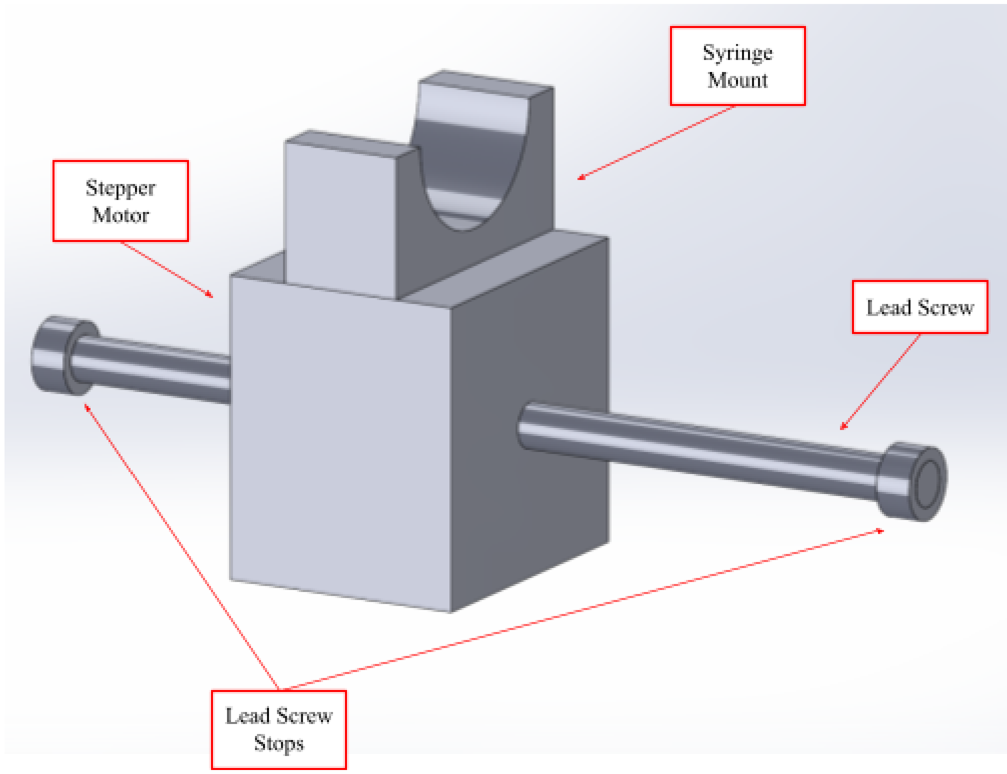


Figure 17: The Linear Actuation System consists of a stepper motor attached to a lead screw with two stops on its ends to mount the screw to the interior case walls. A syringe mount will be mounted to the motor and will house the base of the syringe plunger.

The stepper motor and lead screw are a non-captive linear actuation system, which means the lead screw or the motor can be translated linearly. We plan to mount the lead screw to the interior wall of the case, which will allow for translation of the motor. This causes the motor to act as a lead screw nut, so the syringe plunger will be mounted to it via a 3D-printed fixture to transfer its motion. The syringe barrel will be fixed as the plunger is the component that will push and pull air into and out of the lungs. This method allows for the air storage subsystem and linear actuation subsystem to be parallel to one another instead of collinear, saving space. To further save space, the lead screw will be sized to match the length of the syringe with an extended plunger in addition to the length of the motor as the linear displacement required is the amount to extend and contract the plunger.

Electrical Components

The electrical components within our Alpha design are the motor, the controller, the batteries, and the mechanical interface. Per our functional requirements, the MBB 3.1 should be internally powered, so batteries will be housed within the case to power the device. The stepper motor requires 12 V to operate, so we plan to power it with two 9 V batteries because they are cheap, small, and can be easily integrated into the electrical circuit using small clips. We plan to control the device using an Arduino Uno. We are familiar with using the Arduino software, making it a clear choice for our control system along with its small size. Seen in Figure 18. is a potential layout for the electrical components within the case.

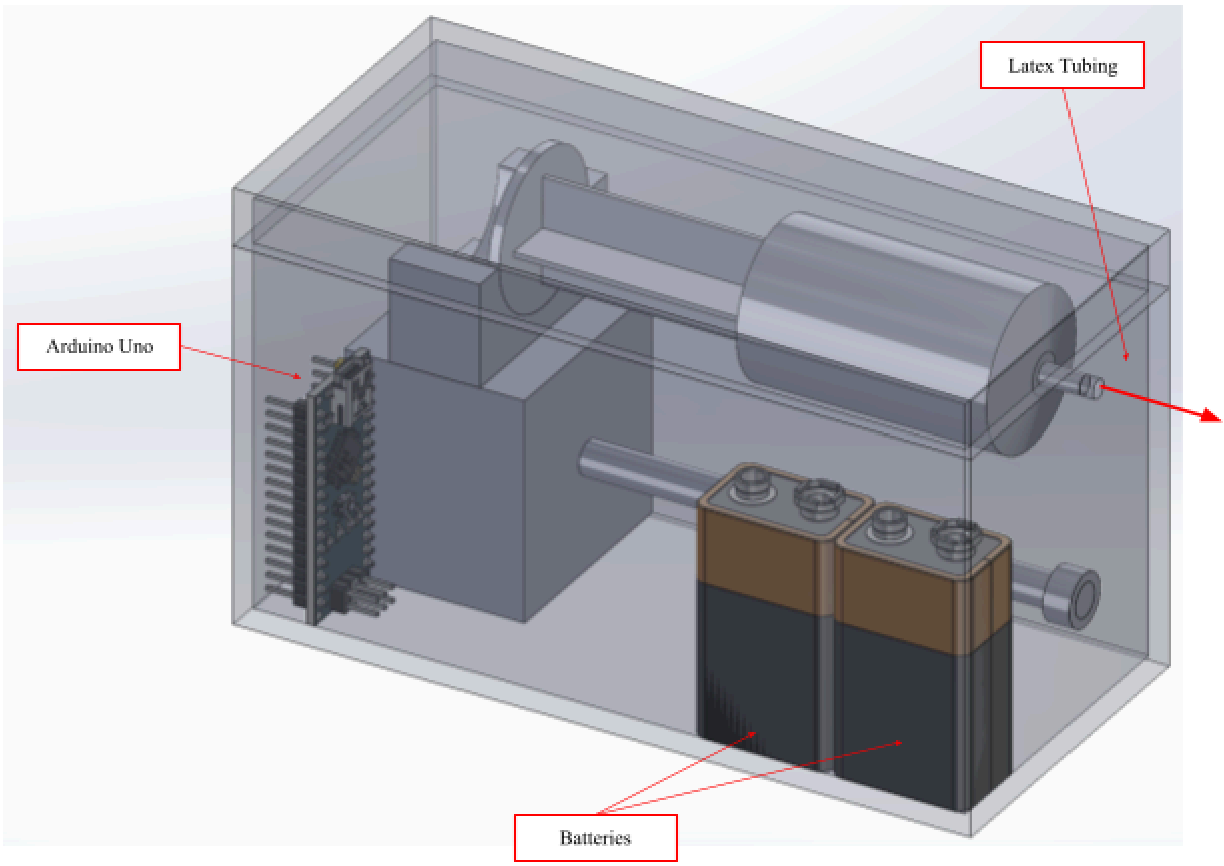


Figure 18: A theoretical layout for the batteries and control system for the MBB 3.1. The main requirement in the electrical design is access to all ports on the Arduino Uno and the battery terminals.

A mechanical interface will be placed somewhere on the exterior of the case to turn the MBB 3.1 on and off and control the four operating modes. We anticipate the placement of these electrical components will change during the prototyping phase due to challenges with harness routing, placement of the interface, and the changes to the dimensions of the case. To mitigate these risks, we plan to finalize the dimensions of the case and the place of the interface shortly into our prototyping phase.

Analysis of the Alpha Design

To reiterate, we used objective decision-making processes to select our Alpha design outlined above. We considered the opinions of our sponsors and informed them of our Alpha design to ensure they were comfortable with our design before selecting it, but we were not influenced by their opinions further than this. Additionally, we have prioritized ethical engineering and design work throughout this process and did not change our numerical data to meet the standards of our sponsors or anyone on the ME 450 Instructional Team.

The Alpha design is well enough designed to be analyzed rigorously. Using first-principles analysis, we have performed various power and noise calculations on the Alpha design and other potential concepts in the selection phase. Furthermore, in the prototyping phase, we plan to perform noise-dampening analysis which is further explained in the following section along with inflation speed measurements, relying on our fluid mechanics knowledge. Our greatest challenge in this project is the time constraint of one semester, however, we are confident that we will be able to complete it in time. We are meeting the schedule outlined in our Gantt chart and have built in many weeks of work for prototyping and iteration to ensure we have a functional final product.

ENGINEERING ANALYSIS

To inform our decisions throughout the design process we conducted engineering analysis on the components we designed, modified, or purchased. This was to help make good design decisions that would lead to a successful solution and help reduce the number of changes that need to be made later in the design process. By doing engineering analysis, we can decide which components to use and how we should design certain parts. Preliminary analysis was conducted to determine which battery, motor, lead screw, and syringe to use for our design. Although we maximized the use of off-the-shelf components for a simplified manufacturing process, we designed novel parts that require stress analysis to aid in the design process. The analysis for each of these decisions will be covered in this section.

Analysis for Lead Screw and Motor Selection

To choose our lead screw and motor we need to make calculations to determine the required motor torque needed with the associated lead screw to inflate and deflate the MBB 2.0. From there we need to ensure that the linear speed achieved by this motor and lead screw at this torque is faster than the max speed required by our system at our 4 breathing modes. The first aspect to consider is the force required to inflate the MBB 2.0. Fortunately, the previous ME 450 team conducted testing to gather this force requirement, which resulted in a value of 5 N. This allows us to perform first principles analysis to determine the torque required to achieve this force with a safety factor of 4. Shown below are the formulas and variables used to calculate the torque. With this torque value, we can find out whether a motor and lead screw combination meets our desired force and speed values using the following formulas:

$$T = \frac{F * l * 10^{-3}}{2 * \pi * \eta}$$

Table 5: All variables used in the equations, their values, and where those values came from.

Symbol	Meaning	Value	Origin of Value
F	Force required to push the syringe plunger	20 N	Previous team's testing put the average force required as 5 N, so to give a safety factor of 4 we are using 20 N [19]
l	Screw lead	8 mm	Specs of lead screw
η	Lead screw efficiency	0.4	Typical efficiency for a lead screw
T_h	Holding torque of the motor	0.26 Nm	Specs of the motor [46]
T	Torque required to inflate and deflate the lung	0.064 Nm	Calculated using formula above

From this table, we can see that the motor will be able to supply the torque required to move the lead screw as the holding torque of the motor is greater than the torque required to inflate and deflate the lung.

We must also consider the speed at which we plan to inflate and deflate the lungs to accurately model the four operating modes. This can be found by calculating the maximum speed the syringe needs to be pushed or pulled for each breathing mode. The total distance the syringe plunger needs to travel is 58.86 mm, which we will use as the distance required to travel in subsequent speed calculations. This value was derived from the total volume of air the syringe needed to hold which already had a safety factor of 1.33 so we don't need to add an additional safety factor to this value. The first operating mode, Deep Breathing, requires the lungs to be inflated in less than or equal to 2 seconds, making the speed the plunger must travel 29.43 mm/s. The Piggyback operating mode requires 4 puffs each at 1-second intervals. The speed required for each puff can then be found by dividing the distance the syringe plunger travels, one-fourth of the total distance the syringe can travel or 14.72 mm, by the time interval, in this case 1 second. This results in a plunger speed of 14.72 mm/s. The third breathing mode, Articulation, requires the lungs to incrementally deflate, specifically 4 increments each lasting one second. The speed required to fulfill this mode is therefore also 14.72 mm/s. The final operating mode, Regular Breathing, considers a breath to be half the volume of the lungs, so the plunger only needs to travel half the total distance or 29.43 mm. This mode occurs at 16 breaths per minute, which means each inhalation should take 1.88 seconds, resulting in a speed of 15.65 mm/s. Therefore, the maximum speed the plunger must travel to meet all breathing modes is 29.43 mm/s. We can use the required torque calculated above and the torque-speed curve of the motor to obtain the angular velocity. Using the following equation allows us to calculate the linear speed of the lead screw.

$$v = \frac{\omega}{60} * l$$

Table 6: All new variables that were not introduced in Table 5 above, their values, and where those values came from.

Symbol	Meaning	Value	Origin of Value
ω	Motor angular velocity	~580 RPM	Found from torque-speed curve at 0.08 Nm [46]
v	Linear speed	77.33 mm/s	Calculated using formula above

From this table, we can see that our lead screw and motor combination will be able to achieve the fastest linear speed needed from the syringe plunger. The linear speed achieved at the highest required torque is faster than the fastest linear speed achieved for our breathing modes.

Analysis for Battery Selection

The internal power source we selected to use in the MBB 3.1 was a battery because they are commonly used as internal power sources and are easy to implement. However, we still need to ensure that the batteries we select can power the electrical components used in our design. The components that we need to power are our microcontroller, which is an Arduino Nano, and our motor, which is a stepper motor. To determine whether our battery will be able to power the microcontroller and motor, there are two aspects to look at. First, we must analyze the voltage output of our battery compared to the voltage required by our components. The Arduino Nano requires 5 volts to operate [53], and the stepper motor requires 12 volts to operate [46]. Therefore we would need at least 12 volts supplied by our battery. Since traditional double A batteries only hold 1.5 V we would need 8 of these batteries to meet our voltage requirement [54]. This would occupy too much space and be inconvenient to use that many batteries. Therefore, we decided to use two 9-volt batteries, which ultimately saves space compared to 8 double A batteries and provides a more convenient connection method using connector clips that snap on and off. In addition, we calculated the lifetime of the batteries selected using the following formula:

$$t = \frac{V_b * B_c}{V_m * I_m}$$

Table 7: All variables used in the equations, their values, and where those values came from.

Symbol	Meaning	Value	Origin of Value
V_b	Battery Voltage	18 V	9 V for each 9 volt battery
B_c	Battery Capacity	0.58 Ah	Found from battery specs [55]
V_m	Motor Voltage	12 V	Operating voltage from motor specs [46]
I_m	Motor Current	0.4 A	Max current motor would use from motor specs [46]
t	Battery Lifetime	2.175 hours	Calculated from the formula

From this we can see that our batteries will last 2.175 hours of continuous use. The previous team had talked with Professor Porter about the average use case of the MBB to be about 60 seconds per use and expected 320 uses per year [19]. This means that with these batteries the MBB 3.1 would be able to run for 130 uses before changing batteries

Stress Analysis of 3D-Printed Parts

While designing the plunger mount and syringe barrel mount we must consider the loads that are applied to these parts when deciding the specific dimensions of these parts. These loads will cause stress in these parts and if we are not careful in their design then it could cause yield or fracture leading to a failure of our system. For both these systems the largest source of stress would be the bending stress that arises from the force exerted pushing the syringe plunger into the syringe to inflate the lung. In both cases, we can model the systems as cantilevered beams with a load on the end. In the case of the plunger mount the part is mounted onto the lead screw nut, which will be considered as the cantilevered side, and the force is applied at the end connected to the plunger mount, which comes from the reaction force from the syringe. In the case of the barrel mount, the bottom of the mount is bolted into the case, while the top holds the barrel of the syringe. So the bottom of the piece is the cantilevered side, and the top of the beam in the model would be to the center point of the circular barrel holder. A free-body diagram of the model can be seen in Figure 19 below.

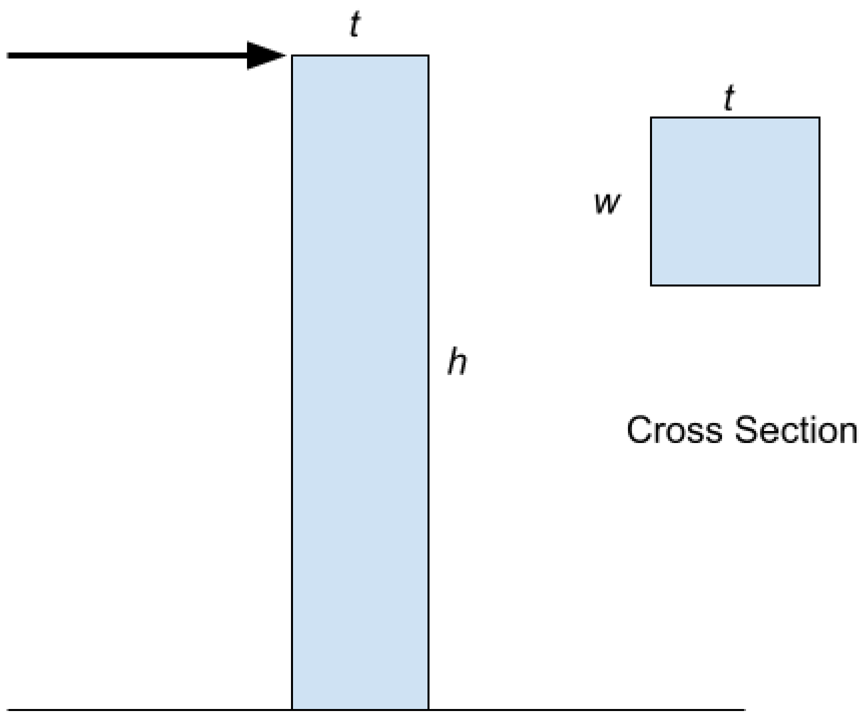


Figure 19: Free-body diagram of the plunger mount, modeled as a cantilever beam with a force at the end. Cross section dimensions are shown on the right.

To calculate the stress that is experienced by the two mount we can use the following equations for bending stress, second moment of area, and bending moment:

$$\sigma = \frac{M*t}{I} \qquad I = \frac{1}{12} * w * t^3 \qquad M = F * h$$

Table 8: All variables used in the equations, their values, and where those values came from.

Symbol	Meaning	Value for plunger mount	Value for barrel mount	Origin of Value
t	Thickness	10 mm	30 mm	Found from CAD of part
w	Width	22 mm	20 mm	Found from CAD of part

h	Height	35.5 mm	21.16 mm	Found from CAD of part
F	Force	10 N	10 N	Safety factor of 2 applied to empirically obtained value of force to inflate the lung
I	Second moment of area	1833.33 mm^4	45000 mm^4	Calculation from second equation
M	Bending Moment	355 Nmm	211.6 Nmm	Calculation from third equation
σ	Bending Stress	1.94 MPa	0.14 MPa	Calculation from first equation

We are considering 3D-printing these parts so we just need to compare the bending stress calculated with the yield stress of the 3D-printed material. We are going to try and have the material be resin for both the prints. A standard resin print has a flexural yield strength of around 50-60 MPa [56], which is greater than the stresses we calculated so our designs will not break underneath our normal load. However, considering we are well below the flexural yield stress for our material there is room for us to optimize our design. This is not a high priority of ours as much of the dimensions that we could change for our 3D prints wouldn't affect our overall case size by nature of their position, in addition the 3D prints will not weigh much so it will not lead to large weight reductions.

FINAL DESIGN AND BUILD

Mechanical Design

Using the above design development process and analysis outlined in the above sections, we created our final design for the MBB 3.1, shown below in Figure 20.

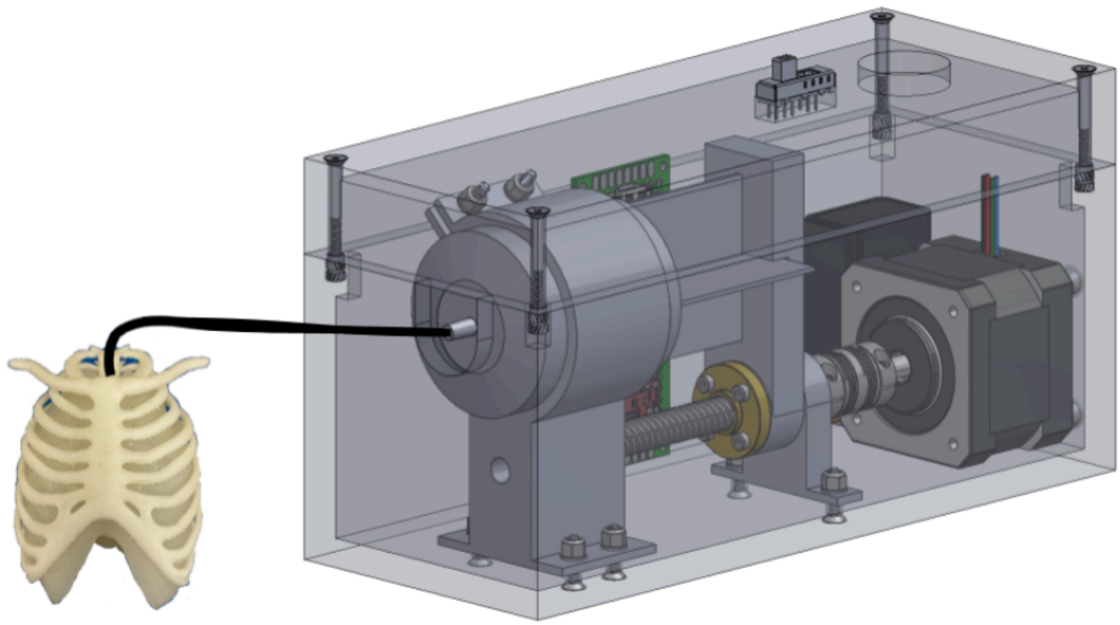


Figure 20: Final Design of MBB 3.1.

Our design is essentially a linearly actuated syringe system that moves a set volume of air into and out of the MBB's lungs using the mechanics of a syringe. It is actuated by a stepper motor, which is controlled by an Arduino Nano and motor driver (green component that is partially hidden behind the syringe) and powered by 9V batteries (placed at the back corner of the MBB 3.1). We've switched from a Non-Captive stepper motor to a regular stepper motor as we have concerns about the additional friction that the motor movement would cause, and since we have not received the non-captive motor yet we have not been able to test it. The dial at the top of the component box allows the user to set the specific breathing mode in which they want displayed. A hole (shown on the left side of the Figure) allows the tip of the syringe to be accessible from the outside, which enables the user to attach and detach the tubing that extends from the syringe tip to the external MBB lungs–this feature is explained further in the Verification and Validation section for Requirement #5. The barrel of the syringe is secured in a mount that clamps around the outside of the barrel. Components are fastened within the component box using flat head screws to maintain a smooth outer surface. The top of the component box can be separated from the bottom for assembly and maintenance using flat head shoulder screws, which screw into heat set inserts placed at the corners of the case. A more detailed picture of the transmission is shown below in Figure 21.

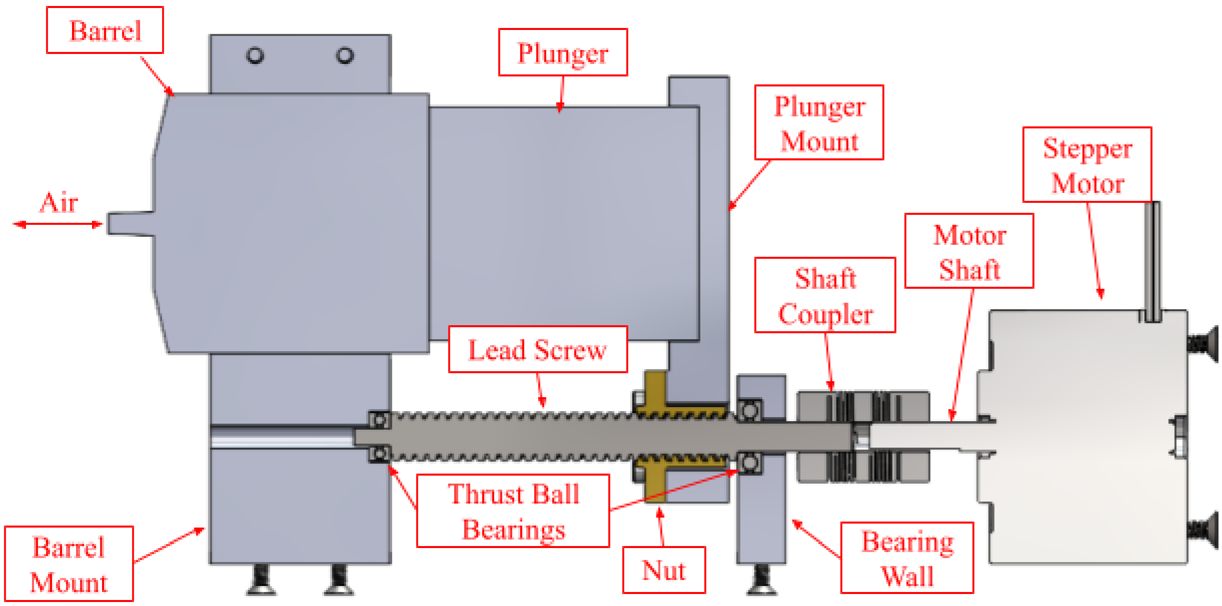


Figure 21: Detailed cross-section of MBB 3.1 transmission.

When a user sets an input by turning the dial at the top of the MBB 3.1, the Arduino tells the stepper motor how to move, rotating the motor shaft. The shaft coupler transfers the rotary motion and torque from the motor shaft to the lead screw. As the lead screw rotates, the nut translates linearly along the lead screw. The plunger mount moves with the nut, which pushes the plunger in and out of the barrel, causing air to be pushed and pulled out of the syringe tip shown on the far left side.

Through conversations with our graduate student mentor, we learned that lead screws are never going to be perfectly straight and will always have some sort of inconsistency. Thus, it was important to mitigate the potential negative effects of these inconsistencies through our design. The use of thrust ball bearings ensures that our lead screw will be able to rotate as intended, and any unintended loads will be transferred to the barrel mount and bearing wall, protecting our more critical components. Our mitigation strategies did not end there, though, as binding in our system could potentially be an issue if the nut and plunger mount were rigidly attached. Thus, in order to handle this concern, we moved forward with "floating the nut," which would allow the nut to deviate vertically (due to lead screw inconsistencies) while keeping the plunger mount level. The details of this design are shown below in Figure 22.

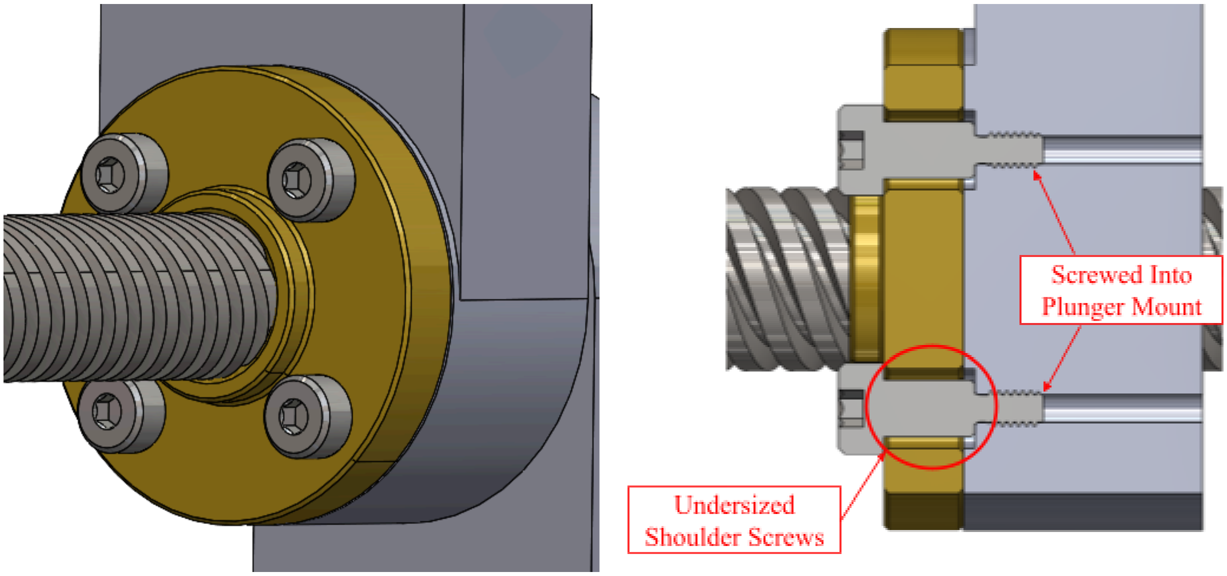


Figure 22: Floated nut design using undersized shoulder screws.

The nut is fastened to the plunger mount using four undersized shoulder screws that screw into the plunger mount. The shoulder diameter is 1 mm less than the diameter of the holes in the nut. This allows for the nut to be able to move vertically without simultaneously causing the plunger mount to also move vertically. If they both moved vertically together, the system could experience binding as the plunger should only move horizontally into and out of the barrel. Any deviation vertically could prevent this necessary movement from happening. Thus, the undersized shoulder screws account for a ±0.5 mm bend in the lead screw, which would otherwise lead to binding.

Electrical Design

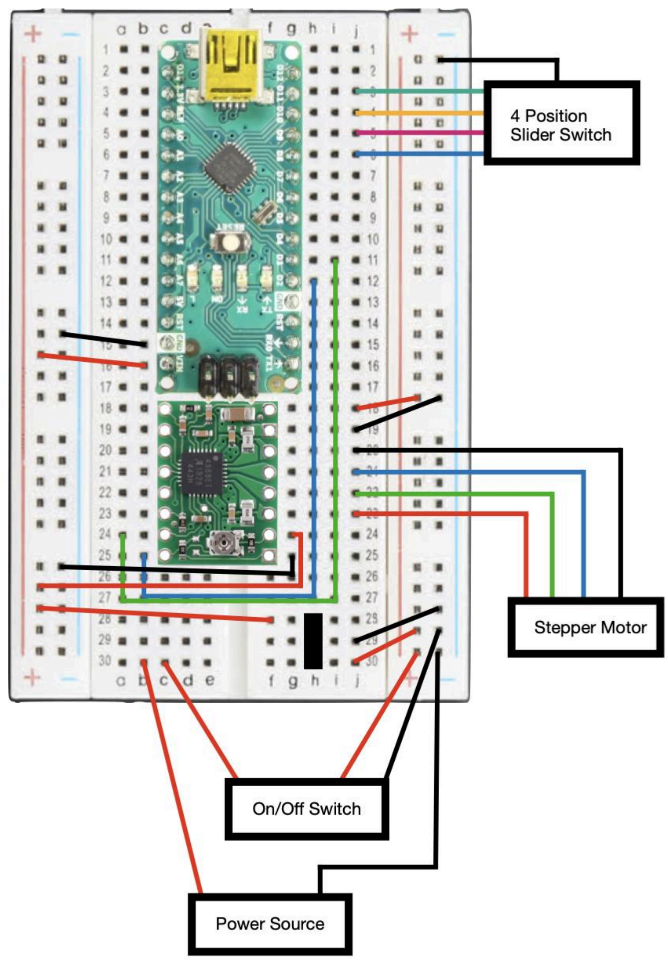


Figure 23: Wiring diagram.

Figure 23 shows the wiring diagram for the Arduino Nano and motor driver, which allows us to control our stepper motor. The Arduino takes in the input from the battery after its voltage has been stepped down to 5 volts using a voltage regulator, which is the black box in the diagram, as that is the operating voltage of the Arduino. Then using a 4 position slider switch, it connects to 4 digital pins on the Arduino to indicate which breathing mode should be running. The Arduino then communicates with the motor driver to actuate the stepper motor at a specified speed and direction, depending on the operating mode set by the user. The specifics for the amount of movement and the speed of movement is decided in the code. We have tested this wiring by running the motor alone at the 4 different breathing modes using the switch to change between them.

Manufacturing Plan

Our manufacturing plans are rather simple, with only four total parts needing to be fabricated: the barrel mount, plunger mount, bearing wall, and lead screw. The barrel mount, plunger mount, and bearing wall was 3D printed using an SLA printer, and only the plunger mount required further milling for the tapped holes needed for the shoulder screws. The lead screw was purchased, cut down to size, and lathed at both ends to turn them into shafts. The drawings and manufacturing plans for these parts are shown in the appendix.

Bill of Materials

Table 9: Bill of Materials.

Part No.	Part Title	Material	Dimension(s) [mm]	Supplier	Quantity	Price (per unit) [$]
1	Lead Screw	SUS304 Stainless Steel	83 L, 8 D	VICHSAMWY	1	7.80
2	Lead Screw Nut	Copper	8 ID, 22 OD	VICHSAMWY	1	-
3	Arduino Nano		18 x 45 x 5	Arduino	1	26.61
4	Stepper Motor		42 x 42 x 34	Stepper Online	1	12.50
5	9V Battery		48 x 25 x 15	Duracell	2	4.50
6	Motor Driver		20.4 x 15.5 x 11.3	WWZMDiB	1	2.66
7	Case Top	Plastic	185.5 x 75 x 22.5	3D Printed	1	-
8	Case Bottom	Plastic	185.5 x 75 x 71.6	3D Printed	1	-
9	Power Switch	Plastic	16 D, 29 H	LOVEMYSWITCHES	1	1.90
10	Shaft Coupler (2463K3)	7075 Aluminum	15 D, 22 L	McMaster-Carr	1	58.05
11	Bearing Wall	Plastic	40.5 x 8 x 31.4	3D Printed	1	-
12	5mm Thrust Ball Bearing (7806K57)	Bronze	5 ID, 12 OD, 4 L	McMaster-Carr	1	8.66
13	3mm Thrust Ball Bearing (7806K53)	Bronze	3 ID, 8 OD, 3.5 L	McMaster-Carr	1	9.86
14	Barrel Mount	Plastic	30 x 49 x 88	3D Printed	1	-
15	Barrel	Plastic	43 D, 53.5 L	A AKRAF	1	3.00
16	Plunger	Plastic	45 x 39 x 39	A AKRAF	1	-
17	Plunger Mount	Plastic	10 x 22 x 71	3D Printed	1	-
18	Undersized Shoulder Screw (90278A713)	18-8 Stainless Steel	4 D, 9 L	McMaster-Carr	4	4.76
19	Heat-Set Inserts (94459A439)	Brass	4.1 D, 5.9 L	McMaster-Carr	4	0.22
20	Flat Head Shoulder Screw (91294A540)	10.9 Alloy Steel	5 D, 25 L	McMaster-Carr	4	0.72
21	Barrel Mount Head Screw (91292A017)	18-8 Stainless Steel	4.5 D, 14 L	McMaster-Carr	2	0.09
22	Motor Flat Head Screw (91294A128)	10.9 Alloy Steel	6 D, 8 L	McMaster-Carr	4	0.58
23	Mounting Flat Head Screw (92125A090)	18-8 Stainless Steel	5D, 12 L	McMaster-Carr	6	0.29
24	Washer (93475A196)	Stainless Steel	2.7 ID, 6 OD, 0.4 to 0.6	McMaster-Carr	8	0.02
25	Locknut (94205A101)	Stainless Steel	5 D, 3.8 L	McMaster-Carr	8	0.20
26	Breadboard	Plastic	82 x 54 x 9	DEYUE	1	1.31
27	9V Battery Leads	Plastic	20 x 10 x 2	McMaster-Carr	2	0.19
28	Syringe Dispense Tip	Plastic	8 D, 30 L	Hisco	1	0.35
29	Rubber tubing	Plastic	4 D, 300 L	Hisco	1	0.79
30	Linear Switch	Copper Alloy	13.8 x 19 x 6	C&K	1	0.63
	Total Cost					$172.11

Finally, our bill of materials is shown above in Table 9. Before including the cost of 3D printed parts, our prototype will cost $172.11, which exceeds the target manufacturing cost of $40. Looking at the cost breakdown, though, we can see that the largest contributors to the cost include the shaft coupler, Arduino Nano, stepper motor, thrust ball bearings, and lead screw. These components were all purchased either from McMaster-Carr or Amazon in accordance with the ME450 restrictions, which led to higher costs as opposed to purchasing directly from suppliers or sites like AliExpress. In the future, our sponsor can source components from these cheaper suppliers, which should drastically reduce costs. For now, though, our prototype costing $172.11 is well within our project budget of $400.

Final Prototype

In the end we were able to construct a functional prototype of our design using the linear syringe actuation system. The only slight change that needed to be made compared to our earlier design was to make the hole from which the tip of the syringe would stick out a larger slot, for ease of assembly. For our verification plans physical builds were needed. First we needed the linear actuation system connecting to the syringe to test its ability to achieve each of the four breathing modes using the internal battery source. Next we needed to assemble the entire system within the case to be operated at each breathing mode, to test the noise. Figure X below shows the assembly of the linear syringe system.

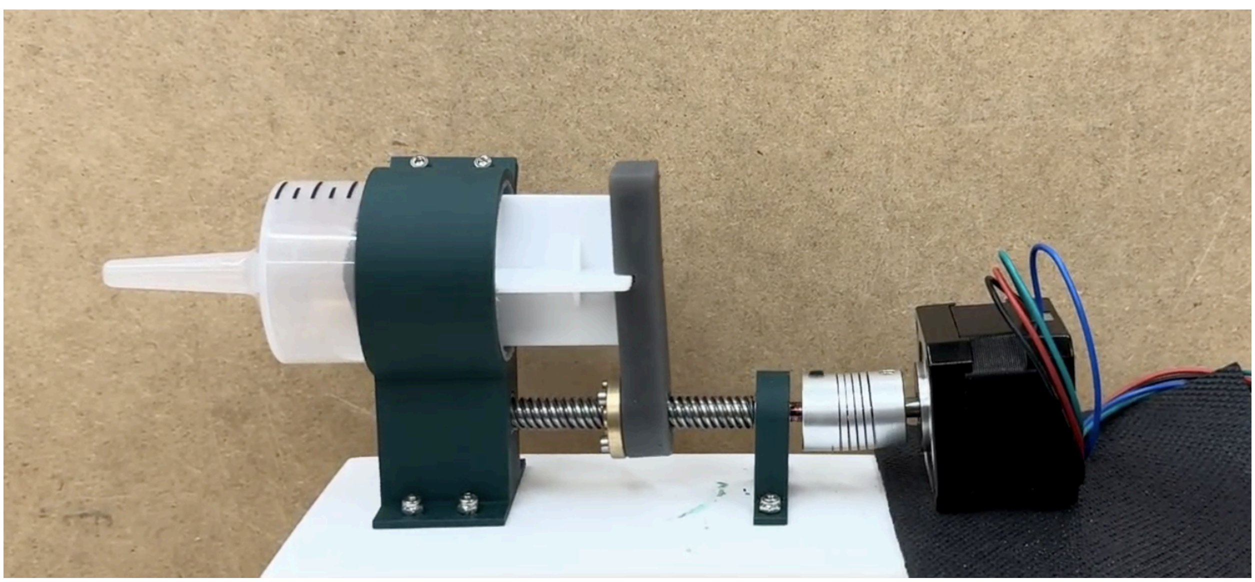


Figure 24: Linear Syringe System

For the linear system to work as intended the barrel mount and bearing wall needed to be mounted, which we did by mounting them to the bottom of our 3D-case, that way we could still easily view our system. This allowed us to test our motor and lead screw to ensure they were capable of achieving all our breathing modes. From this we were able to determine that our linear system was a good choice in inflating the latex lung and worked as we imagined it. We were also able to quickly edit numbers in the code to fine tune our system to get the movement we desired.

While this worked to ensure our design's functional ability, there was still the aspect of noise that needed to be evaluated. While our major sound producing components are within this build, we recognized that the vibration of these items in the case could add to the sound produced, and at the same time the case being enclosed could help reduce the sound, especially with added foam. Therefore to adequately test this we required a full final build with the entire system enclosed within the case. Figure 25 below shows our final build.

Figure 25: Final Build of the prototype

Here the entire linear system shown above, as well as the arduino, is contained within the case. The on/off switch and slider switch are also mounted to the top of the case and functional. This allowed us to accurately verify the noise created by our design in the final stage.

VERIFICATION

Before completing the First Build, a variety of potential designs went through preliminary testing and analysis to determine if a given solution will meet our requirements and specifications. This analysis served as a way to compare these designs during the selection phase and allowed us to select an optimal Alpha design. In the process of completing the First Build, a more thorough verification and validation of the design is required. Each functional requirement was verified to answer the question, "Does the solution work as we intend it to?", or to see if the engineering specification is met. The following sections outline the requirements and specifications given a high priority, as these are critical for the success of the MBB 3.1. Refer to the Appendix for the verification plans for the medium and low priority requirements.

Requirement #1: Operate at Four Breathing Modes

Our first requirement entails being able to inflate the MBB 2.0 at certain speeds to a desired volume for each breathing mode. This involves ensuring that our selected motor and lead screw can achieve the necessary torque to push and pull the plunger at the correct speeds to achieve each breathing mode. While theoretically the motor and lead screw should achieve the desired torque and speed to operate at all breathing modes, in practice this might not be the case. We are assuming a lead screw efficiency of 40%, but unaccounted environmental factors may cause this to decrease and no longer meet the requirements. Therefore to verify that our final design does in fact meet the specifications we conducted empirical tests.

Method of Empirical Testing

We performed a series of tests on a prototype of the MBB 3.1, as components of the Final Build such as the case do not impact this test. We ran the prototype at a given breathing mode and measured the inflation and deflation rates using a stopwatch. We conducted 5 trials and ensured that the results are within the times described in the specification. We also completed a visual inspection of the latex lungs to ensure they are inflated to the respective volume designated for each mode. This was conducted for all 4 breathing modes. This experiment ensured the MBB 3.1 can operate at the appropriate speeds and inflate the lungs to the correct volume, meeting the specification.

Requirement #2: Operate at an Appropriate Noise Level

This requirement states that the MBB 3.1 must operate at less than or equal to 50 dB at all operating modes. This is more difficult to analyze with first principles analysis, and no one in our team currently has the knowledge set to determine the sound that would be made by the system components. Therefore, the best way for us to test this would be to assemble a prototype and test the noise level of this design. This however, isn't the end of the testing process, as there are additional aspects we could add to our design outside of the functional components that would affect the noise level. We experimented with different dampening measures, such as utilizing damping mounts and filling empty space within our design with a variety of materials to dampen noise.

Method of First Empirical Test

First, we tested the prototype at all breathing modes with no extra dampening added. Keeping the decibel meter about 72 centimeters away from the prototype, simulating the functional grip reach of an adult [30]. This gave us decibel values for the noise level of our prototype. We repeated this 5 times for each breathing mode and compared the average with our 50 dB limit. Unfortunately we were not able to meet our requirement and ended up being around 63 dB. This means we do not meet this requirement, therefore we proceeded to test other noise-dampening methods to see if we could reduce the noise further.

Method of Second Empirical Test

This test measured the noise levels of each breathing mode with a variety of noise-dampening foams placed in various spots. The first test conducted would be filling empty space within our design with a variety of foams to dampen noise. When sound waves enter foam, they continuously bounce off the irregular porous structure of the foam converting to heat through dissipation, decreasing the noise level [52]. We tested polyurethane foam, melamine foam, polyethylene foam, and acoustic foam, which all are regularly used for noise damping environments. This reduced the noise produced but not enough. This led to a max decibel value of around 60 dB. Figure 24 below outlines potential placement of foam for this experiment.

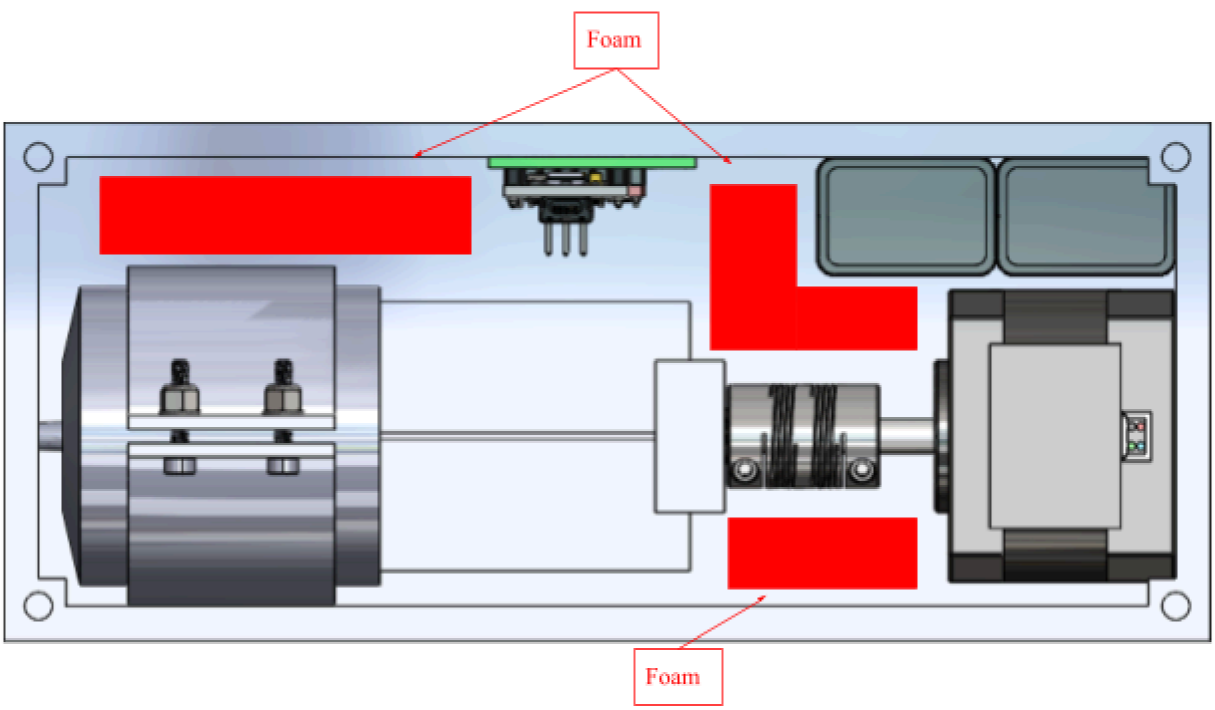


Figure 26. Top view of the MBB 3.1 with testing locations for noise-dampening foam.

We also explored the use of damping mounts for components such as the motor and lead screw. The motor was our loudest component because it is the only electrically driven device. Motors naturally vibrate due to imbalances in the motor's rotor and the changing magnetic fields that induce motion. This vibration creates noise when the motor comes in contact with other components, in our example when it is bolted to the side of the case and resting on the ground of the case. This vibration was found to be a large component in the noise of the system when conducting the first test, so we tried to test rubber shocks and foam on the contact points of the case and motor as shown in Figure 25. However, this caused issues with the linear system as the tolerances were too tight, therefore regardless of the noise dampening resulting from these noise-dampening methods this could not be explored.

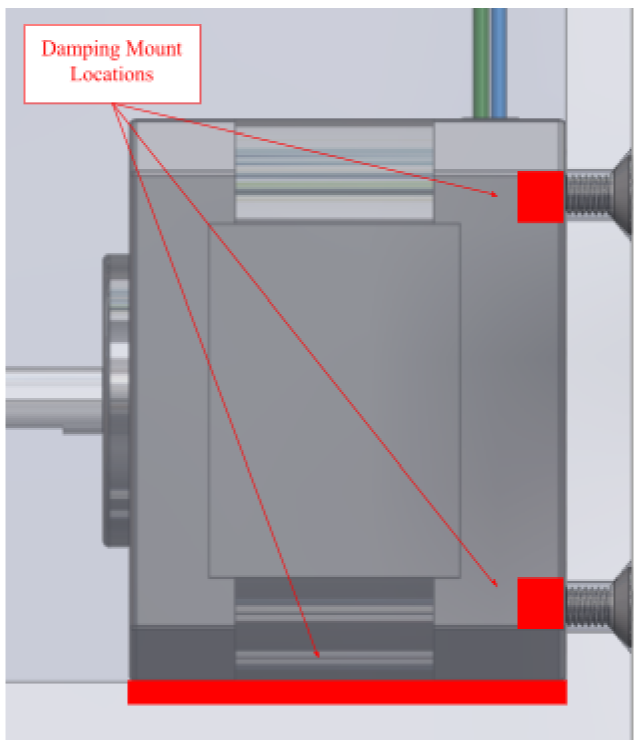


Figure 27. Noise-absorbing dampers was tested where the motor is bolted to the side of the case and on the bottom where it comes in contact with the case.

The final aspect that we explored was to add dampening foam to the bottom of the case. We noticed that the vibrations from the motor would often cause lots of vibration of the case relative to the platform it was resting on. To help reduce this we added foam pads to the bottom of the case. This worked well, however, in the end the noise was only reduced to a value of 56 dB, which was still 6 dB above our 50 dB limit.

Requirement #3: Be Portable

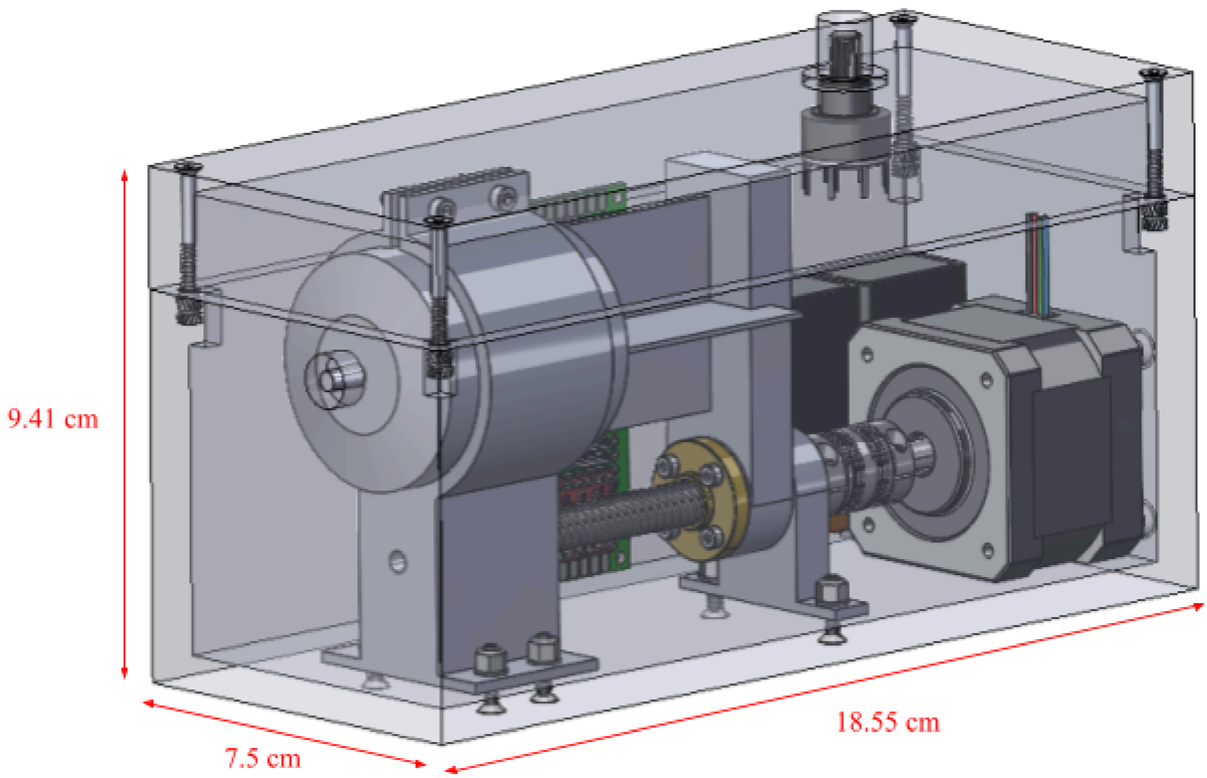


Figure 28: Dimensions of MBB 3.1 case.

This requirement states that the MBB 3.1 must have a volume less than or equal to 1400 cm^3 and a weight less than or equal to 1 kg to ensure its portability. This specification was verified both in Solidworks and when the Final Build was completed. Solidworks has evaluation features that let users measure the dimensions of parts and define the material density to calculate the weight. In the CAD model for the MBB 3.1, the dimensions of the case are 18.55 cm long, 7.5 cm wide, and 9.41 cm tall. This results in a volume of 1309.17 cm^3 which meets the requirement. Furthermore, Solidworks estimates the weight of the system to be 0.835 kg, again meeting the requirement. When the Final Build was completed, we measured the dimensions of it using a set of calipers to ensure they are within the specification, as expected the values were the same as the CAD model. However, the weight of Final Build was slightly different than that of the model. The model did not include electrical components such as wire or solder, which although small, will still add to the weight of the system. Furthermore, the density of certain components such as batteries and the PCBs are unknown, so they were only estimated in the model. When weighed the final weight ended up being less than the model, being 0.782 kg, which once again is below our specification.

Requirement #4: Be Internally Powered

This requirement states that the MBB 3.1 must be powered using an internal source of energy. This requirement was developed because the MBB 3.0 was powered using a plug in the wall, limiting the environments in which it could be used. This requirement does not require a theoretical or empirical analysis as the device is either internally powered or it is not. As discussed in the Engineering Analysis section above, the Final Build is powered by two 9 volt batteries located inside the case, meeting the requirement.

Requirement #5: Be Non-Invasive to the MBB 2.0

This requirement states that there are no design changes to the MBB 2.0 and that the MBB 3.1 can integrate seamlessly with the lungs. The MBB 2.0 consists of the latex lungs and are inflated and deflated by manually pumping a hand bulb. Our sponsor wishes that the MBB 3.1 does not affect the latex lungs of the 2.0, and if needed, the electro-mechanical actuation system of the 3.1 can be removed and replaced with the hand bulb. Once again, this requirement is rather binary, and is non-invasive to the MBB 2.0 or not. The MBB 3.1 utilizes a rubber tube that is attached on one end to the syringe tip and on the other end the latex lung as seen below in Figure X.

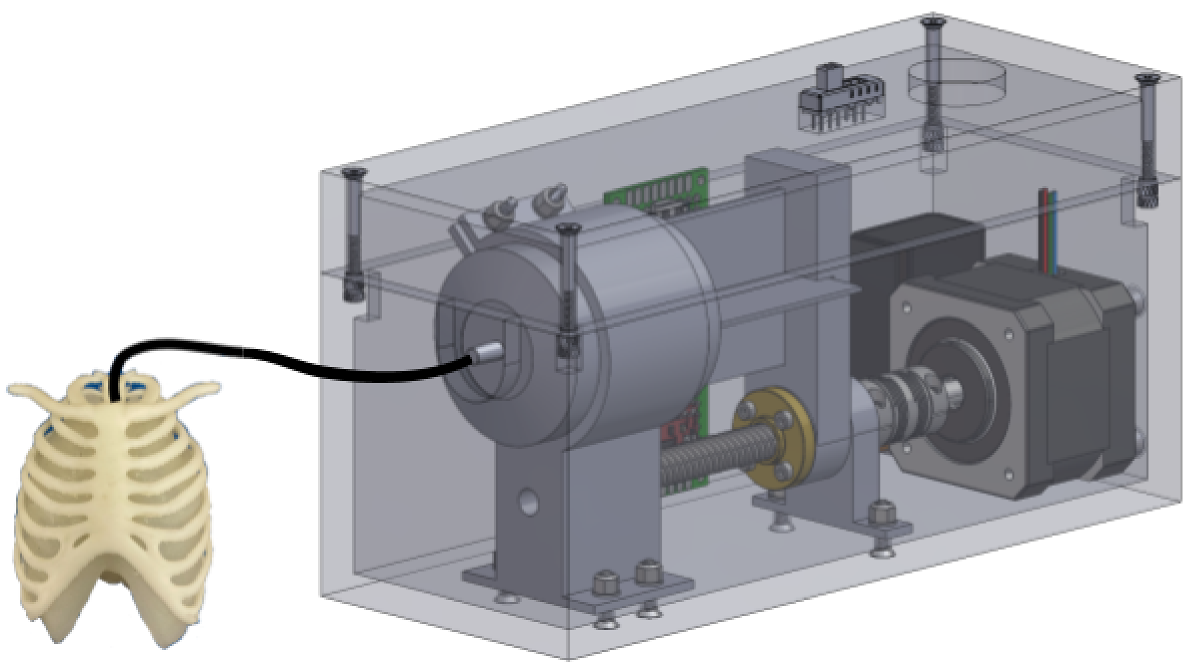


Figure 29. Diagram of how MBB 3.1 connects to the latex lung using a rubber tube.

The rubber tube attaches to the latex lung via a plastic connector. This connector can be attached and detached from the lungs within 1 second and without damage to the latex, meeting the requirement.

Requirement #6: Be Safe for Users

This requirement states that the MBB 3.1 must meet the BS EN IEC 62368-1 standard. This is an electrical standard for small electronic devices such as the MBB 3.1, and relates to its electrical safety. This standard has two main components, the first being there is no exposed connection other than the connector pins and the second being that all components are grounded safely. To ensure the first part, we insulated all wires and ensure accurate soldering of the microcontroller and motor driver to the PCB. We checked this electric circuit with our ME Sponsor as well.

Method of Empirical Testing

To test that the circuit is properly grounded, we first completed a continuity test. We disconnected the circuit from the power source and placed one probe of a multimeter on the grounding pin and the other probe on a known ground source within the system. We set the multimeter to its continuity setting and if it beeps then the system is accurately grounded. We then completed a test when the circuit is powered by placing one probe of the multimeter on the grounding pin and the other on various ground points throughout the circuit. The voltage across the probes was measured and the voltage drop was 0 volts indicating the circuit was accurately grounded. Since our electrical system was properly insulated and it passed the grounding tests, we concluded that the MBB 3.1 met the electrical standard and passed the requirement.

Requirement #7: Be Automatically Operated

To meet this requirement, there must be no user input to operate the MBB 3.1 after a breathing mode has been selected. The device should complete all inflation and deflation automatically until the user turns the device off. To test this requirement, we operated the device at a given breathing mode for 3 minutes, the average length of time a breathing mode will be used without switching modes or turning the device off, and verified that it met the specification of the respective breathing mode without user interference. This was repeated 5 times for each breathing mode. Although this test seems trivial, it produced measurable results with little effort allowing us to answer if the requirement is met.

Requirement #8: Be Affordable

This requirement is met if we keep the cost of parts under $40. Throughout the design process, budget has played a role in our design decisions, specifically when selecting the air storage and actuation systems in the design generation and selection process and more recently in our motor and lead screw selection. We have also developed a Bill of Materials (BOM) which is pictured in Table 9 above to account for the total cost of all the components used in the MBB 3.1. Therefore, ensuring the total cost of all the components listed in the BOM is below $40 is the method we used to verify this requirement. The BOM shown in Table 9 lists the total price of the MBB 3.1 to be $172.11, which as of this moment exceeds our requirement. However, as mentioned above many of these components are currently purchased from vendors that are approved by the ME 450 course, as well as from sites where accessing their CAD was straightforward. However, there is no such restriction when it comes to the manufacturing of this product outside of the ME 450 class. Therefore, we can look for cheaper alternatives of many of the parts in this BOM, that are either identical or similar enough and substitute them for the items currently in the BOM.

Requirement #9: Be Robust

Another requirement that we had was for our design to be robust. This means that we want our design to survive an impact such as a drop from a table without ceasing to function. While it may be possible to conduct either first-principle analysis through hand calculations or even through simulation software, the complexity of this is relatively high, as there would be many components contained within the box. Determining whether or not any of those components stop working due to a shock, or for any components or wires to come loose due to the shock accurately would be very complicated. To figure out how to do this accurately would be very time-intensive and our team doesn't think this is an effective use of time. The specification for this requirement describes a test plan to satisfy it, so we ran this test as a method of verification.

Method of Empirical Test

As said in the specification for the robustness requirement, the test involves a drop from 76cm on each face of the case. 76cm represents the average height of a desk, which is where this device would most likely be placed. This was mentioned in the requirements and specifications section of the report. To conduct this test, we measured 76cm from the ground, held the case up with one face pointing towards the ground, and then dropped it. After the drop, we attempted to run the MBB 3.1 at all the modes to see if it still functions as we intended. We repeated this for each face. To mitigate the potential failures caused by this test, we included shock absorption materials within the case. Fortunately, these materials also served to dampen the noise of the MBB 3.1, making this absorption material versatile.

Requirement #10: Convenient Profile Interface

This requirement is met if the interface used to turn on and off the device and control the breathing modes is less than 25mm in diameter and 15mm tall or that the device uses a remote interface on a smartphone. The design we implemented features a 4 position slider switch as the interface and like the portability requirement, this specification was verified both in Solidworks and when the Final Build was completed. The evaluation tool in Solidworks indicated that the switch is within the size requirement. After the Final Build was completed, we measured the dimensions of it using a set of calipers to ensure they are within the specification, as expected these values did not change between the CAD model and our Final Build. Although we do not plan to implement a remote interface because of the short timeline of this project, the physical switch was verified to meet this requirement.

Requirement #11: Designed for Manufacturability

This requirement entails designing the device with manufacturability in mind, specifically at a quantity of 10 units per year, minimizing part count and complexity, and using as many off-the-shelf (OTS) components as possible. To verify this requirement, we conducted a design for manufacturability analysis on the Final Build. While designing the MBB 3.1, we considered its assembly. We aimed to minimize the amount of assembly steps by including as few components as possible. We also minimized the amount of fasteners used and standardized the fastener type to further decrease the amount of assembly steps and the necessary tools to assemble the device. We then compared the amount of OTS components to novel components in the design, which had a ratio of 21:5. OTS parts are generally mass-manufactured, saving money and they are more reliable because they were obtained from another manufacturer. The use of OTS parts in the MBB will save time and money and simplify the manufacturing process, making this design manufacturable. Finally, we analyzed the complexities and manufacturing processes of our novel components. We have 3 novel components in our design, which will be 3D printed in our Final Build, but our Sponsor wishes for the final product to be metal. Although manufacturing these components in metal is out of our project scope, we designed our components to be easily machined, specifically reducing complex geometries, avoiding the use of thin walls, incorporating filets, and standardizing hole dimensions. This will ensure whether the part is 3D printed or machined, the manufacturing process will be as simple as possible, therefore supporting manufacturability. Through this analysis, we were able to verify the requirement and say with confidence that the design considered manufacturing.

Requirement #12: Be Presentable

This requirement is met if we score greater than 3.5 on a Sponsor-determined Likert scale, which deems our Final Build presentable. To verify this requirement, we have worked with our Sponsor to develop a survey on presentability and overall aesthetics of the device. After the Final Build was completed, we had our Sponsor complete this survey and check if the score is greater than 3.5 which determined the requirement was verified.

Requirement #13: Volume Inflation Indication

The final requirement is met if there is a volume indicator on the outside of the case of the MBB that indicates whether lungs are filled to a low, medium, or high capacity. In initial design, this indicator is an LED that will shine red if the volume is 0-14.75 mL, yellow if 14.75-29.5 mL, and green if 29.5-44.5 mL, representing if the lung is one-third full, two-third full, or full, respectively. However, given our short timeline, the other issues that we encountered, and the low priority of this requirement we ended up not implementing this feature into our final design. This would be something that can be addressed for future iterations.

VALIDATION

The First Build was then validated to answer the question, "Does the solution address the design problem we set out to solve?", and we focused on testing the MBB 3.1 with users. The verification and validation of the MBB 3.1 served as a benchmark in our success in solving the problem we're given in terms of an engineering success and a stakeholder success. For this we established 2 main ideas that we needed to address for validation, user happiness and benefactor.

User Happiness

This aims to identify how happy teachers are with using this product when teaching music students diaphragmatic breathing. A good method to do this would be to trial the product with music teachers for 30 days. We would select a group of music teachers who are likely to use the MBB 3.1 in classroom teaching environments. Provide them with the MBB 3.1 and instructions on how to use it. After 30 days, collect user feedback on their satisfaction with it and use this metric to determine the success of the MBB 3.1 as a teaching device. To give a simple numerical answer to this we would ask the teachers to rate their satisfaction on a scale of 1-10, as well as leaving comments about issues or suggestions.

Benefactor Happiness

This aims to determine how useful this product is for students trying to learn diaphragmatic breathing. The method we would use is similar to the method for user happiness and would likely occur at the same time. We would select a group of music students who are learning to play wind instruments. Provide them with a series of music lessons that use the MBB 3.1. After the lessons, collect user feedback on their satisfaction with it and their understanding of the music lessons. Similar to our method for user happiness, we would ask the students to rate their satisfaction on a scale of 1-10, and leave comments about issues and suggestions.

DISCUSSION

Although we succeeded at creating a prototype that is able to function how we intended there are some critiques of our own design process and final design to discuss. This is important to understand the limitations of our process and of our design, as well as the problems we faced and how we addressed them. This will be beneficial for further future improvements to the design.

First there were some limitations with defining the problem statement. Defining the problem is an integral part to the design process, and while we managed to create a clear definition for the problem, given more time and resources we may have been able to further explore certain aspects more in depth. For example, a big question to investigate was how this device can be used to maximize the help given to students. We had a latex lung capable of showing diaphragm movement during inhalation and exhalation but as to how to show this to best help students was not something we had much information of. Given our lack of expertise on the subject, and the limited time the most we could do was talk to Professor Porter, look through videos of how she has taught with them, and attempt to create 4 breathing modes similar to those she's used. However, a more indepth search into the most beneficial way to use this may lead to a better set of modes to have for our design. We could have conversations with music students that are either struggling with diaphragmatic breathing or music students in general to determine what would be the most beneficial to be seen on the latex lung. This way we could ensure that our mechanism for inflating the lung would help students the most.

In terms of the actual design to address our current problem statement, this design worked very well to achieve our 4 defined breathing modes. It was able to be switched from each breathing mode accurately. Our choice of the linearly actuated syringe system, actuated with a stepper motor and using a lead screw to lead to linear motion was very effective. It allowed us precise control over how much inflation and the speed of inflation through changing the step count and steps per second within the code. We were also able to fit this within the desired size requirement we set although it was a tight fit.

Which leads to one of the weaknesses of our design. To minimize the size of our prototype we had to squeeze many components close together, which made for a rather difficult assembly. This was mainly an issue with the syringe barrel mount and mounting the arduino. It was very difficult to disassemble and assemble, meaning making changes after assembly was very time consuming. There are a couple of changes that could be made to address this, the first simply being to increase the size of the case, however, we would have to check this with our sponsor. This would overall help the assembly everything, and allow space to compartmentalize barriers for the Arduino and Batteries making it easier to place and remove them.

Another weakness our design had was the noise it made. This wasn't something we expected as we observed our motor was very quiet at the required speeds while testing it. However, we didn't consider the vibration it would have and how much noise that would create. There were two main places of noise, one was where the motor contacted the bottom case, and the second was the contact point between the bottom case and the top case. Both of these could be mitigated significantly to just about reduce the noise beneath our 50 dB limit if we were able to add foam, however, the added foam raised and tilted the motor too much which caused issues with its connection to the linear system. Our design of the top and bottom case also didn't allow for much space to add any noise dampeners between them. Another large source of noise was the contact point between the bottom of the case and the surface it would rest upon, however, we added foam pads to the bottom of the case to mitigate this. Other than foam, we believe this issue could be further solved by reducing the vibration of the motor. To our surprise, the motor didn't vibrate the most at our fastest speed but rather at our slower speeds. One option is to increase the speeds to help reduce the vibration, however, we believe there are ways to reduce the vibration in general. One such way would be to use a higher step count for our motor. This would be a simple change as one additional wire would be needed to tell the motor driver to operate at the higher step count. However, this would reduce the torque our motor is able to produce but we did not have any specification in our motor's data sheet for how much this would reduce, and we did not have sufficient time for testing. To address this, a different motor with specifications for a higher step count could be found, or additional testing on whether the motor operating at a higher step count would still supply sufficient torque could be done.

Outside of this there were still some other problems we faced in our design process that we were able to address. One of the main problems had to do with the electrical side, while we all had a basic understanding of electronics none of us had done as much electrical design work as this required. In addition, mistakes with the electrical wiring would quickly lead to damaged components. To help mitigate this we ordered extra components ahead of time so damaging components wouldn't lead to us needing to wait for these components to arrive after reordering. This was helpful as we did end up damaging an Arduino, but didn't have to wait to continue testing. We also made sure to make wiring diagrams that we sent to our ME sponsor with more experience to verify that our wirings were correct, and then also had him look at our wiring in person to ensure our wiring was good. This helped stop us from making mistakes that could have led to damaged components. Our lack of experience with dealing with electronic wiring could also mean our testing for the safety of the electronics of our design may not be completely accurate. We did our best to follow the standards in BS EN IEC 62368-1, however, we could have made mistakes due to our inexperience. Which could pose a danger to the end-user of the device. Therefore, it may be a good idea to have an outside party with more experience with electronics to conduct safety tests.

REFLECTION

As a product designed for the music community, there are various contextual factors that are relevant to our final product, and we used a stakeholder map to characterize the potential societal impacts of our design. The MBB 3.1 improves public health and safety by promoting safer teacher-student boundaries through its touchless teaching capabilities. In terms of a global context, the portability of the MBB 3.1, with its battery-powered design as opposed to being powered through a wall outlet, makes it suitable for just about any teaching environment around the world. A potential social impact associated with the use of our product is that it may be priced out of reach for underserved communities even though it has been designed to keep costs relatively low—automating the breathing modes may be adding a cost that is too high for some music teachers. However, if the product is economically successful, this would positively impact our sponsor who has invested capital into the development of this product.

The members of our team come from a diverse array of cultural backgrounds, and we all are pursuing different careers with our degrees post-grad. These differences lended themselves to differing ways of thinking from each team member that ultimately benefited the project. We had established a consensus for the goals of the project early on in the timeline, and with our sights set on the future, we held open dialogues to discuss what methods we would use to accomplish our goals. The diversity of our group was helpful in uncovering shortfalls throughout all stages of our project, which may not have been caught if we all operated in a similar manner. Specifically, the benefit of our differences became apparent as we discussed different design concepts early in the project, and as we delegated tasks later on that suited each person's strengths. We also relied on our sponsor's expertise in music teaching to guide the direction of our project, which influenced how the MBB 3.1 displayed the four breathing modes as well as what form the component box took.

As four engineers with limited experience and knowledge of the music world, we relied heavily on input from our sponsor and other stakeholders to understand the purpose and goals of our project. Because of our lack of knowledge, it was sometimes difficult to grasp the impact of our efforts, but we had multiple meetings with our sponsor to take in their input and then held open discussions within the team to ensure we considered all options to satisfy the needs of our project. At times, our sponsor's desires wouldn't necessarily align with what was feasible from our engineering perspective and timeline. In these cases, we would give suggestions or guide the conversation in a direction that better met what was possible while still keeping our sponsor happy with the project.

There weren't many ethical dilemmas faced in the design of this project, but we often thought about the environmental impact of our work. There are a few components in our design that are made of plastic, such as the casing and the mounts within the component box. Throughout the project, we had to print multiple iterations of these components as we adjusted our design, which added onto our overall plastic consumption. However, we understood that the need to print several versions was a natural part of the prototyping process, and that we could potentially use different materials in the future such as recycled plastic or metal. Using recycled materials could increase the manufacturing cost if this product were to enter the marketplace, though, so this is an issue that should be considered carefully. Aside from just environmental impact, though, our personal ethics align with the professional ethics expected to be upheld by the University of Michigan and future employers. Specifically, we all want to work on projects that have a positive benefit on society and as we work on these projects, we want to be faithful agents for the teams we work on so that we can produce the best work possible.

RECOMMENDATIONS

The main issues with our design mentioned in the discussion were the noise level and its assembly. The easiest fix to reduce noise level would be to increase the step count at which the motor operates at. Our system is controlled using an Arduino, which operates at a very low cycle rate. As discovered and confirmed by our ME sponsor, stepper motors that operate at a low cycle rate tend to be very loud, which may be related to the higher torque output. Therefore, to make the motor quieter and reduce its vibrations, we can increase the step count by changing the wiring of the system and the code controlling it. This is a very easy and fast fix that if does not work has no negative consequences on the system, so this is our first recommendation. Attempts were made to dampen the noise level of the device using foam. Foam was placed underneath and behind the motor, the component that caused the most noise, which propagated through the walls of the case. However, the actuation components within the case were designed with as little tolerance as possible so the case could be as small as possible, which was desirable for our sponsor. Therefore, the addition of approximately 3 millimeters of foam behind the motor caused the system to bind and not function. If foam is a desirable method to dampen the motor for future iterations of this device, we recommend increasing the length of the case by the thickness of the foam used to reduce the risk of the system binding. A similar consideration should be made if placing foam between the bottom of the motor and the interior floor of the case. That being said, we do not believe this is the most effective solution for physical noise reduction. We recommend using rubber shock-absorbing washers between the wall and the motor. The motor will no longer be directly in contact with the wall and the vibrations from the motor will be absorbed in the rubber, reducing its propagation through the case walls, which created a high noise level. Furthermore, in the current design, the motor is mounted to the wall of the case and rests on the interior floor. We also recommend to “float” the motor, or mount it a few millimeters above the interior floor so it is no longer in contact with it. This would decrease the area in which the motor is in contact with the case, reducing its ability to propagate noise. Reducing the point of contact of the motor to strictly the wall means it is now a cantilever, so calculations and testing must be performed to ensure it does not deflect and cause the actuation system to bind. Our final recommendation to decrease the noise level is to put a rubber gasket along the interface between the top part of the case and the bottom part of the case. The case components were 3D printed, which meant they did not sit perfectly flush against one another. When the motor was operating, the vibrations traveled up the wall and caused this interface to rattle, no matter how securely attached they were. A rubber gasket between these two surfaces would help to absorb the vibrations and further reduce noise. Finding an off the shelf gasket the correct dimensions for the case may be challenging, so we recommend trying other noise damping methods before searching for this component or custom making it.

Our design also was challenging to assemble. It had poor access to fasteners, causing the mounting of components within the case very difficult and it was extremely challenging to access the electrical components once the circuit board was secured to the wall of the case. The port to upload code to the Arduino was completely blocked, which meant the entire circuit board would need to be removed in order to make software updates to the system, which is undesirable. A design change that would overcome both of these issues would be to change where the interface between the top and bottom cases were. Currently, the top case is rather shallow and the bottom case is very deep, meaning the walls of the bottom case are high and block access to components within it. If this was to be reversed, such that the bottom case was shallow and the top case was deep, then the walls of the bottom case would not block access to components. This would allow for better tool access, making assembly easier and faster. Furthermore, the circuit board would now be mounted to a wall of the top case while all other components are mounted to the bottom case. Removal of the top case would then provide easy access to the circuit board as no other components would get in the way, allowing software updates to occur. Another small detail to simplify assembly would be to use regular hex nuts instead of locknuts. Given the assembly troubles we already faced, locknuts were nearly impossible to use. We relied on lack of friction between the hex nuts and screw threads before tightening the nut down, so the added friction of locknuts caused additional challenges in our assembly. We did not run into issues with the hex nuts loosening during operation, so we do not believe locknuts are necessary for our design and would recommend using hex nuts in the future.

PROJECT PLAN

In order to organize our project timeline and mitigate risks throughout the process, we've created a Gantt chart to provide the team with actionable steps to follow throughout the semester, as shown in Figure 30.

TASK NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	DR1				
1.1	Introduction	8/27/24	8/30/24	3	100%
1.2	DR1 Presentation	9/3/24	9/24/24	21	100%
1.3	DR1 Report	9/24/24	10/1/24	7	100%
2	DR2				
2.1	Concept Generation & Selection	9/24/24	10/17/24	23	100%
2.2	DR2 Presentation	10/3/24	10/10/24	7	100%
2.3	Design Development	10/17/24	10/22/24	5	100%
2.4	DR2 Report	10/15/24	10/22/24	7	100%
3	DR3				
3.1	Design Development	10/22/24	10/29/24	7	100%
3.2	DR3 Presentation	10/29/24	11/5/24	6	100%
3.3	Alpha Protytpe Build	10/23/24	11/9/24	16	100%
3.4	DR3 Report	11/5/24	11/12/24	7	100%
4	DR4				
4.1	Design Updates	11/10/24	11/14/24	4	100%
4.2	Second Round Build	11/14/24	11/18/24	4	100%
4.3	Second Round Verification	11/18/24	11/21/24	3	100%
4.4	Stakeholder Validation	11/18/24	11/21/24	3	100%
4.5	DR4 Presentation	11/16/24	11/21/24	5	100%
5	DESIGN EXPO & FINAL REPORT				
5.1	Contingency Time for Final Changes	11/21/24	12/3/24	12	100%
5.1	Design Expo Poster	11/28/24	12/3/24	5	100%
5.3	Final Report	12/3/24	12/16/24	13	100%

Figure 30: Full-semester Gantt chart.

We have divided our semester plan into five phases based on the ME 450 milestones. Within each phase are a set of high-level tasks, and the colored boxes on the right side correspond to the weeks within the project timeline that the tasks will be completed. The Duration column shows how many days are allocated for each task. While the full-semester Gantt chart displays the project at a high level, more detailed subtasks are shown in later figures.

Understanding that we will simultaneously be completing ME 450 assignments while making progress toward our sponsored project, we have designated time for working on the project itself while leaving time at the end of each phase to complete the ME 450 group assignments within each phase shown. The time designated for ME 450 assignments will not entirely pull our focus away from the project, though, as the first tasks in the successive phase overlap with the ME 450 tasks in the current phase. Creating these overlapping yet distinct tasks helps our team understand that we need to set time aside to complete the assignments while still emphasizing the importance of continuing work on the project to be able to meet our final deliverable goals.

As mentioned in previous sections, our design process is meant to be iterative, and thus we have designated time for iteration in our project timeline. Notably, there is time designated for two rounds of design, building, and verification. And if additional updates are needed at the end of the semester, there is a three week stretch of contingency time in Phase 5 for any final changes. These designated times will allow our group to be intentional about iteration in order to achieve the best possible end product.

Due to the nature of this project being a semester long and only spanning 16 full weeks, the time we have to work may certainly feel a bit crunched throughout the project. However, after having thorough conversations with our sponsor and mentors, and understanding the scope of the project as explained in previous sections, we believe our expected deliverables are absolutely achievable by the end of the semester. Budget-wise, because our product is a small device meant to be marketed at a low price, we are not worried about exceeding our budget during the development of our prototypes.

TASK NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE	DR1					DR2			DR3			DR4		EXPO & FINAL REPORT		
							1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	**DR1**																					
1.1	**Introduction**		**8/27/24**	**8/30/24**	**3**	**100%**																
1.1.1	Meet the Team	Entire Team	8/27/24	8/30/24	3	100%																
1.1.2	Meeting with Prof. Porter & MBB Introduction	Entire Team	8/29/24	8/30/24	1	100%																
1.2	**DR1 Presentation**		**9/3/24**	**9/24/24**	**21**	**100%**																
1.2.1	Perform Background Research	Elijah & Rohan	9/3/24	9/10/24	7	100%																
1.2.2	Develop Problem Statement	Cole & Josh	9/3/24	9/12/24	9	100%																
1.2.3	Create Stakeholder Map	Cole	9/10/24	9/19/24	9	100%																
1.2.4	Define Requirements and Specifications	Entire Team	9/10/24	9/19/24	9	100%																
1.2.5	Identify Anticipated Challenges	Josh	9/10/24	9/19/24	9	100%																
1.2.6	Confirm Requirements with Prof. Porter	Entire Team	9/17/24	9/19/24	2	100%																
1.2.7	Prepare DR1 Slides	Entire Team	9/19/24	9/24/24	5	100%																
1.2.8	Presentation Practice	Entire Team	9/21/24	9/24/24	3	100%																
1.3	**DR1 Report**		**9/24/24**	**10/1/24**	**7**	**100%**																
1.2.7	Revisions Based on Presentation Feedback	Entire Team	9/24/24	9/26/24	2	100%																
1.2.8	Submit DR1 Report	Entire Team	9/24/24	10/1/24	7	100%																

Figure 31: Phase 1 subtasks.

Figure 29 above shows more detailed subtasks that were accomplished in Phase 1. This phase involved a lot of early communication with our sponsor and mentors, as well as becoming familiar with the previous semester's MBB 3.0, to fully understand and define the problem our group is aiming to solve. Because of the introductory nature of this phase, much of the subtasks were assigned to the entire team as it was important for the entire team to be involved in the early stages of this project. The flow of this phase went smoothly for our group, and it informed how we chose to lay out our plan for Phase 2 going forward, which is shown below in Figure 30.

TASK NUMBER		TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
2		**DR2**				
2.1		**Concept Generation & Selection**	**9/24/24**	**10/17/24**	**23**	**100%**
	2.1.1	First Round Brainstorming & Analysis	9/24/24	10/1/24	7	100%
	2.1.2	Second Round Generation & Analysis	10/1/24	10/10/24	9	100%
	2.1.3	"Alpha Design" Selection	10/10/24	10/17/24	7	100%
2.2		**DR2 Presentation**	**10/3/24**	**10/10/24**	**7**	**100%**
	2.2.1	Prepare DR2 Slides	10/3/24	10/10/24	7	100%
	2.2.2	Meetings with Prof. Awtar & Revanth	10/8/24	10/10/24	2	100%
	2.2.3	Presentation Practice	10/8/24	10/10/24	2	100%
2.3		**Design Development**	**10/17/24**	**10/22/24**	**5**	**100%**
	2.3.1	Concept Review with Prof. Awtar & Revanth	10/15/24	10/16/24	1	100%
	2.3.2	Select Electro-Mechanical Components	10/15/24	10/17/24	2	100%
	2.3.3	CAD Prototyping	10/17/24	10/22/24	5	100%
2.4		**DR2 Report**	**10/15/24**	**10/22/24**	**7**	**100%**
	2.4.1	Revise DR1 Using Feedback	10/15/24	10/17/24	2	100%
	2.4.2	Update Project Plan	10/15/24	10/17/24	2	100%
	2.4.3	Submit DR2 Report	10/15/24	10/22/24	7	100%

Figure 32. Phase 2 subtasks.

One of the biggest pieces of feedback from last semester's MBB team was that they did not spend enough time on concept generation, and went with the first and most straightforward design that would work. Taking this advice into consideration, we chose to allocate two weeks of time to narrow down our concept to our "alpha design" when scheduling Phase 2. Prior to the completion of this section, we wanted to have our alpha design chosen by the deadline of 10/10 in time for the DR2 presentation. However, after speaking with our lab section instructor, we elected to delay this decision until 10/17 to allow for our team to further analyze potential solutions to make the most accurate choice for our Alpha design. This change has been updated within Figure 21. We would like to mitigate the risk of long lead times, and our deadline of 10/17 to select electro-mechanical components will allow us to order parts early enough such that minor delays will not have a significant impact. Moreover, looking back at the full-semester Gantt chart in Figure 19, there are three total weeks allocated between 2.2 Design Development and 3.1 First Round Building, which means there should be ample time for parts to arrive and be integrated into the first prototype. Figure 31 below represents Phase 3 of our design process, where we will focus on the detailed design and our prototype build.

TASK NUMBER		TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
3		**DR3**				
3.1		**Design Development**	**10/22/24**	**10/29/24**	**7**	**100%**
	3.1.1	CAD Review with Prof. Awtar & Revanth	10/22/24	10/24/24	2	100%
	3.1.2	CAD Updates	10/24/24	10/29/24	5	100%
3.2		**DR3 Presentation**	**10/29/24**	**11/5/24**	**6**	**100%**
	3.2.1	Prepare DR3 Slides	10/29/24	11/5/24	6	100%
	3.2.2	Meetings with Prof. Awtar & Revanth	10/29/24	10/31/24	2	100%
	3.2.3	Presentation Practice	11/3/24	11/5/24	2	100%
3.3		**Alpha Protytpe Build**	**10/23/24**	**11/9/24**	**16**	**100%**
	3.3.1	Order Parts	10/23/24	10/24/24	1	100%
	3.3.2	Manufacture Components	10/23/24	11/5/24	12	100%
	3.3.3	Code Controls	10/23/24	11/5/24	12	100%
	3.3.4	Create Wiring Diagram	10/23/24	11/5/24	12	100%
	3.3.5	Assemble	11/5/24	11/7/24	2	100%
	3.3.6	First Round Verification	11/7/24	11/9/24	2	100%
3.4		**DR3 Report**	**11/5/24**	**11/12/24**	**7**	**100%**
	3.4.1	Revise DR1 Using Feedback	11/5/24	11/7/24	2	100%
	3.4.2	Update Project Plan	11/5/24	11/7/24	2	100%

Figure 33: Phase 3 subtasks.

Phase 3 largely consisted of the completion of our detailed engineering design in the first week. Using our selected Alpha design, and changes were made based on the results of further testing and analysis. After consulting with Professor Awtar and our mentor to ensure our design is feasible before moving forward with prototyping. We have purposely made the prototyping phase long to ensure ample time to order parts and iterate on the design, even going back to the selection process if a new design is necessary. The prototyping phase encompasses the manufacture and assembly of all components, but also the creation of a wiring diagram and development of software to control the device. We have given ourselves a week to complete both the electrical and software tasks because we feel most unfamiliar with them, spending a longer period working on them will ensure they are done correctly. Because of the ample time we have built in for prototyping and potential errors, we feel confident that we will be able to complete this project within the semester. Going into Phase 4, the tasks therein have been assessed in Figure 32.

TASK NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
4	**DR4**				
4.1	**Design Updates**	**11/10/24**	**11/14/24**	**4**	**100%**
4.1.1	Meet with Prof. Awtar & Revanth to go in depth with CAD review	11/10/24	11/12/24	2	100%
4.2.2	Update design (if necessary)	11/12/24	11/14/24	2	100%
4.2	**Second Round Build**	**11/14/24**	**11/18/24**	**4**	**100%**
4.2.1	Assemble	11/14/24	11/16/24	3	100%
4.3	**Second Round Verification**	**11/18/24**	**11/21/24**	**3**	**100%**
4.2.1	Meet with Prof. Awtar & Revanth to verify requirements	11/18/24	11/19/24	2	100%
4.4	**Stakeholder Validation**	**11/18/24**	**11/21/24**	**3**	**100%**
4.4.1	Meet with Prof. Porter to validate requirements	11/18/24	11/19/24	1	100%
4.5	**DR4 Presentation**	**11/16/24**	**11/21/24**	**5**	**100%**
4.5.1	Prepare DR4 Slides	11/16/24	11/19/24	3	100%
4.5.2	Meetings with Prof. Awtar & Revanth	11/16/24	11/19/24	3	100%
4.5.3	Presentation Practice	11/17/24	11/20/24	3	100%

Figure 34: Phase 4 subtasks.

Phase 4 was crucial for making adjustments to our design in order to ensure that our product could achieve its intended function. One issue that we initially ran into was that the holes and slots in our 3D prints came out smaller than we anticipated, so we had to adjust the sizing to be bigger and then reprint them. We also discovered that we needed a longer screw to mount our motor than we had planned for, so we had to order more parts which set us back a couple days. Thankfully, though, our built-in iteration time made these obstacles a non-issue for us in terms of time.

TASK NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
5	**DESIGN EXPO & FINAL REPORT**				
5.1	**Contingency Time for Final Changes**	**11/21/24**	**12/3/24**	**12**	**100%**
5.2	**Design Expo Poster**	**11/26/24**	**12/3/24**	**7**	**100%**
5.2.1	Prepare Poster	11/26/24	11/30/24	4	100%
5.2.2	Feedback from Prof. Awtar & Revanth	11/30/24	12/2/24	2	100%
5.2.3	Update Poster Using Feedback	12/2/24	12/3/24	1	100%
5.3	**Final Report**	**12/3/24**	**12/16/24**	**13**	**100%**

Figure 35: Phase 5 subtasks.

Phase 5 came quickly and was essentially a continuation of Phase 4. We ran into some issues with the electrical wiring of our circuit, which led to a short circuiting of our Arduino. However, after careful analysis of our circuit assembly, we identified the issue, replaced the Arduino, and everything worked smoothly. In the end, we had a fully functioning product to show at the Design Expo and we are very happy with the MBB 3.1 final product.

CONCLUSION

A strong understanding and execution of breathwork is critical for wind musicians in achieving proper musical tone, volume, and expression. The My Breathing Buddy (MBB) is a manually pumped lung, rib cage, and diaphragm simulator that demonstrates breathwork to help musicians visualize and understand breathing mechanics from an anatomical perspective. A need has been generated for the MBB to become automated to simplify its use and allow music teachers to focus on other aspects of the students' performance, such as posture. Through discussions with our project sponsor and research on our own, we devised a group of stakeholders, and from their needs a list of functional requirements and engineering specifications for the MBB 3.1. A variety of concepts were generated to determine a viable solution to the problem, first focusing on divergent thinking. Once the solution space was thoroughly explored, we used convergent thinking techniques to narrow the design space to 5 potential solutions. These designs were further analyzed before selecting one as our Alpha design. Off-the-shelf components were selected to develop this design and it was modeled in CAD. After additional analysis and conversations with our stakeholders, changes were made to the Alpha design and a final detailed design was developed. This design minimized part count and focused on decreased complexity of novel parts to simplify the manufacturing process. The design has begun to go through a rigorous verification process to ensure all the functional requirements and engineering specifications have been met. Theoretical and mathematical analysis has been used to verify multiple requirements and a variety of empirical tests have been planned. These tests will occur once a prototype of the detailed design has been finished. A validation testing plan has also been created and has been performed on the Final Build to check if the MBB 3.1 is a successful solution to the problem statement. After some minor changes to the case of the MBB 3.1, the Final Build has been assembled and has been delivered to Professor Amy Porter. Thus completing the goal of this assignment.

ACKNOWLEDGMENTS

We would like to thank our sponsor Professor Amy Porter for creating the My Breathing Buddy and this ME450 Project, we were able not only able to grow as engineers during this project but also learn about the anatomy of the respiratory system and techniques used in music instruction. We would also like to thank Professor Shorya Awtar and Revanth Damerla for guiding us throughout this project and making sure we were completing a rigorous exploration of the engineering design process. Finally we would like to thank the entire ME450 staff for their support, the ME Undergraduate Machine Shop for their manufacturing and assembly advice, and special thanks to Kemal Duran for his assistance in troubleshooting our electrical subsystem.

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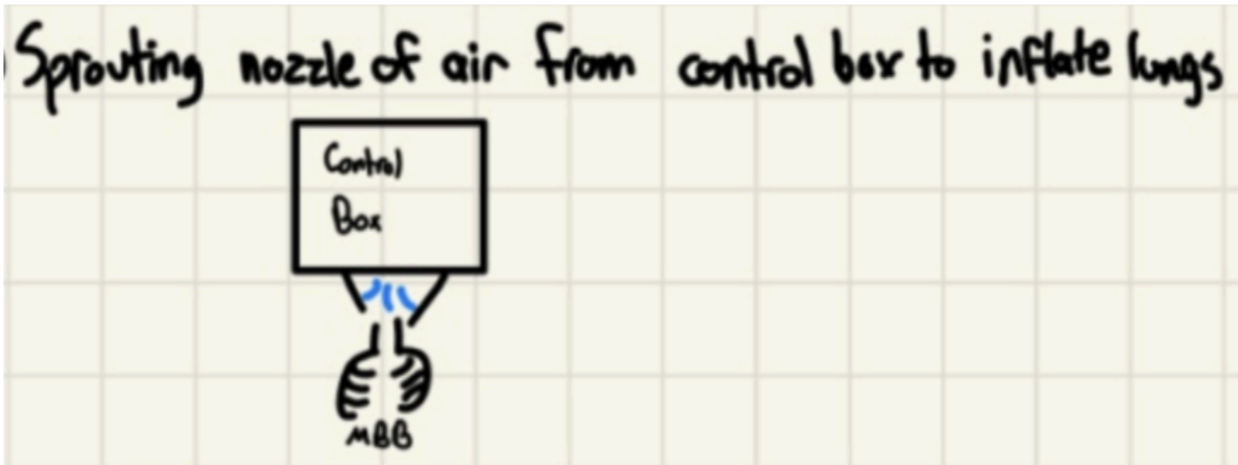
APPENDIX

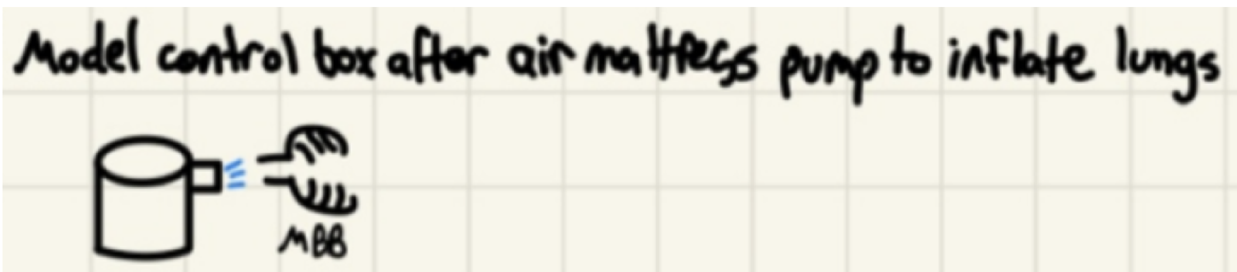
Fan Requirement Calculation

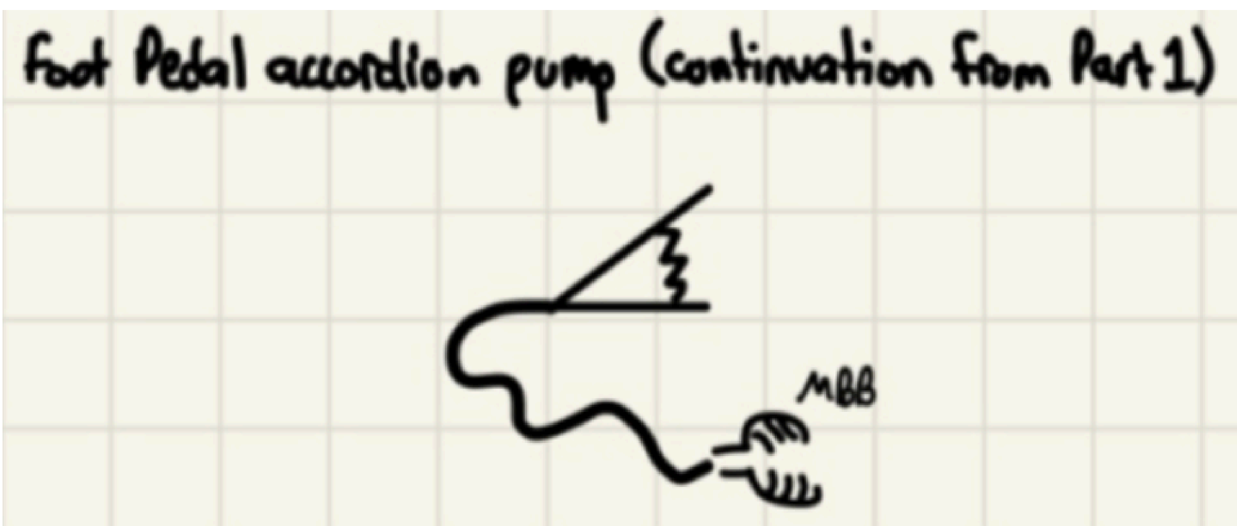
- Average maximum pressure to inflate lungs: 2063.43 Pa [19]
- Average minimum pressure to inflate lungs: 832.34 Pa [19]
- Using Bernoulli's equation[42]:
  - $P = \frac{1}{2} \rho v^2$
    - *P: Pressure*
    - *ρ: Density of Air*
    - *v: Air Speed*
  - Therefore max air speed required to inflate lungs is 36.9 ms^{-1}
- Fan moves 3.5 cubic feet per minute which is about 0.002 cubic meters per second
- Area of the fan outlet is 0.0009 square meters [33]
- Dividing volumetric flow rate by the area of the fan outlet gives an air speed of 2.83 ms^{-1}

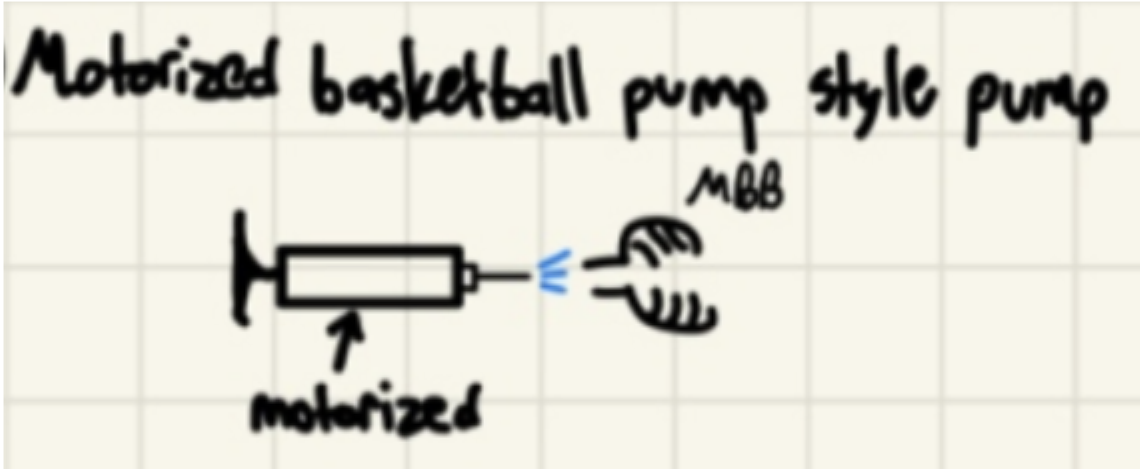
List of 20 Concepts Developed during Concept Generation

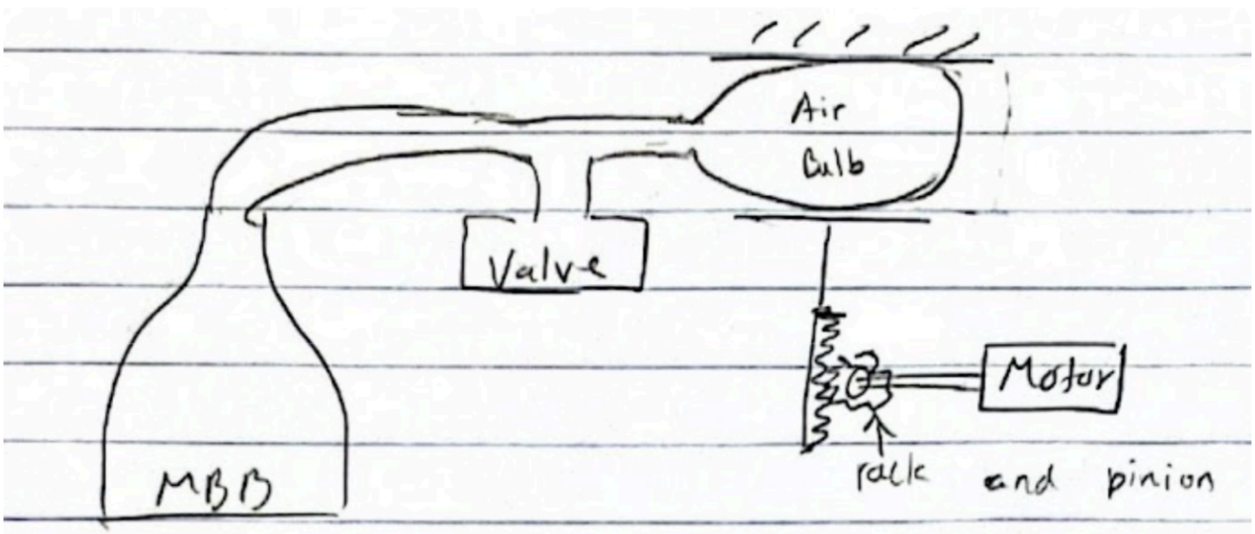
1. 

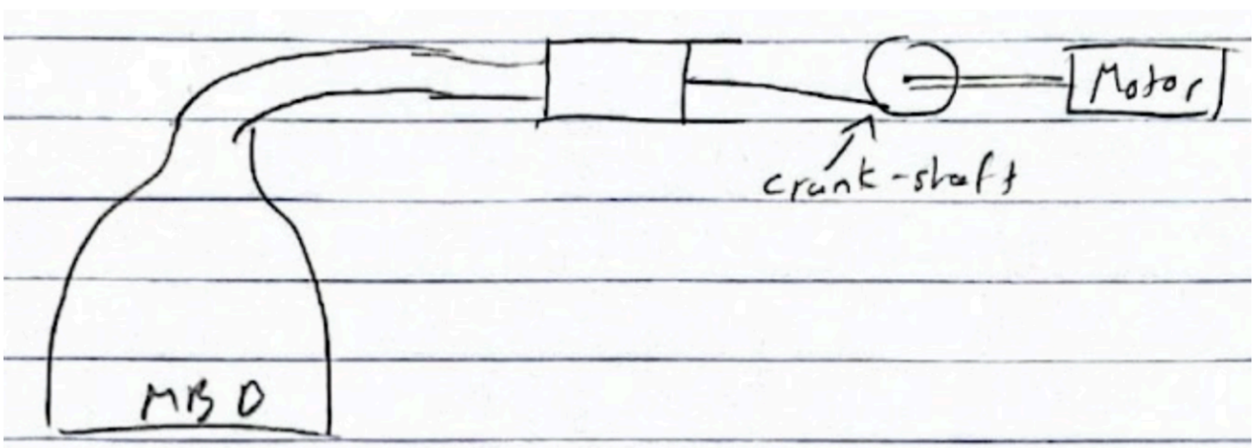
2. 
Sprouting nozzle of air from control box to inflate lungs
Control Box
MBB

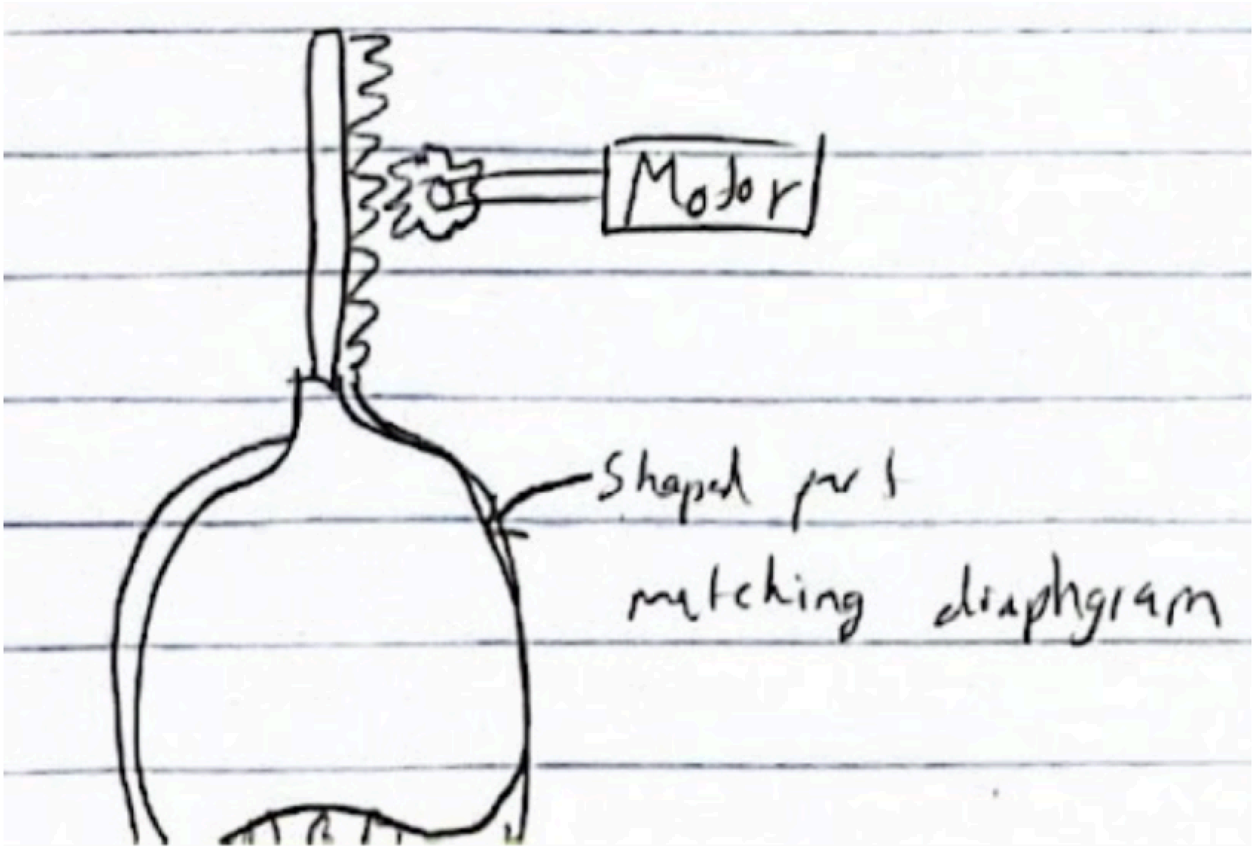
3. 
Model control box after air mattress pump to inflate lungs
MBB

4. 
Foot Pedal accordion pump (continuation from Part 1)
MBB

5. 
Motorized basketball pump style pump
MBB
motorized

6. 
Air
bulb
Valve
Motor
rack and pinion
MBB

7. 
Motor
crank-shaft
MBB



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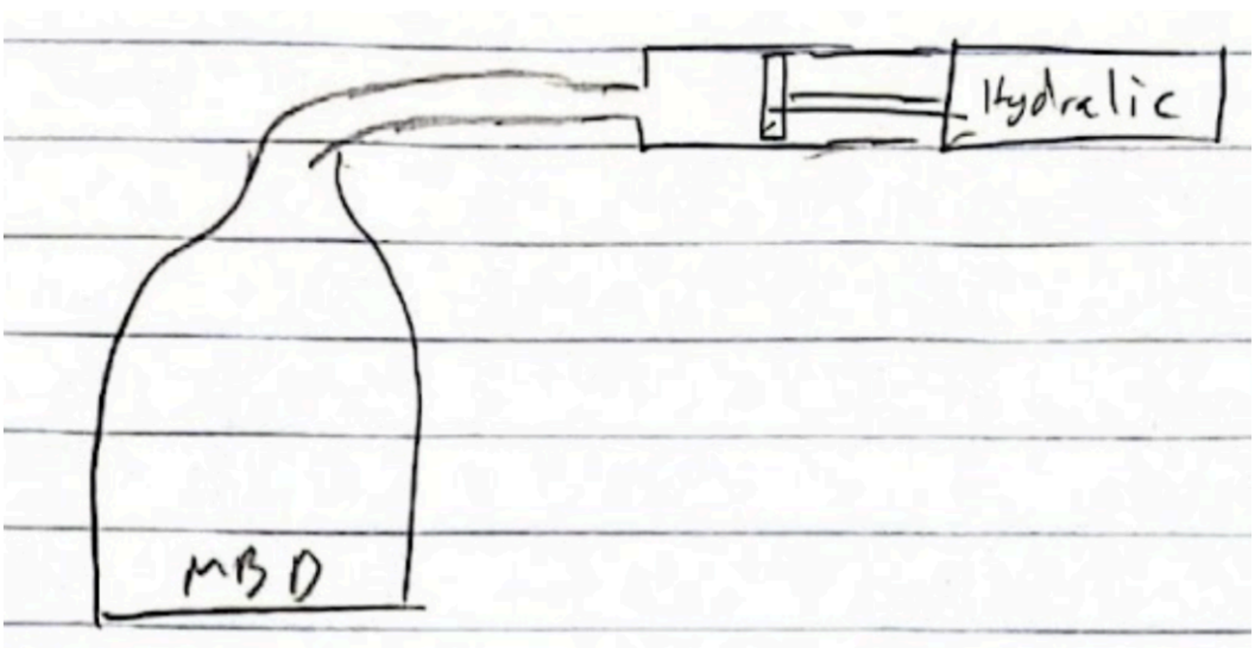
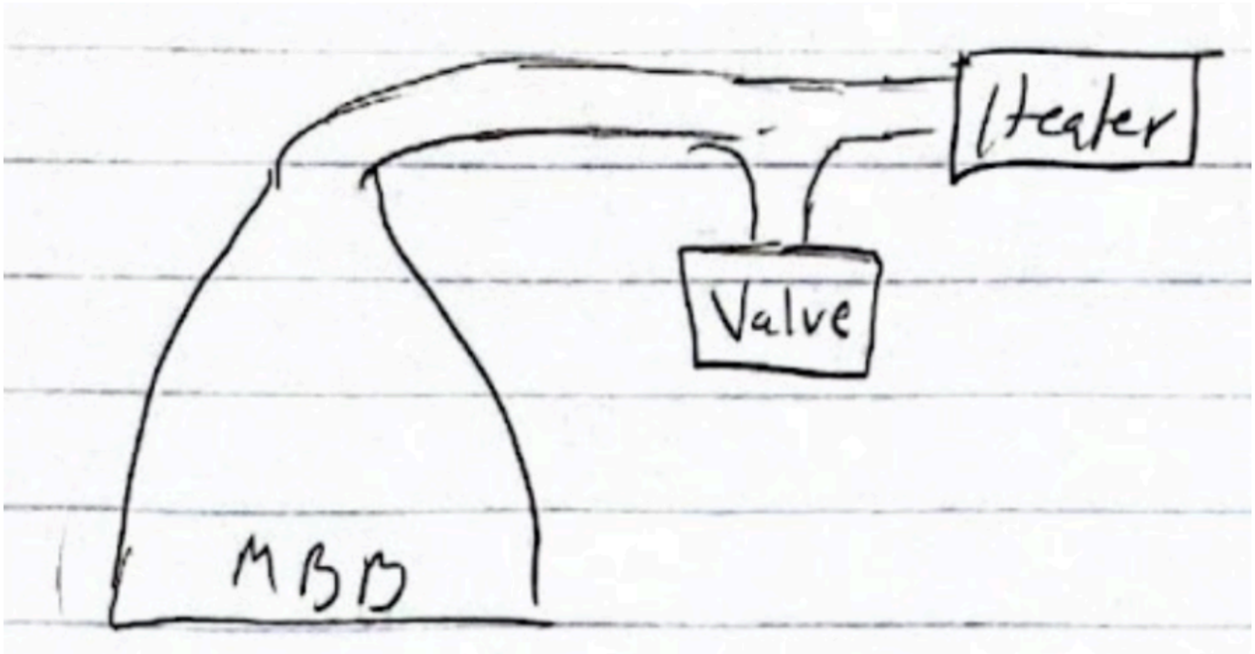
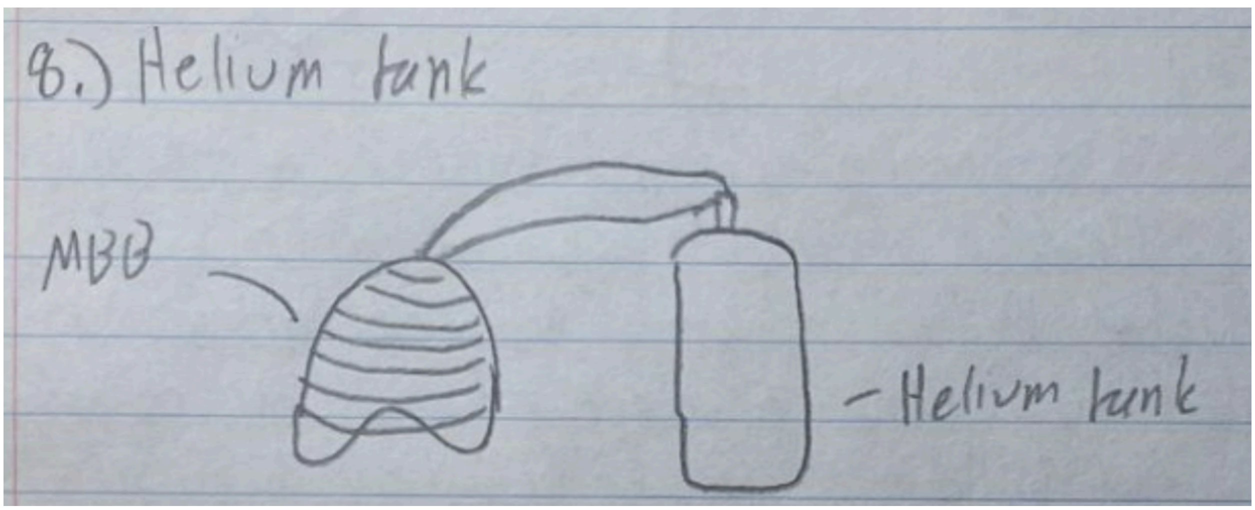


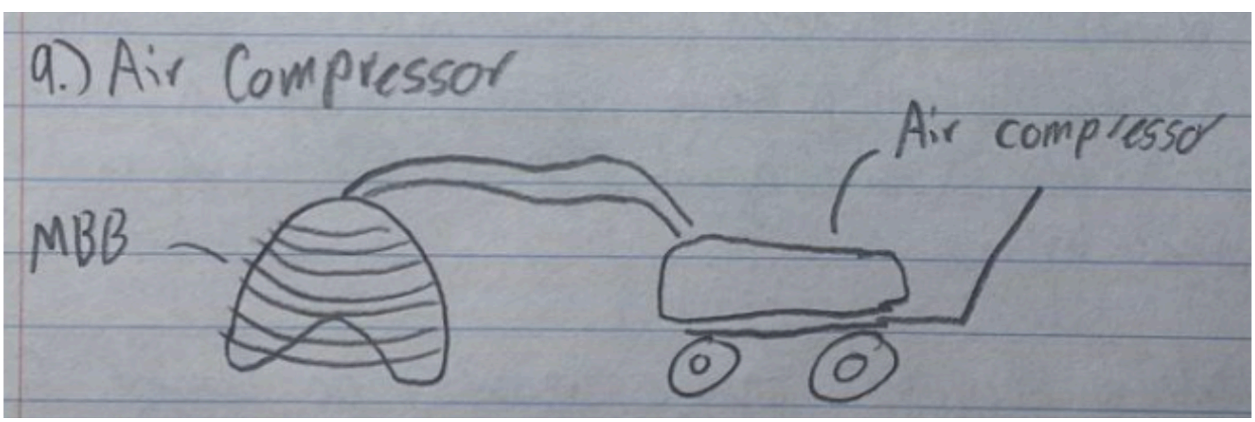
9.


Heater
Valve
MBB

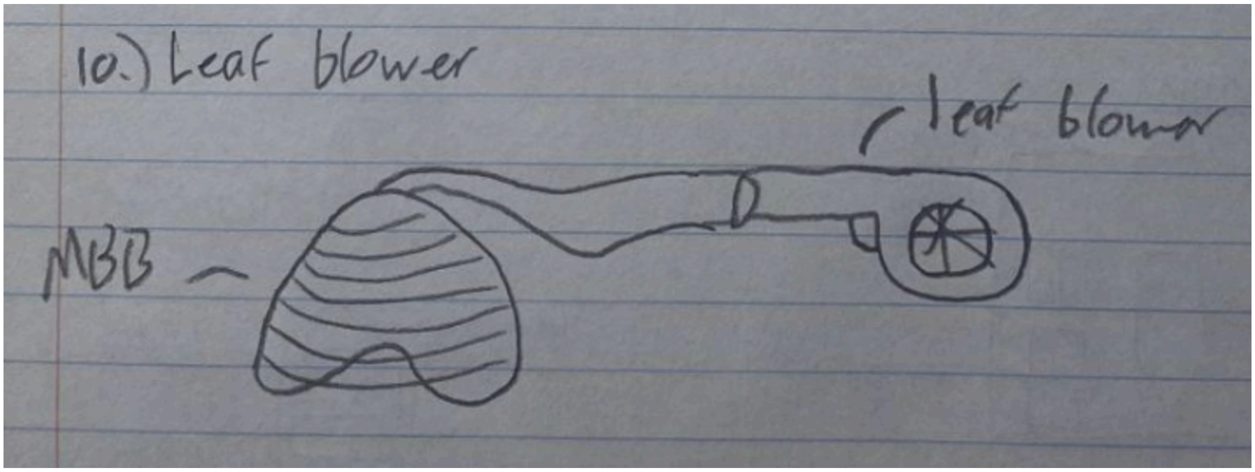
10.

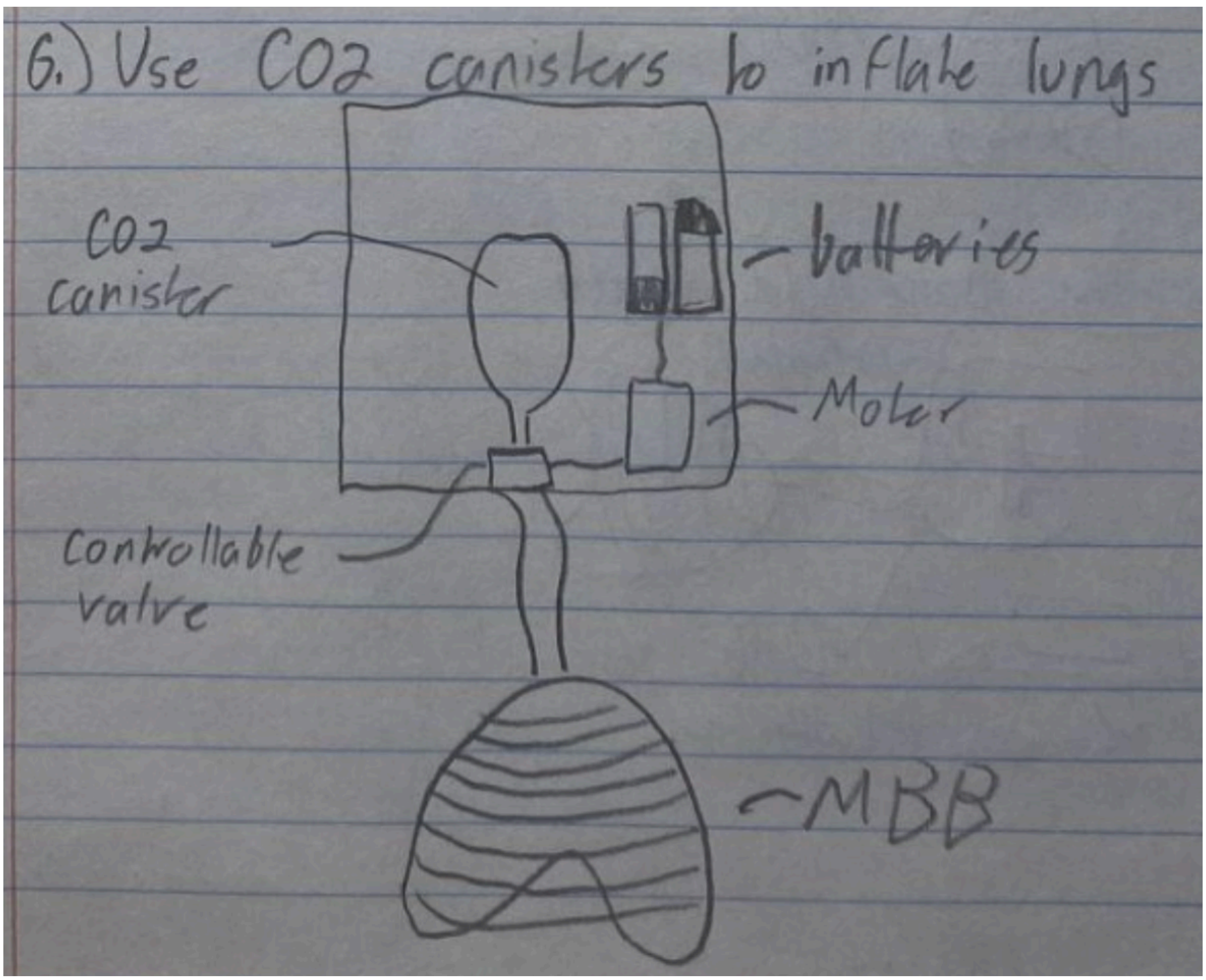

8.) Helium tank
MBB
Helium tank

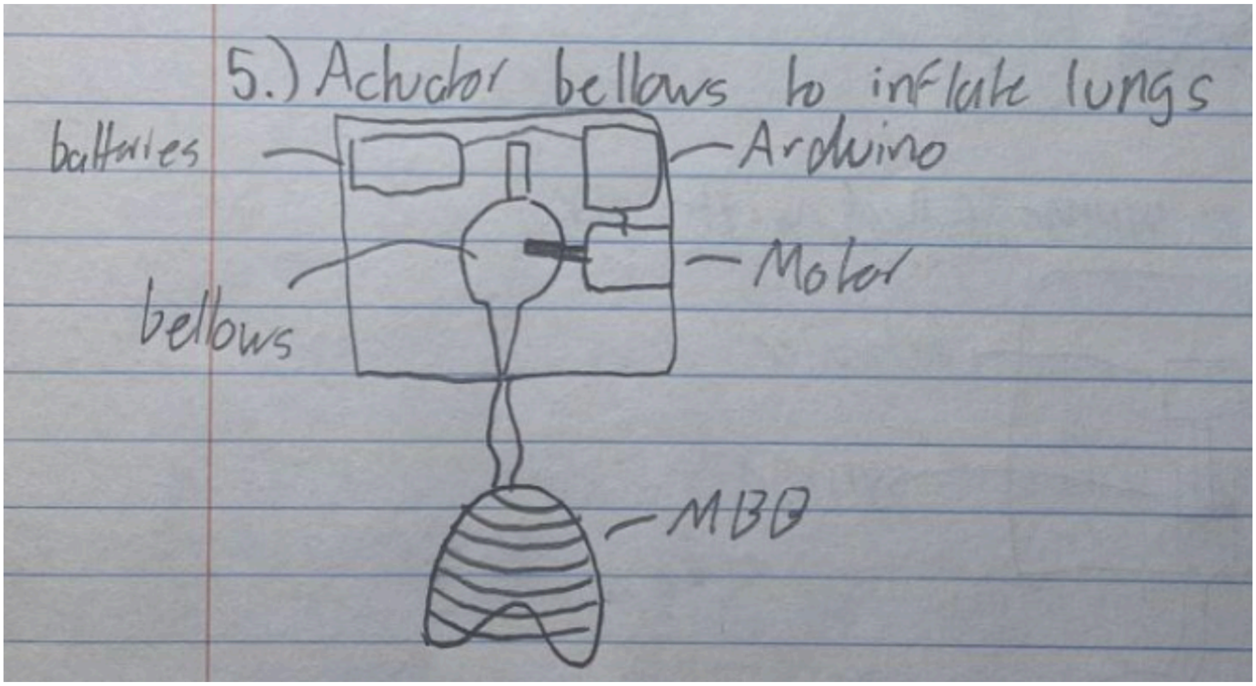
11.

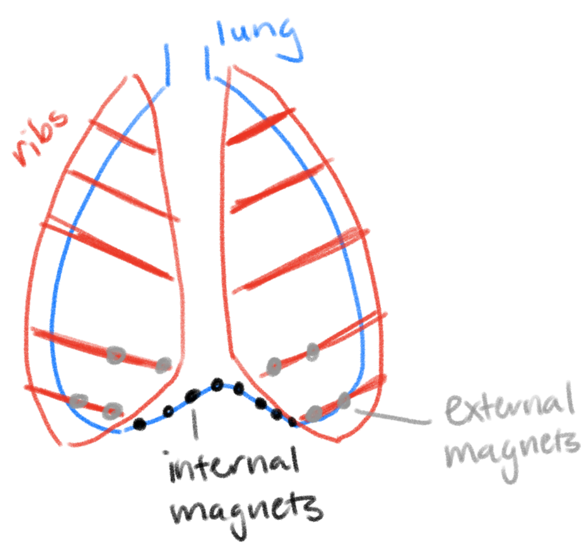

9.) Air Compressor
Air compressor
MBB

12.

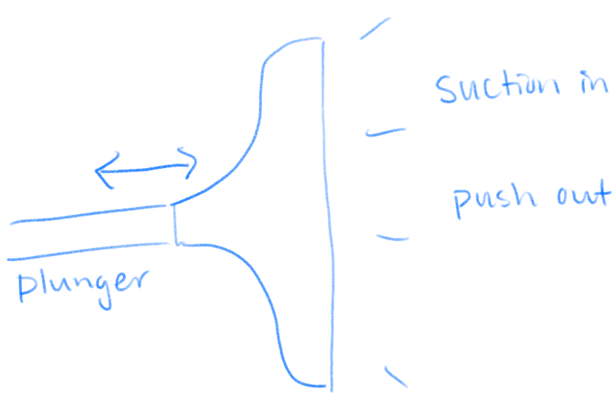
13. 
10.) Leaf blower
leaf blower
MBB

14. 
6.) Use CO2 canisters to inflate lungs
CO2 canister
batteries
Motor
controllable valve
MBB

15. 
5.) Actuator bellows to inflate lungs
batteries
Arduino
Motor
bellows
MBD


lung
ribs
external magnets
internal magnets

16.


Suction in
push out
plunger

17.

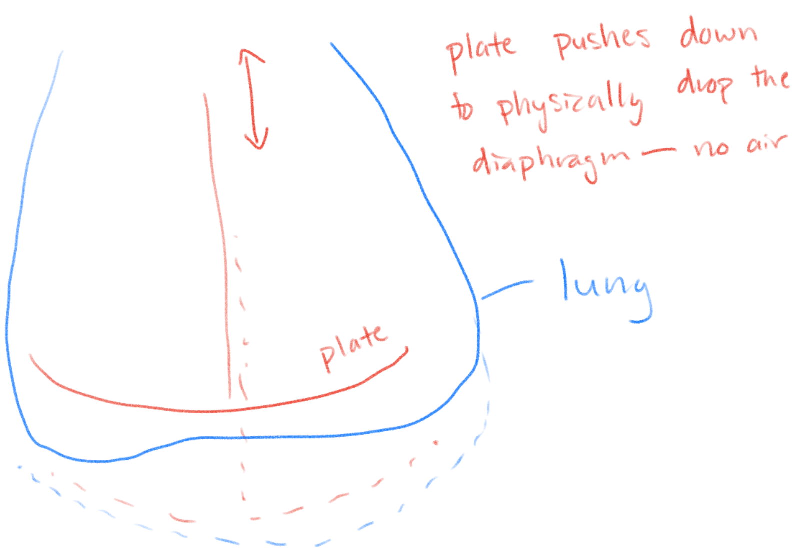
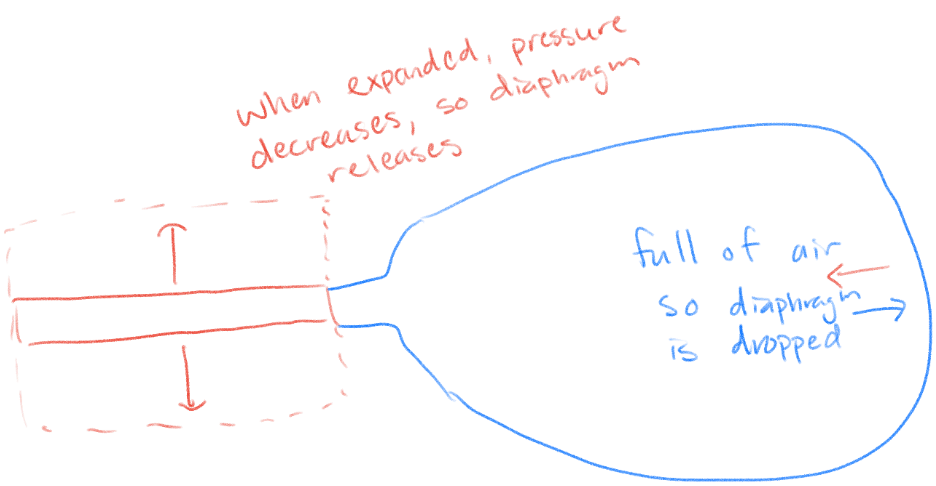
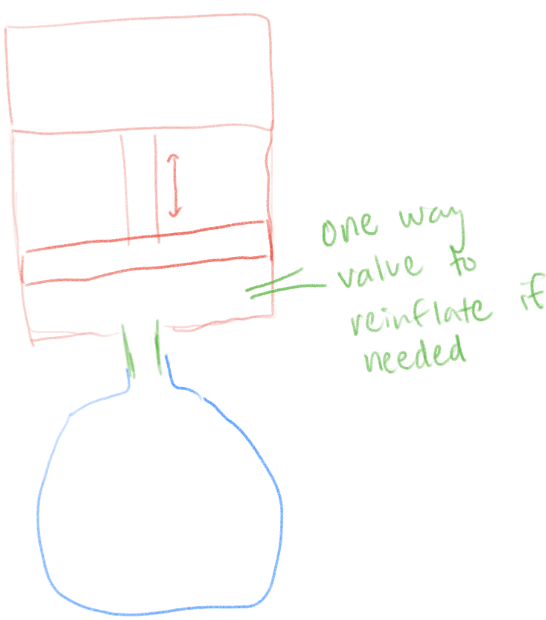


plate pushes down to physically drop the diaphragm — no air
lung
plate

18.

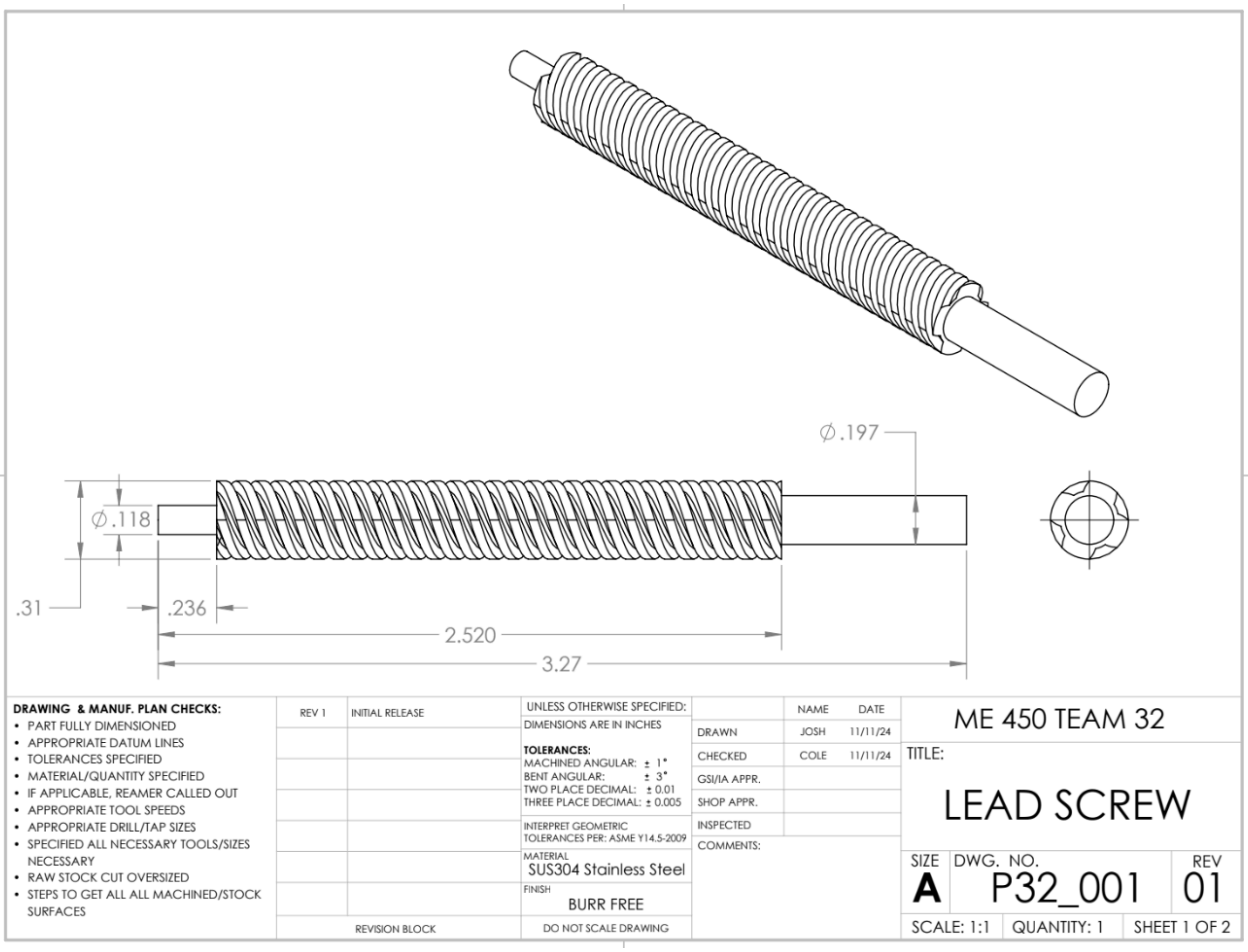

when expanded, pressure decreases, so diaphragm releases
full of air
so diaphragm is dropped

19.


one way valve to reinflate if needed

20.

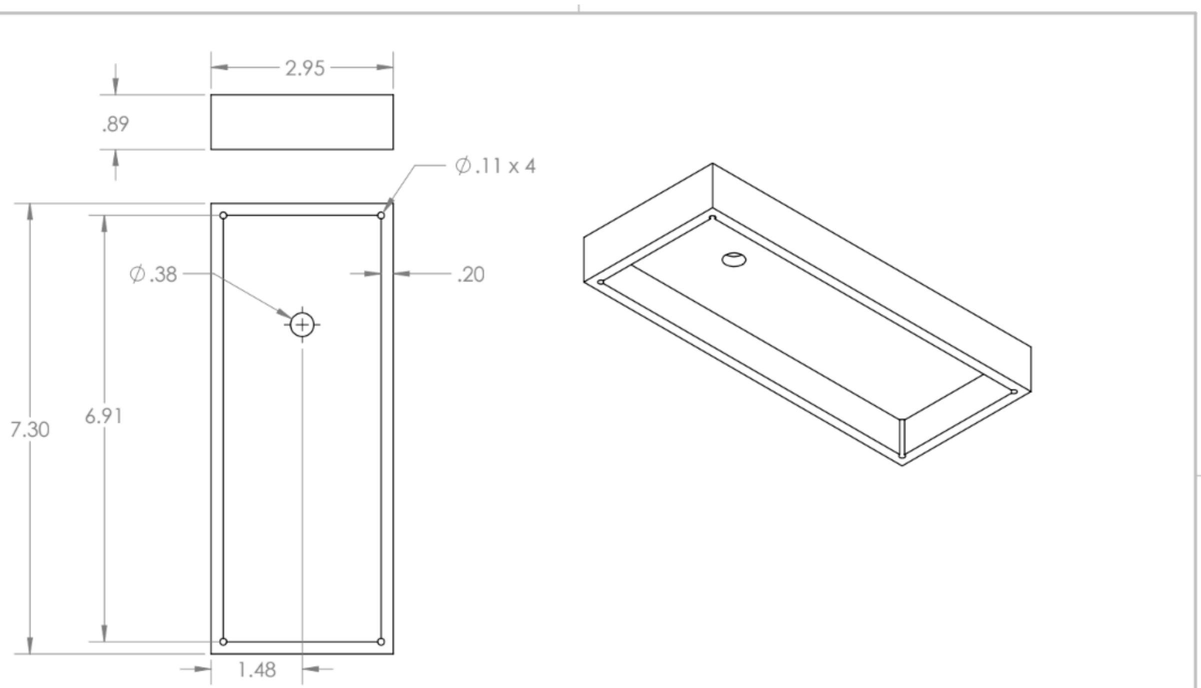
Engineering Drawings and Manufacturing Plans



MANUFACTURING PLAN
RAW MATERIAL STOCK: PURCHASED STAINLESS STEEL LEAD SCREW

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut lead screw > 1.5" of final length then deburr	Bandsaw	Vise	Deburring tool	300 ft/min
2	Mount with ~0.5" exposed and face one end to create flat surface, repeat with other side	Lathe	Collet	Turning tool	750 RPM
3	Cut to full length turn down to the full length of the final screw needed	Lathe	Collet	Turning tool	750 RPM
4	Turn down the end to the smaller diameter shown in the drawing, debur	Lathe	Collet	Turning tool, Deburring tool	750 RPM
5	Remove from collet and replace so that the other end is sticking out. Turn down the end to the larger diameter shown in the drawing, debur	Lathe	Collet	Turning tool, Deburring tool	750 RPM
6	Remove from collet	Lathe			

SHEET 2 OF 2



DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL: PLA Plastic

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EASW	11/11/24
CHECKED		
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:
WILL BE 3D PRINTED.

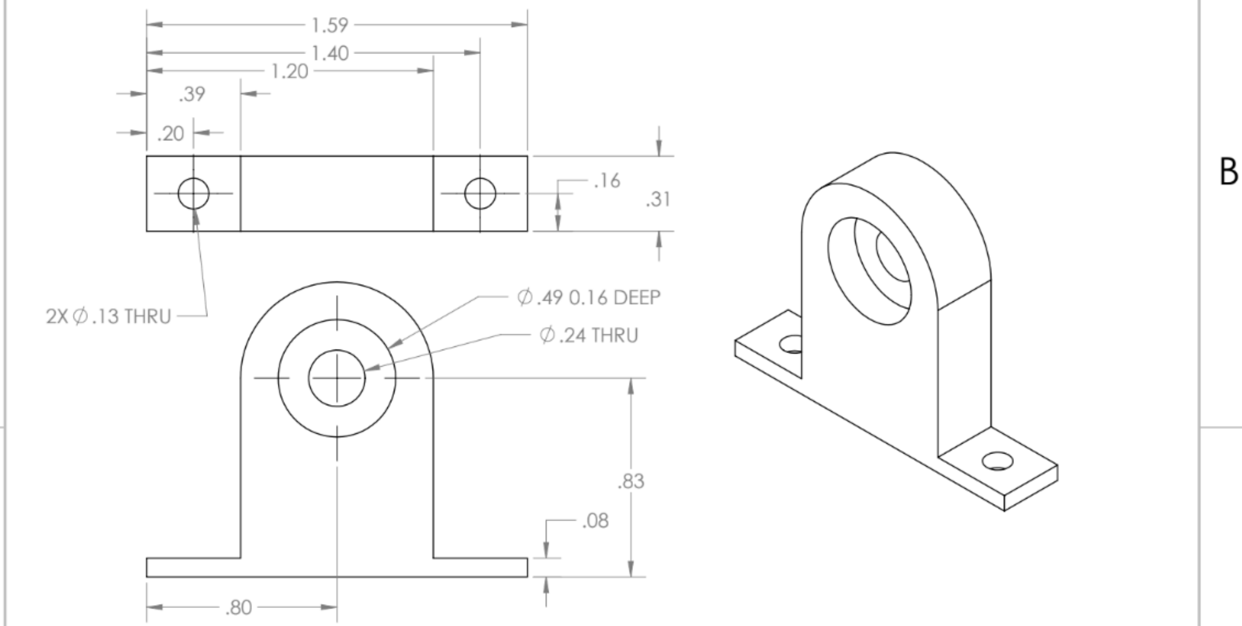
ME 450 TEAM 32

TITLE:

CASE TOP

SIZE	DWG. NO.	REV
A	P32_002	01

SCALE: 1:2 | QUANTITY: 1 | SHEET 1 OF 2



DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL: PLA

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	CJY	11/12/24
CHECKED	XX	XX/XX/XX
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:
THIS PART WILL BE 3D PRINTED.

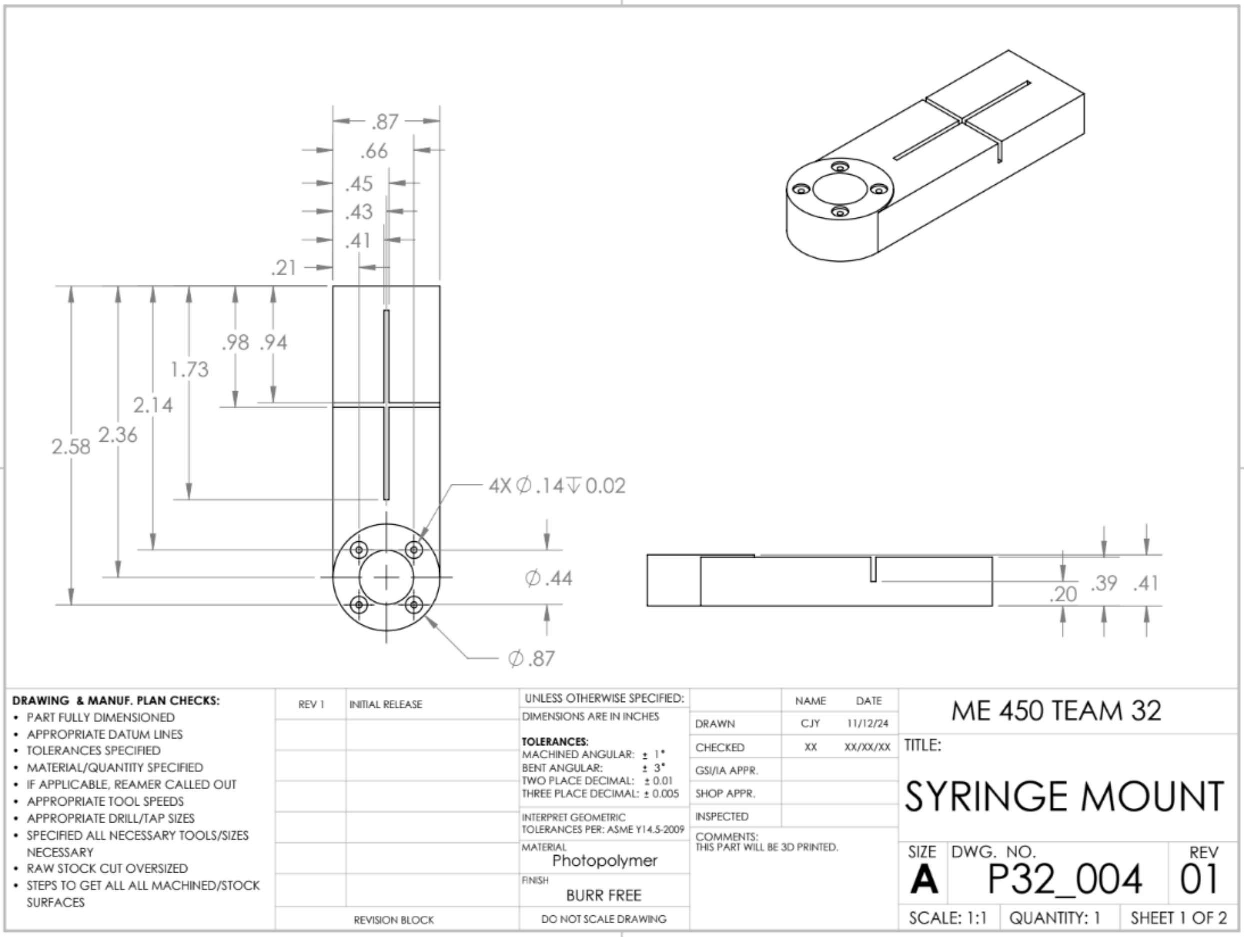
ME 450 TEAM 32

TITLE:

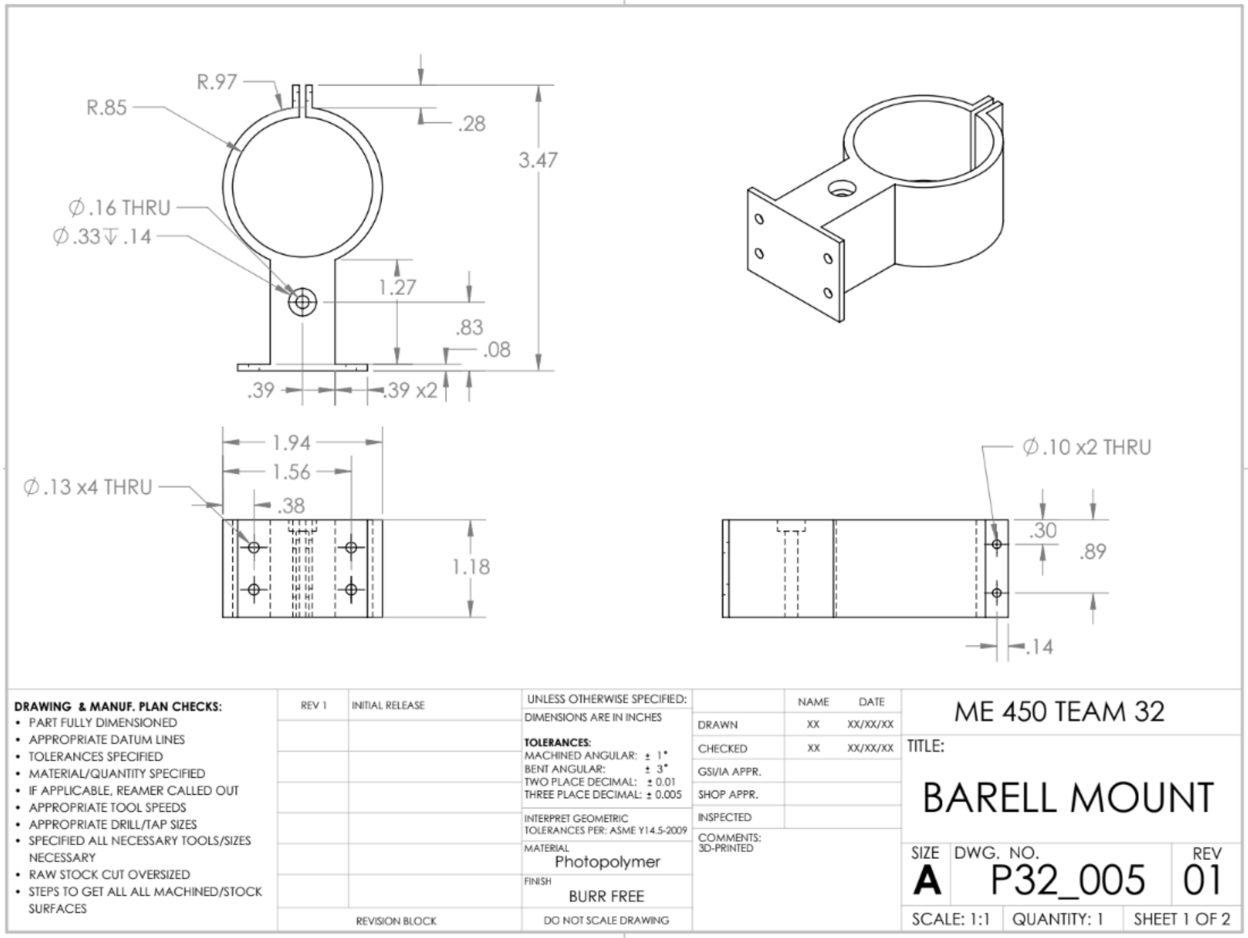
THRUST BEARING WALL

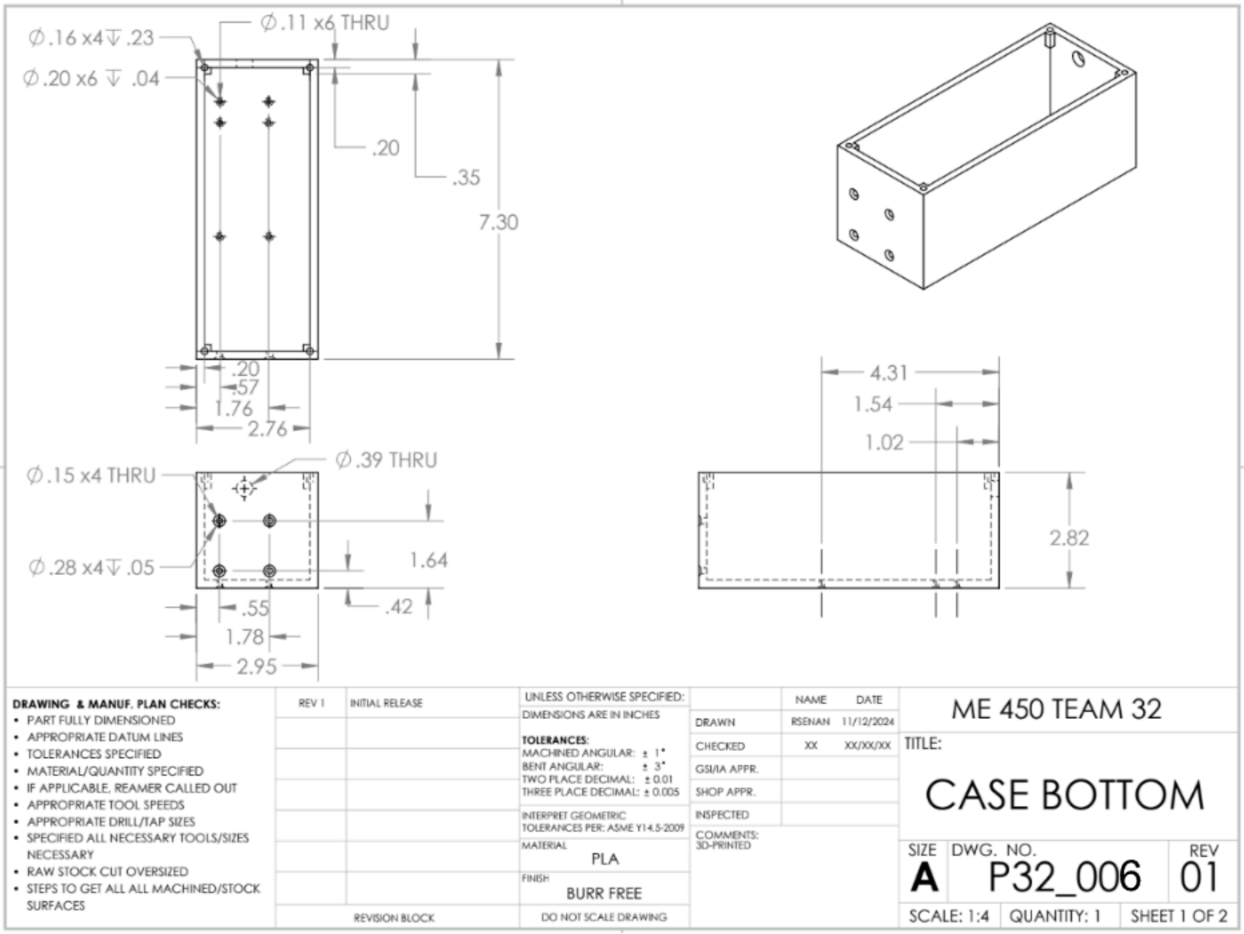
SIZE	DWG. NO.	REV
A	P32_003	01

SCALE: 2:1 | QUANTITY: 1 | SHEET 1 OF 2



.87
.66
.45
.43
.41
.21
.98
.94
1.73
2.14
2.36
2.58
4X Ø.14 ↧ 0.02
Ø.44
Ø.87
.20
.39
.41
DRAWING & MANUF. PLAN CHECKS:
• PART FULLY DIMENSIONED
• APPROPRIATE DATUM LINES
• TOLERANCES SPECIFIED
• MATERIAL/QUANTITY SPECIFIED
• IF APPLICABLE, REAMER CALLED OUT
• APPROPRIATE TOOL SPEEDS
• APPROPRIATE DRILL/TAP SIZES
• SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
• RAW STOCK CUT OVERSIZED
• STEPS TO GET ALL ALL MACHINED/STOCK SURFACES
REV 1
INITIAL RELEASE
REVISION BLOCK
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL
Photopolymer
FINISH
BURR FREE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CJY
11/12/24
CHECKED
XX
XX/XX/XX
GSI/IA APPR.
SHOP APPR.
INSPECTED
COMMENTS:
THIS PART WILL BE 3D PRINTED.
ME 450 TEAM 32
TITLE:
SYRINGE MOUNT
SIZE
A
DWG. NO.
P32_004
REV
01
SCALE: 1:1
QUANTITY: 1
SHEET 1 OF 2


R.97
R.85
.28
3.47
∅.16 THRU
∅.33↧.14
1.27
.83
.08
.39
.39 x2
1.94
1.56
∅.13 x4 THRU
.38
1.18
∅.10 x2 THRU
.30
.89
.14
DRAWING & MANUF. PLAN CHECKS:
• PART FULLY DIMENSIONED
• APPROPRIATE DATUM LINES
• TOLERANCES SPECIFIED
• MATERIAL/QUANTITY SPECIFIED
• IF APPLICABLE, REAMER CALLED OUT
• APPROPRIATE TOOL SPEEDS
• APPROPRIATE DRILL/TAP SIZES
• SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
• RAW STOCK CUT OVERSIZED
• STEPS TO GET ALL ALL MACHINED/STOCK SURFACES
REV 1
INITIAL RELEASE
REVISION BLOCK
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL
Photopolymer
FINISH
BURR FREE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
XX
XX/XX/XX
CHECKED
XX
XX/XX/XX
GSI/IA APPR.
SHOP APPR.
INSPECTED
COMMENTS:
3D-PRINTED
ME 450 TEAM 32
TITLE:
BARELL MOUNT
SIZE
A
DWG. NO.
P32_005
REV
01
SCALE: 1:1
QUANTITY: 1
SHEET 1 OF 2

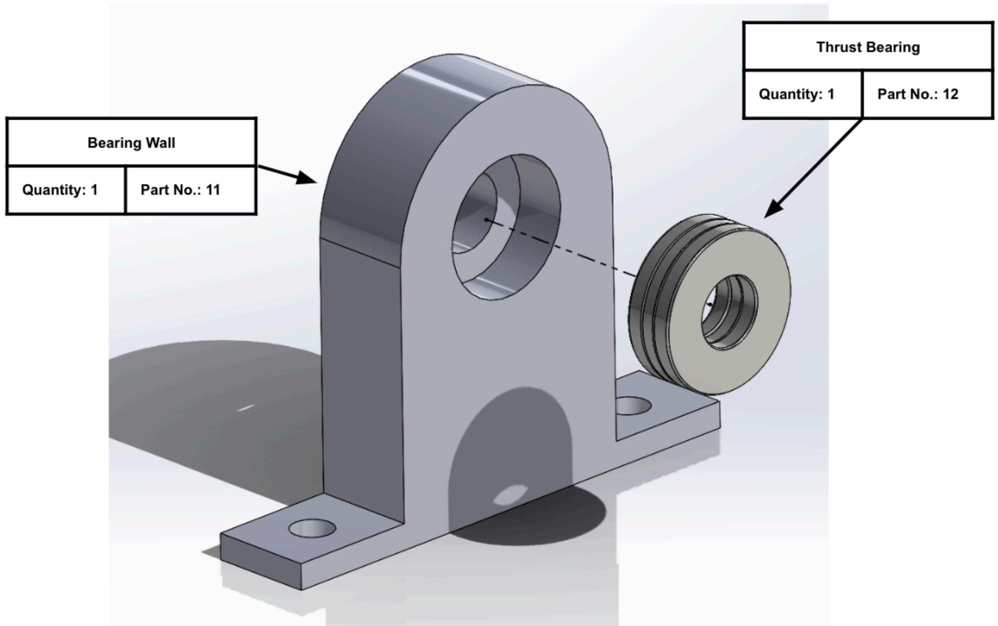


Bill of Materials

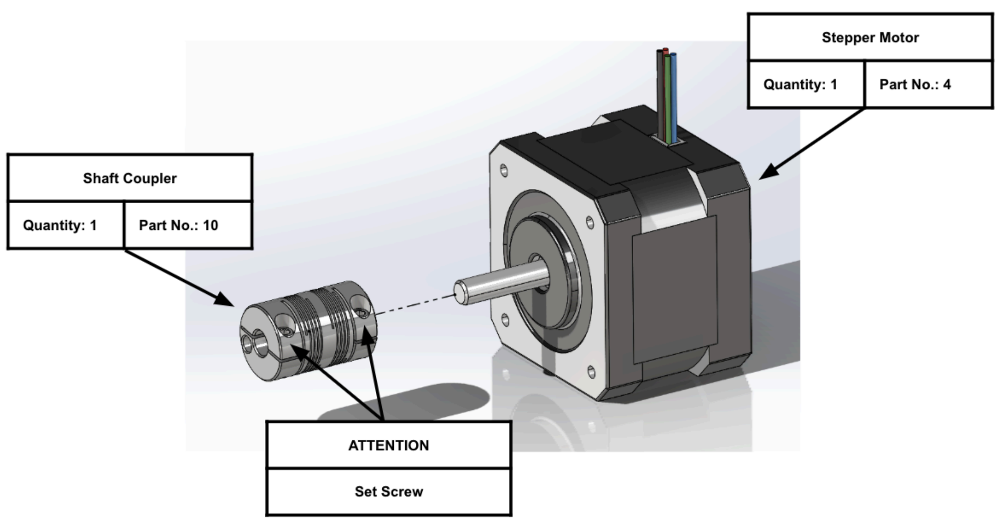
Part No.	Part Title	Material	Dimension(s) [mm]	Supplier	Quantity	Price (per unit) [$]
1	Lead Screw	SUS304 Stainless Steel	83 L, 8 D	VICHSAMWY	1	7.80
2	Lead Screw Nut	Copper	8 ID, 22 OD	VICHSAMWY	1	-
3	Arduino Nano		18 x 45 x 5	Arduino	1	26.61
4	Stepper Motor		42 x 42 x 34	Stepper Online	1	12.50
5	9V Battery		48 x 25 x 15	Duracell	2	4.50
6	Motor Driver		20.4 x 15.5 x 11.3	WWZMDiB	1	2.66
7	Case Top	Plastic	185.5 x 75 x 22.5	3D Printed	1	-
8	Case Bottom	Plastic	185.5 x 75 x 71.6	3D Printed	1	-
9	Power Switch	Plastic	16 D, 29 H	LOVEMYSWITCHES	1	1.90
10	Shaft Coupler (2463K3)	7075 Aluminum	15 D, 22 L	McMaster-Carr	1	58.05
11	Bearing Wall	Plastic	40.5 x 8 x 31.4	3D Printed	1	-
12	5mm Thrust Ball Bearing (7806K57)	Bronze	5 ID, 12 OD, 4 L	McMaster-Carr	1	8.66
13	3mm Thrust Ball Bearing (7806K53)	Bronze	3 ID, 8 OD, 3.5 L	McMaster-Carr	1	9.86
14	Barrel Mount	Plastic	30 x 49 x 88	3D Printed	1	-
15	Barrel	Plastic	43 D, 53.5 L	A AKRAF	1	3.00
16	Plunger	Plastic	45 x 39 x 39	A AKRAF	1	-
17	Plunger Mount	Plastic	10 x 22 x 71	3D Printed	1	-
18	Undersized Shoulder Screw (90278A713)	18-8 Stainless Steel	4 D, 9 L	McMaster-Carr	4	4.76
19	Heat-Set Inserts (94459A439)	Brass	4.1 D, 5.9 L	McMaster-Carr	4	0.22
20	Flat Head Shoulder Screw (91294A540)	10.9 Alloy Steel	5 D, 25 L	McMaster-Carr	4	0.72
21	Barrel Mount Head Screw (91292A017)	18-8 Stainless Steel	4.5 D, 14 L	McMaster-Carr	2	0.09
22	Motor Flat Head Screw (91294A128)	10.9 Alloy Steel	6 D, 8 L	McMaster-Carr	4	0.58
23	Mounting Flat Head Screw (92125A090)	18-8 Stainless Steel	5D, 12 L	McMaster-Carr	6	0.29
24	Washer (93475A196)	Stainless Steel	2.7 ID, 6 OD, 0.4 to 0.6	McMaster-Carr	8	0.02
25	Locknut (94205A101)	Stainless Steel	5 D, 3.8 L	McMaster-Carr	8	0.20
26	Breadboard	Plastic	82 x 54 x 9	DEYUE	1	1.31
27	9V Battery Leads	Plastic	20 x 10 x 2	McMaster-Carr	2	0.19
28	Syringe Dispense Tip	Plastic	8 D, 30 L	Hisco	1	0.35
29	Rubber tubing	Plastic	4 D, 300 L	Hisco	1	0.79
30	Linear Switch	Copper Alloy	13.8 x 19 x 6	C&K	1	0.63
	Total Cost					$172.11

Assembly Plan

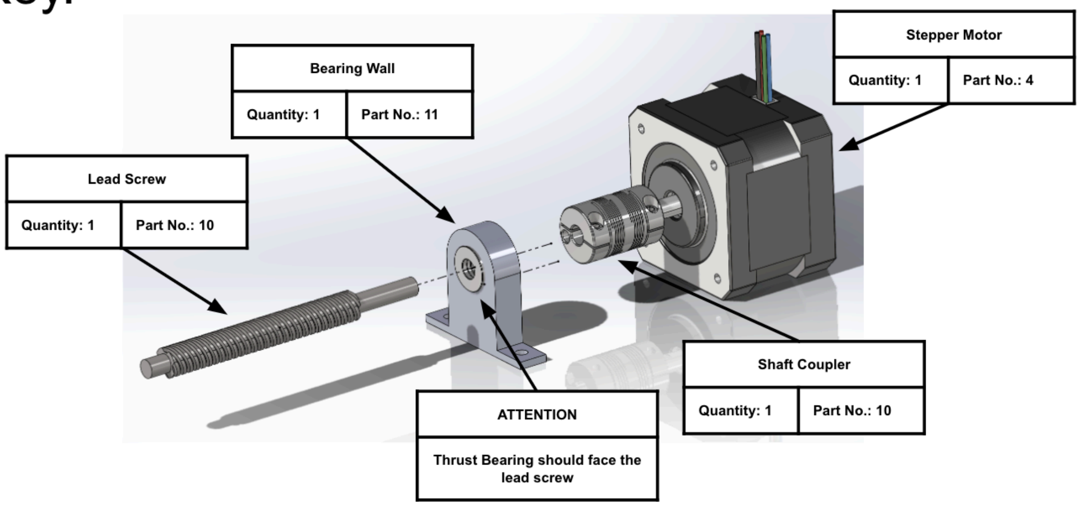
1. Insert Thrust Bearing into Bearing Wall.



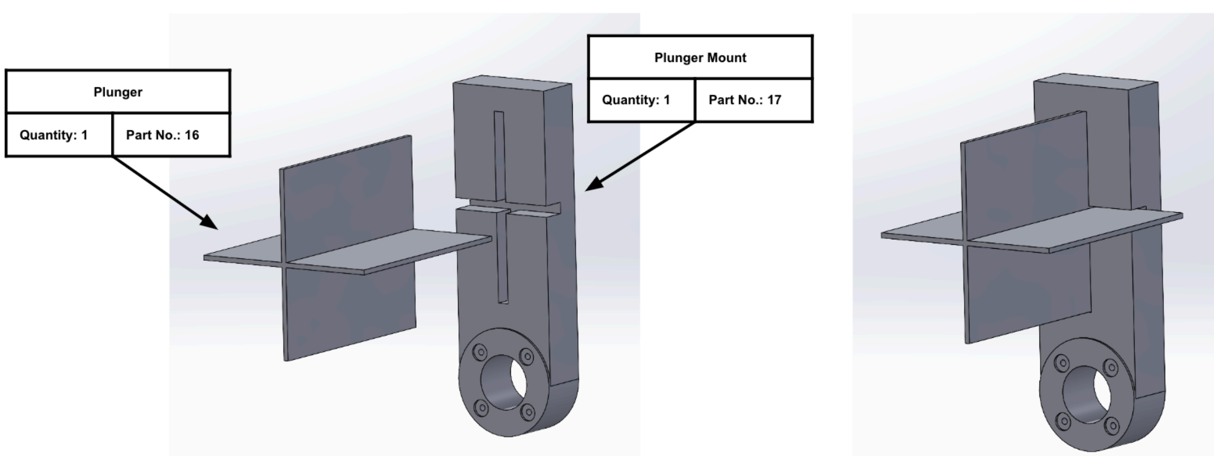
2. Place Shaft Coupler on motor shaft and tighten set screw using a M3 Allen Key.



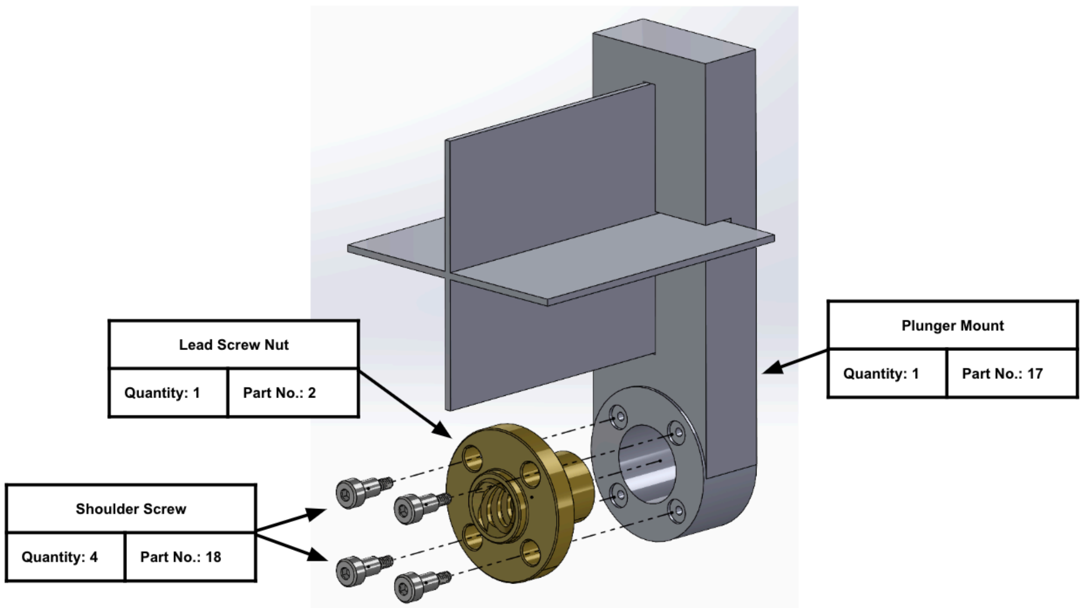
3. Slide the long end of the Lead Screw through the Bearing Wall and secure to Shaft Coupler using an M3 Allen Key.



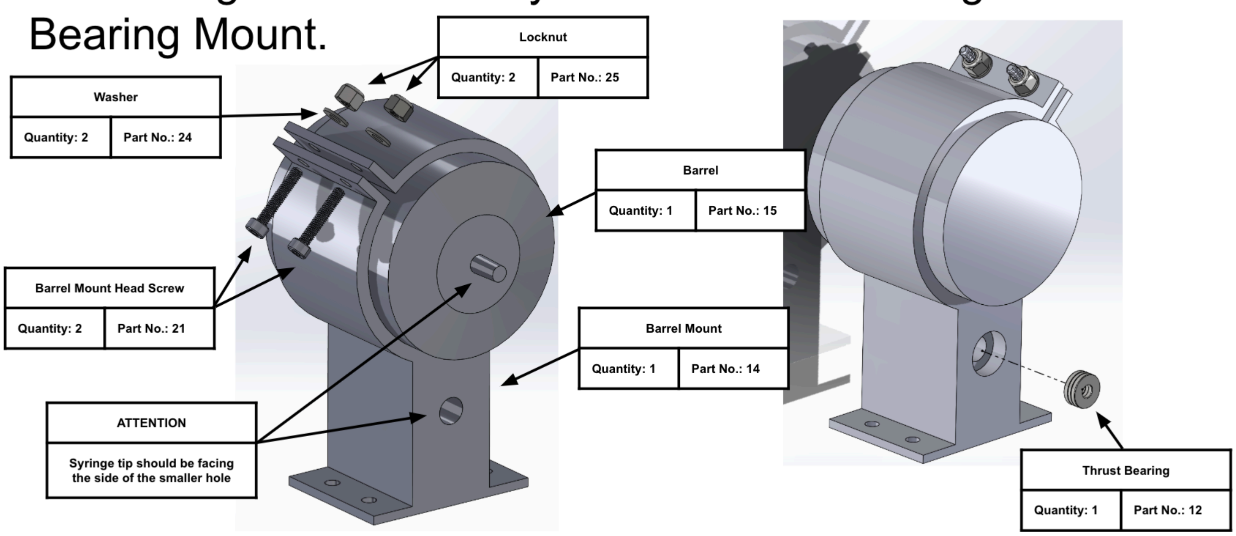
4. Using hot glue, attach the Syringe Plunger to the Plunger Mount.



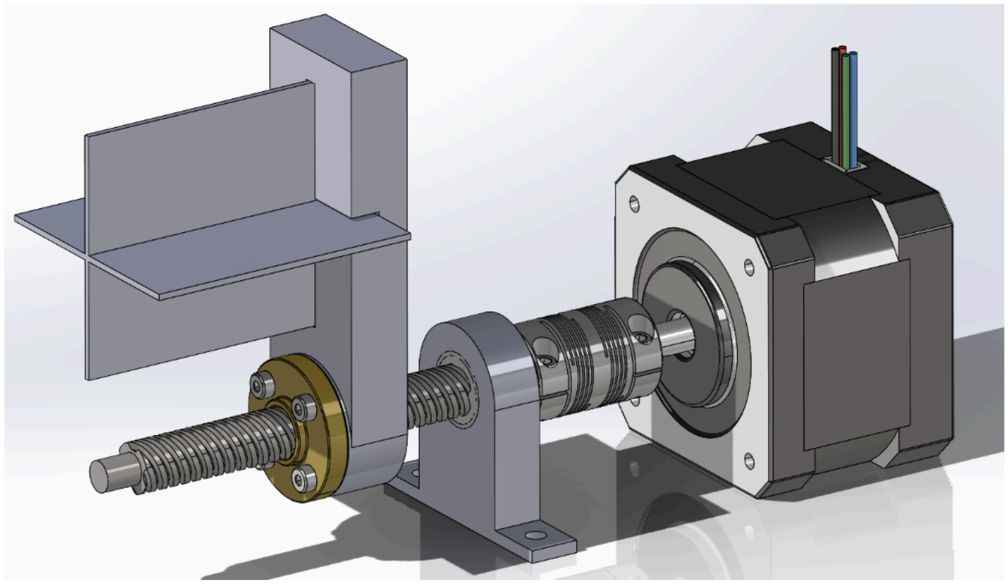
5. Attach Lead Screw Nut to Plunger Mount using 4 Shoulder Screws and a M2.5 Allen Key.



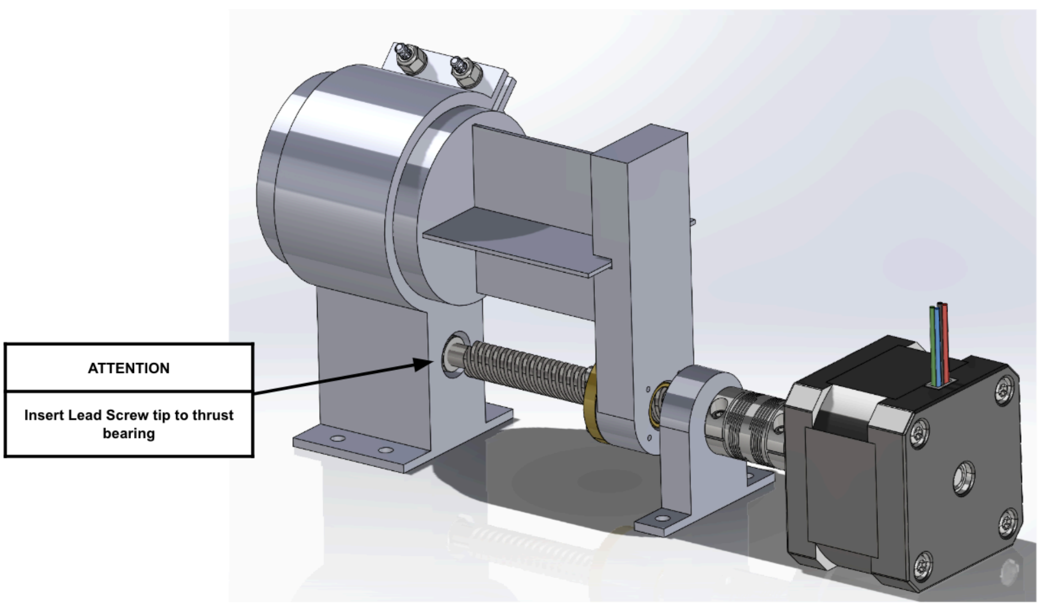
6. Insert Plunger Barrel into the Barrel Mount and fasten bolts using M2.5 Allen Key. Insert Thrust Bearing into Bearing Mount.



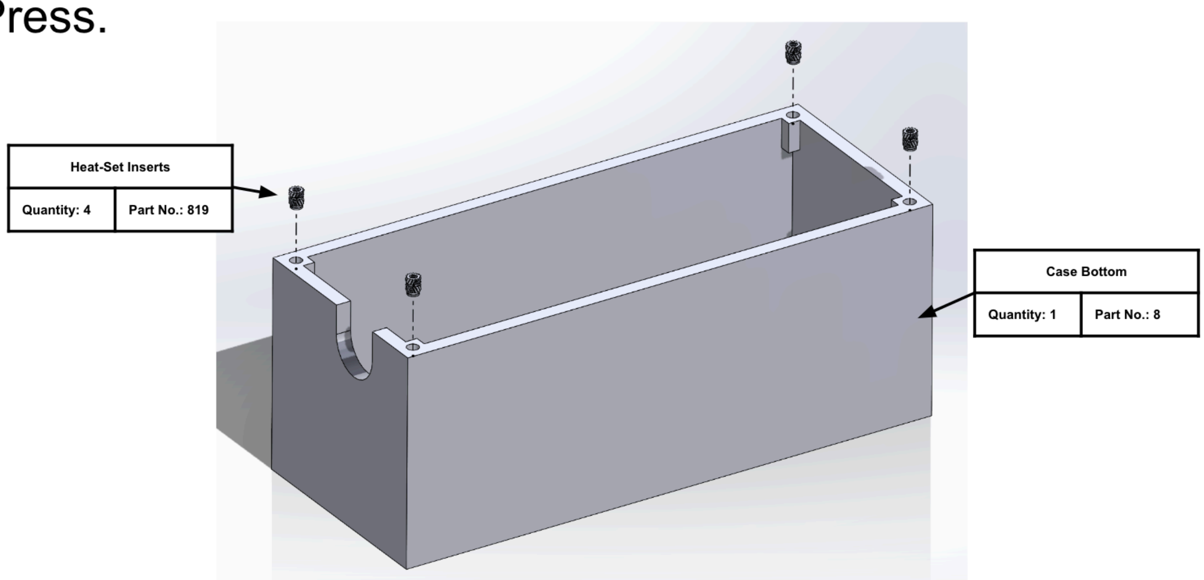
7. Screw Lead Screw Nut onto Lead Screw.



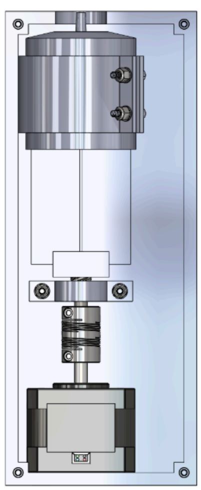
8. Insert Plunger into Barrel and Lead Screw end into Thrust Bearing.

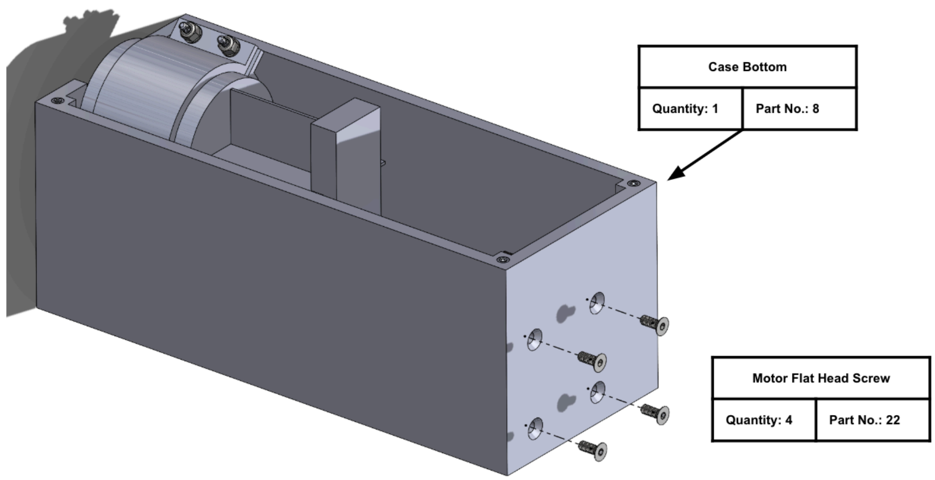


9. Place Inserts into the Case Bottom using an Arbor Press.

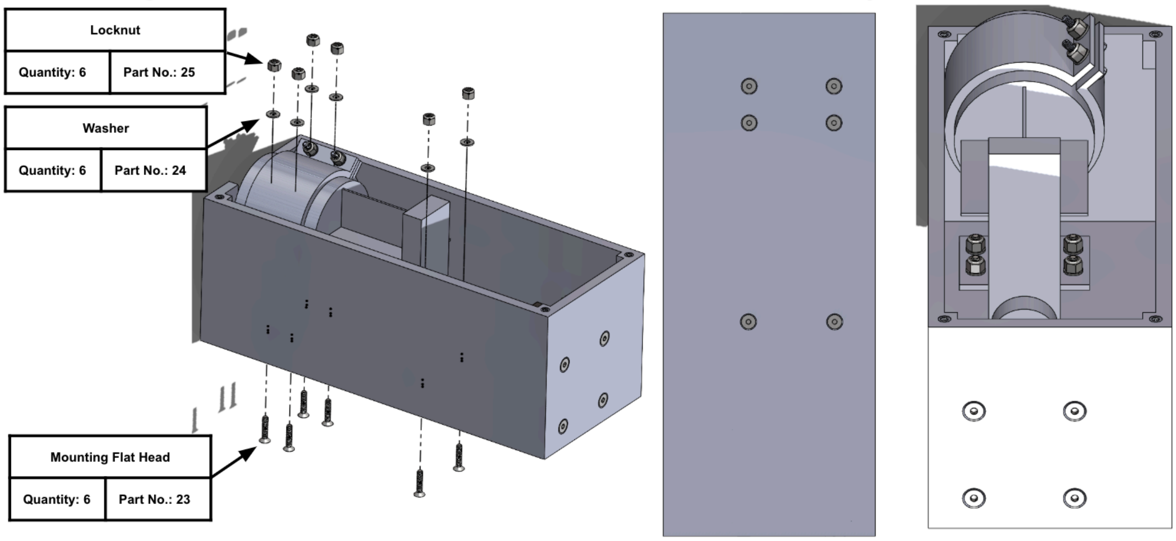


10. Place system into the Case Bottom and fasten motor back using 4 screws and an M3 Allen Key.



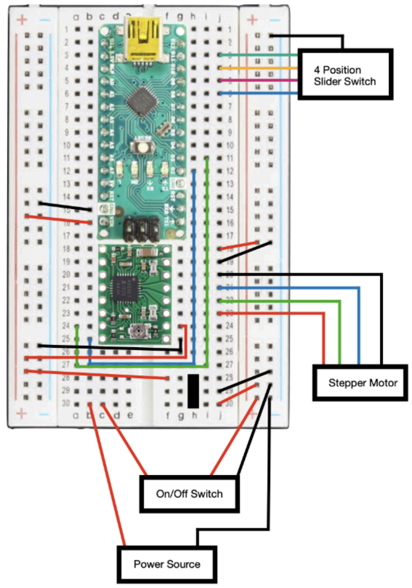


11. Mount Bearing Wall and Barrel Mount to Case Bottom using 6 fasteners and an M2.5 Allen Key.

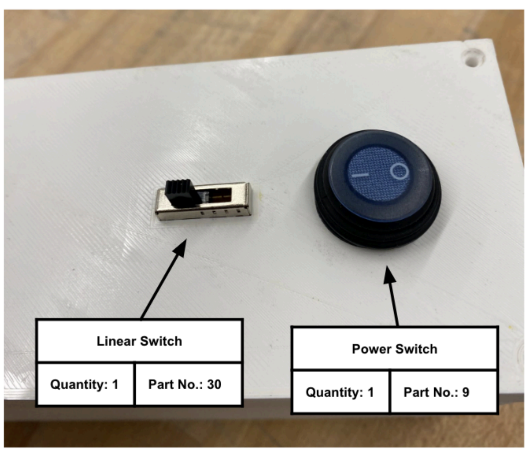


12. Solder two 9V battery leads in series.

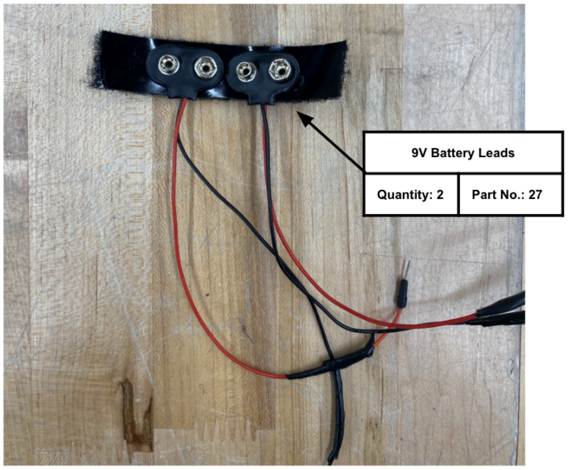
13. Solder board according to the wiring diagram shown below, excluding both switches.

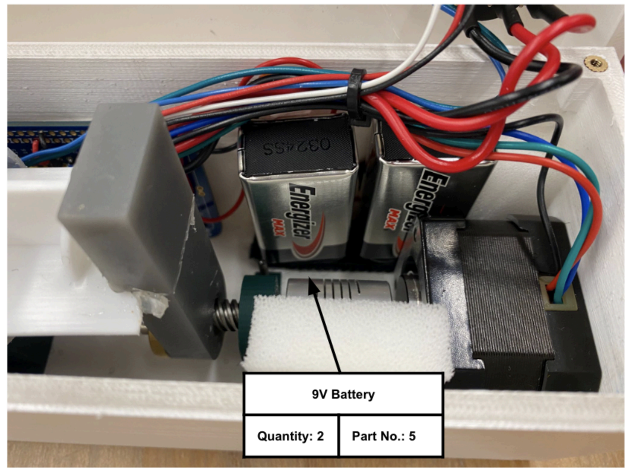


14. Place the Power Switch and Slide Switch into the case top from the exterior of the case and solder to board.

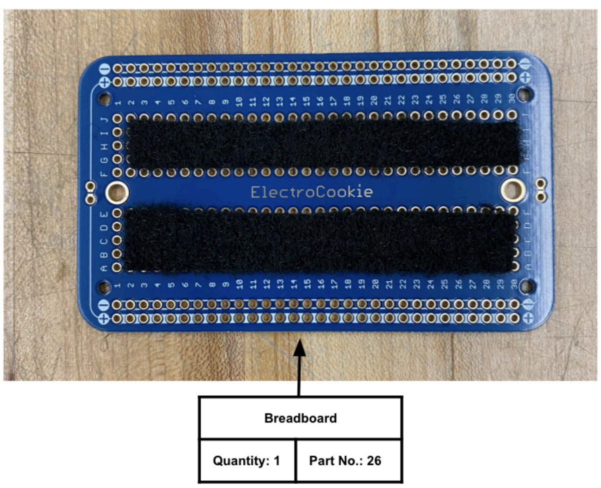


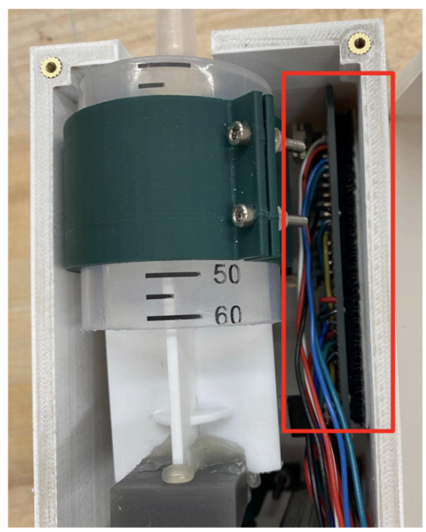
15. Attach two 9V battery leads to one side of a piece of velcro and place the other side of velcro on the case bottom and attach batteries.



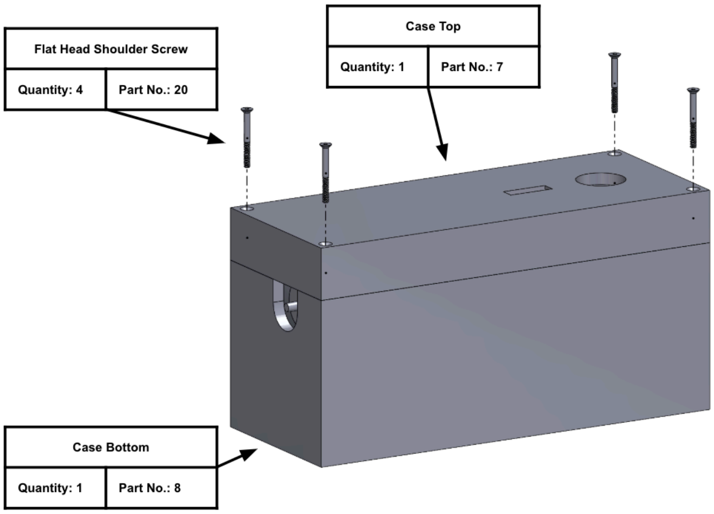


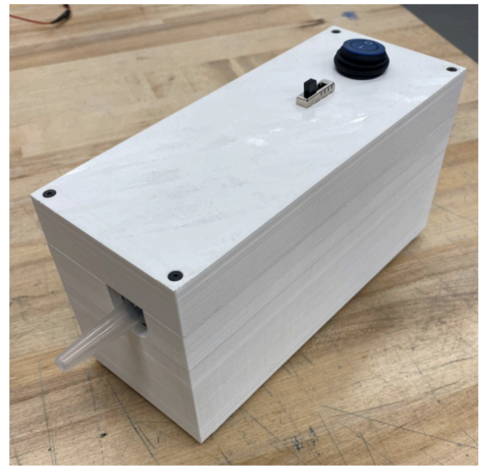
16. Attach board to one side of velcro and the other side to the interior wall of the case shown below.



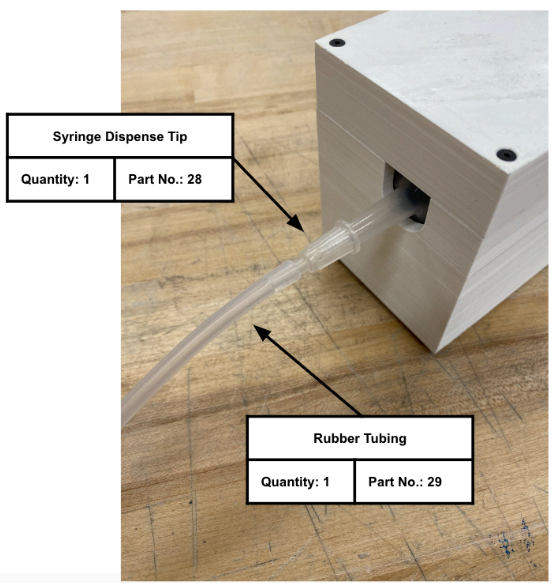


17. Attach the case top to the case bottom using an M3 Allen Key.





18. Attach the Syringe Dispense Tip to the Syringe on one end and the rubber tubing on the other end.



BIOS

Elijah Williams

Elijah Williams is a senior dual-degree Mechanical Engineering/Applied Physics transfer student from Morehouse College. While attending the University of Michigan he has added a concentration in energy and has joined the program in sustainable engineering (PISE). After graduating, he plans to work in the renewable energy industry as a field engineer. Originally from Los Angeles, California, Elijah moved to Kennesaw, Georgia at about 8 years old. He believes the jump from seeing large amounts of traffic and the daily grind of Los Angeles to the more natural background of Kennesaw is what sparked his interest in renewable energy/the environment. Outside of academia, Elijah enjoys spending his free time reading books, playing video games, or playing pickup basketball games at the NCRB or the IM on campus at the University of Michigan.

Cole Young

Cole Young is a senior in Mechanical Engineering with a concentration in Robotics and a minor in Computer Science at the University of Michigan. Cole is originally from Boston Massachusetts and would describe himself as a “tinkerer.” Growing up, he enjoyed taking apart and putting back together small electronics and woodworking with his grandfather, which piqued his interest in engineering. Cole pursued Mechanical Engineering because of its broad applicability, as he enjoys working on projects in a variety of fields. Cole has participated in research at the University of Michigan working on synthetic biology and has completed internships at Caterpillar working on autonomous mining trucks and Anduril, working on autonomous submarines. After college, Cole hopes to pursue a career in Robotics Engineering, as it unites his interests in Mechanical Engineering and Computer Science. In his free time, Cole enjoys spending time outside, hiking, and rock climbing.

Rohan Senan

Rohan Senan is a senior in Mechanical Engineering with a minor in Computer Science at the University of Michigan. Rohan was born in Bangalore, India but spent the majority of his life living in Lagos, Nigeria before coming to Ann Arbor, Michigan for university. During his childhood Rohan would often wonder how various mechanical contraptions functioned which sparked the initial interest in Engineering. Choosing to major in Mechanical Engineering as a way of learning about various applications of engineering. Rohan has spent time in the University of Michigan Solar Car Team where he has worked on designing a solar powered car, and an internship at Novelis working on simulations of forming methods. Rohan aims to pursue a career where he can combine his knowledge of computer science and mechanical engineering, such as autonomous systems and robotics. In his free time Rohan enjoys playing a variety of sports such as volleyball, soccer, and basketball, as well as playing video games.

Josh Lee

Josh Lee is a senior in Mechanical Engineering at the University of Michigan. Josh was born and raised in Honolulu, Hawai‘i, yet has always held an affinity for Michigan. Despite his family roots being planted over 4,000 miles away from Ann Arbor, he is a third-generation UM student—his grandfather, father, and sister attended UM for law school, undergraduate, and law school, respectively. During high school, Josh became involved in his school's ceramic department where he came to love creating functional products (mainly coffee mugs and cereal bowls), and he felt that studying mechanical engineering would be a good way to merge his passion for products and interest in STEM. He learned that much of the joy in creating products is seeing how they can make others happy. In the future, Josh aims to find a career working on projects that benefit everyday people while still finding time to foster his passion for ceramics.