Final Report

University of Michigan ME 450 Team 12

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"We have fully abided by the University of Michigan College of Engineering Honor Code"
Signed April 26, 2021
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Table of Contents

1. Executive Summary

Team 12 is tasked to design and manufacture a 2D clinostat to perform reduced gravity biological experiments. Researchers are exploring the physical and biological impact of long duration space travel on the human body [1]. Microscopic worms known as *Caenorhabditis elegans*, or *C. elegans*, are used as a model to study the effects of microgravity on biological systems. A 2D clinostat provides a simple and cost effective method of simulating reduced microgravity on earth.

Some literature and existing documents related to clinostat experiments and clinorotation analysis was then reviewed. As the rotational speed of the clinostat is a crucial factor and part of the specifications, some research regarding how rotational speed affects the simulated microgravity for specimens was summarized. One experiment about how simulated microgravity using 2D clinostat affects *C. elegans*' genes expressions is also discussed.

The requirements and specifications for the 2D clinostat project showcase the important factors that our design will need to meet in order to be considered successful. The requirements and specifications are ordered in terms of priority and split between sponsor and team driven. Through priority ordering, the team showcases the major focus of the project and the major needs that the design will need to satisfy.

A discussion of the entire concept generation process that the team underwent is presented to showcase the exploration of the entire design space that was done. Through both the morphological chart and individual designs with the 77 design heuristics, the final design was created using the best ideas from all team members. A concept comparison chart is then shown to compare the benefits and drawbacks associated with each design and to examine the feasibility of the final design.

A discussion of the different subsystems starts with the mechanical components in the gear train, test tube grippers, and the camera mount. Afterwards, the entire mechanical system of the clinostat is presented to show the interactions between all the mechanical parts. The electrical system is then presented to give readers an understanding of the control system for the motors and how the user will interact with the clinostat. The finalized prototype is then discussed and the procedures that the team did to conduct verification testing are shown.

The project management showcases the organizational structure within the team and the budget showcases how much each individual component within the design will cost. These sections lead to discussions on inclusivity, environmental factors, standards, and ethics. These discussions provide insight into how the team interacted with its stakeholders throughout the project and how the clinostat will serve as a valuable contribution to research in developing countries. Our reports closes with potential problems that we foresee in the future and a discussion of our next steps.

2. Project Objective and Value to Sponsor

Dr. Eleni Gourgou is an assistant research scientist at the University of Michigan. Her research focuses on understanding the impact of elements in the environment and their effects on organism's physiological states, such as their learning and locomotion. There has recently been a need to test the model organisms Dr. Gourgou works with in a microgravity environment, and she has requested a 2D clinostat to be designed and manufactured. A 2D clinostat will be able to simulate microgravity conditions for the model organism, *Caenorhabditis elegans*, without having to leave Earth. The creation of the clinostat will reduce time and cost for Dr. Gourgou's research and allow her to refine microgravity experiments on Earth. Our ME 450 team working under Professor Allen Liu will spend the Winter semester of 2021 creating a 2D clinostat as our team's senior capstone design project.

3. Background

Caenorhabditis elegans, or *C. elegans* for short, is a microscopic transparent worm. The worms reach adulthood within 3 days and, at adulthood, its total length reaches approximately 1 mm [1]. *C. elegans* can be found all over the world, however its natural history and ecological significance is largely unknown. Figure 3.1 depicts a scanning electron micrograph image of the transparent *C. elegans* worm.

Figure 3.1. Image of *C. elegans* [2]

C. elegans research has spanned for decades with researchers now having fully mapped the worm's nervous system and cell lineage. In addition, its high reproduction rate and short lifespan makes *C. elegans* an ideal organism to be used to study the biology of ageing, neurobiology, genetics, and memory [1]. The research conducted by Dr. Gourgou will be experimenting the biological behavior of *C. elegans* in microgravity conditions. The International Space Station provides opportunities to research *C. elegans* behavior in a space laboratory setting however space experimentation adds factors such as cost, exposed radiation, and launch induced hyper gravitational forces [1]. Simulating microgravity on earth is a simple and cost effective method which simplifies the efforts needed by researchers to identify the stress factors which induce biological changes in *C. elegans.* For decades, the clinostats have been used by researchers to test a variety of specimens in simulated near weightless environments.[1].

A clinostat is a device used to test specimens under microgravitational conditions. The first clinostat was created by Julius Sach in the end of the 19th century, experimenting plant growth under a microgravity environment [3]. Since then, the family of clinostats expanded to incorporate the one, two, and three dimensional clinostat variations. The difference between the variations are the number of vectors of rotation incorporated with the device. The 2-Dimensional (2D) clinostat has two directional vectors: the gravitational vector and the axis of rotation [4]. For this project, a 2D clinostat will be used to simulate reduced microgravity conditions for *C. elegans*.

Clinostat creates a state of reduced microgravity by rotating a container with the specimens at constant velocity. During rotation, the velocity vector of the container walls are directed inward which eliminates any relative fluid flow in the container. As a result of this process, the gravitational vector on the specimens is continuously rotating which creates a simulated microgravity environment for the specimens [4]. This process of simulating microgravity is shown below in Figure 3.2. Figure 3.3 shows an example of a 2D clinostat used to rotate multiple test containers.

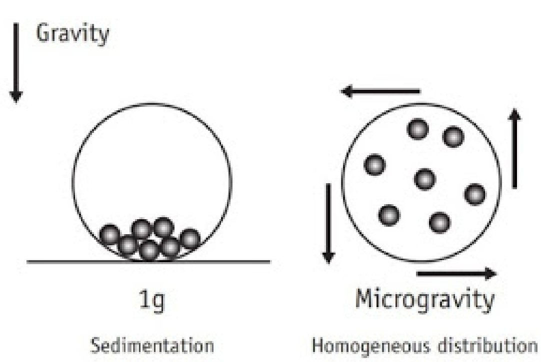


Figure 3.2. The simulation of microgravity inside a clinostat. [5]

Figure 3.3. An example of a 2D clinostat. [6]

The angular velocity of the sample containers must be properly set, with an upper and lower bounds, in order to maintain the suspended worms in a state of relative motionlessness. If the angular velocity drops below the lower limit then the worms are subjected to the gravitational force and as a result will accumulate at the bottom of the container [4]. If the angular velocity were to exceed the upper limit, then the clinostat will behave like a centrifuge which results in the worms being forced to the walls of the container [4]. The gravitational vector of the specimens of the clinostat are continuously rotating as described above. This vector rotates on the same plane, perpendicular to the ground at which the inclination angle is 90° [3]. Researchers are able to change the angle of inclination by tilting the axis of rotation of the worms. A change in the inclination angle of the axis of rotation will induce a gravitational force onto the worms. This method is preferably used to observe *C. elegans* worms in different gravitational environments such as the gravity of Moon or Mars without altering the angular velocity of the clinostat [3]. The inclination angle with respect to the ground plane is visualized in Figure 3.4.

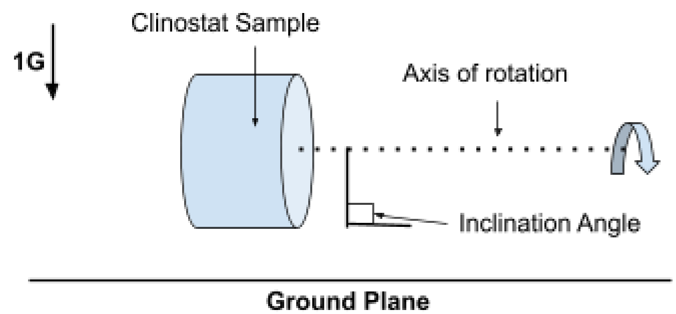


Figure 3.4. A diagram which shows the orientation of the clinostat with respect to gravity and ground plane.

4. Project Scope

This team is responsible for manufacturing a 2D clinostat, thus the project scope is confined to designing the clinostat and meeting our core deliverables to our sponsor. The complete design of mechanical and electrical components in the clinostat is within this project's scope. This assures a quality analysis of the motor and transmission components to deliver the needed torque to rotate the specimens at a fixed angular velocity. The clinostat's power criteria is taken into consideration as voltage from a standard outlet needs to be regulated to power the electric components of the device.

The preparation of the test containers are not within the project scope. The requirements and specification section below will specify the criterias for the container fixture, but the team is not responsible for the preparation of *C. elegans* for experimentation. The final design of the clinostat is a proof of concept design made specifically for a laboratory setting. Thus mass production of the clinostat is not a crucial element taken into design consideration. The project has two stretch goals of first implementing an alarm system to notify the user of a disturbance in either the mechanical or electrical components of the clinostat. Second, a timer can also be implemented to give users more testable parameters. Since these features are only stretch goals, they are not a priority in the completion of the clinostat, but the features will be considered if the team has sufficient time during the final weeks of manufacturing.

5. Literature Review

Many experiments of plants, cells, and micro-organisms have been conducted using 2D clinostats. The speed of rotation is important to the experiments, because it needs to provide functional weightlessness adequately for the specific type of specimen. Dedolph and Dipert (1971) separated the motion of a spherical particle in fluids under clinorotation into two parts: a circular motion under the influence of gravity, the radius of which is inversely proportional to the angular velocity (ω), and a radial motion due to centrifugal forces, the velocity of which is proportional to ω^2 [6]. This suggests that although fast rotational speed may reduce the gravitational effects, it imposes a larger centrifugal force that could make the particle move toward the radial direction. Figure 5.1 shows the clinostat rotation and the particle's circular motion path under clinorotation. A larger rotational speed will decrease the particle's path radius, and better simulate a microgravity condition.

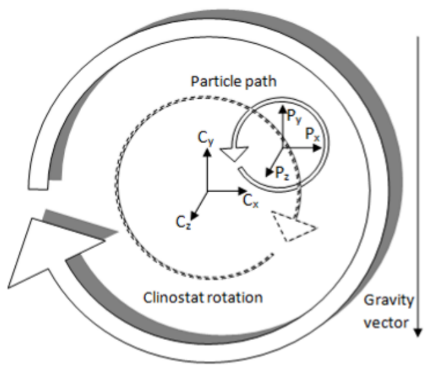


Figure 5.1. The particle's circular motion path during clinorotation. [7].

A typical clinostat for plant or large item study usually rotates at a rate of 1 to 2 rpm [8] to minimize centrifugation. For smaller organisms such as *C. elegans*, a speed of 10 rpm is commonly used. Fast-rotating clinostats (typically 50–120 rpm) have been developed for small (<1 mm) organisms in fluids to avoid sedimentation caused by gravity, making organisms stationary. However, at 60 rpm, the rotation axis should not exceed 1-1.5 mm because of increasing centrifugal forces [9]. At 60 rpm, the centrifugal force at 1mm radius is $4.2*10^{-3}$ *g* [10]. Considering the size of *C. elegans* is larger than 1mm and that the rotation axis is larger than 1.5mm, the fast-rotating clinostats is not suitable for this project.

One study has shown that simulated microgravity using clinostat induced changes on gene expression of *C. elegans*. During this experiment, researchers first cultured *C. elegans* for three weeks on ground control condition. Then, they exposed *C. elegans* to clinostat-simulated microgravity (10 rpm) for four days. Through integrative RNA-sequencing and mass spectrometry analyses, it is shown that hundreds of genes were differentially expressed during exposure to simulated microgravity. And 75% of the changes in gene expression persisted after return to ground conditions for four days [6]. This study shows *C. elegans* is an efficient model to identify the impact of space on biological systems. In addition, the results of genes that relate to learning and memories in this research will help our sponsor to make some comparisons and connections to her research.

6. User Requirements and Engineering Specifications

Specifications and requirements for the 2D clinostat have been both sponsor- and team-driven. For the sponsor-generated requirements, the specifications were determined based on the sponsor's experimental setup and needs. For the team-driven requirements, the specifications were determined and justified through literature review. In Table 6.1, all the user requirements and engineering specifications for the 2D clinostat have been listed along with whom they were determined by, their priority in the project, and their justifications.

Table 6.1. User requirements and engineering specifications for the 2D clinostat

User Requirements	Engineering Specifications	Determined By?	Priority	Justification
Clinostat must be a 2D clinostat	Clinostat will rotate the specimens along the horizontal axis, perpendicular to the gravitational vector	Sponsor	High	The definition of a 2D clinostat is stated in the specifications. Spinning along the horizontal axis, perpendicular to gravity, will average out of the gravitational vector which creates a microgravity environment [11]
The clinostat should be able to handle multiple specimens of *C. elegans* at the same time	Clinostat can test at least 8 specimens of *C. elegans* simultaneously	Sponsor	High	Redundancy is needed for researchers running the *C. elegans* experiments so they are certain their experimental results are correct. 8 specimens would offer the redundancy needed while also being more specific to help narrow the design space
The clinostat can hold liquid scintillation vials (with screw caps attached) test tubes (12,13)	Specimen holder will be a universal holder for test tubes it will have a variable hold size of 0.5" and 1" in width and	Sponsor	High	The test tubes that the clinostat needs to hold were given by the sponsor and their experimental setup. Narrowing the focus of the clinostat for test tubes help the creation of the final design

	8"± 1" height			
The clinostat should be able to run for long periods of time	Clinostat must continuously operate without human intervention for at least 3 days	Team	High	From the literature review, previous experiments on *C. elegans* ran for at least three days because three days is the time it takes for the worm to reach adulthood. Having a continuous running clinostat would allow our sponsor to examine multiple generations of *C. elegans* [6]
Clinostat must rotate at a speed to create a microgravity environment	Clinostat will be able to rotate between 0 rpm to 20 rpm	Team	High	Found in our literature review, multiple articles describing the microgravity experiments on *C. elegans* have clinostats rotating at 10 rpm. The team decided to include a range of rpm in order to accommodate other organisms in future experiments for the sponsor [6]
The clinostat has to have at least one built in camera systems used for magnification	Clinostat has at least one stationary cameras with *x5- x10* adjustable magnification positioned on two test tubes or culture flasks that hold specimens	Sponsor	Medium	The sponsor would like to examine specimens in vitro so that any microgravity effects can be examined in *C. elegans* real time. Adjustable stationary magnification of *x5 - x10* was requested by the sponsor as an add-on to the clinostat. The sponsor preferred a stationary camera that observed the test tubes while they spun
Clinostat must operate on a standard lab bench	Clinostat must be at most 2' x 2' x 2' in total volume	Team	Medium	The clinostat will be placed into the sponsor's laboratory which has limited spacing due to other equipment. The sponsor has informed the team of the volumetric space available. In addition,

				clinostats found from literature review have been able to fit within the volumetric constraints placed in our specifications
Specimens must be operated in a room temperature environment	Operating conditions will be at ambient conditions, which is 20°C ± 3°C	Team	Low	From the literature review and asking the sponsor, experiments on *C. elegans* have been conducted in room temperature conditions. Even on the International Space Station, where microgravity experiments were run, the operating conditions were kept at room temperature. The team has decided to thus incorporate a range of temperature that room temperature to account for any fluctuations [6]
The clinostat should run with minimum noise due to being in a shared area	The clinostat will have a maximum sound level of 50 db ± 2 db	Team	Low	The sponsor has informed the team that the clinostat will be placed in a shared lab environment and should not disturb others. The team has thus set a noise requirement of not being louder than a library setting which is what the decibel values represent [14]

For the requirements and specifications, they were shown in appearance of highest to lowest priority. The reasoning behind the first five requirements and specifications being set to high priority is because all those specifications are needed to create a functioning 2D clinostat that can be used to perform the experiments that the sponsor requires. All five specifications will be heavily considered during the concept generation phase and will be repeatedly checked.

For the requirements and specifications focused on the magnification system and the volumetric constraints, they were set to being medium priority because the specifications are not as important to the functionality of the clinostat. Although the sponsor has asked for a magnification system and for the size of the clinostat to not be too large, these specifications will be focused on after the initial concepts of the clinostat have been determined. The team expects that volumetric constraints will be easy to meet.

As for the last two requirements and specifications on the room temperature and noise level, these specifications will have very limited impact on the design of the clinostat and can be modified later into the design process. The team expects that temperature requirements will be met with any design because the clinostat will be placed into a room temperature environment. Meanwhile, the team also expects the noise requirements to be met because a damping exterior can be created as an add-on if excessive noise from the mechanical parts causes problems.

After all the current requirements and specifications were set, the team looked at David Garvin's Eight Basic Dimensions to determine completeness. The performance criteria has been met by multiple specifications which describe aspects of the functionality of the clinostat, such as the operating axis of rotation and the rotation rate. The features criteria has been met by specifications on additional features of the clinostat, such as the camera system and volumetric constraints. The reliability criteria has not been addressed but since the final product will only be a proof of concept, it is acceptable to not currently have a reliability expectation. The conformance criteria has also not been addressed because the sponsor has requested a custom made clinostat design. The durability criteria has been met by the specification on operation time for the clinostat. Since continuous rotation of three days is requested, the clinostat will have durable parts. The serviceability criteria has not been met. However, the clinostat will only be a prototype and it is expected that additional parts will be produced as needed since all designs will be released to the sponsor. The aesthetics criteria has been met because many of the specifications were set by the sponsor in order to help fulfill her experimental needs. The perceived quality criteria is difficult to determine. However, since our product has no previous logo or branding, it can be considered as not being met. Overall, the team believes that for a proof of concept prototype, the requirements and specifications are sufficient in quality.

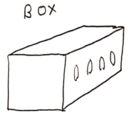
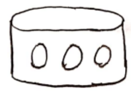
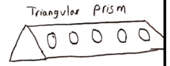
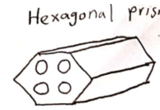
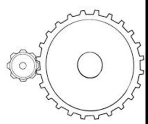
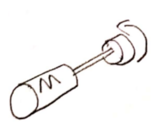
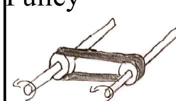
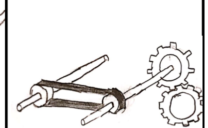
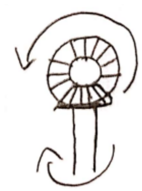
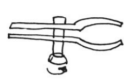
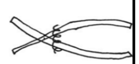
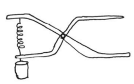
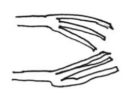
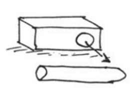
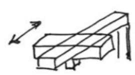
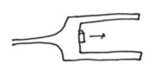
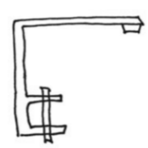
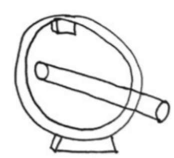
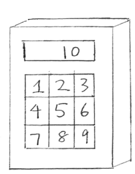
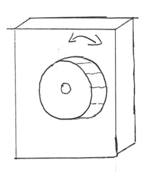
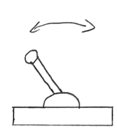
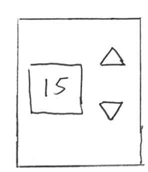
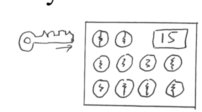
7. Concept Generation

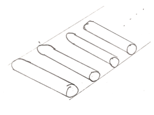
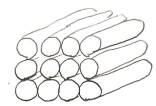
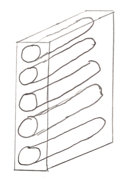
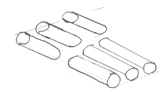
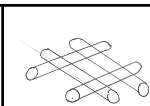
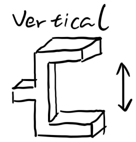
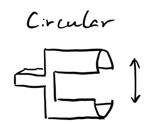
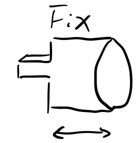
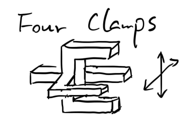
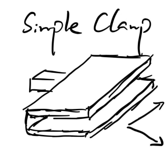
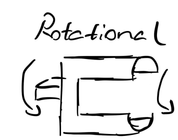
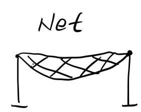
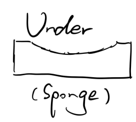
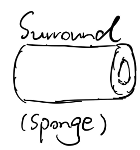
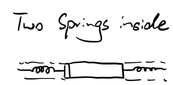
The team conducted an extensive brainstorming session focusing on different possible features to include in the clinostat. The team started a brief divergent ideation process to explore the design space to address methods to address the user requirements. The primary goal is to focus on creating sketches and categorizing the subsystems. The goal is to create at least 10 sketches of the complete structure and 5 designs of the individual subsystems. The subsystems were based on the mechanical and electrical components of the clinostat, also taking into consideration safety and aesthetics of the device. The team decided that the main attributes that need to be considered for the clinostat is a rotation system, sample configuration, clamp design, end holder fixture, camera fixture, and speed control panel. The sketches from the brainstorming session can be found in Appendix A.

8. Morphological Chart

After the brainstorming session, the team utilized a morphological chart to collect a variety of design concepts for the critical subsystems in the clinostat. Every subsystem listed within the morphological chart will be needed to meet the requirements and specifications described in section 6. Table 8.1 below shows the morphological chart.

Table 8.1 Morphological Chart

Body Container	Box 	Circular 	Triangular prism 	Triangular pyramid 	Hexagonal prism 	
Rotation System	Gears 	Direct Motor 	Pulley 	Pulley + Gear 	Bevel Gear 	
Test Tube Gripper	Clamp with Lead Screw 	Garden Shear 	Motorized Clamp 	Fingerlike Clamp 	Medicine Cap 	
Camera Mount	Stationary Camera 	Slider 	Clamp Mounted 	U-Clamp 	Circular 	
Speed controller	Dial Pad 	Physical Knob 	Lever 	Voice Control 	Up & Down buttons 	Key slots 
Specimen	Horizontal	Stacked	Vertical	Tubes on	Crossed	

Configurations				opposite ends 		
Specimen end holder						
Safety Mechanism						

The body container shape subsystem will determine the overall structure that our design will follow and a variety of geometric shapes were examined in our design exploration. It is important to evaluate this subsystem because the overall shape of our design will have an impact on other subsystems and spacing available for test tube placement.

The rotation subsystem will determine the method that the clinostat rotates test tubes and is important to consider to see if each idea can meet the variable rpm values set in the specifications. When judging the rotation system, the manufacturability and longevity of each idea was heavily examined because the team has tight deadlines and needs to achieve a design that can have robust continuous rotation.

The test tube gripper subsystem contains ideas on the different methods for holding onto test tubes while they are rotating horizontally to the gravitational vector. Many of the ideas were based on existing commercially available clamps and fasteners in order to reduce the time spent on manufacturing while also decreasing the risk for failure. Important considerations for the team were the ability of each idea to have a variable hold size and be able to be easily mounted to allow for horizontal rotation.

The camera mount subsystem shows different designs on creating a mobile mount for the camera so that the user will have flexibility in the positioning of the camera over different specimens. This flexibility is desired in the case where a specimen sample is unusable, such as the worms have died, and will allow the user to not have to stop the entire clinostat to reset the experiment.

The speed controller subsystem shows the user interface to control the rpm of the clinostat. With the stretch goals of needing an alarm to detect if rotation stopped and a timer to set rotation, the team considered the programmability and additional use for each idea. It was also important for the ideas to be very intuitive to use so that additional users would not need many instructions to operate the clinostat. For this reason, the ideas within this subsystem were based on existing control systems.

The specimen configuration subsystem shows the different potential arrangements for the test tubes and gives the team an understanding of the complexity that each arrangement's rotation system will need. In addition to rotation complexity, the arrangements showcase how much space can be saved with each idea and the potential for further expansion of the design if the user needs change.

The specimen end holder subsystem was considered by the team on the recommendation of the sponsor due to fears of the moment arm of the test tubes being too high. Since a clinostat design requires the test tubes to be constantly held horizontal to the gravitational vector, an end holder can prevent bending in the test tube gripper system. The team will consider the moment arm over the next weeks to determine what type of end holder is required to keep the test tubes horizontal.

The safety mechanism subsystem was considered by the team in case of failure with the test tube grippers and specimen end holder to provide a softer landing for the test tubes. Since the test tubes are glass and the medium inside will be nutrient-feed water with worms, it is important for the design to not have test tubes shatter. If such a failure were to occur, the team foresees that the liquid medium with worms would be very difficult to clean and could have an impact on the electrical systems within the design.

9. Individual Designs

The designs from the morphological chart were then used to create individual designs. The following figures show the four initial design concepts which will be reviewed further for potential design selection.

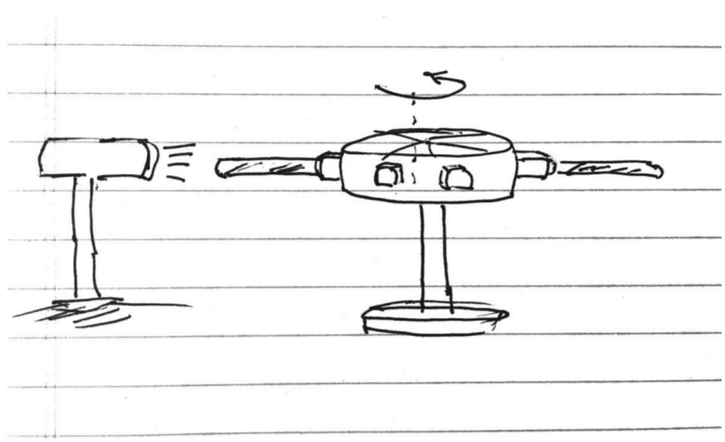


Figure 9.1. Drum design

The first design concept shown in figure 9.1 is a drum design that focuses on utilizing the most surface area as possible to accommodate multiple test tubes and explore the implications of a body shape that differs from a rectangle. This design results in a complex rotation system that requires precise angles in the bevel gears to allow test tubes to be placed in 360 degrees. In addition, the camera mount is placed outside of the design which allows greater flexibility in camera placement.

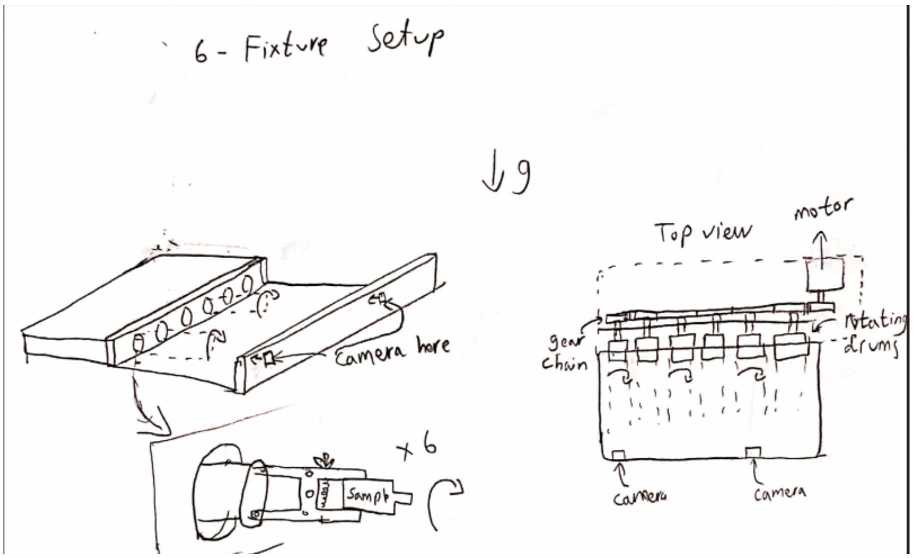


Figure 9.2. 6-fixture setup

The second design concept pictured above in figure 9.2 includes the clamp/leadscrew design and the gear train rotation system from the morphological chart. This design also features the box shape model and is designed to hold six samples of *C. elegans* without an end fixture. The drawbacks on this design is the fixed camera position. This impedes on the flexibility of camera orientation since the camera is only positioned to observe two of the same samples at any given time. The benefit to this design is the space for housing which allows the rotation system and the wiring to be protected within the clinostat. This adds an element of visual aesthetics as well as a safety element to separate the user from the moving components inside the clinostat.

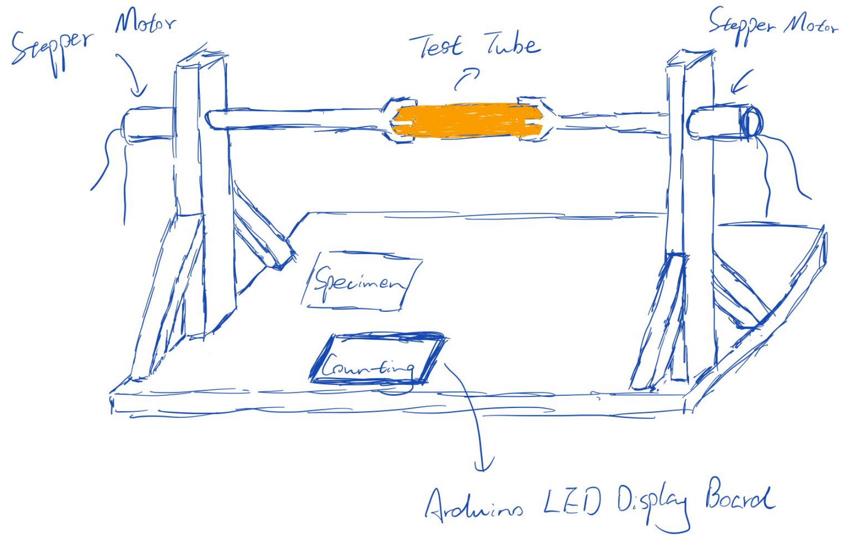


Figure 9.3. Double stepper motor design

The third design shown above in figure 9.3 uses one stepper motor on each side to ensure both sides of the test tube rotate at the same speed. Also, an Arduino LED display board is put at the bottom board to show the rotations or time of proceeding experiment. The bottom space is intentionally left blank for test tubes, specimens, and flasks. One side of this design can be replaced by a bearing, with one stepper motor controlling multiple test tubes rotating at the same speed. If three test tubes are considered as a group, multiple groups can be added and rotating at different speeds to test the influence of speed on samples. The drawback on this design is that there is no camera system however we only used this design to get ideas for the structure and user display for the clinostat. The user display refers to the LED display board.

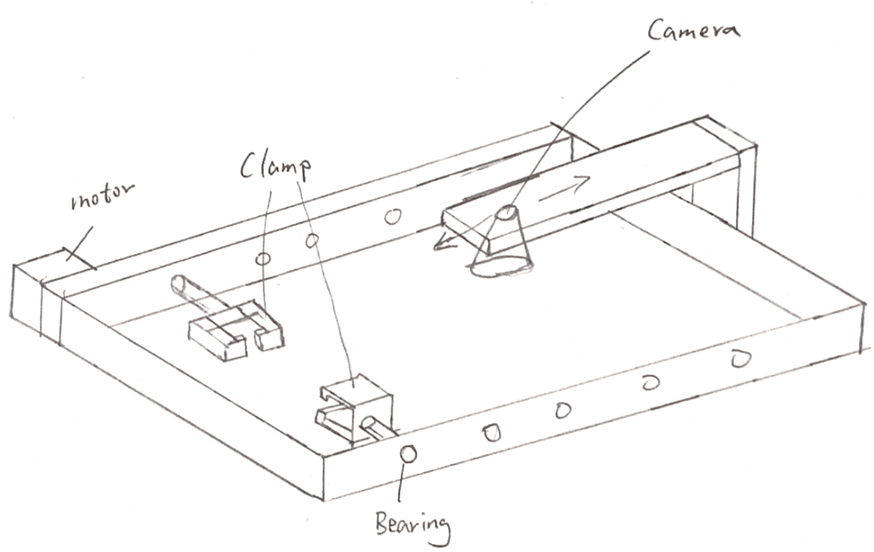


Figure 9.4. Sliding camera design

The fourth design shown in figure 9.4 is similar to the second design but incorporates a second clamp as the end holder for the specimens and allows the camera mount to have greater flexibility. The two clamps for holding each test tube at both ends provide some safety in case one of the clamps fails and also help keeping the test tubes horizontal to the gravitational vector. The camera mount has a rail for the camera to slide in the horizontal direction. This allows the user to slide the camera to observe different specimens.

10. Design Heuristics

Design Heuristics is a process driven by life-experience used to generate various concepts with novelty. It is an efficient tool to generate judgements and decisions quickly to solve problems. Though it does not guarantee the determinate solution, it allows users to generate the best guesses quickly. In the process of generating the team's designs, separate original designs were made first, with intentions to solve for the questions in unique ways. After the first drafts were created, design heuristics were used to modify each design such as "add level", "expose interior", and "layer", and the modifications are shown below.

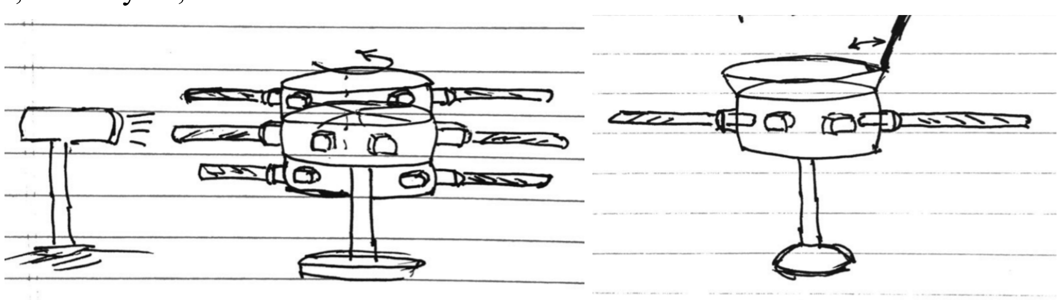


Figure 10.1. Design Heuristics of the *Drum design*, with "add levels" on the left and "expose interior" on the right.

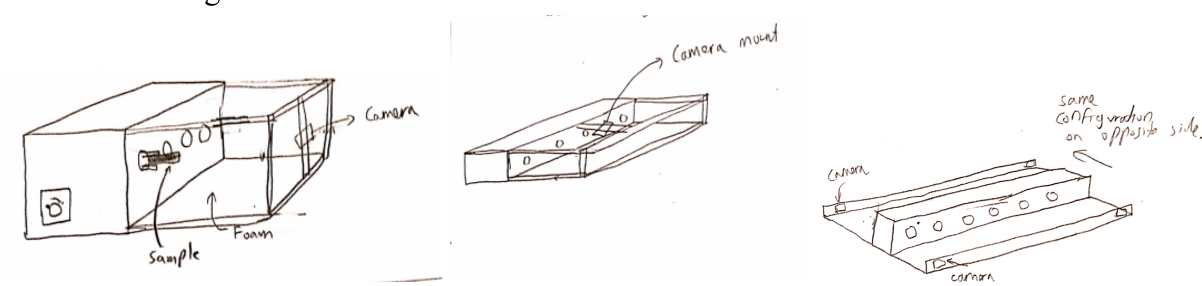


Figure 10.2. Design Heuristics of the *6-fixture setup*, with "ad motion" on the left, "reconfigure" in the middle, and "add to existing product" on the right.

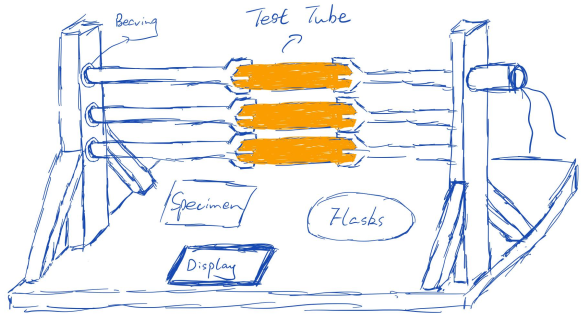


Figure 10.3. Design Heuristics of the *Double stepper motor design*, with “add levels” and “reconfigure” shown in the graph.

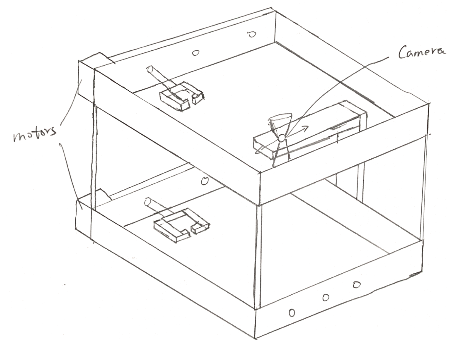


Figure 10.4. Design Heuristics of the *Sliding camera design*, with “stack” and “utilize opposite surface” shown in the graph.

11. Concept Comparison Chart

To compare the 4 individual designs, the team applied a concept comparison chart, as shown in Table 11.1. Unlike a Pugh chart which uses numbers to score each design, this concept comparison chart rated criteria and designs using three rankings, low, medium and high to avoid the difficulty in being objective in differentiating values. Five considerations that could impact the final product’s capability to fulfill the requirements were taken into account. The team gives manufacturability, ease of repairing and camera mobility high priority, because these criteria are directly related to the specifications of our design. The flexibility of design and aesthetics were analyzed but these considerations were not the driving factor for our design selection. For individual design one, the team gives it low in terms of manufacturability, flexibility of design and ease of repairing due to the round shape of the container, the complex internal structure and the use of bevel gears for transmission. It scores a medium in camera flexibility because it allows the user to reposition the camera. For individual design two, the team rates it a medium for manufacturability, because although the configuration of test tubes is simpler, to have the gears meshed together requires precision in manufacturing and to have grippers attached to the transmission system provides some additional challenge. It receives a high in ease of repairing because changing the grippers for each test tube is relatively simple in this design. In addition, the parts in this design such as gears can be replaced if damaged. It has a medium in terms of camera flexibility. Although there are different locations to mount the camera, the camera can only be placed at fixed locations. For individual design three, it has a high in manufacturability, because the stepper motors are directly connected to the test tube grippers and there is no transmission system. It also receives a rating of high in both flexibility to change design and ease of repairing because the structure and rotational system can be repaired quite easily. However, the camera flexibility is medium, because it doesn't provide a mechanism to hold the camera. For individual design four, the team gives it a medium for manufacturability and flexibility of design changes, because it also incorporates a gear train system like concept three. It has a high in flexibility of camera system, because the camera slider allows the user to easily slide the camera to different locations.

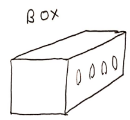
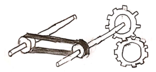
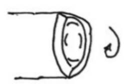
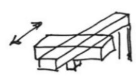
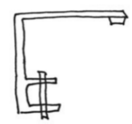
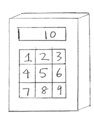
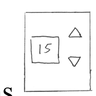
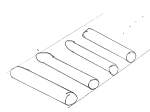
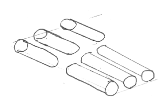
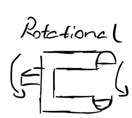
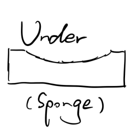
Table 11.1 Concept Comparison Chart

CONSIDERATIONS	VALUE	DESIGN 1 Drum	DESIGN 2 6-fixture horizontal setup	DESIGN 3 Double Stepper Motor	DESIGN 4 Sliding Camera Mount
Ease of Manufacturing of Rotation system	High	Low	Medium	High	Medium
Ease of repairing and longevity	High	Low	High	High	Medium
Flexibility of Camera system	High	Medium	Medium	Low	High
Flexibility of design if user needs change	Medium	Low	Medium	High	Medium
Aesthetics	Low	Medium	High	Low	Medium

12. Tentative Low Fidelity Design

The tentative final design was determined using both the morphological chart and the individual designs in parallel. Table 12.1 showcases the preferred designs that the team decided upon using an initial gut check and then secondary checks with the sponsor and the ME 450 teaching team. The team then examined the best ideas that came from each individual design through Table 11.1 and combined the best ideas together. That combination of ideas was cross checked with the preferred design in the morphological chart and iterated upon to create the final tentative design idea. The team also considered the design heuristics as possibilities for expansion for the user in the future if additional test tube holders are needed.

Table 12.1 Preferred Designs in Morphological Chart

Body Container		
Rotation System	Pulley + Gear 	
Test Tube Gripper	 Medicine Cap	
Camera Mount	Slider 	U-Clamp 
Speed controller	Dial Pad 	Up & Down buttons 
Specimen Configurations	Horizontal 	Tubes on opposite ends 
Specimen end holder		
Safety Mechanism		

The tentative final design shown in Figure 12.1 was the result of multiple iterations that combined the best ideas from each individual design. From the drum design, the idea of having an accessible interior to the housing was added so that the user would be able to easily repair the clinostat. From the 6-fixture setup, the overall structure of the body and the layout of the test tubes were taken into consideration. From the double stepper motor design, the idea of incorporating an interface for the rpm control added. From the sliding camera design, the idea of a slider for the camera mount was added to increase the flexibility of the camera. In addition, the preferred designs in the morphological chart were also added in the tentative final design. However, it is important to note that the preferred designs are not shown in the CAD image.

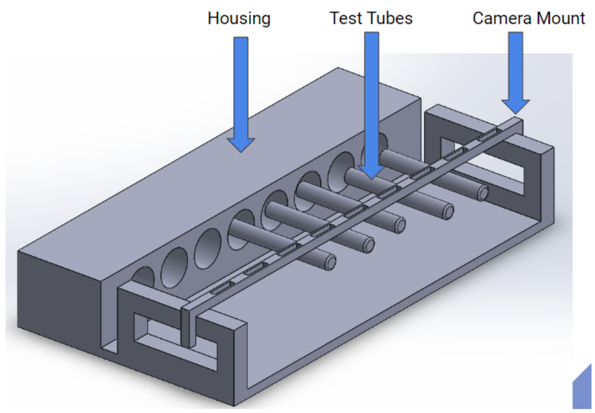


Figure 12.1. Tentative low fidelity design CAD in Solidworks

The tentative design was then examined by the team using the same criteria in the concept comparison chart to judge the feasibility of the final idea. It was found that ease of manufacturing of the rotation system and the flexibility of the design for change were medium because the consideration of the "medicine cap" idea would both require time to manufacture and limit the holder to only test tubes.

Table 12.3 Final Tentative Design Concept Chart

CONSIDERATIONS	VALUE	TENTATIVE FINAL DESIGN
Ease of Manufacturing of Rotation system	High	Medium
Aesthetics	Low	High

Flexibility of design if user needs change	Medium	Medium
Ease of repairing and longevity	High	High
Flexibility of Camera system	High	High

13. Mock up

A cardboard prototype of the clinostat was created based on the design from the CAD model above. The figure below shows the prototype.

Figure 11.1. Pictured above is the cardboard prototype of the clinostat

The model allowed the team to visualize the dimensions of the clinostat as well as the ease of portability. The slots on the side of the clinostat were initially created to act as a track for the camera beam. Upon visualizing the prototype, the team decided that the track can also be used as a handle to carry the clinostat between testing locations. This however was an idea that was disregarded in the final design because in the interest of cost, the side walls were made from acrylic instead of aluminum and the slots would have broken under the weight of the entire clinostat. The prototype and the CAD model both show that with this design configuration, there is a maximum of eight *C.elegans* samples that can be housed in the clinostat. The spacing for each clamp was determined based on sponsor provided test tube diameters and a potential clamp available to incorporate with the design. This clamp is introduced in section 16 below.

14. Overall Subsystems

The overall subsystems that the team found to be vital to the clinostat design were the gear train, the test tube gripper, the camera mount, and the electrical subsystem. These subsystems were fully designed by an individual member of the team with collaborating with the sponsor and faculty mentor. Below each subsystem's components are described in detail and justifications are given on why each design will function in the clinostat.

15. Gear Train

The gear train system is used for transmitting the rotation from motor to test tubes. The spacing between each test tube is 2.5 inch; therefore, the team selected the gear to have 2.5'' pitch diameter. After browsing through all the possible gears available, the team selected a spur gear made of aluminum. It is not clear what type of aluminum this gear is made of, so the team assumes it to be casted 2024-T4 aluminum for analysis. The gear module is 0.8mm.

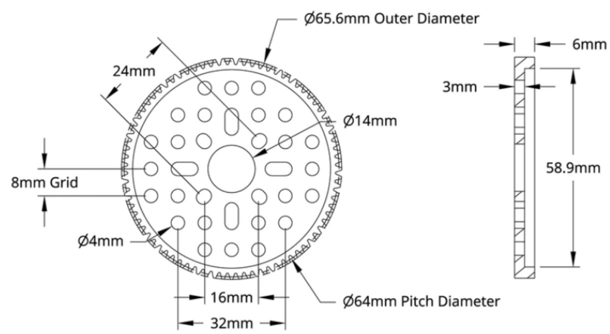


Figure 15.1. Drawing of the spur gear used for transmission [17]

The motor selected for the design is Pololu 37D Metal Gearmotor. In order to determine the best gear ratio for connecting the motor shaft to the gear train, a load-inertia matching is performed based on Eq. 1, in which N is the optimal gear ratio, J_L is the load inertia and J_M is the rotor inertia. The load inertia for the shafts, test tubes, shaft collars and shaft connectors is 63430.12 gmm^2. This is obtained from the solidworks model. The motor's rotor inertia is calculated based on the rotor's dimension, shown in Eq. 2 - Eq. 3, in which m is the mass of the rotor and r is the radius of the rotor, ρ is density of stainless steel, and l is the length of the rotor.

$$N = \sqrt{\frac{J_L}{J_M}} = \sqrt{\frac{63430.12gmm^2}{16.25\ gmm^2}} = 62.5 \quad (1)$$

$$J_M = \frac{1}{2}mr^2 \quad (2)$$

$$J_M = \frac{1}{2}\rho\pi r^4 l = \frac{1}{2} \times 0.00799g/mm^3 \times \pi \times (3mm)^4 \times 16mm = 16.25gmm^2 \quad (3)$$

According to the load inertia matching, the optimal gear ratio between rotor and load is 62:1. The team considered to select a motor of high speed and use a 62:1 gear train to step down to 20 rpm. However, adding a gear train to do so will increase the complexity to our design. Instead, the team decided to use a motor that can provide high torque and low no-load speed with an internal gear box that is close to the optimal gear ratio. The gear selected is 150:1 Metal Gearmotor 37Dx73L mm 24V with 64 CPR Encoder. The motor's specifications are shown in Table 15.1.

Table 15.1 Specifications of selected metal gearmotor [18]

voltage	no-load performance	stall extrapolation
24 V	68 RPM, 100 mA	56 kg · cm (780 oz · in), 3 A

The team then used the motor's load vs speed curve to estimate the amount of force exerted on the gear. According to Figure 15.2, assume operating at 12V and 20 rpm, the torque from the motor is at maximum 145 kgmm. Converting the torque to force as shown in Eq.4 , 22.2 Newtons will be exerted on the gear.

$$F_T = \frac{T}{R} \times 9.8m/s^2 = \frac{145kgmm}{64mm} \times 9.8m/s^2 = 22.2\,N \quad (4)$$

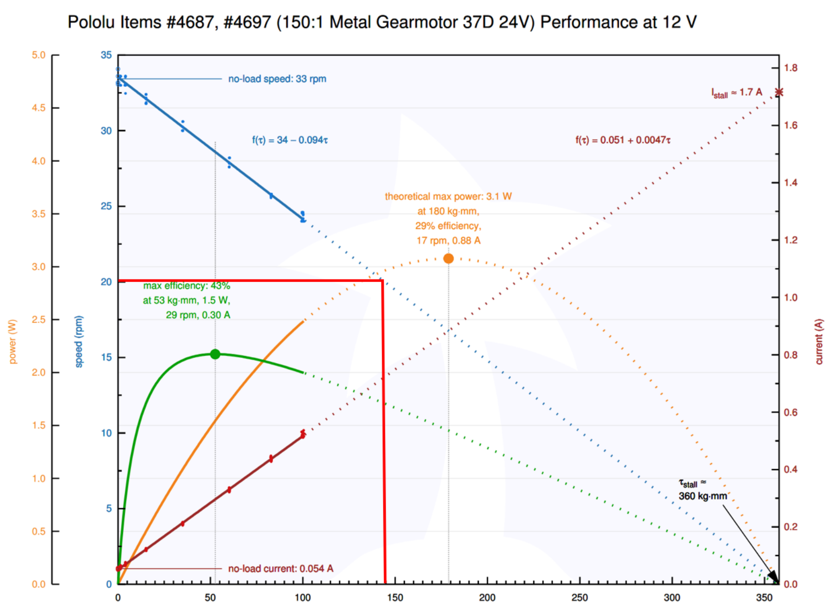


Figure 15.2. Torque-speed curve of selected motor [18]

To ensure the gear will not break due to bending stress during operation, the Lewis equation (Eq. 5)[19] is used to estimate the maximum allowable tangential force exerted on the gear. σ is the bending stress exerted on the gear, F is the tangential force, b is the face width of the gear, and m

is the gear module. The velocity factor K_V can be calculated from Eq. 6, in which V is the pitch line velocity at 20 rpm. The Lewis form factor Y for the gear of 80 teeth is obtained from Figure 15.3 using linear interpolation (Eq. 7). The yield strength of aluminum is 276 MPa [20]. Using the yield strength of aluminum as the allowable bending strength, the allowable tangential force F_{allow} exerted on the gear is calculated from Eq.8. Using a safety factor of 3, the allowable tangential force is 189 N. The maximum transmitted load, F_T, previously calculated is 22.2 N. Therefore, the gear will not break due to the bending stress.

$$\sigma = \frac{K_v F}{bmY} \tag{5}$$

$$K_V = \frac{3.05 + V}{3.05} = \frac{3.05 + \frac{\pi \times 64mm \times 20rpm}{60}}{3.05} = 1.022 \tag{6}$$

$$Y = \frac{0.447 - 0.435}{100 - 75} \times (80 - 75) + 0.435 = 0.4374 \tag{7}$$

$$F_{allow} = \frac{\sigma bmY}{K_V} \times \frac{1}{S.F.} = \frac{276MPa \times 6mm \times 0.8mm \times 0.4374}{1.022} \times \frac{1}{3} = 189\ N \tag{8}$$

Number of Teeth	Y
28	0.353
30	0.359
34	0.371
38	0.384
43	0.397
50	0.409
60	0.422
75	0.435
100	0.447
150	0.460
300	0.472
400	0.480
Rack	0.485

Figure 15.3. Lewis form factor for different number of teeth [19].

To avoid surface fatigue failure, also known as surface wear or pitting, due to many repetitions of high contact stresses, the surface contact stress on the gear tooth is calculated based on Eq. 9 [19]. σ_C is the surface contact stress, K_V is the velocity factor, b is the face width of gear, Φ is the pressure angle of gear, F_T is the tangential load. r is the instantaneous radii of curvature of the tooth profile calculated from Eq.10, in which d is the gear's pitch diameter. C_P is the elastic coefficient calculated from Eq.11, where v is the Poisson's ratio of aluminum (0.33) and E is the Young's modulus of aluminum (10600 ksi) [20]. Under the previously calculated maximum tangential load of 22.2 N (5lbf), the surface contact stress is 98.48 MPa. If the clinostat is to be operated under 20 rpm, 12 hours per day for 2 years, the number of cycles is around 10^7. According to the S-N curve of aluminum shown in Figure 15.4, the failure stress at 10^7 cycles is around 150 MPa. Therefore, the gears will not fail due to surface wear.

$$\sigma_C = - C_p [\frac{K_v F_T}{b cos\phi} (\frac{2}{r})]^{1/2} = - 1376.3[\frac{1.022 \times 5lbf}{0.23622cos20} (\frac{2}{0.4275''})]^{1/2} = - 14283psi = - 9 \quad (9)$$

$$r = \frac{d \times sin\phi}{2} = \frac{2.5'' \times sin20}{2} = 0.4275'' \quad (10)$$

$$C_P = [\frac{1}{\pi \times 2 \times (\frac{1-v^2}{E})}]^{1/2} = [\frac{1}{\pi \times 2 \times (\frac{1-0.33^2}{10600000psi})}]^{1/2} = 1376.3 \quad (11)$$

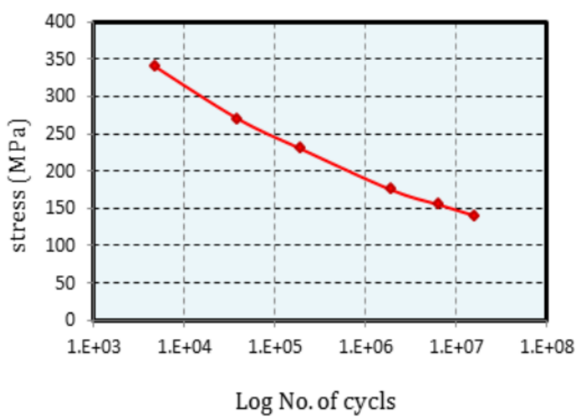


Figure 15.4. S-N curve of 2024-T4 aluminum [21]

16. Test Tube Grippers

The test tube grippers was a subsystem examined in the design phase to understand what method of holding onto test tubes would be viable for the clinostat. Since the design would need to accommodate a range of test tube diameters and be able to allow for horizontal rotation, it was a challenge to find the most suitable idea that could be manufactured in one semester. The team believed the "medicine cap" idea to be the most viable and created a CAD system based on the way a "medicine cap" would work. In Figure 16.1, the full system for the test tube grippers can be seen.

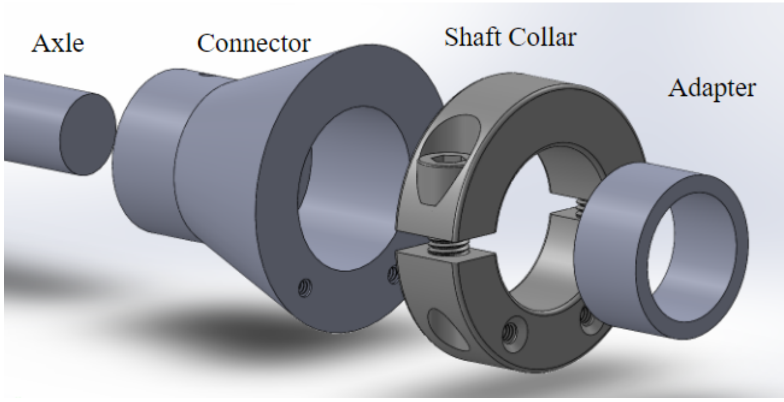


Figure 16.1. The test tube gripper subsystem

As shown in the figure, an axle will connect to the gear train system described previously and will be connected to a connector piece through a spring pin. The connector will then connect the axle to the shaft collar. Since there is no need for high precision and the connector only needs to have an increasing diameter as it goes from the axle to the shaft collar, the connector will be 3D printed to save time and money. However, there will need to be two quarter inch holes in order to connect the connector to the shaft collar.

A premade shaft collar is used to grip concentrically onto the test tube while maintaining a secure connection. Two countersink screws will be used to attach the shaft collar to the connector piece because a flat interface will provide a safer system. When a researcher goes to insert the test tube into the shaft collar, the team wants there to not be any protrusions on the shaft collar face that could injure the researcher. In addition, since the inner diameter of the shaft collar is one inch, it will allow the clinostat to fulfill the requirement of holding a variable test tube diameter up to one inch. The adapter will help with the variable diameter requirement by being a compressible material that can be increased in width in order to secure small diameter test tubes. Below is a table describing the advantages and disadvantages of different materials that the team considered for the adapter.

Table 16.1. Adapter Material Selection

	Aluminum	**Rubber**	**Cork**
Advantages	Sturdy, can be machined to high precision, set screw can anchor test tubes, fluid can be cleaned	Elastic, compressible, can protect test tubes, less degradation, fluid can be cleaned	Lightest of all material, can protect test tubes

Disadvantages	Glass tube is fragile and concentrated pressure of set screw will cause long term problems, replacement needs machining	Machining not as precise as aluminum, no method for securing other than compression	Machining not precise, prone to degradation and weather fluctuation, not as compressible

With there being so many disadvantages in an aluminum adapter, the team decided that aluminum would not be a feasible solution. Although aluminum provides high precision in controlling the location of the test tube, the problems would be the possibility of the test tubes breaking and more precise machining. The cork adapter seemed reasonable in being extremely light to reduce the weight of the entire test tube gripper system. However, with cork being extremely susceptible to changes in humidity and seasonal temperature fluctuations, it was decided to not be a feasible solution. Cork also was seen as being easily degraded and unsuitable for the long time scale that the clinostat would need to function. Rubber was seen to be compressible, resistant to degradation, and easy to clean which were qualities that would be ideal for protecting test tubes for long periods of time. Although there were disadvantages with machining rubber to be suitable for the shaft collar, the team was able to find pre-machined adhesive rubber strips. These strips would be easily attached to the insides of the shaft collars and be quickly manufactured.

The four components to the test tube gripper system were examined for their gravitational force, bending moments, bending stress, and overall deflection. For all the calculations, the worst case scenarios were used in which the overall axle and test tube lengths were 0.1524 meters or 6 inches. In Figure 16.2, a force diagram of the test tube gripper system is shown.

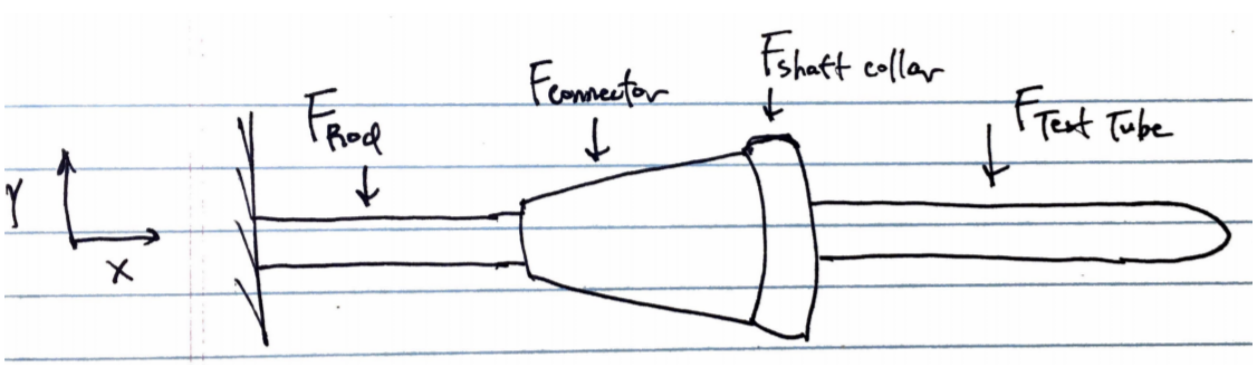


Figure 16.2. Gravitational forces on test tube gripper system

The rod, shaft collar, and test tube were all assumed to be perfect cylinders and the connector was assumed to be a perfect cut cone. For the material, the rod and shaft collar were 6061 aluminum, the connector was PLA, and the test tube was considered to be completely filled with water. A limitation to these approximations is that the adapter piece, all screws, and the glass in the test tube were considered to be negligible. However, these minor parts of the test tube gripper system can be considered offset because the rod and test tube lengths and diameters were extended to max and a safety factor was included into the calculations. In addition, the test tube gripper system was considered to be a cantilever beam and this would be assuming that a permanent fixture would be mounted on the end of the gear train. Figure 16.3 shows the measurement locations used for cylinders and the cut cone.

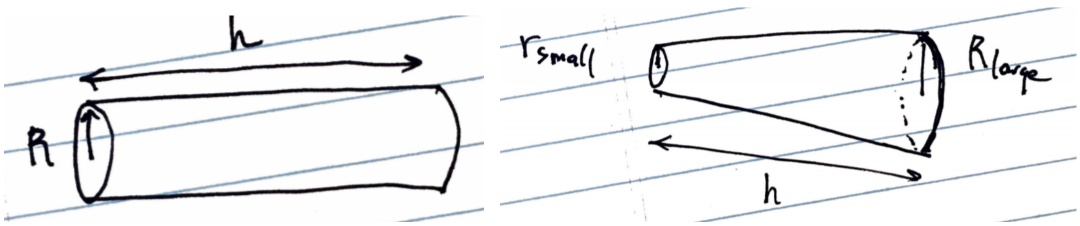


Figure 16.3 Measurement locations used for cylinder on the left and cut cone on the right

Gravitational forces on all four components are shown below with all length measurements in meters and forces in newtons:

$$F_{rod} = \pi r_{rod}^{2} h_{rod} \rho_{aluminum} g = \pi(0.00635)^{2} 0.1524(2700\, kg/m^{3})g = 0.51\, N,$$

$$F_{connector} = \frac{1}{3}(\pi h_{connector}(r_{small}^{2} + r_{small} R_{large} + R_{large}^{2}))\rho_{PLA} g$$

$$= \frac{1}{3}(\pi 0.0254((0.0127^{2} + 0.0127(0.0254) + 0.0254^{2}))(1250\, kg/m^{3})g$$

$= 0.37\, N$, where *r* represents the smaller radius of the cut cone and *R* represents the larger radius of the cut cone,

$$F_{shaft\ collar} = \pi r_{shaft\ collar}^{2} h_{shaft\ collar} \rho_{aluminum} g = \pi(0.0127)^{2} 0.0127(2700\, kg/m^{3})g = 0.17\, N$$
,

$$F_{test\ tube} = \pi r_{test\ tube}^{2} h_{test\ tube} \rho_{water} g = \pi(0.01)^{2} 0.1524(1000\, kg/m^{3})g = 0.47\, N.$$

In order to increase the safety of the design, these gravitational forces were all rounded up in the calculations. With these gravitational forces, the bending moments for each component were calculated assuming that all forces were concentrated in the center of each component:

$$M_{rod} = F_{rod}(L_{rod\ center}) = 0.51\,(0.0762) = 0.039\, Nm,$$

$$M_{connector} = F_{connector}(L_{connector\ center}) = 0.37(0.1524 + \frac{h(R_{large}^{2} + 2r_{small}R_{large} + 3R_{small}^{3})}{4(R_{large}^{2} + r_{small}R_{large} + r_{small}^{2})})$$

$$= 0.37(0.1524 + \frac{0.0254(0.0254^{2} + 2x0.0254x0.0127 + 3x0.0127^{3})}{4(0.0254^{2} + 0.0254x0.0127 + 0.0127^{2})} = 0.059\, Nm,$$

$$M_{shaft\ collar} = F_{shaft\ collar}(L_{shaft\ collar\ center}) = 0.17(0.1524 + 0.0254 + 0.00635) = 0.031\ Nm$$

,

$$M_{test\ tube} = F_{test\ tube}(L_{test\ tube\ center}) = 0.47(0.1524 + 0.0254 + 0.0127 + 0.0762) = 0.13\ Nm$$

.

With the bending moments, the total bending stress on the entire test tube gripper system was calculated to be the following where M is the total moment, y is the distance to the neutral axis, and I is the moment of inertia [22]:

$$Total\ Bending\ Stress = My\,/\,I = My/\left(\frac{\pi}{4}R^4\right) = 0.261(0.00635)/\left(\frac{\pi}{4}(0.00635)^4\right) = 1.30\ MPa$$

After cross examination with a stress-strain curve from literature, we found that the total bending stress that the aluminum rod would experience is not in the zone of permanent deformation. This was an expected result that was corroborated in the calculations and the team moved forward with determining the total deflection that the bending stress on the rod would cause. Figure 16.3 showcases the stress-strain curve that was examined.

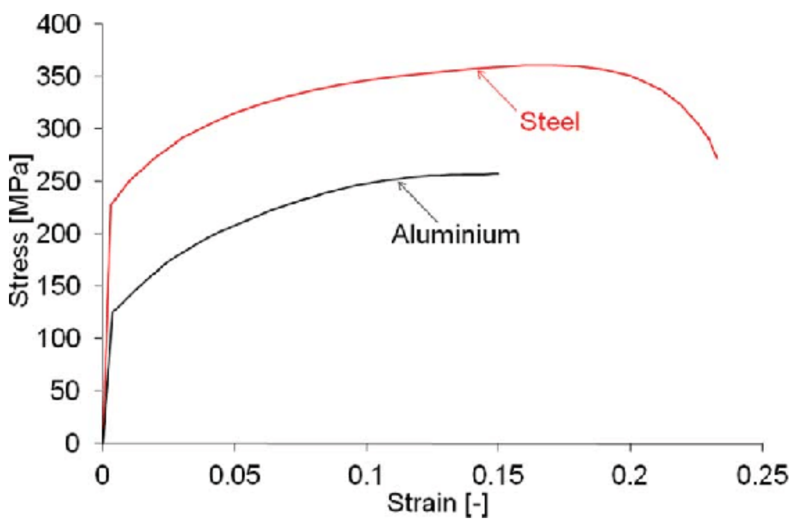
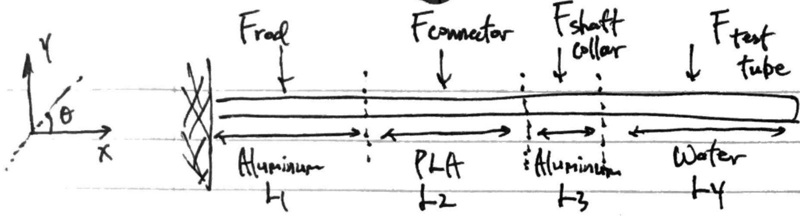


Figure 16.3. Stress-Strain curve of aluminum and steel with permanent deformation zones [23]

The total deflection in the aluminum axle rod was calculated below where each section of the test tube gripper system is analyzed [22]:



I.C.

SECTION 1

$$E_1 I_1 \frac{dy^2}{dx^2} = F_{rod}\, x_1 \qquad \begin{cases} x_1 = 0,\ y = 0 \\ x_1 = 0,\ \theta = 0 \end{cases}$$

$$E_1 I_1 \frac{dy}{dx} = \frac{F_{rod}\, x_1^2}{2} + c_1$$

$$E_1 I_1 \frac{dy}{dx} = \frac{F_{rod}\, x_1^2}{2} \rightarrow \theta_1 = \frac{1}{69\times10^9\,Pa\left(\frac{\pi}{4}(0.00635\,m)^4\right)}\left(\frac{0.51\,N(0.1524\,m)^2}{2}\right)$$

$$= 0.00006 = 6\times10^{-5}$$

$$E_1 I_1 y = \frac{F_{rod}\, x_1^3}{6} + c_2$$

$$E_1 I_1 y = \frac{F_{rod}\, x_1^3}{6} \qquad y_1 = \frac{1}{69\times10^9\,Pa\left(\frac{\pi}{4}(0.00635\,m)^4\right)}\left(\frac{0.51\,N(0.1524\,m)^3}{6}\right)$$

$$= 3.4\times10^{-6}\,m$$

SECTION 2

$$E_2 I_2 \frac{dy^2}{dx^2} = F_{connector}\, x_2 \qquad x_2 = L_1,\ \theta = 6\times10^{-5}$$

$$x_2 = L_1,\ y = 3.4\times10^{-6}\,m$$

$$E_2 I_2 \frac{dy}{dx} = \frac{F_{conn}\, x_2^2}{2} + c_1$$

$$E_2 I_2 \theta_2 = \frac{F_{conn}\, x_2^2}{2} + E_2 I_2 (6\times10^{-5}) - \frac{F_{conn} L_1^2}{2}$$

$$E_2 I_2 y = \frac{F_{conn}\, x_2^3}{6} + \left(E_2 I_2 (6\times10^{-5}) - \frac{F_{conn} L_1^2}{2}\right) x_2 + C_2$$

$$E_2 I_2 y = \frac{F_{conn}\, x_2^3}{6} + \left(E_2 I_2 (6\times10^{-5}) - \frac{F_{conn} L_1^2}{2}\right) x_2 + E_2 I_2 (3.4\times10^{-6})$$

$$- \frac{F_{conn} L_1^3}{6} - \left(E_2 I_2 (6\times10^{-5}) - \frac{F_{conn} L_1^2}{2}\right) L_1$$

$x_3 = L_2,\ \theta_2 = 6\times10^{-5}$

$x_3 = L_2,\ y_2 = 3.46\times10^{-6}\ m$

SECTION 3

$$E_3 I_3 \frac{dy^2}{dx^2} = F_{shaftc}\, x_3$$

$$E_3 I_3 \frac{dy}{dx} = \frac{F_{shaftc}\, x_3^2}{2} + c_1$$

$$E_3 I_3 \theta_3 = \frac{F_{shaftc}\, x_3^2}{2} + E_3 I_3 (6\times10^{-5}) - \frac{F_{shaft} L_2^2}{2}$$

$$E_3 I_3 y_3 = \frac{F_{shaft}\, x_3^3}{6} + \left(E_3 I_3 (6\times10^{-5}) - \frac{F_{shaft} L_2^2}{2}\right) x_3 + C_2$$

$$E_3 I_3 y_3 = \frac{F_{shaft}\, x_3^3}{6} + \left(E_3 I_3 (6\times10^{-5}) - \frac{F_{shaft} L_2^2}{2}\right) x_3 + E_3 I_3 (3.46\times10^{-6}) - \frac{F_{shaft} L_2^3}{6} - \left(E_3 I_3 (6\times10^{-5}) - \frac{F_{shaft} L_2^2}{2}\right) L_2$$

$x_4 = L_3,\ \theta_3 = 6\times10^{-5}$

$x_4 = L_3,\ y_3 = 3.78\times10^{-6}\ m$

$$\boxed{\theta_4 = 6\times10^{-5} \qquad y_4 = 0.00039\ m}$$

$$E_4 I_4 \frac{dy}{dx} = \frac{F_{test}\, x_4^2}{2} + c_1$$

$$E_4 I_4 \theta_4 = \frac{F_{test}\, x_4^2}{2} + E_4 I_4 (6\times10^{-5}) - \frac{F_{test} L_3^2}{2}$$

$$E_4 I_4 y_4 = \frac{F_{test}\, x_4^3}{6} + \left(E_4 I_4 (6\times10^{-5}) - \frac{F_{test} L_3^2}{2}\right) x_4 + C_2$$

$$E_4 I_4 y_4 = \frac{F_{test}\, x_4^3}{6} + \left(E_4 I_4 (6\times10^{-5}) - \frac{F_{test} L_3^2}{2}\right) x_4 + E_4 I_4 (3.78\times10^{-6}) - \frac{F_{test} L_3^3}{6} - \left(E_4 I_4 (6\times10^{-5}) - \frac{F_{test} L_3^2}{2}\right) L_3$$

The deflection that was found is extremely negligible with a value of 0.00039 meters. Although the deflection is minimal, the team decided to incorporate pillow blocks into the gear train system on either side of the gear to reduce the possibility of deflection at the end of the test tube gripper system. These additional supports will shorten the axle length and reduce bending effects. It is important to note that the calculation shown in this section is only an approximation of the deflection value since each piece within the entire subsystem has assumptions regarding their shape. Figure 16.4 showcases the pillow block addition to the gear train system.

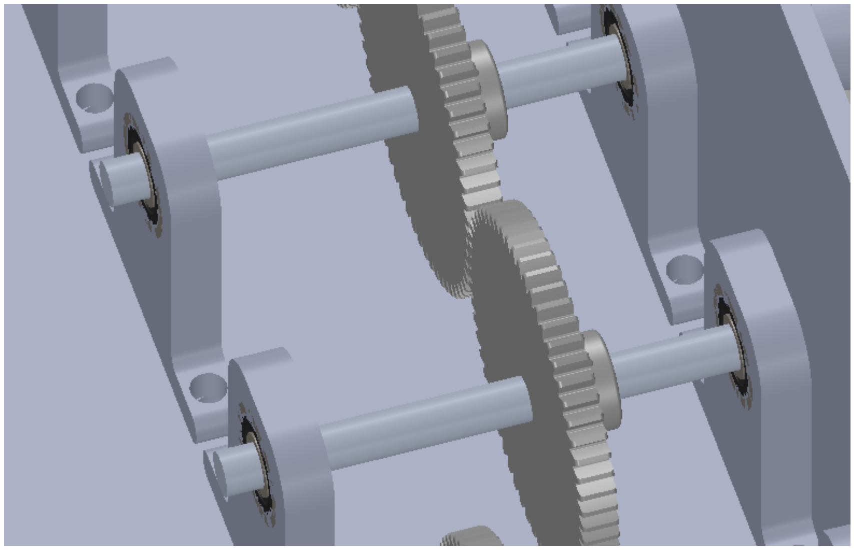


Figure 16.4. Two pillow block setup in gear train for axle stabilization

17. Camera System

The camera mount will be used to hold a handheld digital camera which is used to observe the *C.elegans* worms in vitro. The main objective of the camera is for the user to detect whether the worms are alive or deceased. The camera needs to be able to show magnified images of *C.elegans* in the test tube. A magnification test was conducted on a standard laboratory microscope to find the optimal magnification level at which the worms would be visible. This ideal magnification is at 400x. The team therefore researched potential cameras that have a magnification capability of 400x.

The team selected and purchased a USB Bysameyee digital microscope with a magnification range of 40-1000x. The image of the digital microscope is shown in Figure 17.1 below.

Figure 17.1. Image of the USB Bysameyee digital microscope

The reasoning of the selection of this camera was because of having a desired magnification range, handheld capability, and onboard LED lighting. The low cost of this digital microscope was, however, the greatest factor in the selection of this device. The team then conducted a glare and magnification test to determine the quality of the purchased camera. This test was conducted by bringing the camera close to a test tube containing *C.elegans* worms without letting the camera touch the outer surface of the test tube. The image from the digital camera is shown below in Figure 17.2.

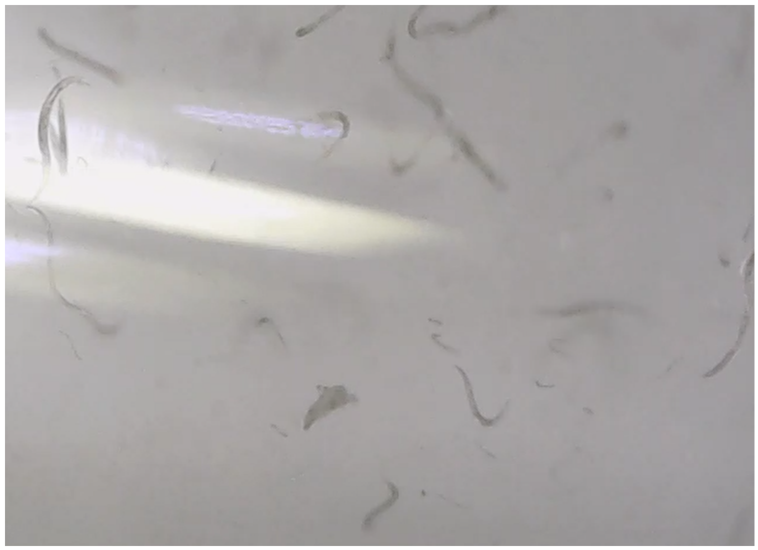


Figure 17.2. The image of *C.elegans* worms under the digital microscope

The image shown in figure 17.2 indicates that the glare is evident however the worms are visible. Since the objective of the camera is to check the mortality of the worms, the camera successfully provides the necessary magnification which allows the user to observe worms in vitro.

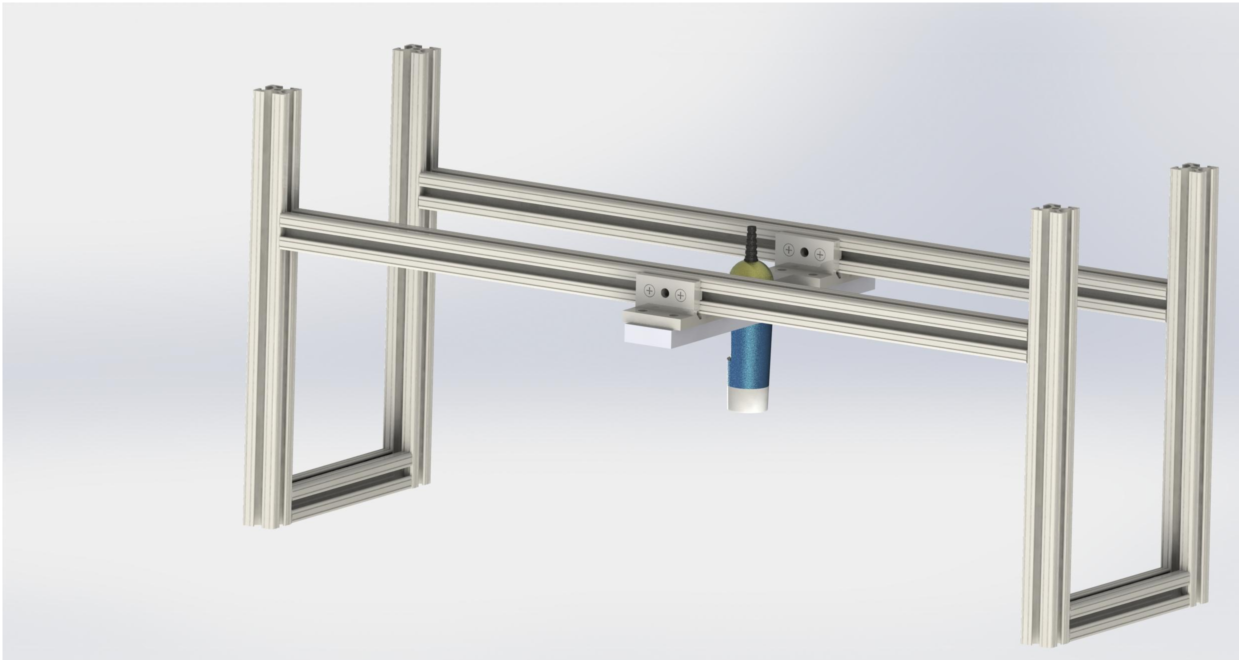


Figure 17.3. The camera mount for digital microscope

Figure 17.3 shows the structure of the camera mount. The middle horizontal bar with the camera connector will be 3D printed to save time and cost, and it will be connected to the other two horizontal bars using T-Slotted Framing. Other bars will be 1 by 1 inch aluminum extruded bars, which can easily be acquired from Mcmaster Carr or from our machine shop. The bars will be fixed in position using the Miniature T-Slotted Fittings, allowing the camera to be moved both horizontally and vertically. The camera mount will serve as a stand positioning outside the clinostat side panels. This system will need further development and it is likely that the camera mount system will be pushed beyond the design handoff date to our sponsor.

18. Finalized CAD Design

The gear train and the test tube gripper shown in the sections above are combined and housed in a single housing structure.The final housing structure is based on the housing design shown in section 12. The solidworks CAD model of the finalized design is shown in the figures below.

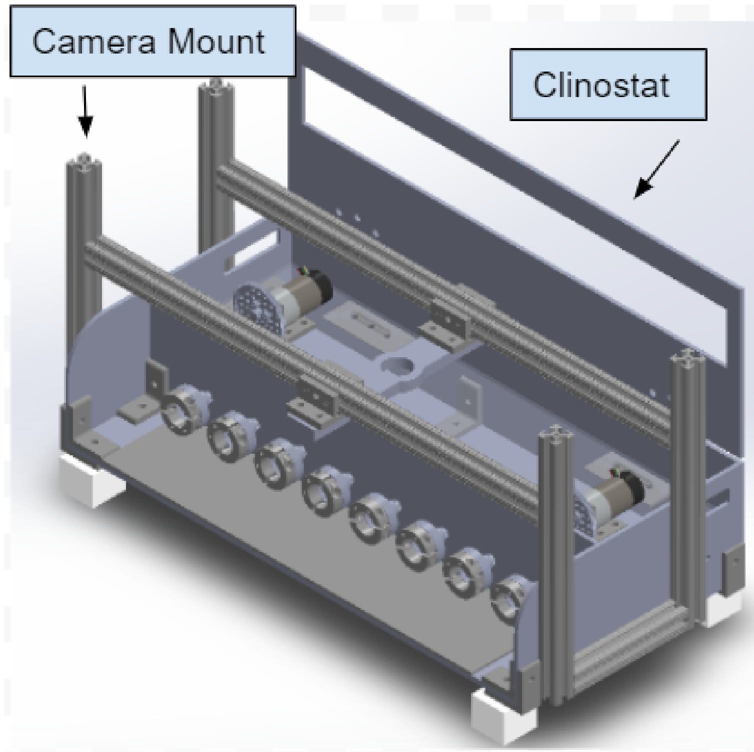


Figure 18.1. Overall assembly of the clinostat with the camera mount

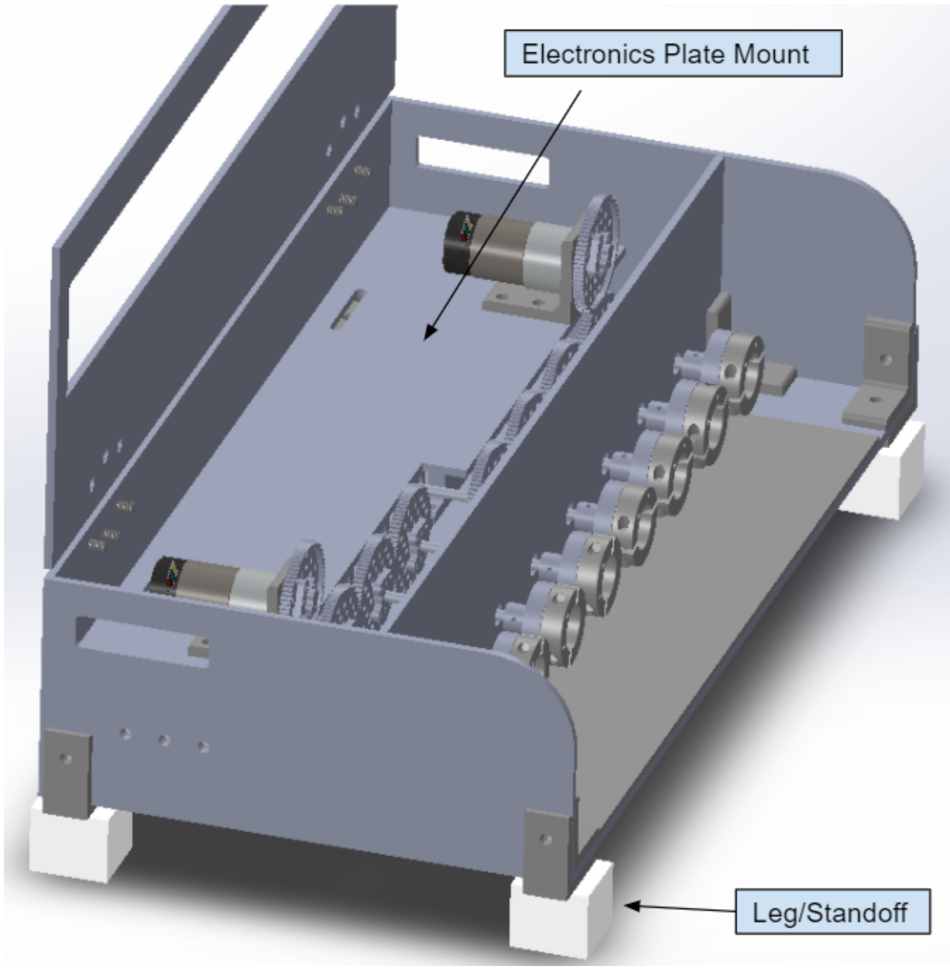


Figure 18.2. Front perspective view of the clinostat with labels

The breadboard is used to hold a switch, buttons, and an LCD screen. This is part of the electrical subsystem which will be discussed in section 19. The electronics mount panel is used to hold all electronic components which include both motors, microcontrollers, and a motor driver. This panel will be manufactured from a 6061 aluminum sheet.

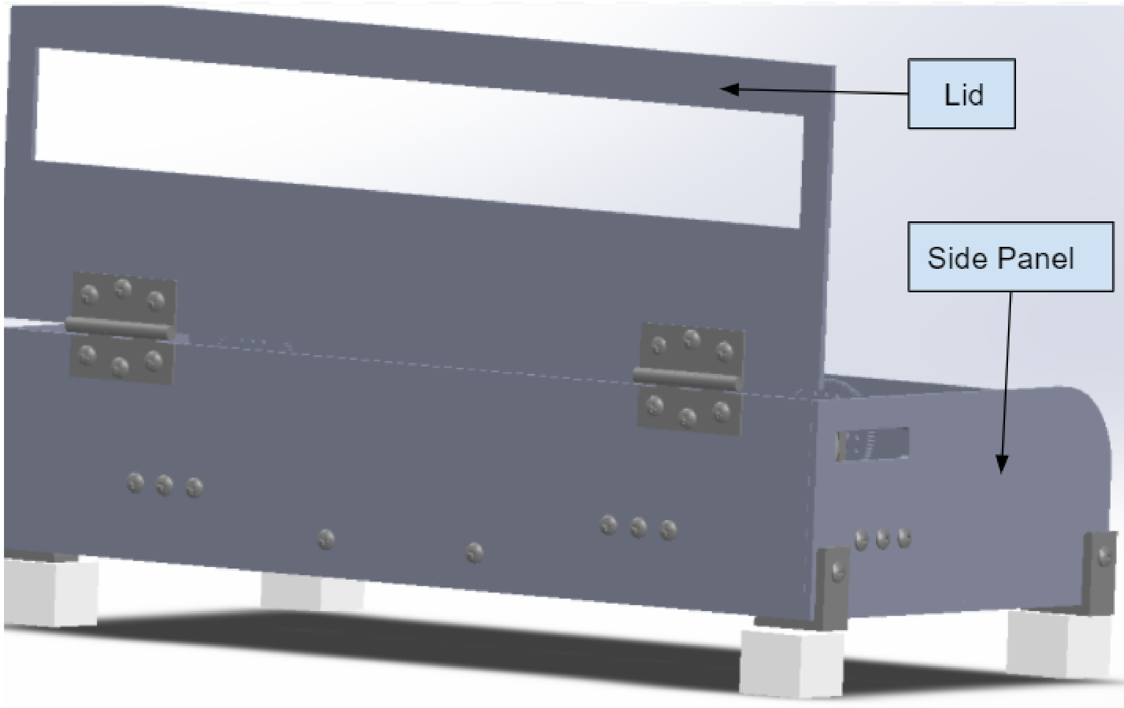


Figure 18.3. Back perspective view of the clinostat with labels

The clinostat has two side panels on opposite segments of the structure. The side panel has a slotted hole which is used as a handle to transport the clinostat. The side panels and the lid are both manufactured from 6061 aluminum sheets. The lid is attached on hinges which allows the panel to open up to reveal the electronics, motor, and gear train within the clinostat.

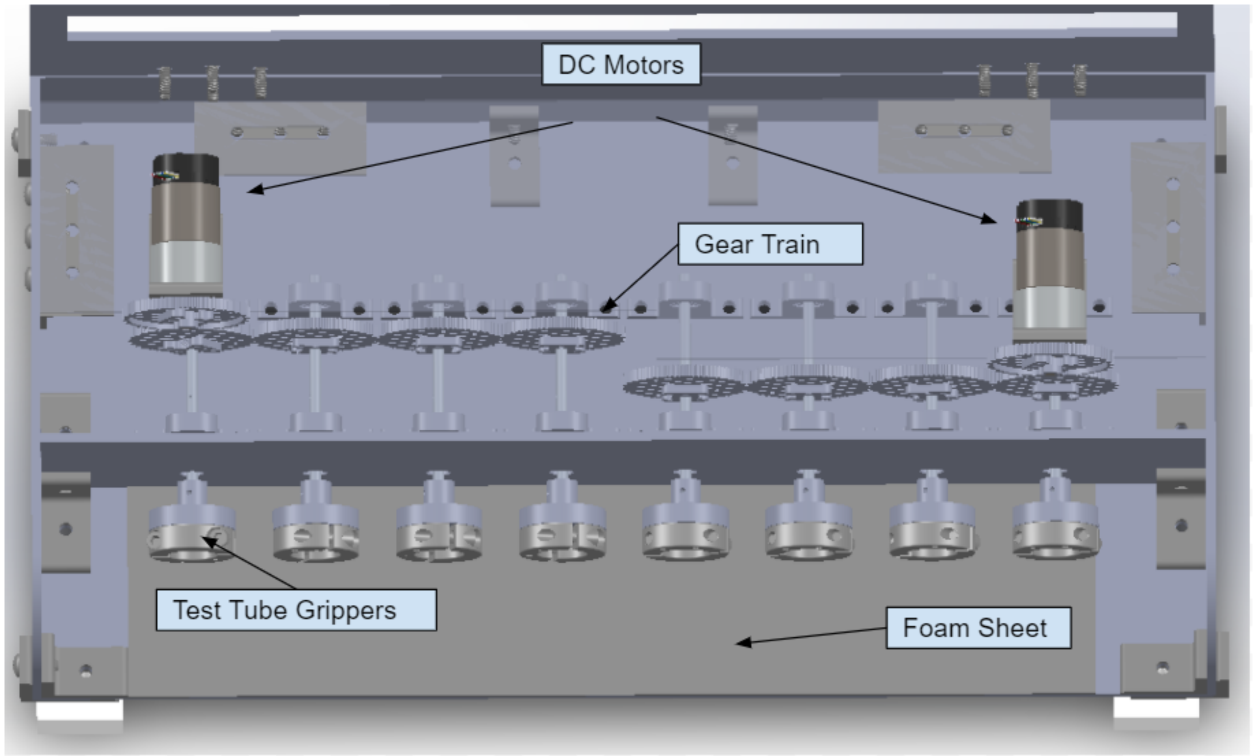


Figure 18.4. The top view image of the clinostat with labels

Figure 18.4 shows the incorporation of the test tube grippers with the gear train system. A foam sheet is placed under the test tube gripper which is used as a safety net in case the test tube breaks or slips out of the gripper. This method expedited the clean up of the test tube in case this occurs during an experiment.

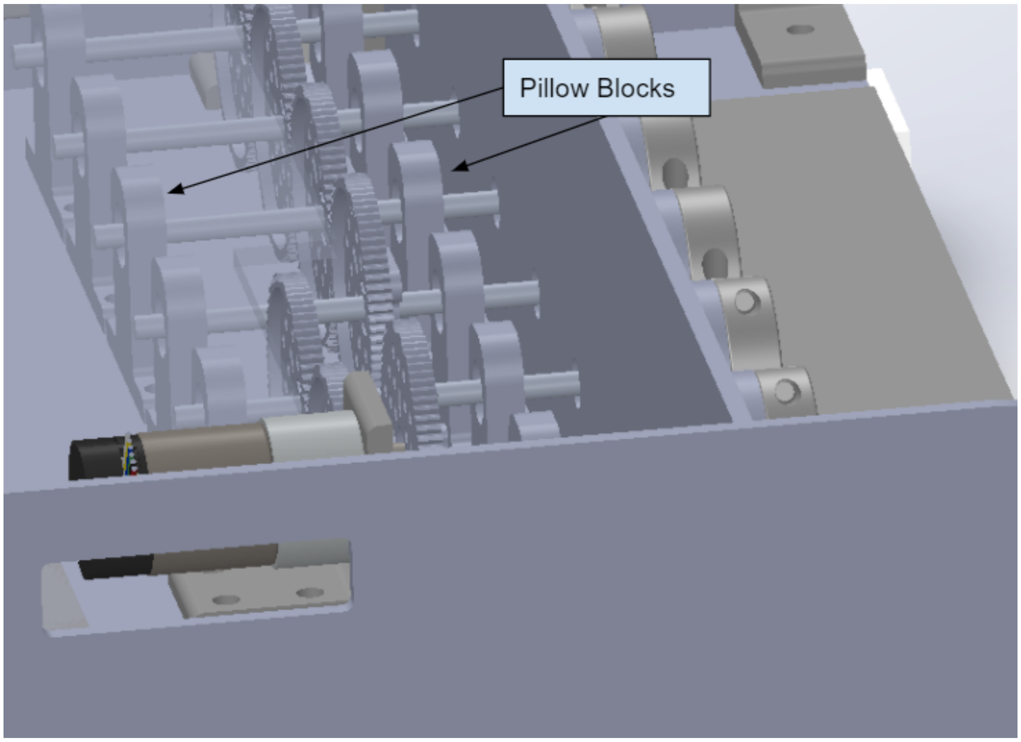


Figure 18.5. Image of the pillow blocks inside the clinostat

The pillow blocks shown above are custom made out of 6061 aluminum stock.

19. Electrical System

The electrical components are used to provide power and control to the mechanical systems of the clinostat. The clinostat will be controlled by an ELEGOO microcontroller which is programmed using an Arduino IDE. The two DC motors are driven using a dual H-bridge motor driver. The H-bridge and the ELEGOO Mega microcontroller are each powered directly from a standard wall outlet. The electrical system includes components which can aid the user in controlling the clinostat's mechanical functions. This is accomplished by having two push buttons which enable the user to increment or decrement the speed of the clinostat and there is also a third push button which allows the user to select a particular motor to control. The ability to control each individual motor is beneficial since this allows the user to stop one set of four *C.elegans* experiments without altering the second set. Lastly, there is a on/off switch which will stop or start the selected motor. The wiring diagram for each component is shown in Appendix B.

The electronics is enclosed within the clinostat thus the team design an electronics panel which will house the entire electrical subsystem including the two DC motors. The ELEGOO microcontroller, the H-bridge, and the breadboard are arranged in a specific configuration on the electronics holder panel as shown in Figure 19.1.

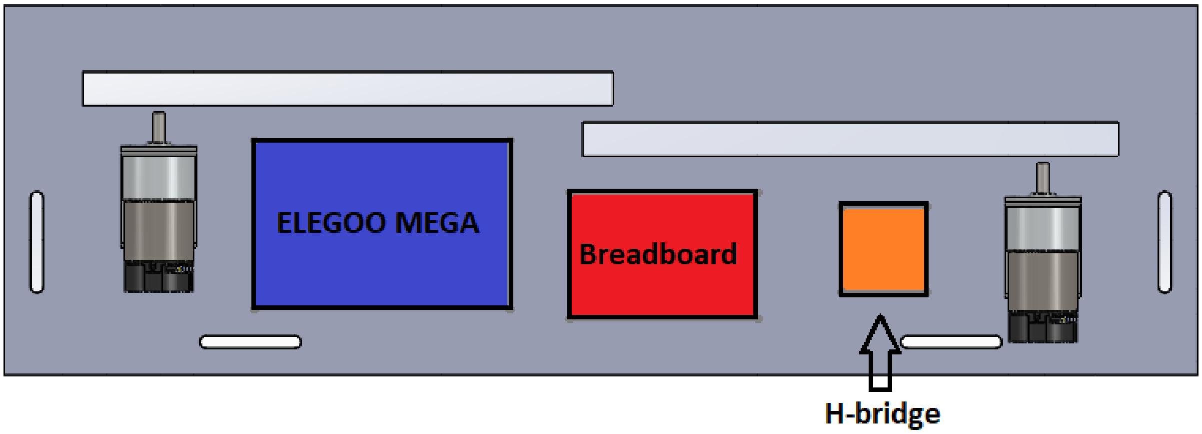


Figure 19.1. Image of the electronics holder panel showing the configuration of the electronics

Each of the electrical components are accessible by opening the lid of the clinostat. This process makes it easier for the user to examine and troubleshoot any issues with the wiring of the electrical system.

The user controls will be attached to an electrical breadboard. The LCD screen, pushbuttons, and the on/off switch will be incorporated into the breadboard. In addition, each of the motors will be separately controlled with their own on/off switch which will allow them to individually operate.

20. Final Prototype and Manufacturing

The final prototype of the clinostat involves machining and programming the proof of concept structure to validate our requirements and specifications. The machining process took 4 weeks to complete. The acrylic stock was laser cutted to manufacture the side panel, back panel, bottom panel, lid, and electronics plate. The aluminum stock was water jetted to form the hole patterning for the bottom panel. The pillow blocks for the gear train subsystem were manufactured on the water jet and post machined on the mill. The entire test tube gripper system was first manufactured on the lathe and then on the mill. All panels are connected using aluminum angle brackets which were machined on the mill. Sharp edges from the L-shaped electronic mount were padded with rubber for safety purposes. The finished Clinostat is shown in the figures below.

Figure 20.1. Image of the entire clinostat

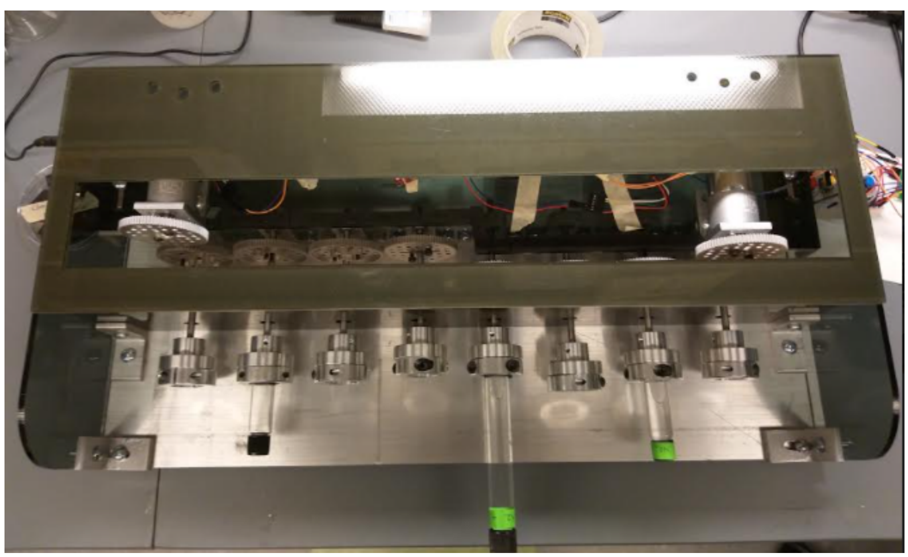


Figure 20.2. Top view image of the clinostat

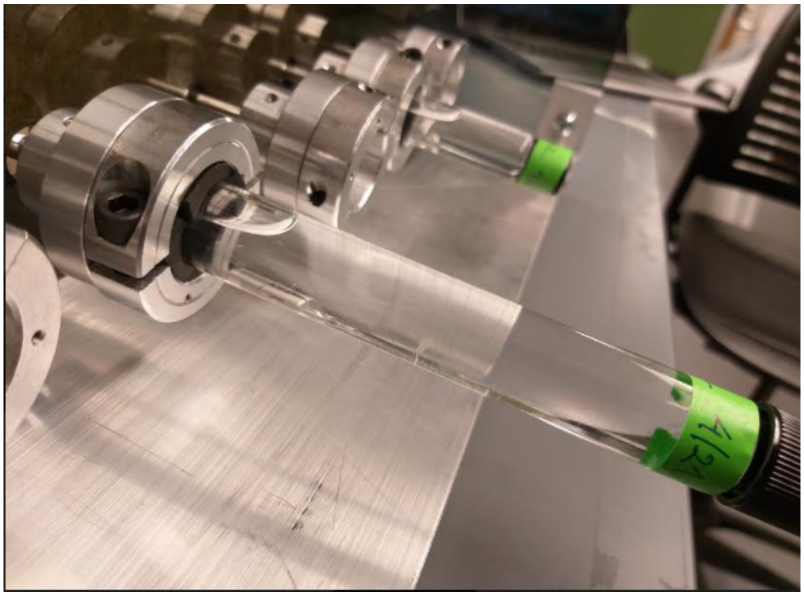


Figure 20.3. Image showing the test tube gripper with *C.elegans* worms

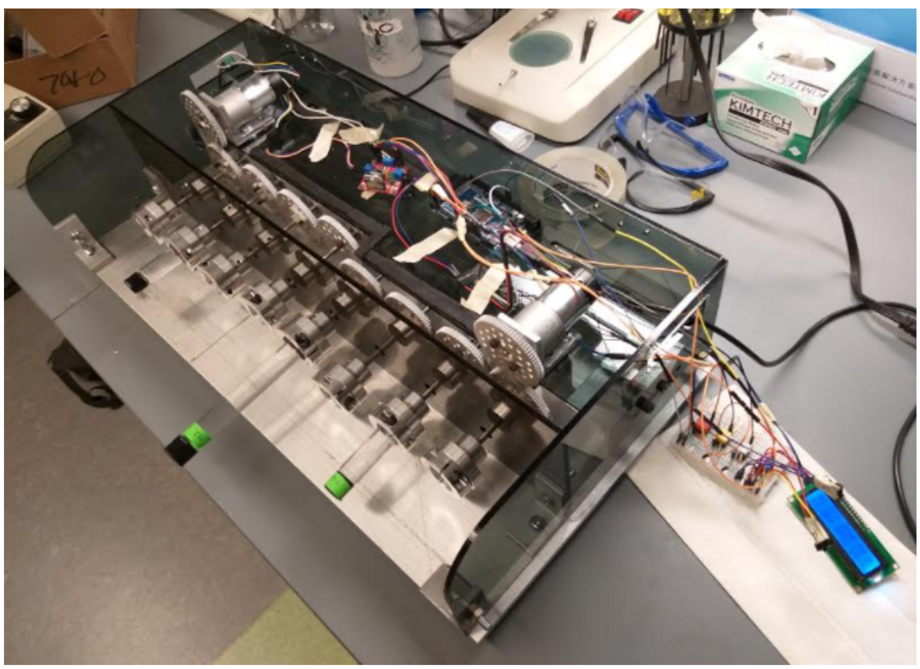


Figure 20.4. Image of the clinostat without the lid

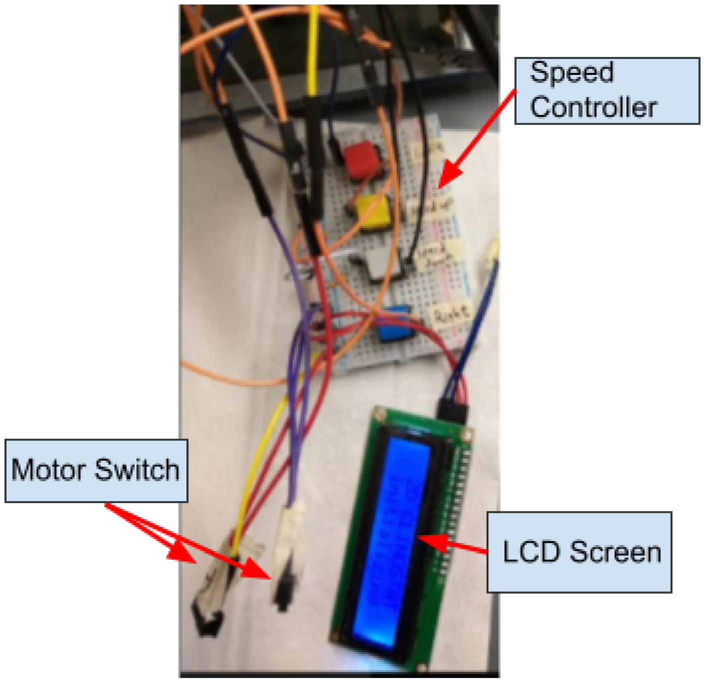


Figure 20.5. Image of the user controls.

21. Validation Testing

The clinostat's functions were tested to confirm whether the user requirements and engineering specifications were verified. The table below shows the summary of validation results for the user requirements and engineering specifications.

Table 21.1. User requirements and engineering specifications verification for the 2D clinostat

User Requirements	Engineering Specifications	Validation Test Method	Validation Result	Verification Status
Clinostat must be a 2D clinostat	Clinostat will rotate the specimens along the horizontal axis, perpendicular to the gravitational vector	Observation of the test tube rotation	Each test tube rotates on its own vertical axis	Pass
The clinostat should be able to handle	Clinostat can test at least 8 specimens of *C.*	Observation of the maximum number of test tubes the	Clinstat can test 8 test tubes simultaneously	Pass

multiple specimens of *C. elegans* at the same time	*elegans* simultaneously	clinostat can hold		
The clinostat can hold liquid scintillation vials (with screw caps attached) test tubes (12,13)	Specimen holder will be a universal holder for test tubes it will have a variable hold size of 0.5" and 1" in width and 8"± 1" height	Attempt to hold two test tubes of different lengths and diameters.	Clinostat grippers can clamp a test tube with a diameter of 0.75" and a diameter of 0.85"	Pass
The clinostat should be able to run for long periods of time	Clinostat must continuously operate without human intervention for at least 3 days	Operate the motor continuously for one hour	The motor successfully operates continuously for an hour	Pass
Clinostat must rotate at a speed to create a microgravity environment	Clinostat will be able to rotate between 0 rpm to 20 rpm	Attempt to increase and decrease the speed of the clinostat motors from 0 to 20 RPM	The clinostat motors are able to increase and decrease its speed. 50% motor duty cycle yielded a rotational speed of 10 RPM which is the speed that simulates the microgravity environment for the worms	Pass
The clinostat has to have a camera systems used for magnification	Clinostat has at least one stationary cameras with *x5- x10* adjustable magnification positioned on the test tubes or	The camera system can focus to observe the *C.elegans* worms clearly	The camera successfully focuses on the *C. elegans* worms	Pass

	culture flasks that hold specimens			
Clinostat must operate on a standard lab bench	Clinostat must be at most 2' x 2' x 2' in total volume	Measure the dimension of the clinostat using a tape measure	The clinostat's dimensions measure 2' x 1/2', and 5/12'	Pass
Specimens must be operated in a room temperature environment	Operating conditions will be at ambient conditions, which is 20°C ± 3°C	Observe to verify if the clinostat operates within the listed temperature range.	The clinostat operates at an environmental temperature of 21°C	Pass
The clinostat should run with minimum noise due to being in a shared area	The clinostat will have a maximum sound level of 50 db ± 2 db	Measure the noise level of the clinostat using a decibel meter or app	The average noise level is 48 dB	Pass

After the verification tests were conducted over a two week period as shown in the table above, the team found that all user requirements and specifications that were set at the start of the project were met within all tolerance levels. The gripper successfully holds the test tubes firmly however, there is evidence of a slight observable bend in the held test tubes due to machining tolerance errors. This is mitigated by manually adjusting the test tubes with the rubber adapters inside the clamp so that the test tubes rotate concentrically. The clinostat was able to operate continuously for one hour without any interruptions. The team is confident that the clinostat will be able to function non-stop for more than one hour, given that no issues were observed during the one hour test. Thus, we are confident that the clinostat will achieve the goal of running continuously for three days. Since all of the user's requirements were met and the clinostat was functioning properly with extended testing, the team is ready to handoff the finalized prototype to our sponsor and close the project up. The team will standby for troubleshooting assistance in the future if problems arise with the clinostat.

22. Project Management and Organization

The whole project is planned to be finished within 3 months. Solution development and verification process has started and this includes the manufacturing and assembly processes, with testing and verification of the requirements and specifications. The final report will be finished by the end of April to show the results of the project.

Weekly meetings are held with Dr. Gourgou and Professor Liu to talk about the team's progress. During the concept generation phase, every team member has designed at least one potential design and two unique subsystem designs. During the manufacturing phase, Kevin and Aoqian will focus on the CAD development and drawings. Albert will focus on the camera mount system and Karthik will manufacture and assemble the final design. The team timeline is shown in Appendix C and the engineering drawings are shown in Appendix D.

Each team member's specific roles and contributions to the team are shown below in Table 22.1.

Table 22.1. Team Member Roles and Responsibilities

Team Member	Role	Responsibilities
Karthik Bijoy	Procurement Lead, Electrical Wiring CO-Manager, Treasurer, Manufacturing Lead	Order all mechanical and electrical parts for the prototype, fill out any forms to order components, Manufacture all components, design the electrical wiring diagrams and create correct connections to the breadboard. Allocates the budget, keeps tab on all monetary costs to make sure project does not exceed past $400 substantially, requests additional funding when absolutely necessary,
Kevin Wen	Portfolio Manager, CAD Manager, Test Tube Gripper System Manager	Manage the Google Drive folder that contains all meeting agendas, deliverables, and CAD. Design the test tube gripper system and create manufacturing plans for all components in the gripper
Albert Ye	Imagining Manager,	Design the camera mount

	Electrical Wiring CO-Manager	system and create all manufacturing plans for the camera mount parts
Aoqian Zhang	Programming Manager, Sponsor Contact, Gear Train Manager	Send out all emails to the sponsor, Dr. Gourgou, and the faculty mentor, Professor Liu. Design the gear train system and create all manufacturing plans for the gear train components

23. Budget and Expenses Report

The project to create a 2D clinostat has been allotted a standard $400 through the University of Michigan's Mechanical Engineering Department sponsors. However, Dr. Gourgou has stated that if additional funding is needed to create a working prototype for the clinostat, she would be able to contribute. Table 23.1 shows the high level allocation of our budget which could potentially change as the project progresses.

Table 23.1. Tentative High Level Budget Allocation

Item	**Cost**
Raw material components, eg. aluminum, axles, gears, bearings, fasteners	$150
Shaft bearings x8	$88
All electrical components, eg. Raspberry Pi, cameras, adjustable lens	$100
Handheld camera	$22
Safety fund for additional parts in case of machining error	$40
Total Costs: $400	

A more detailed budget and bill of materials is shown in Appendix E. Table E.1 shows that highlighted total cost and the team exceeded the $400 max amount but were able to receive additional funding from the sponsor. Since many of the parts do not include spares, the team is planning on discussing with our sponsor on how much additional funding can be allocated.

24. Engineering Inclusivity and Social Context

In order to promote engineering inclusivity, the team identified some expressions of power. First, the team has a hidden power that directly influences our design decisions, because each individual member provides ideas for each subsystem. Therefore it is important for the team to be aware of how each member's background could potentially lead to unintended consequences. The ME450 class schedule has a visible power over the team by establishing deadlines of assignments that limits the time frame for the design. As a result of this power, the team needs to prioritize some requirements, such as test tube holder, gear train, camera mount and electronics, while the timer and alarm system is considered to be stretch goals.

To promote stakeholder engagement, the team created an invited design decision making space, in which our sponsor co-designed with the team and weekly sponsor meetings are held to receive sponsor input and feedback. In addition, adopting a beginner's mindset helped the team to question assumptions and be open to new possibilities throughout the design process.

To better understand the social context and potential impact of the clinostat design, the team created a stakeholder map (Figure 24.1) that includes some stakeholders who may or may not be influenced by the design. Primary stakeholders are directly impacted by the design. Secondary stakeholders are part of the problem context but may not be directly impacted by the design. Tertiary stakeholders are outside of the immediate problem context but may have the ability to influence the success or failure of the design. The color represents the role of each stakeholder group: Resource Providers, Supporters & Beneficiaries of the Status Quo, Complementary Organizations and Allies, Beneficiaries and Customers, Affected or Influential Bystanders.

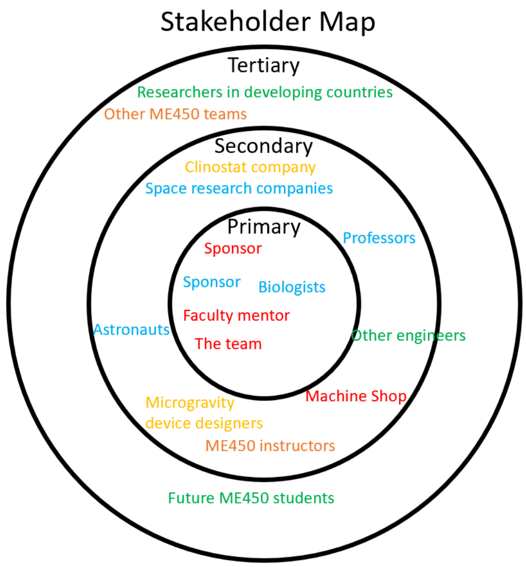


Figure 24.1. Stakeholder Map

25. Environmental Context Assessment

The team first determined the context that our clinostat design would be used in to understand our contributions to sustainable development goals. For goal 9 of industry, innovation, and infrastructure, our design meets the targets 9.5 and 9.b which both discuss enhancing scientific research for developing countries and for all countries [24]. Since the clinostat device creates microgravity environments, the device will definitely enhance scientific research regarding the effects of prolonged exposure to space environments. Through our sponsor's work with *C. elegans*, effects on space are modeled within a "model organism" and her work can potentially help improve understanding of effects on space within humans. For helping developing countries with providing greater access to new technologies, our clinostat device will be able to test multiple specimens simultaneously and has a low budget. If our device were to be mass-produced, the cost would be a great incentive for researchers in developing countries to consider using since the team will operate as a non-profit organization.

The entire clinostat design was also examined for its impact on the environment using an Eco-Audit. The Eco-Audit was performed using the GRANTA Edupack software. All materials were considered in the worst case scenario in order to provide an overestimation in the impact of our clinostat design. The full lifetime cycle was considered to be ten years in order to provide enough time for a researcher to perform multiple long term experiments. In Figure 25.1, a summary of the Eco-Audit can be seen.

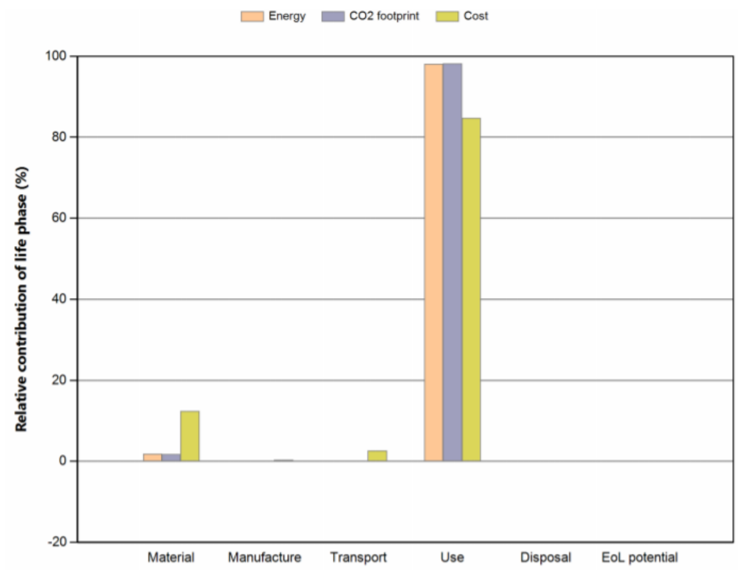


Figure 25.1. Eco-Audit summary of energy, CO_2 footprint, and cost

The summary of contributions in each lifecycle showcases the high impact of the “use” lifecycle which was expected because the clinostat would be continuously running to stimulate microgravity environments. The overall annual costs were found to be an energy consumption of 8.64 kWh per day, an annual cost of $235, and CO_2 emissions of 1800 lb. When compared to a similar clinostat device that only held one sample on Amazon, the commercial clinostat’s annual costs were 8.64 kWh per day, a cost of $160.09, and CO_2 emissions of 1800 lb [25]. Our design does not make gigantic leaps when comparing values between our design and a commercial one, however it is important to note that the Amazon product only has room for one sample. Therefore, the values from the commercial clinostat would need to be increased by eightfold in order to truly have a comparison on equal ground. Our clinostat design innovates upon existing commercial products and will allow researchers to be more efficient in their experiments. Additionally, the team will improve upon the design to include more recyclable materials in the future so that the environmental impact and cost can be further reduced. We believe that these changes will also help researchers in developing countries have greater access to tools for analysing microgravity conditions.

In regards to the CO_2 emissions, from a research paper, it was found that an average human being emits around 4000 lbs of CO_2 per year [26]. Our clinostat would therefore have a minimal impact of being less than half of the CO_2 emissions from one human and the tradeoff for the increased CO_2 in the atmosphere would be potential to understand effects on long term space travel. With current research interests in space exploration and establishing long term outposts on other planets, the team believes that the clinostat design will be worth the increased CO_2 emission into the atmosphere.

For some readers, the full Eco-Audit document that includes all the detailed breakdowns for the analysis might be of interest and it can be found in Appendix F.

26. Engineering Standards

Since this project was custom made for our sponsor's research requirements, no engineering standards were examined or consulted. Instead, the team focused on meeting the specifications and requirements set by our sponsor. Since the team decided to not use any engineering standards, a drawback is that if the clinostat were to be mass produced, there could be problems with meeting safety and manufacturability standards. However, the team believes that since the current design is only a prototype and accomplishes the goals that our sponsor desired that foregoing the engineering standards is acceptable.

27. Engineering Ethics

For engineering ethics, the team made sure to abide by the standard honor code within the College of Engineering at the University of Michigan and produce the best possible design within the time constraints. Although there are components of the design that could be improved, such as making the side walls out of aluminum instead of acrylic, these adjustments were done in the interest of cost and still do not change the structural integrity of the entire design. In addition, the team created the design entirely from their own fabricated ideas and conducted analysis on each subsystem of the design to make sure it would not fail. Afterwards during the assembly process, the entire system was tested multiple times as stated in the validation testing section to determine how well the clinostat met our sponsor's requirements.

28. Peer Recommendations and Feedback

After design review 3 there were no peer recommendations and the team continued onwards improving the clinostat design so the prototype would be fully functional by the sponsor handoff date.

However, the team would like to acknowledge one particular piece of feedback that our peers gave which was using two motors to split the gear train down in half. After fully manufacturing and assembling the clinostat, it is now clear that if the team had gone with a single eight gear train that there would be large binding and the system would not have been able to run as smoothly as possible. Therefore, we would like to thank our peers for suggesting the use of two motors to separate controlling four samples.

Another idea that was presented by our peers that the team now realizes as being a potentially better design would be having test tube grippers on both sides of the axles. In this type of configuration, space and manufacturing time would be reduced and there would be less possibilities of binding in the gear train. Looking back, the team would try to alter the location of the gear train to be in the center of the clinostat and to have test tube grippers on both sides.

Overall the team would like to thank our peers for their support and feedback throughout the semester. There were certainly many design changes that we would not have thought of without their help.

29. Potential Risks and Problems

The major potential risk is that the clinostat breaks down after the handoff to the sponsor and no team members are available to repair the device. The team has thus created a user manual and listed all the components within the build of materials so another user should be able to repair the device by ordering replacement parts. If there are problems that can't be resolved, then the team has left their contact information for the sponsor and left documentation of the entire project. Hopefully through in-person and remote troubleshooting, the clinostat can then be fixed.

30. Next Steps

Currently there is definitely more analysis that could be done for the camera mount system and it is unlikely that the camera mount system will be completed this semester. However, the rest of the clinostat is fully manufactured, tested, and ready for handoff. Our team will put the finishing touches on the clinostat, such as with additional cleaning and tightening of fasteners, and then handoff the entire design with the user manual.

31. Conclusion

In conclusion, our final report builds off of the previous three design review reports. The team has already gone through the problem analysis and concept generation phase and has been focused on the design phase over the past few weeks.

The team decided to split up the entire clinostat design into multiple subsystems and have each individual focus on the design and analysis for their individual parts. The electrical system required no manufacturing so it was given to the only member located in Ann Arbor for machining to equally divide up the work. As for gear train, test tube grippers, and camera mount, their designs were iterated upon.

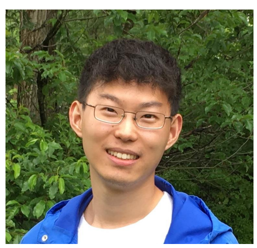
Overall, the team thinks that the prototype was well made and are extremely happy with their progress. Further troubleshooting in case there are problems and a clear procedure for operating the clinostat are all included in our user manual and we believe that the device will serve good use in the research setting. In addition, having understood our design's environmental impact and inclusivity in stakeholders, we believe that our design will be a valuable tool to help improve microgravity research.

32. Acknowledgement

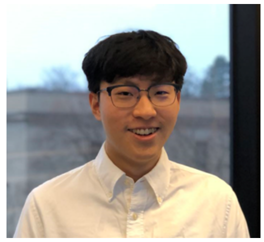
Our entire design team would like to give our deepest gratitude to our sponsor, Dr. Eleni Gourgou, and our faculty mentor, Dr. Allen Liu, for their support and advice throughout the entire project. We would also like to thank the machine shop staff, Charlie Bradley, Don Wirkner, and Jonathon Yenkel in helping our team find hardware and for assisting our team with machining components for the clinostat. Our peers have also been instrumental in shaping our reports and presentations through their feedback. Lastly, we would like to thank the Mechanical Engineering Department for making the clinostat project possible through ME 450.

33. Author Biography

Karthik Bijoy is a senior Mechanical Engineering student from Chicago, Illinois. He decided to major in Mechanical Engineering because of his interests in working hands on with technology and building skills in creative design. In high school, Karthik competed in FIRST Robotics which gave him the skills and experience which nurtured his interests in working with robotics. During his time in undergrad, Karthik was involved with the Michigan Mars Rover team for two year working as a sample acquisition engineer where he first learned how to machine and conduct computer aided models. He is also heavily involved in research in radio interferometry as part of the MDP heliophysics research team. Karthik has always been fascinated by space exploration. His ambition is to work on systems which support human lives outside earth. Upon graduation from his bachelor's degree, he will pursue a master's degree in Aerospace Engineering at the University of Michigan where he will specialize in Space Systems. Outside of academics, he loves to spend his free time biking, exercising, and playing minecraft. He is an avid fan of Formula One Racing and he supports Manchester City FC.



Kevin Wen is a senior in Mechanical Engineering at the University of Michigan from Stony Brook, New York. At Michigan, he enjoys teaching and guiding his peers as a UROP Peer Facilitator and creating designs for the Steel Bridge Team. Outside of class, he enjoys gardening and has created two raised beds to grow vegetables. After graduation, the future is still uncertain but he will continue to search for opportunities to help others. The clinostat project was an exciting capstone experience for him and he would like to thank all the professors and graduate students that helped the team accomplish the final prototype design. Since he spent his last semester at home, he would like to especially thank his parents and little sister for their continual love and support.



Aoqian Zhang is a senior Mechanical Engineering student at University of Michigan from Shenzhen, China. Aoqian's passion in Mechanical Engineering comes from his high school experience designing intelligent soccer-playing robots at the Robotics Club of St. Andrew's College in Canada. During his undergrad years at Michigan, Aoqian was a member of the MDP Mapleseed research team, where he was involved in the development of passive and active flyers for acquiring Earth's atmospheric information. Outside of class, Aoqian enjoys swimming, video gaming and travelling. After graduation, he will attend Carnegie Mellon University for a Master of Science degree in Mechanical Engineering with a concentration in Robotic and control systems.

Yuxuan Ye (Albert) is a senior Mechanical Engineering student at University of Michigan from Dongguan, China. Since primary school, Yuxuan has shown passion about mechanics inside different machines and tried his best to figure out the functionalities of different parts. Yuxuan enjoys playing sports such as basketball, tennis, and swimming. After graduation, Yuxuan will continue his study at University of Michigan for a Master of Science degree. Yuxuan have always been amazed by how miracles could happen when mechanical engineering was combined with medication and thinking about saving more lives in this way. Though his undergraduate degree was able to supply him with a lot of basic knowledge in mechanical engineering, it does not allow him to further delve into medical devices in detail. With a clear direction in the research field, he will be able to focus more on studying cross-section knowledge between medication and mechanical engineering for his own research in an effective way.

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APPENDIX A: TEAM DRAWN FIGURES

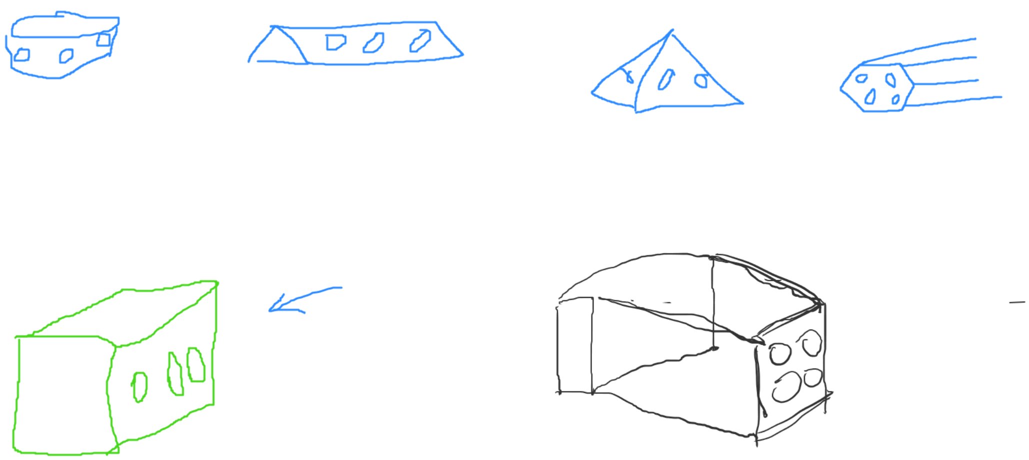


Figure B.1. Image of the sketches created during the ideation process for the clinostat shape

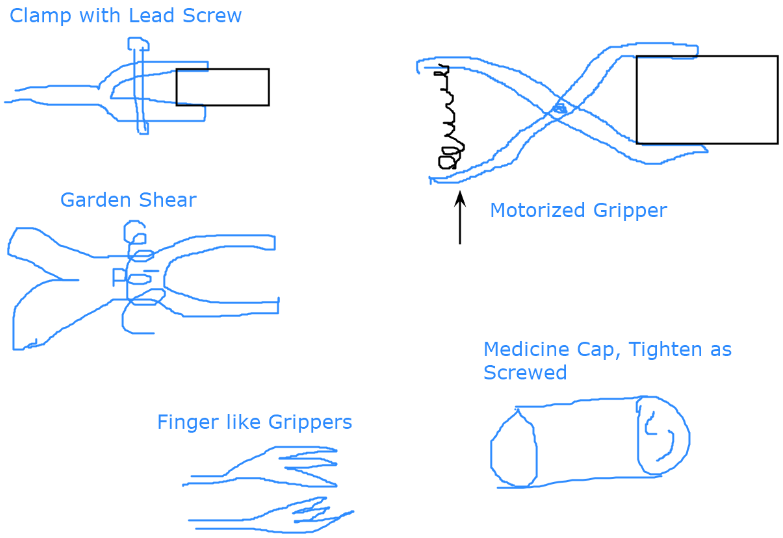


Figure B.2. Image of the sketches created during the ideation process for the test tube gripper

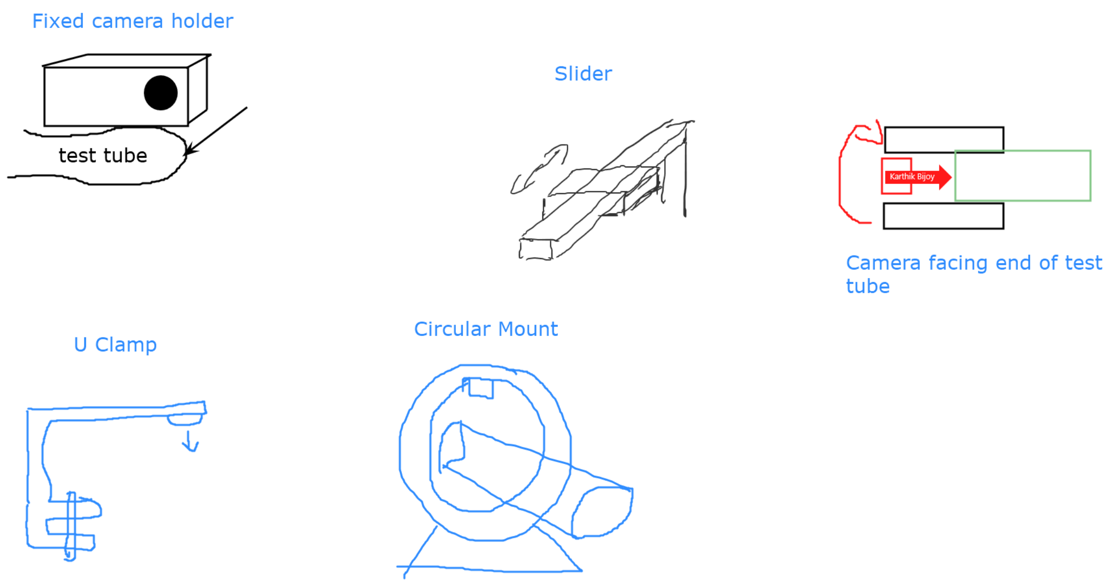


Figure B.3. Image of the sketches created during the ideation process for the camera mount

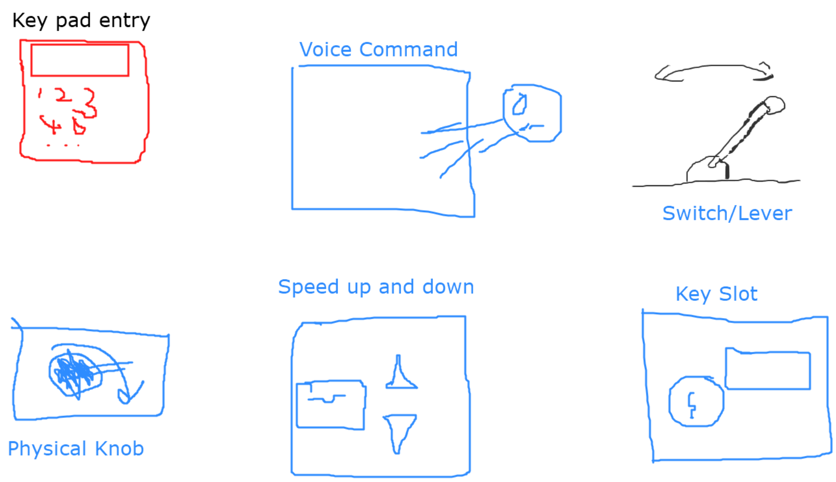


Figure B.4. Image of the sketches created during the ideation process for the speed controller

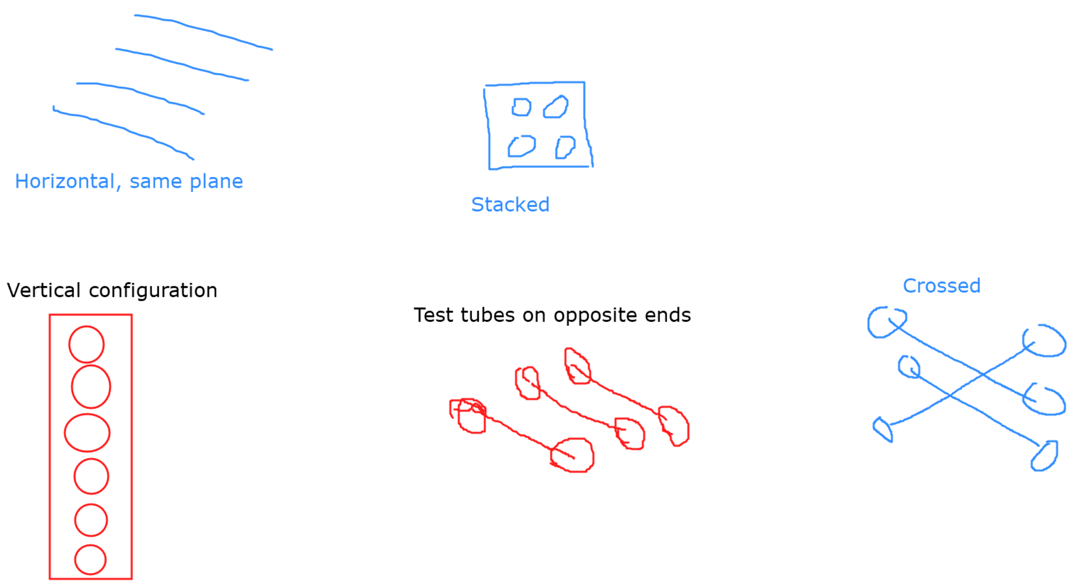


Figure B.5. Image of the sketches created during the ideation process for the test tube configuration

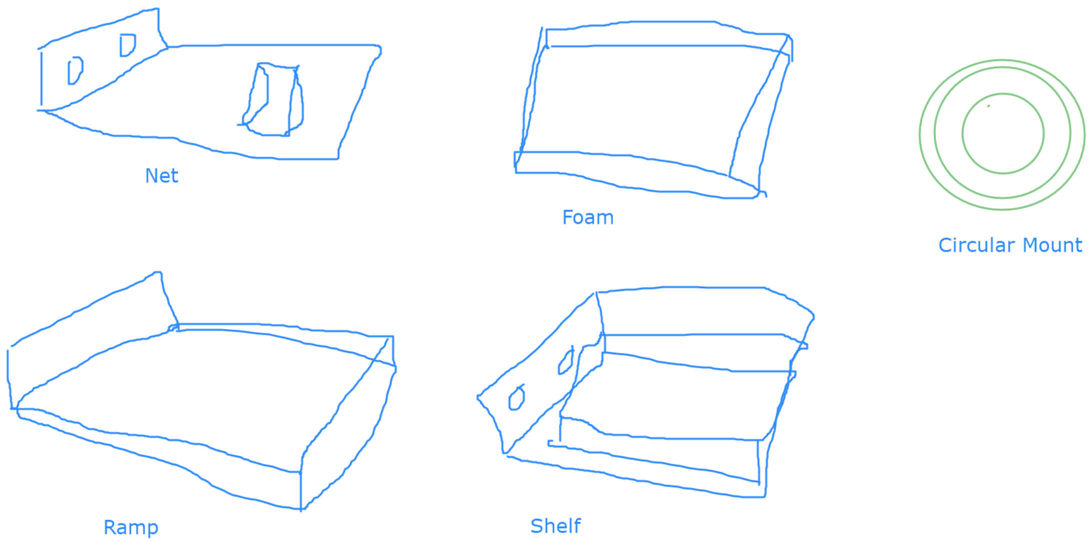


Figure B.6. Image of the sketches created during the ideation process for the clinostat safety mechanism

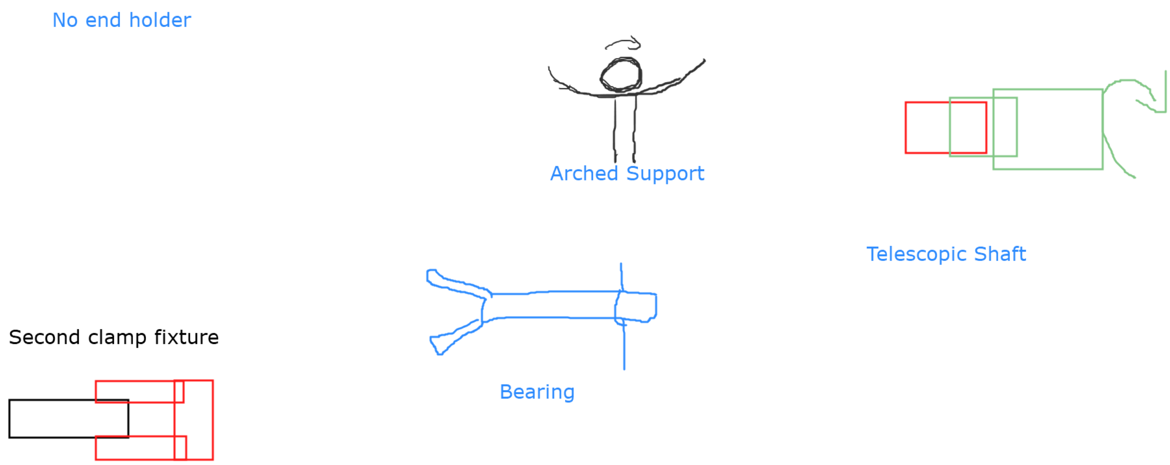


Figure B.7. Image of the sketches created during the ideation process for the end fixture

APPENDIX B: WIRING DIAGRAM

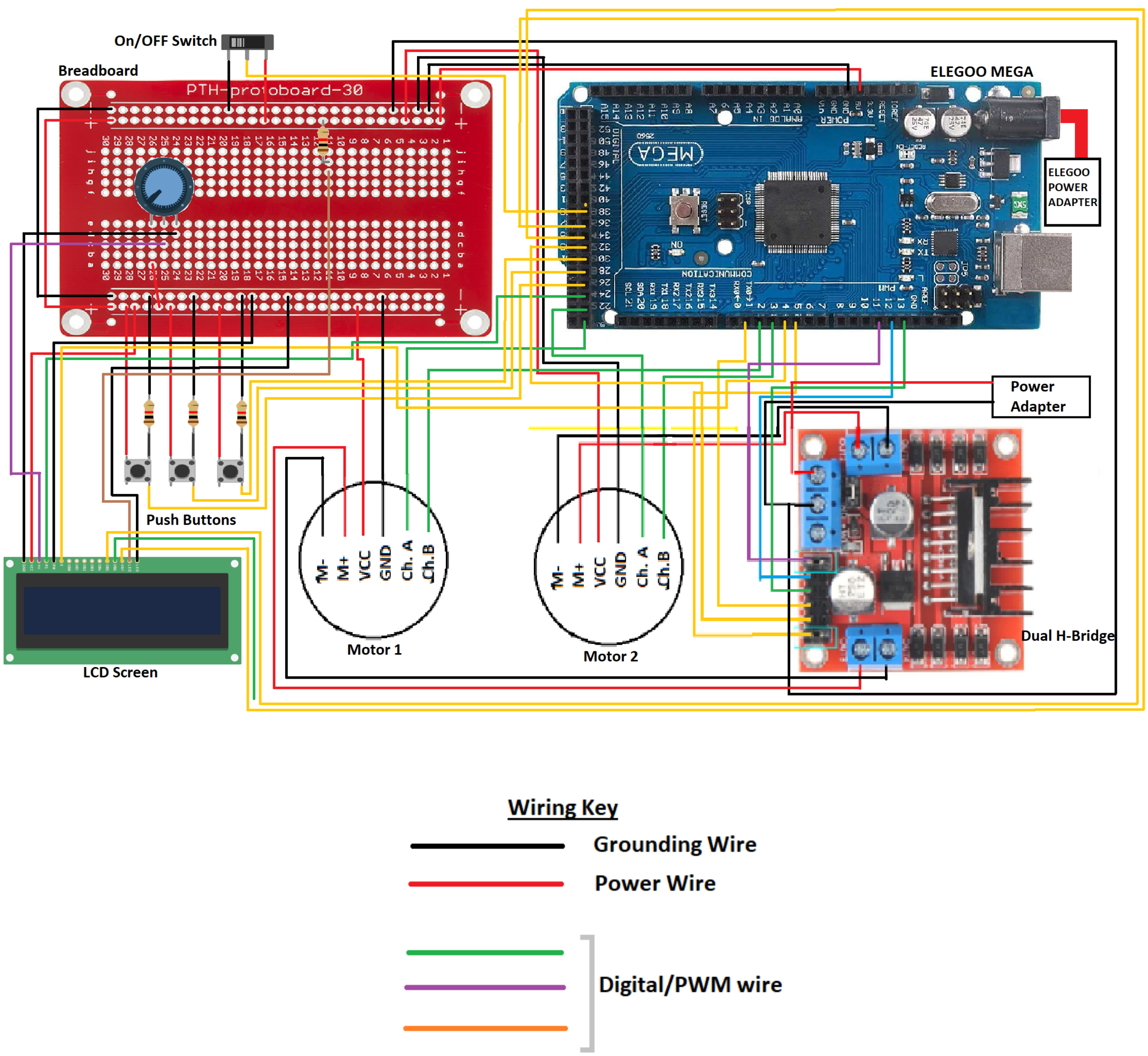


Figure C.1. Wiring diagram for the electrical system

APPENDIX C: PROJECT TIMELINE

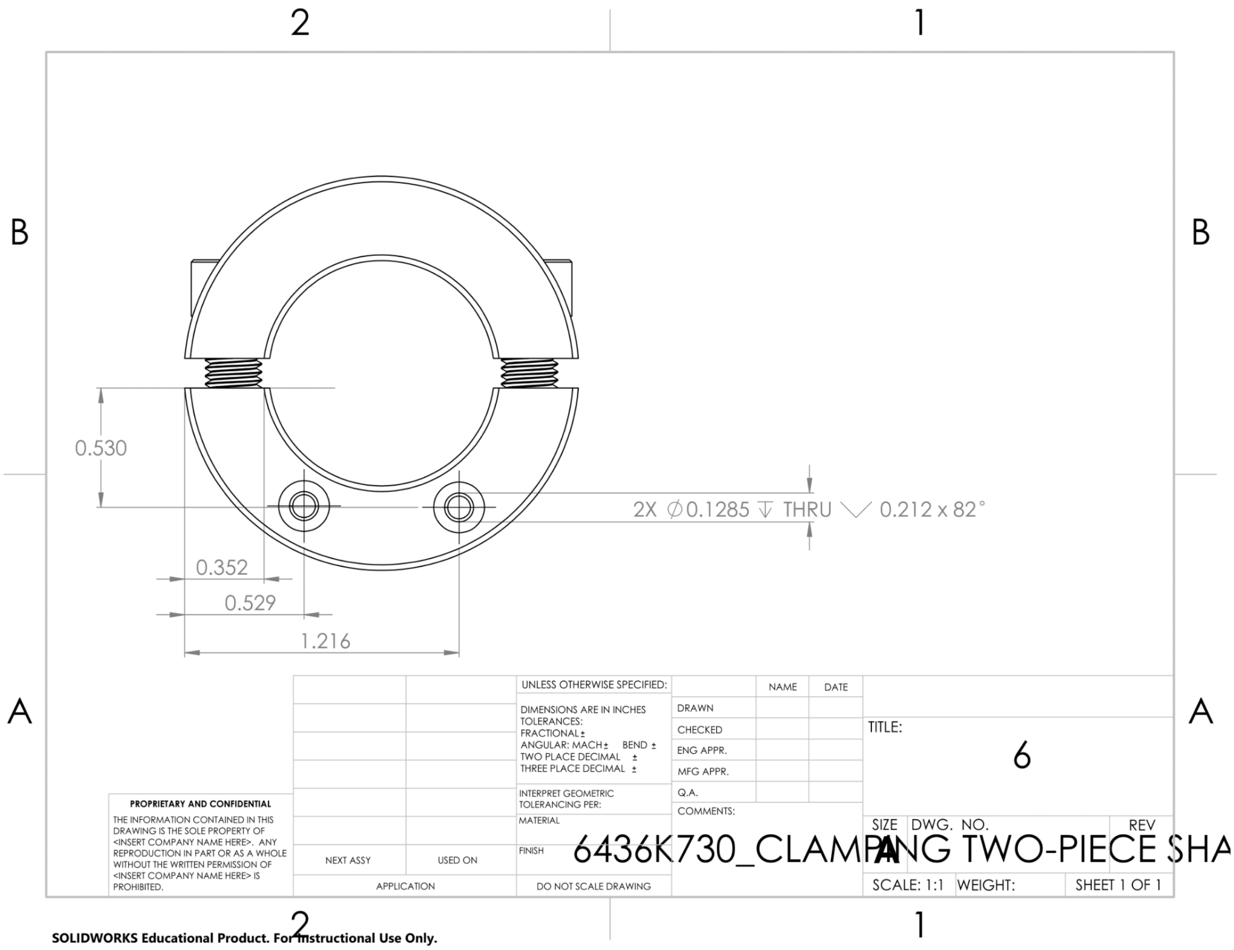
	Month	February								March									April								
	Day	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th	T	Th
Team 12	date	2	4	9	11	16	18	23	25	2	4	9	11	16	18	23	25	30	1	6	8	13	15	20	22	27	29
Phase	Task																										
Milestone	Design Review 1																										
Progress check	Rough draft of design report 1 completed																										
Progress check	Revision of DR 1 and sent to sponsor																										
Milestone	Design Report 1																										
Progress check	Concept generation																										
Progress check	Wide range of concepts delivered to sponsor																										
Progress check	Concept comparison tables/Pugh charts completed																										

Progress check	Design Review 2 slides rough draft completed
Milestone	Design Review 2
Progress check	Design Report 2 report rough draft written
Progress check	Revision of Design Report 2 and sent to sponsor
Milestone	Design Report 2
Progress check	Final Sketch
Progress check	CAD session for design creation
Progress check	Simulations for designs ran
Milestone	Design Review 3
Progress check	Procurement of materials
Progress check	Work on Design Report 3 and

	have rough draft written
Progress check	Revision of Design Report 3 and sent to sponsor
Milestone	Design Report 3
Milestone	Submit Requisition Order for Materials
Progress check	Manufacture mechanical components
Progress check	Assemble electrical components
Progress check	Assemble the Clinostat
Progress check	Testing of all subsystems
Progress check	Verify Specification s and Requirement s
Milestone	Design Expo
Milestone	Final Design Report
Milestone	Design Delivery to sponsor

Milestone	Submit Report to Deep Blue
Milestone	Budget and Expense Report

APPENDIX D: ENGINEERING DRAWINGS AND MANUFACTURING PLAN

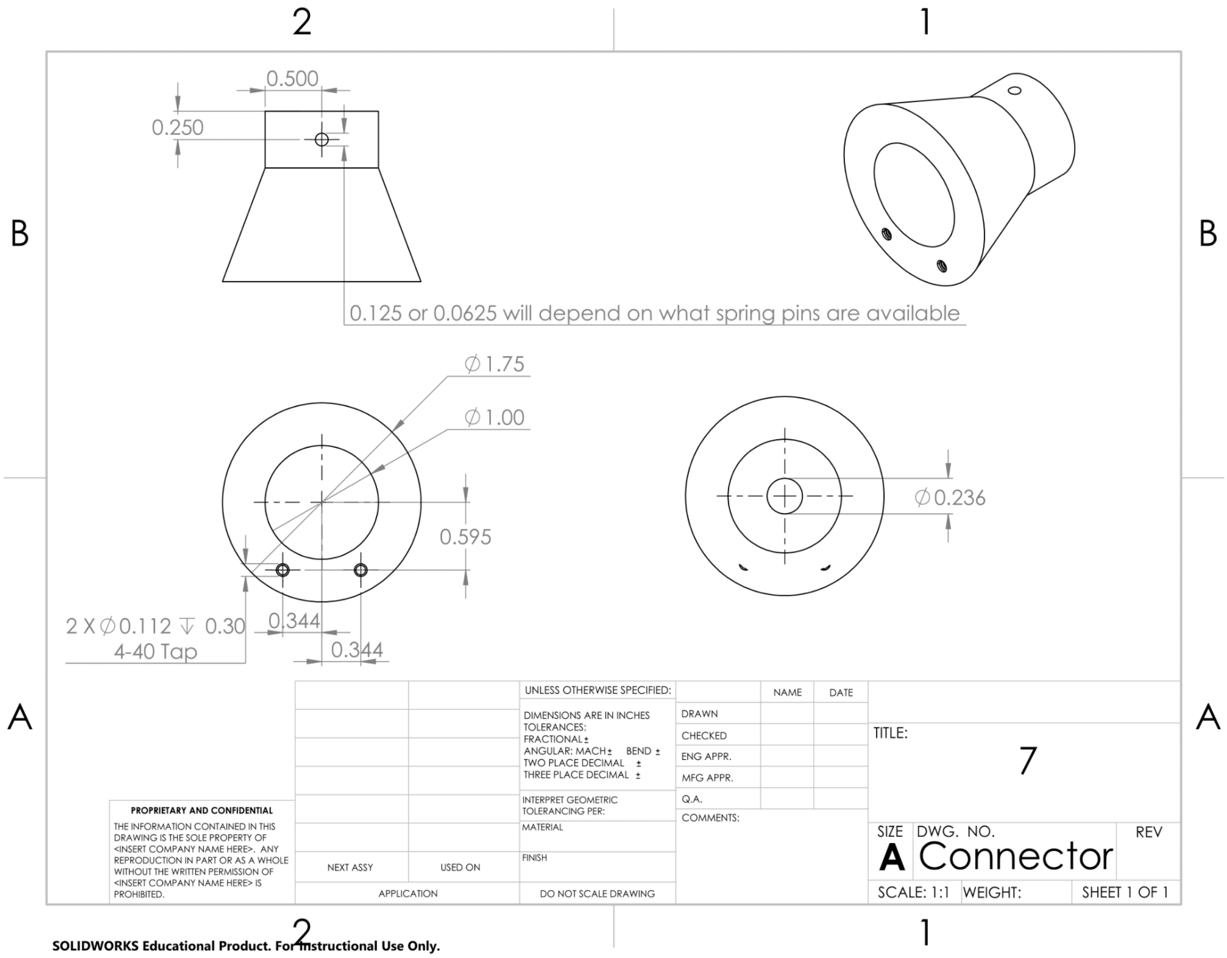


Manufacturing Plan

Part Nur 6
Part Titl Clamping Shaft Collar
Team Name:

Raw Material Stock:

Step #	Process Description	Machine	Fixture(s)	Tool(s)	Speed (RPM)
1	Insert shaft collar into clamp	Mill	Clamp		
2	Center drill at the two hole locations	Mill	Clamp	Centerdrill	1000
3	Drill pilot hole and use countersink drill bit to create the countersink	Mill	Clamp	#30 Drill bit and countersink drill bit	1000
4	Tap holes			4-40 Tap, #43	
5					
6					
7					
8					
9					
10					


0.500
0.250
0.125 or 0.0625 will depend on what spring pins are available
∅1.75
∅1.00
0.595
∅0.236
2 X ∅0.112 ↧ 0.30
4-40 Tap
0.344
0.344
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
7
SIZE
DWG. NO.
REV
A
Connector
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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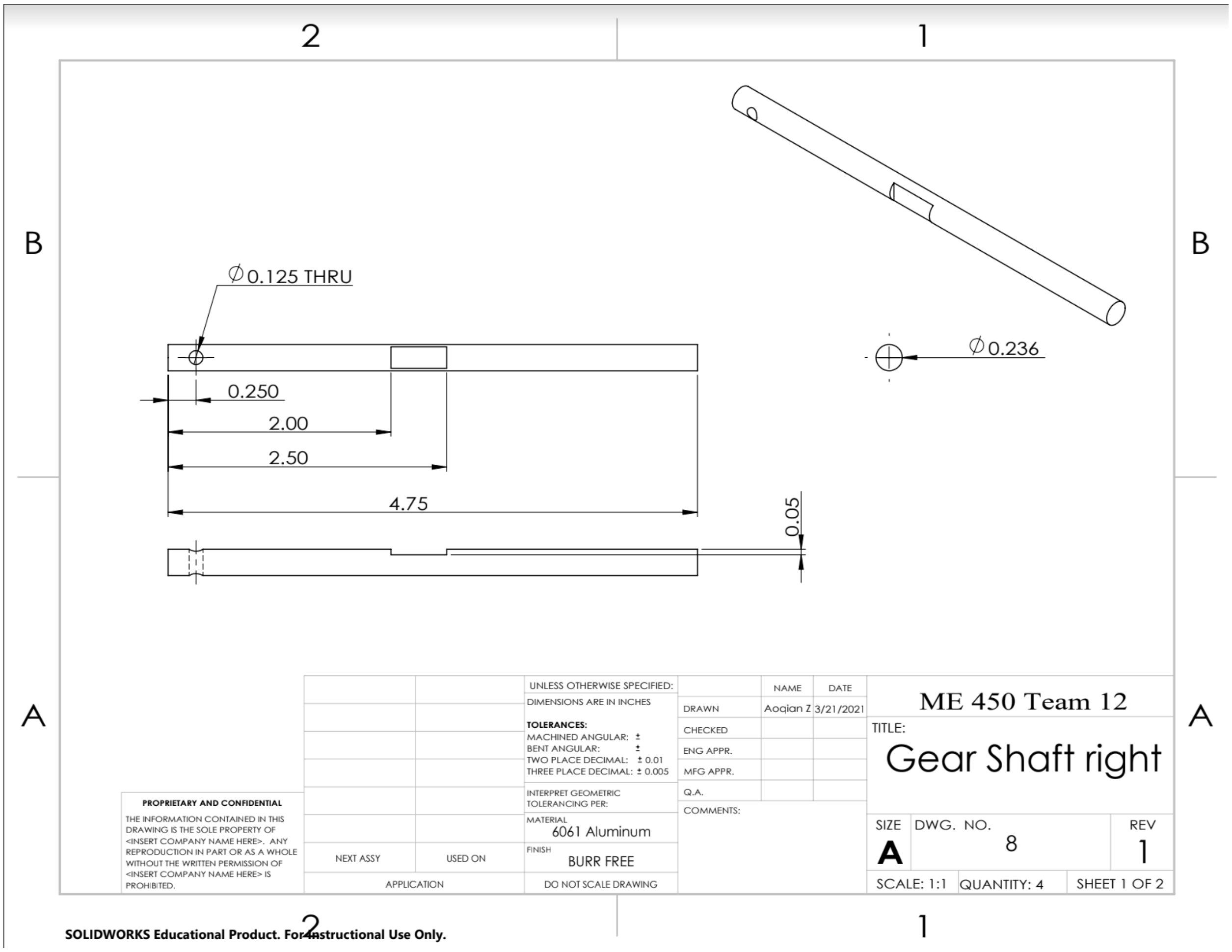
Manufacturing Plan

Part Nur 7
Part Titl Connector
Team Name:

Raw Material Stock:

Step #	***Process Description***	***Machine***	***Fixture(s)***	***Tool(s)***	***Speed (RPM)***
1	Insert connector into clamp	Mill	Clamp		
2	Center drill at the two hole locations, then drill to size	Mill	Clamp	Centerdrill, axle shaft 6 mm drill bit or 15/64 (closest imperial), shaft collar face 1 in drill bit	1000
3	Drill spring pin hole	Mill	Clamp	The drill bit will be dependent on what spring pins are available	
4	Drill two pilot holes in the shaft collar interface	Mill	Clamp	#30 Drill bit	1000
5	Tap holes			4-40 Tap, #43	
6					
7					
8					
9					
10					


Ø0.125 THRU
0.250
2.00
2.50
4.75
0.05
Ø0.236
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ±
BENT ANGULAR: ±
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
BURR FREE
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
Aoqian Z
3/21/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
ME 450 Team 12
TITLE:
Gear Shaft right
SIZE
A
DWG. NO.
8
REV
1
SCALE: 1:1
QUANTITY: 4
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
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2 1

B B

MANUFACTURING PLAN

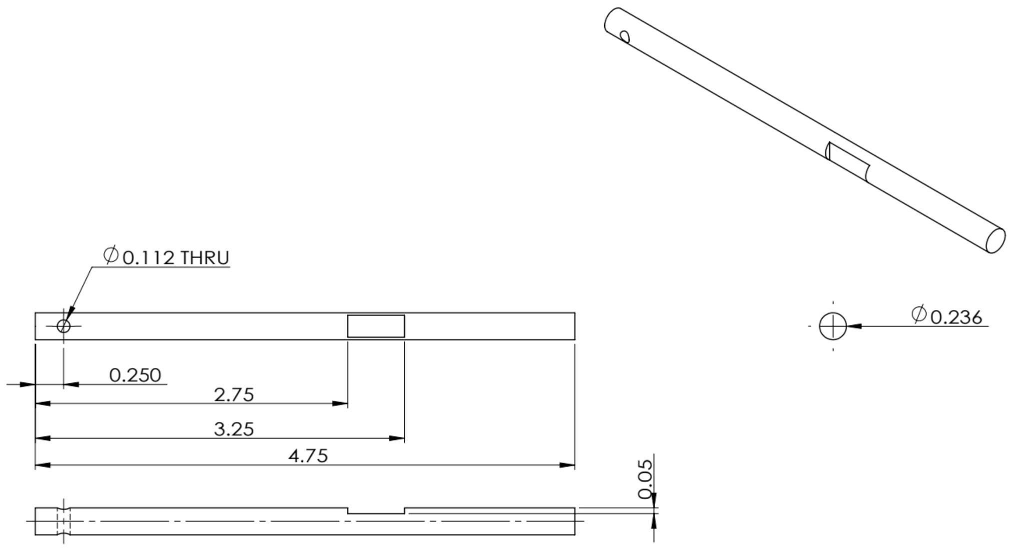
RAW MATERIAL STOCK: 5/16" Aluminum rod

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock >.125" of finished length and deburr	Band Saw		File	100 ft/min
2	With 1/2" exposed, face end flat, center drill end of part, extend and use live center	Lathe	Collet	Cutting tool	1200
3	Turn down diameter to 0.236". Make 0.01 pass each time	Lathe	Collet	Cutting tool	1200
4	Remove burs, flip part around and face the other end	Lathe	Collet	Cutting tool, File	1200
5	Pull part out and measure, machine part to final dimension, set readout to zero	Lathe	Collet	Cutting tool, Callipers	1200
6	Hold shaft in vise axle fixture with >.125" of material sticking out. Locate the X and Y datums	Mill	Vise and Axle Fixture	Edgefinder, collet	1000
7	Center drill and drill spring 1/8" spring pin hole	Mill	Vise and Axle Fixture	Center drill, Drill chuck, 1/8" drill bit	1500
8	Locate and mill the flat surface	Mill	Vise and Axle Fixture	Drill chuck, 3/8" end mill	1000
9	Remove from vise and deburr			File	

A A

SHEET 2 OF 2

2 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ±
BENT ANGULAR: ±
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: 6061 Aluminum
FINISH: BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Aoqian Z	3/21/2021
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

ME 450 Team 12

TITLE:

Gear Shaft left

SIZE: A | DWG. NO.: 9 | REV: 1

SCALE: 1:1 | QUANTITY: 4 | SHEET 1 OF 2

2 1

B B

MANUFACTURING PLAN

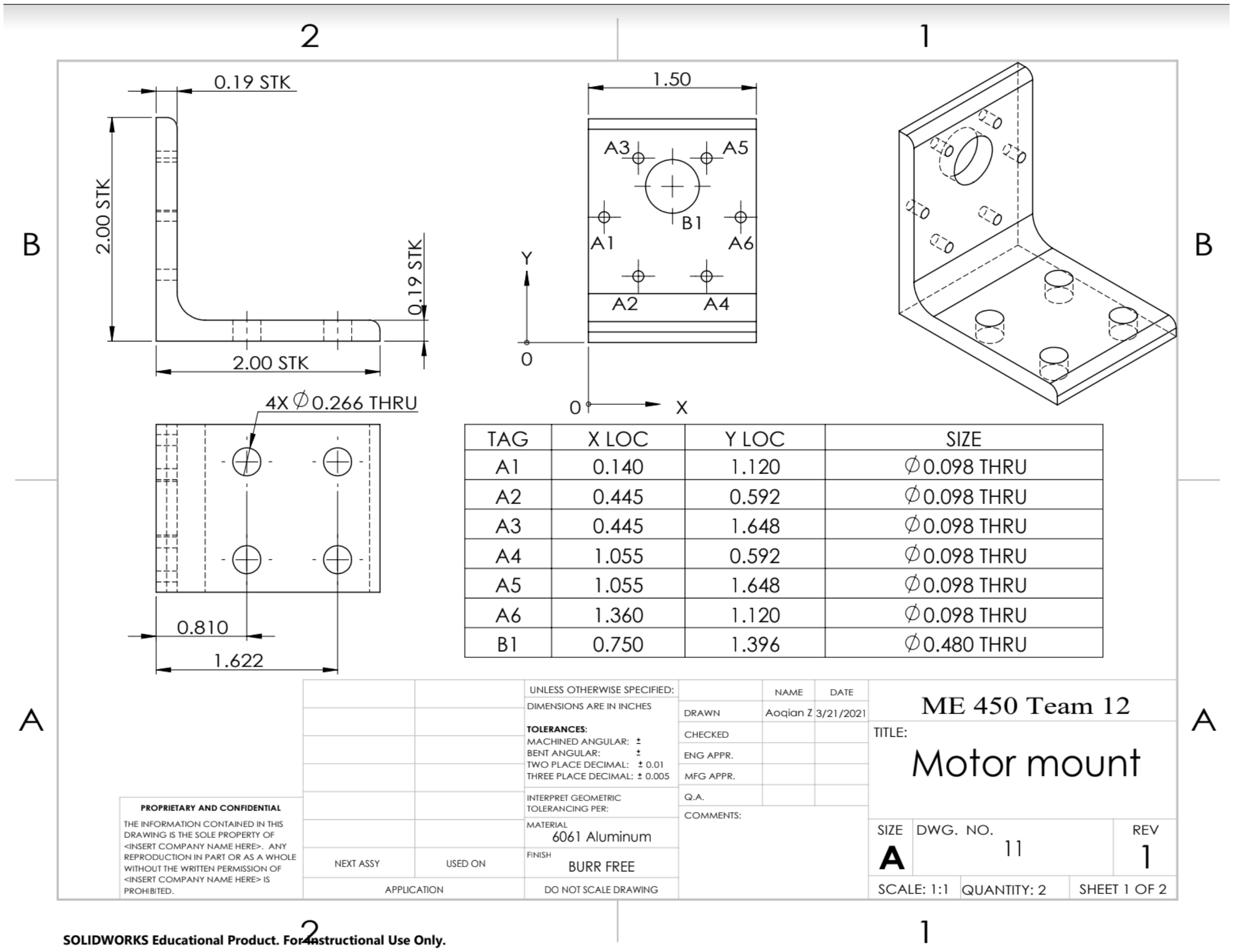
RAW MATERIAL STOCK: 5/16" Aluminum rod

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock >.125" of finished length and deburr	Band Saw		File	100 ft/min
2	With 1/2" exposed, face end flat, center drill end of part, extend and use live center	Lathe	Collet	Cutting tool	1200
3	Turn down diameter to 0.236". Make 0.01 pass each time	Lathe	Collet	Cutting tool	1200
4	Remove burs, flip part around and face the other end	Lathe	Collet	Cutting tool, File	1200
5	Pull part out and measure, machine part to final dimension, set readout to zero	Lathe	Collet	Cutting tool, Callipers	1200
6	Hold shaft in vise axle fixture with >.125" of material sticking out. Locate the X and Y datums	Mill	Vise and Axle Fixture	Edgefinder, collet	1000
7	Center drill and drill spring 1/8" spring pin hole	Mill	Vise and Axle Fixture	Center drill, Drill chuck, 1/8" drill bit	1500
8	Locate and mill the flat surface	Mill	Vise and Axle Fixture	Drill chuck, 3/8" end mill	1000
9	Remove from vise and deburr			File	

A A

SHEET 2 OF 2

2 1



TAG	X LOC	Y LOC	SIZE
A1	0.140	1.120	∅0.098 THRU
A2	0.445	0.592	∅0.098 THRU
A3	0.445	1.648	∅0.098 THRU
A4	1.055	0.592	∅0.098 THRU
A5	1.055	1.648	∅0.098 THRU
A6	1.360	1.120	∅0.098 THRU
B1	0.750	1.396	∅0.480 THRU

2 1

MANUFACTURING PLAN

RAW MATERIAL STOCK: 2" Aluminum L-braket

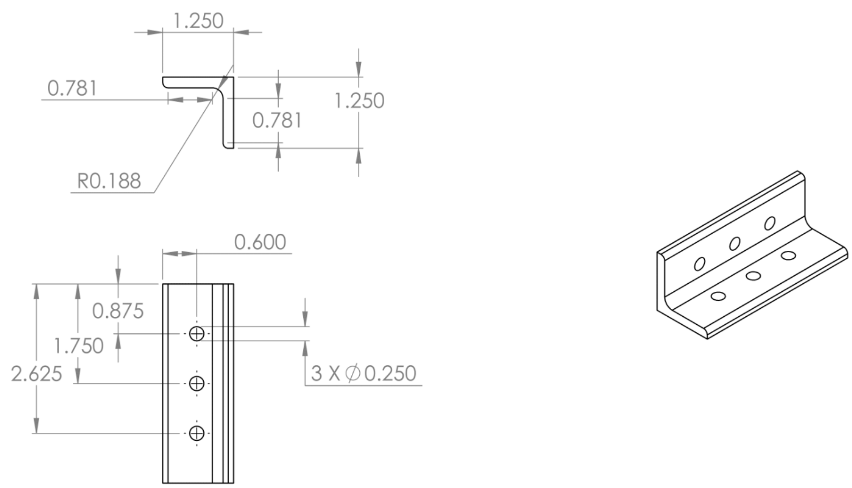
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock >.125" of finished length and deburr	Band Saw		File	100 ft/min
2	Hold part in vise on top of parallels with >.125" of material sticking out	Mill	Vise	1.375 parallels	
3	Mill one end of the part to a fully machined surface.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
4	Remove from vice and deburr			File	
5	Place part in vise and machine other end of part	Mill	Vise	3/4 inch 2-flute endmill, collet	500
6	Measure the part with calipers and bring it to 1.5" length, taking several passes at .050 or less per pass.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
7	Remove from vice and deburr			File	
8	Place part into vice against vice stop and locate the X and Y datum lines	Mill	Vise	Edge finder, collet, vice stop	1000
9	Center drill and drill the 4X 0.266 inch thru. Holes	Mill	Vise	# 3 Center drill, #16 drill bit, drill chuck	1200
10	Remove from vice and deburr, then rotate piece by 90° and place in vice			File	
11	Center drill and drill the 5X 0.098 inch thru. Holes	Mill	Vise	# 3 Center drill, #40 drill bit, drill chuck	1200
12	Center drill and drill the 0.48 inch thru. Holes	Mill	Vise	# 3 Center drill, 31/64" drill bit, drill chuck	1200
13	Remove from vise and deburr			File	

B B

A A

SHEET 2 OF 2

2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL 6061 Aluminum	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE: 13

SIZE A | DWG. NO. L_bracket_elecPlate | REV

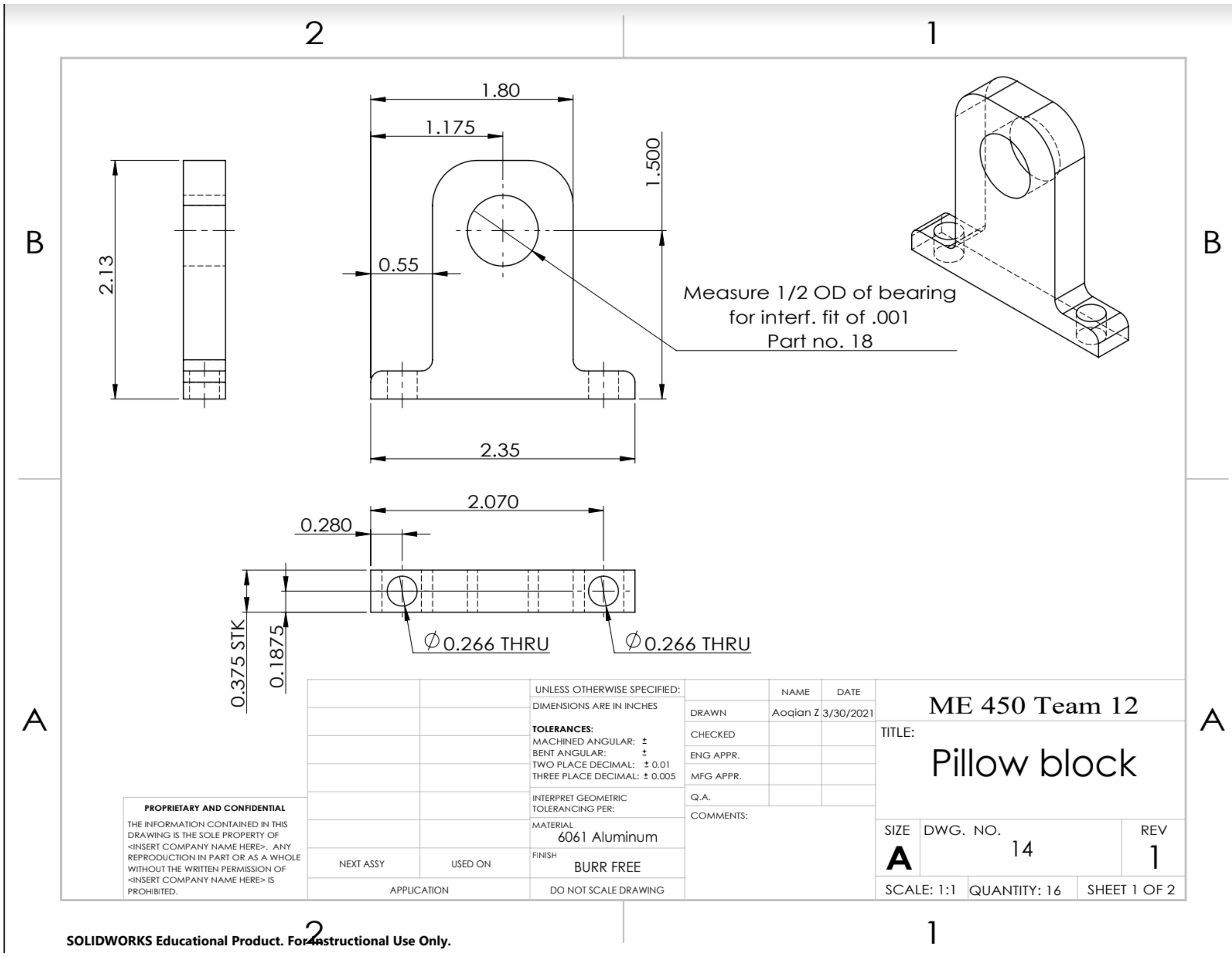
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

Manufacturing Plan

Part Nur 13
Part Titl L bracket for Electronic
Team Name:

Raw Ma 2x2 square rod

Step #	***Process Description***	***Machine***	***Fixture(s)***	***Tool(s)***	***Speed (RPM)***
1	Insert stock material into clamp	Mill	Clamp		
2	Mill off material to be the correct outer dimensions	Mill	Clamp	0.5' end mill	1000
3	Center drill, and drill the 6 holes	Mill	Clamp	E Drill or 1/4 in drill bit	1000
4	Deburr			File	
5					
6					
7					
8					
9					
10					


2
1
B
A
1.80
1.175
1.500
2.13
0.55
Measure 1/2 OD of bearing
for interf. fit of .001
Part no. 18
2.35
2.070
0.280
0.375 STK
0.1875
Ø0.266 THRU
Ø0.266 THRU
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ±
BENT ANGULAR: ±
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
BURR FREE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
Aoqian Z
3/30/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
ME 450 Team 12
TITLE:
Pillow block
SIZE
A
DWG. NO.
14
REV
1
SCALE: 1:1
QUANTITY: 16
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
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NEXT ASSY
USED ON
APPLICATION
SOLIDWORKS Educational Product. For Instructional Use Only.

2 1

B B

MANUFACTURING PLAN

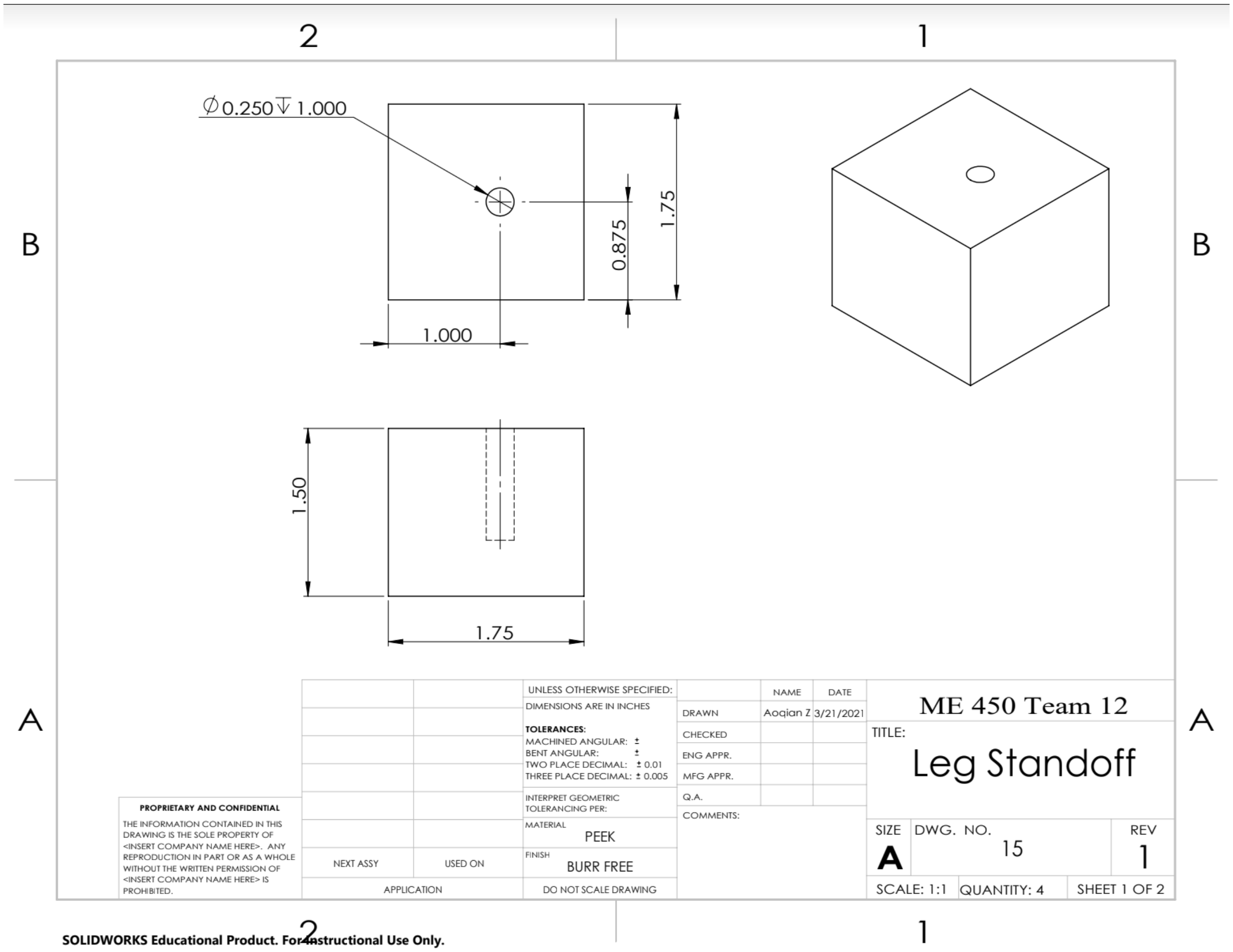
RAW MATERIAL STOCK: 3/8 inch aluminum panel. 18x18 inches

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Water jet	Water jet			
2	Hold water jetted part in vise on top of parallels with >.125" of material sticking out	Mill	Vise	1.375 parallels	
3	Locate the X and Y datum lines	Mill	Vise	Edge finder, collet	1000
4	Center drill and drill the 2X 0.266 inch thru. Holes	Mill	Vise	# 3 Center drill, 0.266 drill bit, drill chuck	1200
5	Remove from vice and deburr, then rotate piece by 90° and place in vice			File	
6	Measure OD of bearing			Micrometer	
7	Select drill bit and center drill/pre-drill 0.015" below measured diameter	Mill	Vise	center drill, selected tool bit, drill chuck	600
8	Select reamer 0.001" below measured diameter	Mill	Vise	selected reamer, drill chuck	100
9	Remove from vise and deburr			File	

A A

SHEET 2 OF 2

2 1


2
1
B
A
∅0.250 ↧ 1.000
1.75
0.875
1.000
1.50
1.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ±
BENT ANGULAR: ±
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PEEK
FINISH
BURR FREE
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
Aoqian Z
3/21/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
ME 450 Team 12
TITLE:
Leg Standoff
SIZE
A
DWG. NO.
15
REV
1
SCALE: 1:1
QUANTITY: 4
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
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2 1

MANUFACTURING PLAN
RAW MATERIAL STOCK: 5/16" Aluminum rod

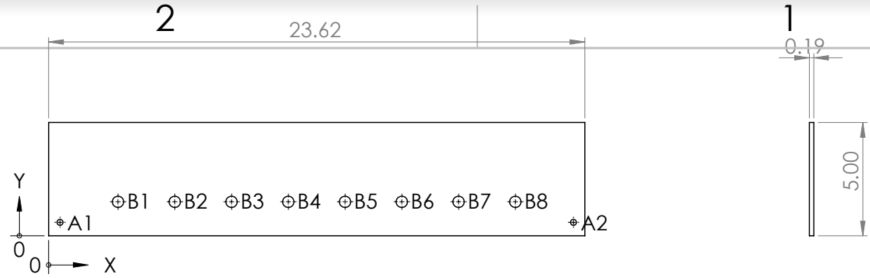
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Fix 3D printed part on vise	Mill	Vise		
2	Locate the X and Y datum lines	Mill	Vise	Edgefinder, collet	1000
3	Center drill and drill the 1/4 inch thru. Holes	Mill	Vise	# 3 Center drill, 1/4 drill bit, drill chuck	1000

B B

A A

SHEET 2 OF 2

2 1



TAG	X LOC	Y LOC	SIZE
A1	0.50	0.59	∅0.266 THRU
A2	23.12	0.59	∅0.266 THRU
B1	3.06	1.50	∅0.500 THRU
B2	5.56	1.50	∅0.500 THRU
B3	8.06	1.50	∅0.500 THRU
B4	10.56	1.50	∅0.500 THRU
B5	13.06	1.50	∅0.500 THRU
B6	15.56	1.50	∅0.500 THRU
B7	18.06	1.50	∅0.500 THRU
B8	20.56	1.50	∅0.500 THRU

LASERCUT

ME 450: Team 12

TITLE:

Holder Panel

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Acrylic

FINISH

	NAME	DATE
DRAWN	KW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Quantity:1

NEXT ASSY | USED ON

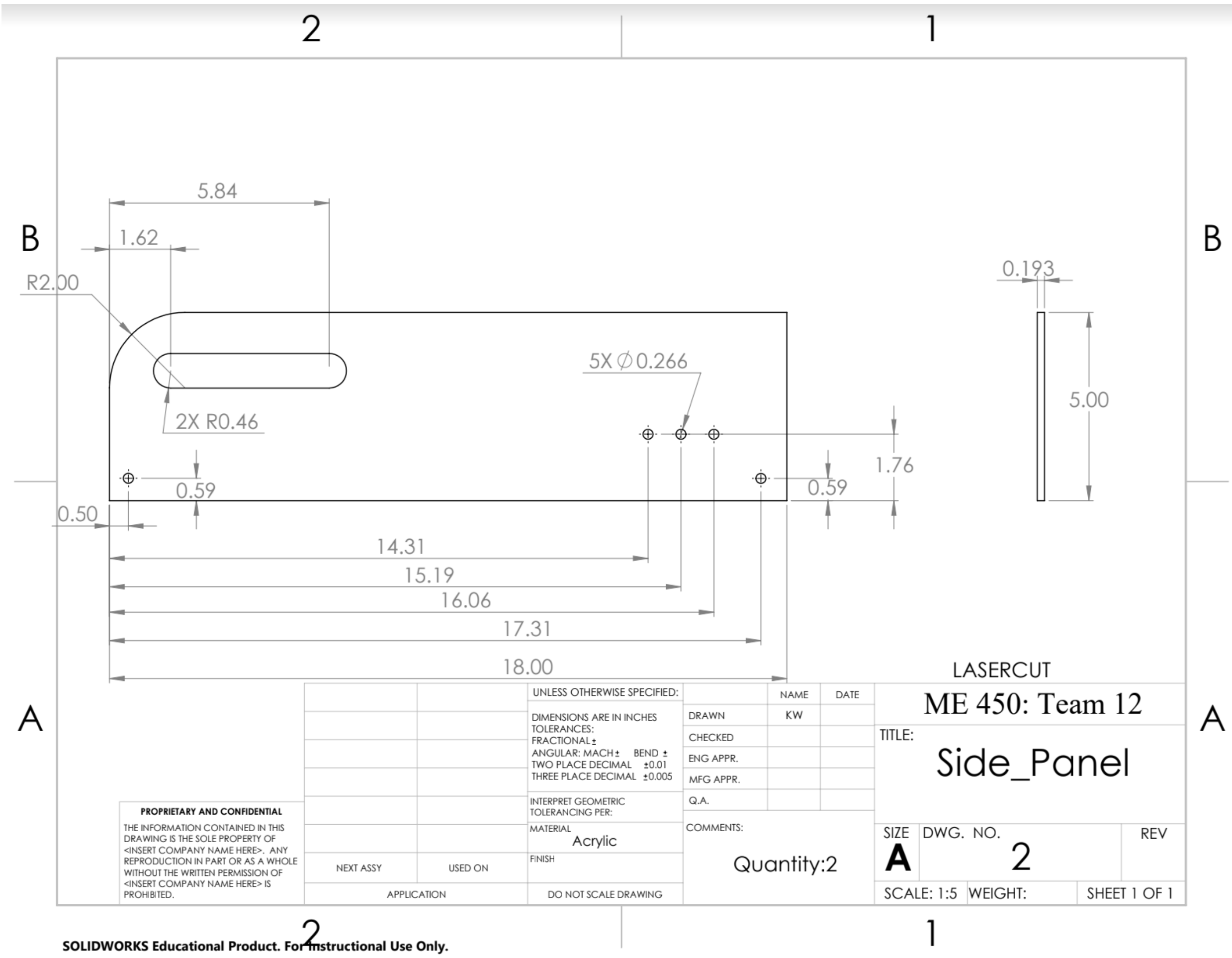
APPLICATION

DO NOT SCALE DRAWING

SIZE A | DWG. NO. 1 | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1

Quantity:1



2
1
B
A
5.84
1.62
R2.00
2X R0.46
5X ∅0.266
0.59
0.50
0.59
1.76
14.31
15.19
16.06
17.31
18.00
0.193
5.00
LASERCUT
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylic
FINISH
NAME
DATE
DRAWN
KW
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Quantity:2
ME 450: Team 12
TITLE:
Side_Panel
SIZE
A
DWG. NO.
2
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
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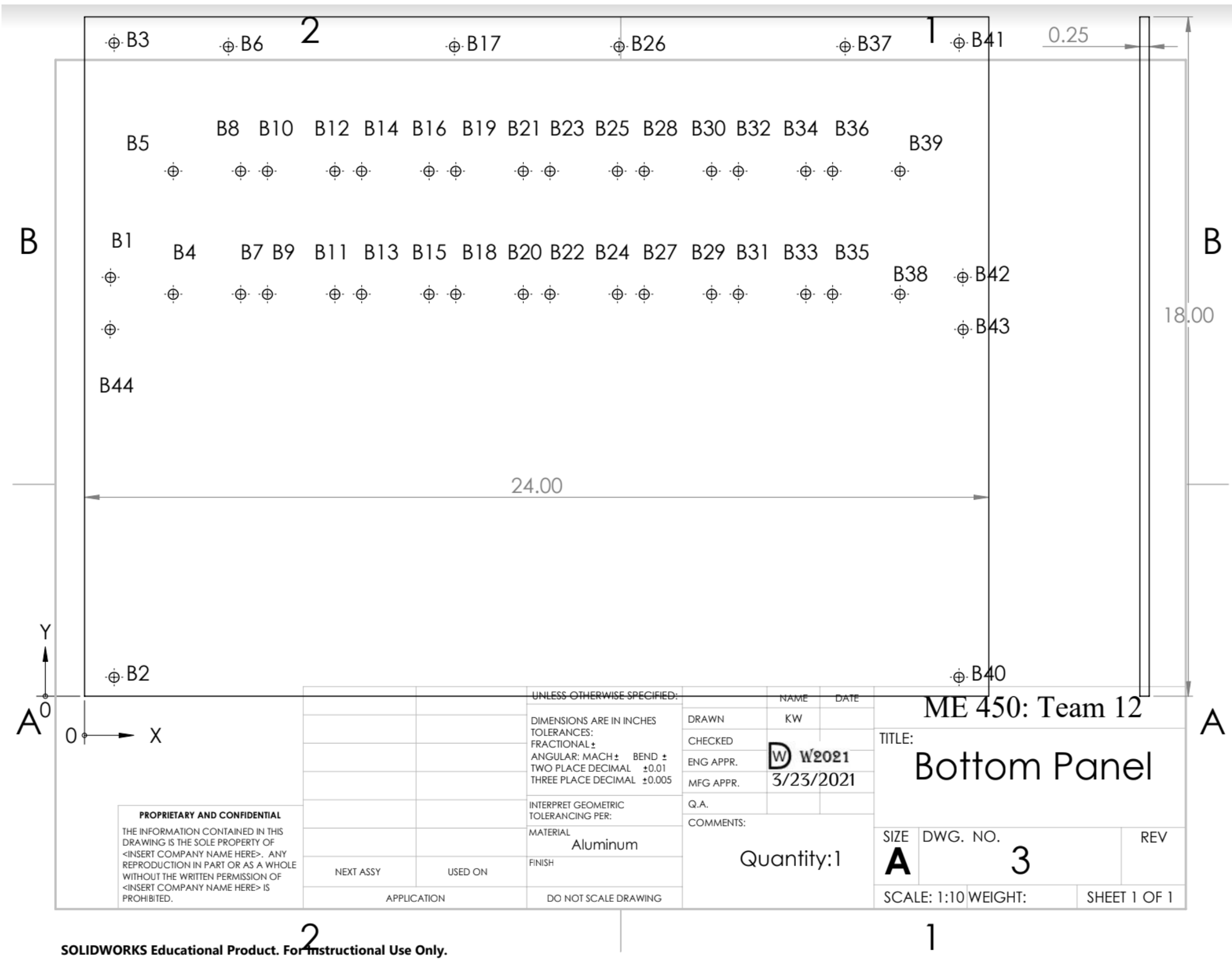
B3
B6
B17
B26
B37
B41
0.25
B5
B8 B10 B12 B14 B16 B19 B21 B23 B25 B28 B30 B32 B34 B36
B39
B1
B4
B7 B9 B11 B13 B15 B18 B20 B22 B24 B27 B29 B31 B33 B35
B38
B42
B43
18.00
B44
24.00
B2
B40
Y
X
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME DATE
DRAWN KW
CHECKED
ENG APPR.
MFG APPR.
Q.A.
W2021
3/23/2021
COMMENTS:
Quantity:1
ME 450: Team 12
TITLE:
Bottom Panel
SIZE A
DWG. NO. 3
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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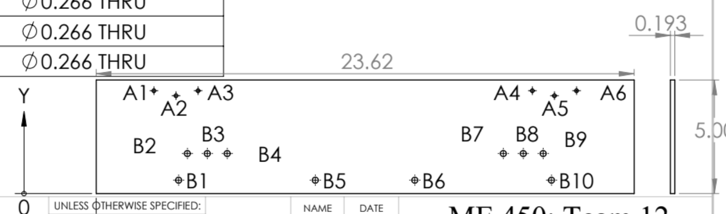
SOLIDWORKS Educational Product. For Instructional Use Only.

TAG	X LOC	Y LOC	SIZE
B1	0.69	11.10	Ø0.266 THRU
B2	0.79	0.50	Ø0.266 THRU
B3	0.79	17.31	Ø0.266 THRU
B4	2.36	10.65	Ø0.266 THRU
B5	2.36	13.91	Ø0.266 THRU
B6	3.82	17.21	Ø0.266 THRU
B7	4.15	10.65	Ø0.266 THRU
B8	4.15	13.91	Ø0.266 THRU
B9	4.86	10.65	Ø0.266 THRU
B10	4.86	13.91	Ø0.266 THRU
B11	6.65	10.65	Ø0.266 THRU
B12	6.65	13.91	Ø0.266 THRU
B13	7.36	10.65	Ø0.266 THRU
B14	7.36	13.91	Ø0.266 THRU
B15	9.15	10.65	Ø0.266 THRU
B16	9.15	13.91	Ø0.266 THRU
B17	9.82	17.21	Ø0.266 THRU
B18	9.86	10.65	Ø0.266 THRU
B19	9.86	13.91	Ø0.266 THRU
B20	11.65	10.65	Ø0.266 THRU
B21	11.65	13.91	Ø0.266 THRU
B22	12.36	10.65	Ø0.266 THRU
B23	12.36	13.91	Ø0.266 THRU
B24	14.15	10.65	Ø0.266 THRU
B25	14.15	13.91	Ø0.266 THRU
B26	14.19	17.21	Ø0.266 THRU
B27	14.86	10.65	Ø0.266 THRU
B28	14.86	13.91	Ø0.266 THRU
B29	16.65	10.65	Ø0.266 THRU
B30	16.65	13.91	Ø0.266 THRU
B31	17.36	10.65	Ø0.266 THRU
B32	17.36	13.91	Ø0.266 THRU
B33	19.15	10.65	Ø0.266 THRU
B34	19.15	13.91	Ø0.266 THRU
B35	19.86	10.65	Ø0.266 THRU
B36	19.86	13.91	Ø0.266 THRU
B37	20.19	17.21	Ø0.266 THRU
B38	21.65	10.65	Ø0.266 THRU
B39	21.65	13.91	Ø0.266 THRU
B40	23.21	0.50	Ø0.266 THRU
B41	23.21	17.31	Ø0.266 THRU
B42	23.31	11.10	Ø0.266 THRU
B43	23.32	9.72	Ø0.266 THRU
B44	0.68	9.72	Ø0.266 THRU

TAG	X LOC	Y LOC	SIZE
A1	2.53	4.53	∅0.160 THRU
A2	3.50	4.31	∅0.160 THRU
A3	4.47	4.53	∅0.160 THRU
A4	19.15	4.53	∅0.160 THRU
A5	20.12	4.31	∅0.160 THRU
A6	21.09	4.53	∅0.160 THRU
B1	3.62	0.59	∅0.266 THRU
B2	4.00	1.76	∅0.266 THRU
B3	4.88	1.76	∅0.266 THRU
B4	5.75	1.76	∅0.266 THRU
B5	9.62	0.59	∅0.266 THRU
B6	13.99	0.59	∅0.266 THRU
B7	17.87	1.76	∅0.266 THRU
B8	18.75	1.76	∅0.266 THRU
B9	19.62	1.76	∅0.266 THRU
B10	19.99	0.59	∅0.266 THRU



LASERCUT

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Acrylic
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KW	
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

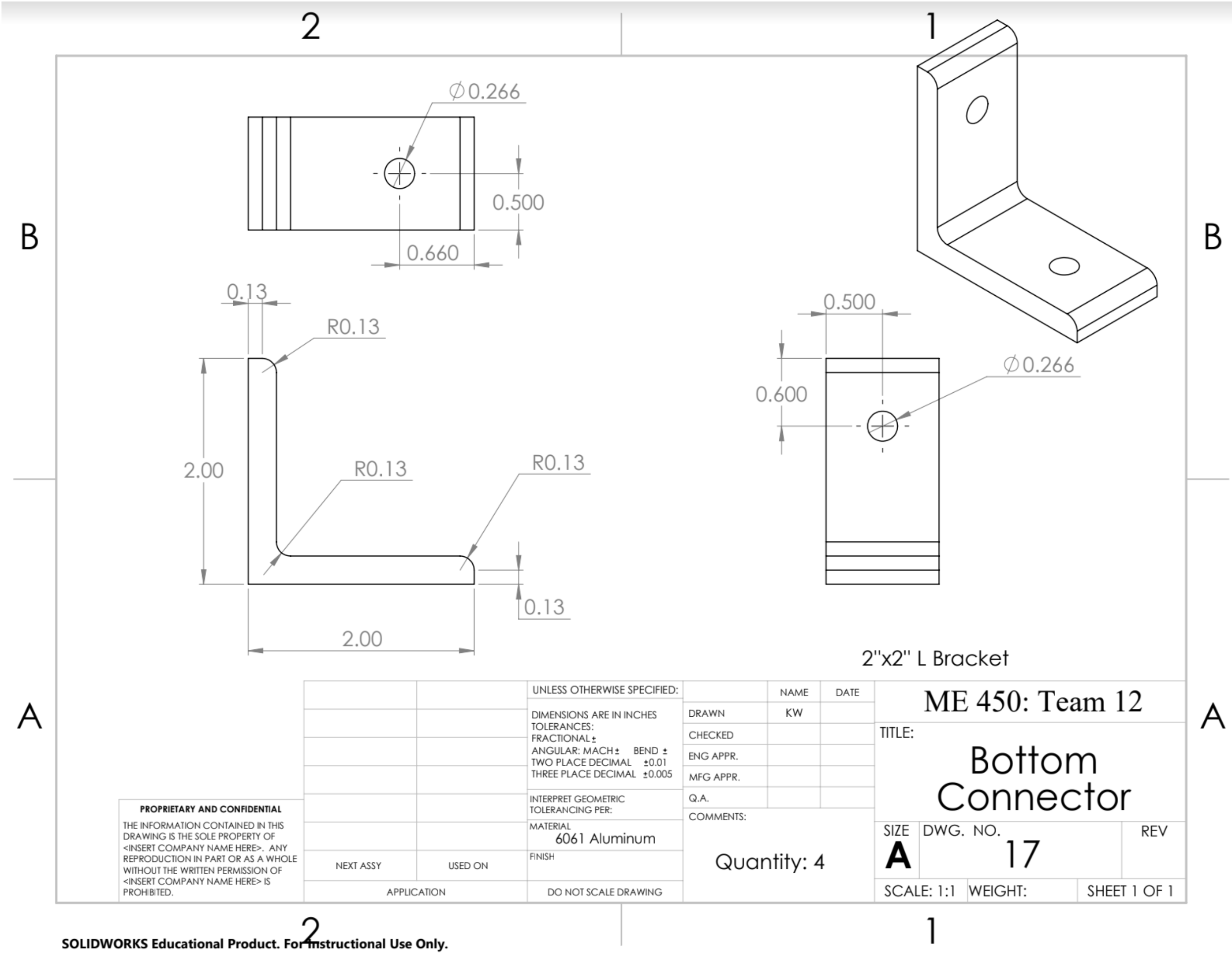
COMMENTS:
Quantity: 1

ME 450: Team 12

TITLE:
Back Panel

SIZE A | DWG. NO. 4 | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1



2
1
B
A
⌀0.266
0.500
0.660
0.13
R0.13
2.00
R0.13
R0.13
0.13
2.00
0.500
⌀0.266
0.600
2"x2" L Bracket
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
KW
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Quantity: 4
ME 450: Team 12
TITLE:
Bottom Connector
SIZE
A
DWG. NO.
17
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
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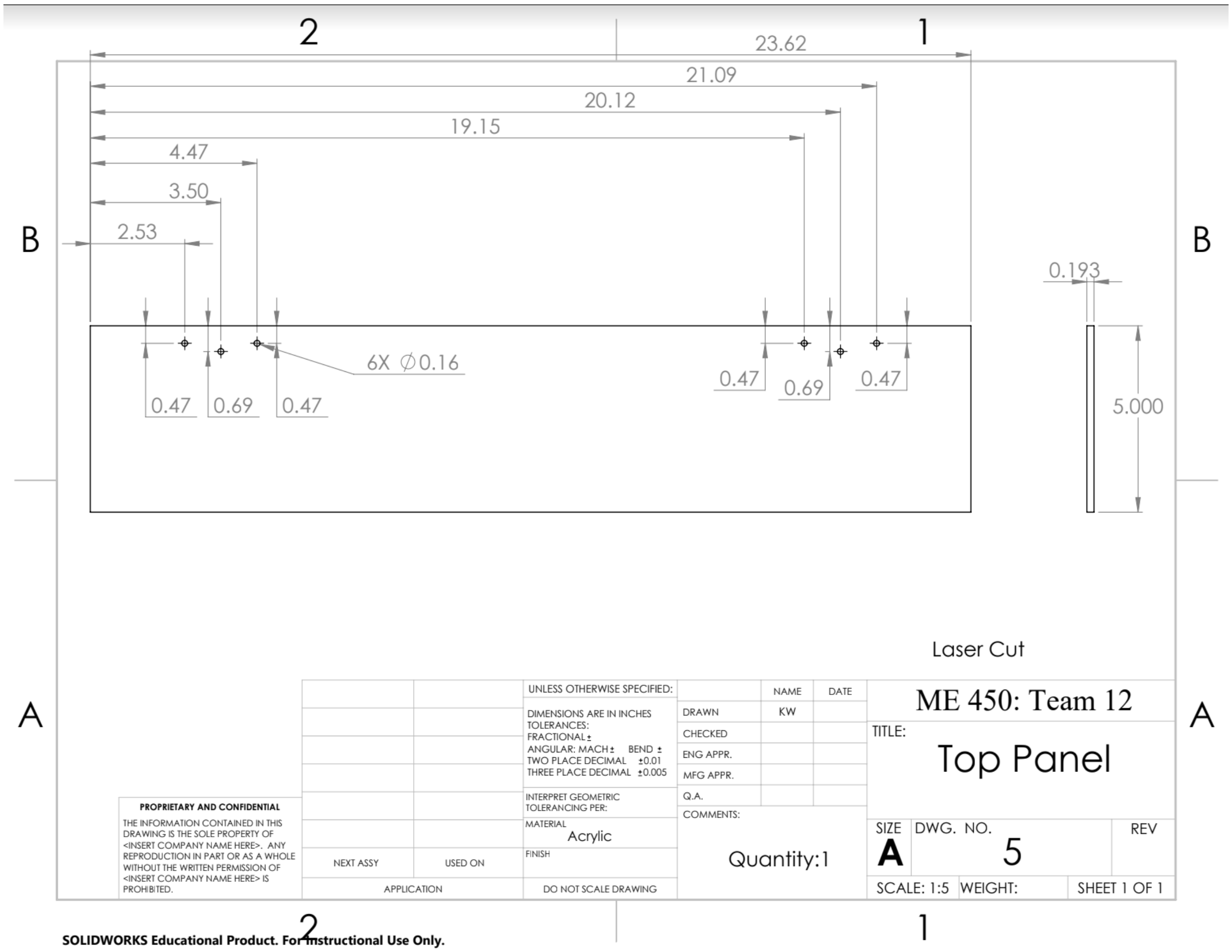
Manufacturing Plan

Part Nur 17
Part Titl Bottom L bracket
Team Name:

Raw Ma 2x2 square rod

Step #	***Process Description***	***Machine***	***Fixture(s)***	***Tool(s)***	***Speed (RPM)***
1	Insert stock material into clamp	Mill	Clamp		
2	Mill off material to be the correct outer dimensions	Mill	Clamp	1/4'' end mill	1000
3	Center drill, and drill the 6 holes	Mill	Clamp	H drill in drill bit	1000
4	Deburr			File	
5					
6					
7					
8					
9					
10					


23.62
21.09
20.12
19.15
4.47
3.50
2.53
6X ∅0.16
0.47
0.69
0.47
0.47
0.69
0.47
0.193
5.000
Laser Cut
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
KW
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Quantity:1
ME 450: Team 12
TITLE:
Top Panel
SIZE
A
DWG. NO.
5
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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APPENDIX E: BILL OF MATERIALS

Table E.1. Build of Materials

Type	Item	Quantity	Unit Cost	Total Price	Supplier
Structural	USB Digital Microscope	1	18.99	18.99	Amazon
	Shaft Collar	8	8.37	66.96	McMaster
	Rubber lining	1	20.67	20.67	McMaster
	Gear	10	10.99	109.9	GoBilda
	Gear set screw hub	10	5.49	54.9	GoBilda
	Ball bearings	8	3.49	27.92	GoBilda
	Acrylic 24x12	3	17.81	53.43	McMaster
	Aluminum angle stock 2'	2	0	0	Acquired X50 Assembly/Machine Shop
	Aluminum 13"x13"x3/8"	1	0	0	Acquired X50 Assembly/Machine Shop
	Aluminum 24x12	1	49.65	49.65	McMaster
	Steel Shafts	4	3.99	15.96	GoBilda
	Surface Hinges	2	8.42	16.84	McMaster
Electrical	10 kOhm resistor	2	0	0	Acquired From Mechatronics Shop
	H Bridge	1	0	0	Acquired From Mechatronics Shop
	H bridge Power Supply	1	8.47	0	Amazon
	DC Motor	2	39.95	79.9	Pololu
	Arduino/ELEGOO Mega	1	16.99	16.99	Amazon
	PushButtons	1	5.95	5.95	AdaFruit
	LCD screen	1	8.99	8.99	Amazon
	Toggle Switch	2	0.66	1.32	DigiKey
	Jumper wires	20	0	0	Acquired From Mechatronics Shop
	Breadboard	1	4.95	4.95	DigiKey
Fasteners	1/2-20 3/4""	48	0	0	Acquired X50 Assembly/Machine Shop
	1/2-20 1/2"	4	0	0	Acquired X50 Assembly/Machine Shop

	4-40 1"	16	0	0	Acquired X50 Assembly/Machine Shop
	1/2-20 Hex nut	48	0	0	Acquired X50 Assembly/Machine Shop
Total				**561.79**	

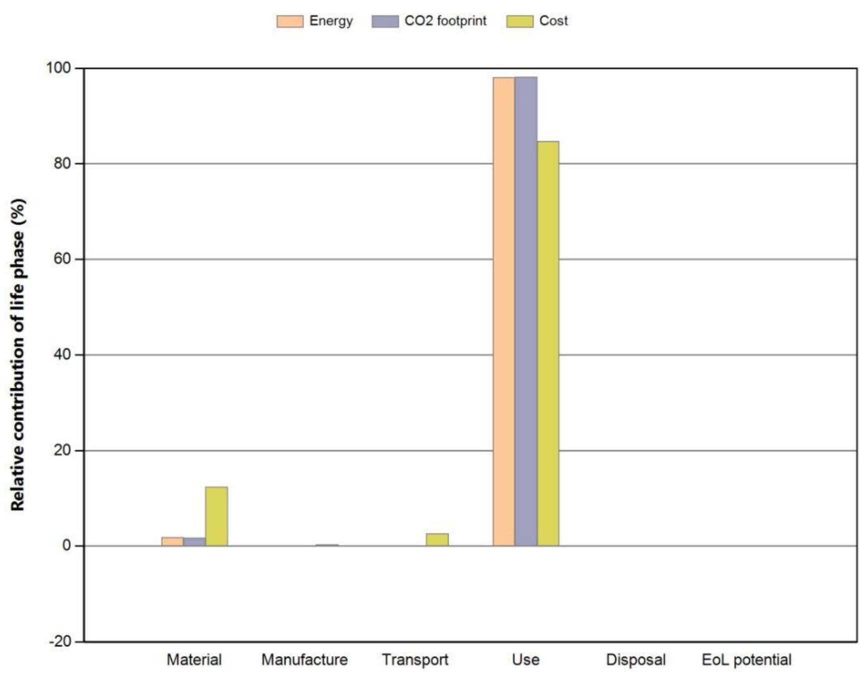
APPENDIX F: CLINOSTAT ECO-AUDIT

GRANTA EduPack

Eco Audit Report

Product name	2D Clinostat
Country of manufacture	World
Country of use	North America
Product life (years)	10

Summary:



Energy details   CO2 footprint details   Cost details

Phase	Energy (kcal)	Energy (%)	CO2 footprint (lb)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	4.99e+05	1.8	312	1.7	289	12.3
Manufacture	2.02e+04	0.1	14	0.1	8.15	0.347
Transport	1.06e+04	0.0	7.03	0.0	60.6	2.58
Use	2.65e+07	98.0	1.76e+04	98.1	1.99e+03	84.7
Disposal	466	0.0	0.301	0.0	0.0626	0.00267
Total (for first life)	**2.71e+07**	**100**	**1.8e+04**	**100**	**2.35e+03**	**100**
End of life potential	0		0			

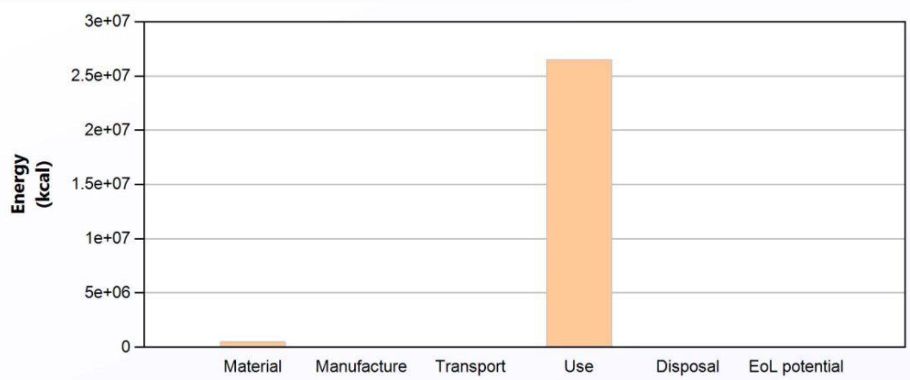
NOTE: Differences of less than 20% are not usually significant.
See notes on precision and data sources.

Page 1 / 10
Sunday, March 14, 2021

Eco Audit Report

Energy Analysis

Summary



	Energy (kcal/year)
Equivalent annual environmental burden (averaged over 10 year product life):	2.71e+06

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	Energy (kcal)	%
Housing, Axles, Holders	Aluminum, commercial purity, S150.1: LM0-M, cast	Virgin (0%)	15	1	15	3.1e+05	62.7
Housing Feet, Connectors	PLA (general purpose)	Virgin (0%)	3	1	3	1.8e+04	3.6
Electric Motors	Power supply unit	Reused part	2	1	2	0	0.0
Wiring	Cable	Virgin (0%)	1.5	1	1.5	1.5e+04	3.0
Camera	Small (hand held) electronic devices	Virgin (0%)	0.5	1	0.5	1.5e+05	30.7
Total				**5**	**22**	**5e+05**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	Energy (kcal)	%
Housing, Axles, Holders	Casting	-	15 lb	1.8e+04	90.4
Housing Feet, Connectors	Polymer extrusion	-	3 lb	1.9e+03	9.6
Total				**2e+04**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (miles)	Energy (kcal)	%
Part Delivery	32 tonne (4 axle) truck	3e+03	1.1e+04	100.0
Total		**3e+03**	**1.1e+04**	**100**

Breakdown by components

Component	Mass (lb)	Energy (kcal)	%
Housing, Axles, Holders	15	7.1e+03	67.4
Housing Feet, Connectors	3	1.5e+03	14.0
Electric Motors	2	9.8e+02	9.3
Wiring	1.5	7.4e+02	7.0
Camera	0.5	2.5e+02	2.3
Total	**22**	**1.1e+04**	**100**

Use:

Summary

Static mode

Energy input and output type	Fossil fuel to electric
Country of use	North America
Power rating (W)	3.6e+02
Usage (hours per day)	24
Usage (days per year)	1.3e+02
Product life (years)	10

Relative contribution of static and mobile modes

Mode	Energy (kcal)	%
Static	2.7e+07	100.0
Mobile	0	
Total	**2.7e+07**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Energy (kcal)	%
Housing, Axles, Holders	Landfill	100.0	3.1e+02	67.4
Housing Feet, Connectors	Landfill	100.0	65	14.0
Electric Motors	Landfill	100.0	43	9.3
Wiring	Landfill	100.0	33	7.0
Camera	Landfill	100.0	11	2.3
Total			**4.7e+02**	**100**

EoL potential:

Component	End of life option	% recovered	Energy (kcal)	%
Housing, Axles, Holders	Landfill	100.0	0	
Housing Feet, Connectors	Landfill	100.0	0	
Electric Motors	Landfill	100.0	0	
Wiring	Landfill	100.0	0	
Camera	Landfill	100.0	0	
Total			**0**	**100**

Notes:

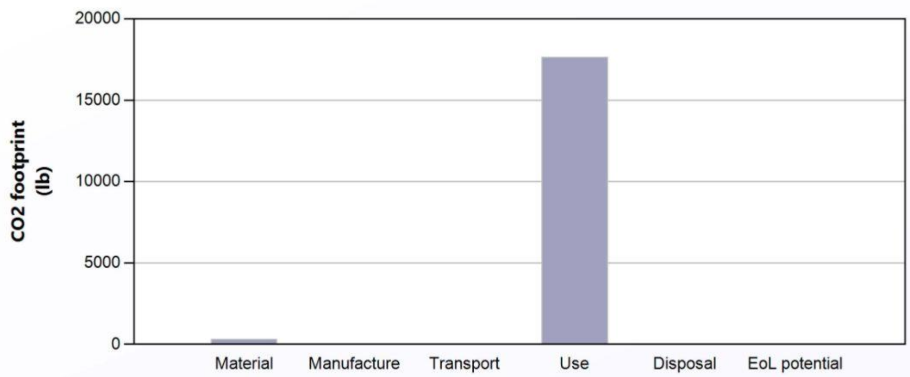
Summary

GRANTA EduPack

Eco Audit Report

CO2 Footprint Analysis

Summary



	CO2 (lb/year)
Equivalent annual environmental burden (averaged over 10 year product life):	1.8e+03

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	CO2 footprint (lb)	%
Housing, Axles, Holders	Aluminum, commercial purity, S150.1: LM0-M, cast	Virgin (0%)	15	1	15	1.9e+02	60.0
Housing Feet, Connectors	PLA (general purpose)	Virgin (0%)	3	1	3	8.5	2.7
Electric Motors	Power supply unit	Reused part	2	1	2	0	0.0
Wiring	Cable	Virgin (0%)	1.5	1	1.5	10	3.3
Camera	Small (hand held) electronic devices	Virgin (0%)	0.5	1	0.5	1.1e+02	34.0
Total				**5**	**22**	**3.1e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Component	Process	% Removed	Amount processed	CO2 footprint (lb)	%
Housing, Axles, Holders	Casting	-	15 lb	13	90.4
Housing Feet, Connectors	Polymer extrusion	-	3 lb	1.3	9.6
Total				**14**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (miles)	CO2 footprint (lb)	%
Part Delivery	32 tonne (4 axle) truck	3e+03	7	100.0
Total		**3e+03**	**7**	**100**

Breakdown by components

Component	Mass (lb)	CO2 footprint (lb)	%
Housing, Axles, Holders	15	4.7	67.4
Housing Feet, Connectors	3	0.98	14.0
Electric Motors	2	0.65	9.3
Wiring	1.5	0.49	7.0
Camera	0.5	0.16	2.3
Total	**22**	**7**	**100**

Use:

Summary

Static mode

Energy input and output type	Fossil fuel to electric
Country of use	North America
Power rating (W)	3.6e+02
Usage (hours per day)	24
Usage (days per year)	1.3e+02
Product life (years)	10

Relative contribution of static and mobile modes

Mode	CO2 footprint (lb)	%
Static	1.8e+04	100.0
Mobile	0	
Total	**1.8e+04**	**100**

Disposal:

Summary

Component	End of life option	% recovered	CO2 footprint (lb)	%
Housing, Axles, Holders	Landfill	100.0	0.2	67.4
Housing Feet, Connectors	Landfill	100.0	0.042	14.0
Electric Motors	Landfill	100.0	0.028	9.3
Wiring	Landfill	100.0	0.021	7.0
Camera	Landfill	100.0	0.007	2.3
Total			**0.3**	**100**

EoL potential:

Component	End of life option	% recovered	CO2 footprint (lb)	%
Housing, Axles, Holders	Landfill	100.0	0	
Housing Feet, Connectors	Landfill	100.0	0	
Electric Motors	Landfill	100.0	0	
Wiring	Landfill	100.0	0	
Camera	Landfill	100.0	0	
Total			**0**	**100**

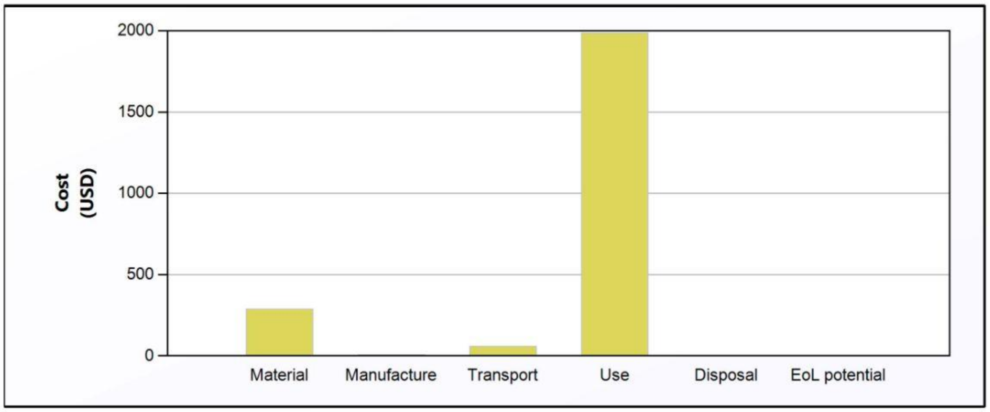
Notes:

Summary

Eco Audit Report

Cost Analysis

Summary



	Cost (USD/year)
Equivalent annual environmental burden (averaged over 10 year product life):	235

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (lb)	Qty.	Total mass processed** (lb)	Cost (USD)	%
Housing, Axles, Holders	Aluminum, commercial purity, S150.1: LM0-M, cast	Virgin (0%)	15	1	15	19	6.5
Housing Feet, Connectors	PLA (general purpose)	Virgin (0%)	3	1	3	4	1.4
Electric Motors	Power supply unit	Reused part	2	1	2	57	19.6
Wiring	Cable	Virgin (0%)	1.5	1	1.5	58	20.2
Camera	Small (hand held) electronic devices	Virgin (0%)	0.5	1	0.5	1.5e+02	52.4
Total				**5**	**22**	**2.9e+02**	**100**

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

Manufacture:

Summary

Country of manufacture World

Component	Process	Length (ft)	% Removed	Amount processed		Cost (USD)	%
Housing, Axles, Holders	Casting	-	-	15	lb	8.2	100.0
Housing Feet, Connectors	Polymer extrusion	-	-	3	lb	0	0.0
Total						**8.2**	**100**

Transport:

Summary

Package dimensions

Height (ft)	Width (ft)	Depth (ft)
2.5	2.5	2.5

Breakdown by transport stage

Stage name	Transport type	Distance (miles)	Cost (USD)	%
Part Delivery	32 tonne (4 axle) truck	3e+03	61	100.0
Total		**3e+03**	**61**	**100**

Breakdown by components

Component	Mass (lb)	Cost (USD)	%
Housing, Axles, Holders	15	41	67.4
Housing Feet, Connectors	3	8.5	14.0
Electric Motors	2	5.6	9.3
Wiring	1.5	4.2	7.0
Camera	0.5	1.4	2.3
Total	**22**	**61**	**100**

Use:

Summary

Static mode

Energy input and output type	Fossil fuel to electric
Country of use	North America
Fuel rate	Domestic
Power rating (W)	3.6e+02
Usage (hours per day)	24
Usage (days per year)	1.3e+02
Product life (years)	10

Relative contribution of static and mobile modes

Mode	Cost (USD)	%
Static	2e+03	100.0
Mobile	0	
Total	**2e+03**	**100**

Disposal:

Summary

Component	End of life option	% recovered	Cost (USD)	%
Housing, Axles, Holders	Landfill	100.0	0.042	67.4
Housing Feet, Connectors	Landfill	100.0	0.0087	14.0
Electric Motors	Landfill	100.0	0.0058	9.3
Wiring	Landfill	100.0	0.0044	7.0
Camera	Landfill	100.0	0.0015	2.3
Total			**0.063**	**100**

Notes:

Summary

APPENDIX G: USER MANUAL

Introduction

The user control system will include buttons to control the two motors and a LCD screen to view the rotation per minute of the motors. There are stickers that are labelled “R” and “L” which control the right and left motors respectively. The design of the clinostat has two motors that control four test tube grippers each. This means that half of the clinostat can act independently. The test tube grippers will also have opposite rotation directions which is normal. The breadboarded is labelled which states that the red button is used to switch the speed controls to the left motor and the blue button at the bottom is used to switch the speed controls to the right motor. The yellow button increases the rotational speed and the grey button decreases the speed.

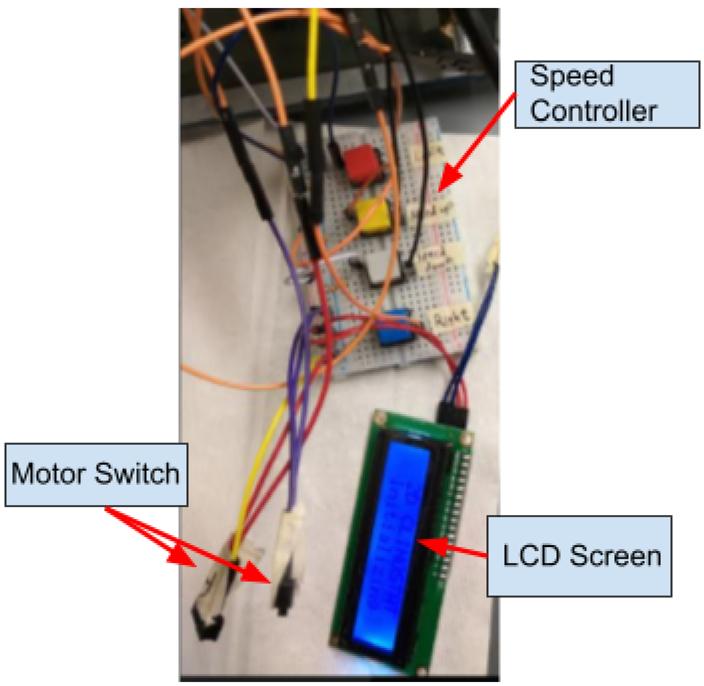


Figure 1: User controls

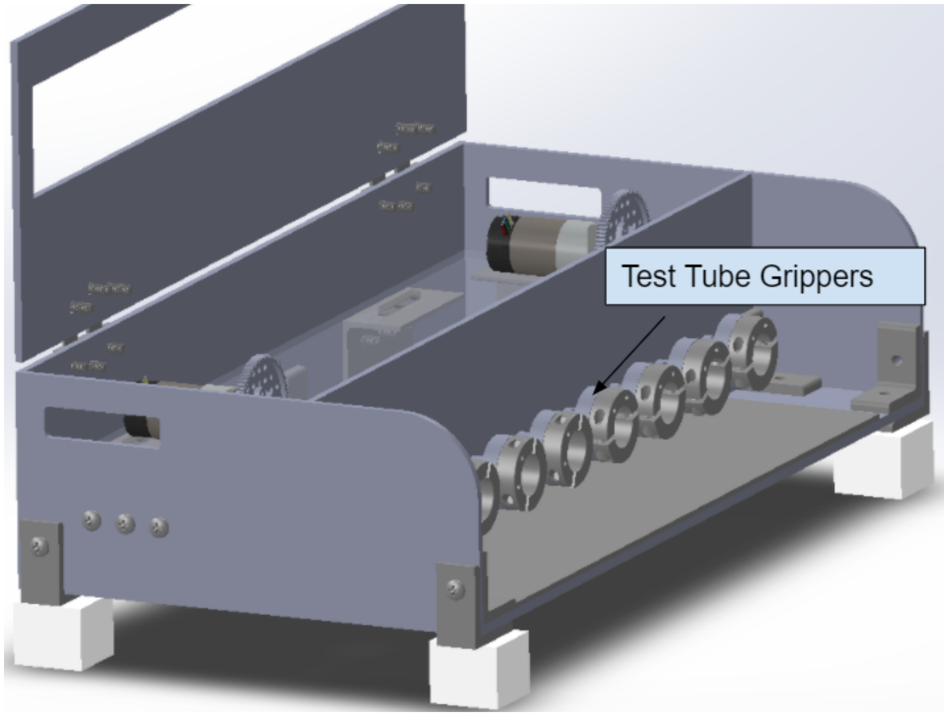


Figure 2: Test tube gripper location

Setting up test tubes

The gripper system is a shaft collar, which means you will need a Hex Key or an Allen Key in order to tighten the test tube gripper onto the test tube. Figure 2 shows the location of the two screws that when tightened cause the gripper to close onto the test tube. Rubber lining has been included to protect the test tube when it is inserted. **It is also important to note that the center of the shaft collar is not perfectly concentric with the axis of rotation. This means that you will have to manually adjust the test tube location by putting in rubber strips.** Figure 3 shows where you will insert the rubber strips into.

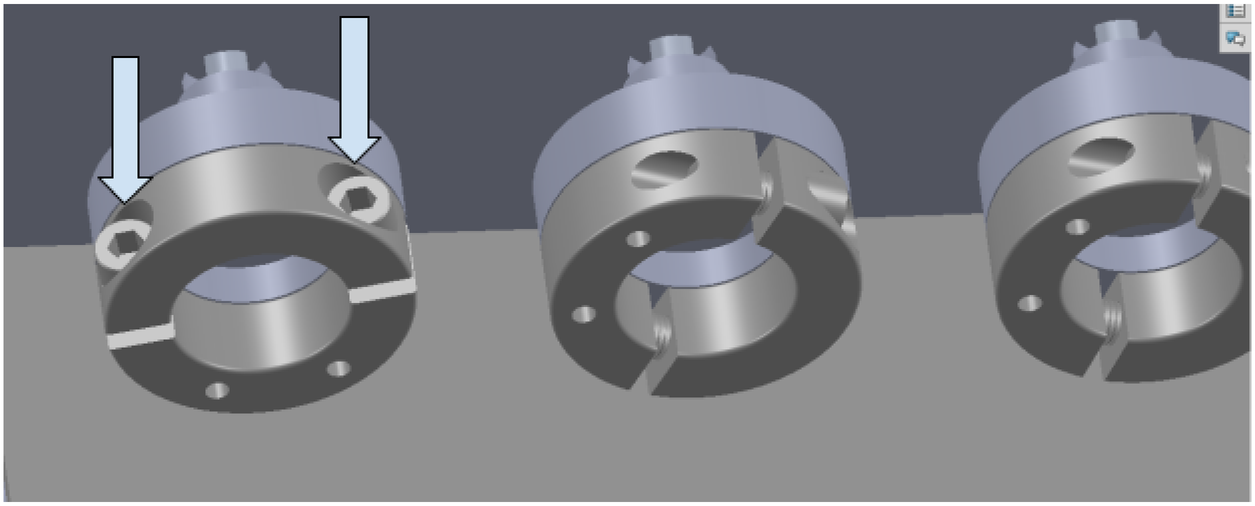


Figure 2: Hex screws that need to be tightened

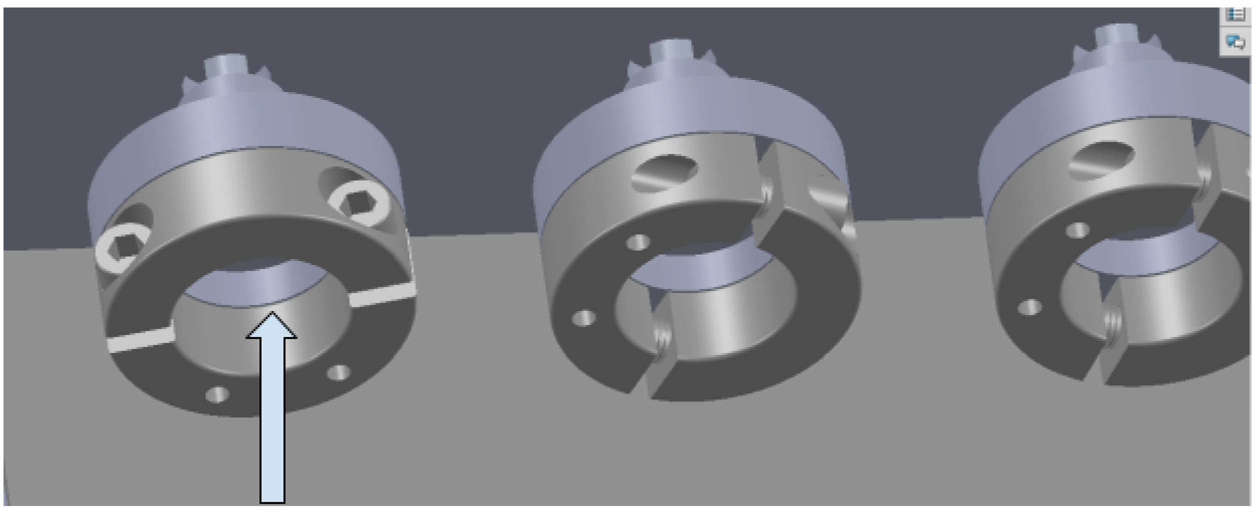


Figure 3: Test tube and rubber lining location

If there are problems with securing the test tube gripper onto the test tube, you can also unscrew the set screw located in Figure 4. **It is important to note that there are two set screws on opposite sides.** This will allow the entire gripper to come off of the axis and allow you to insert the test tube vertically instead of horizontally. Once the test tube is in place, then screw the set screw back into place. Additional 6-32 set screws should be given in case some get lost.

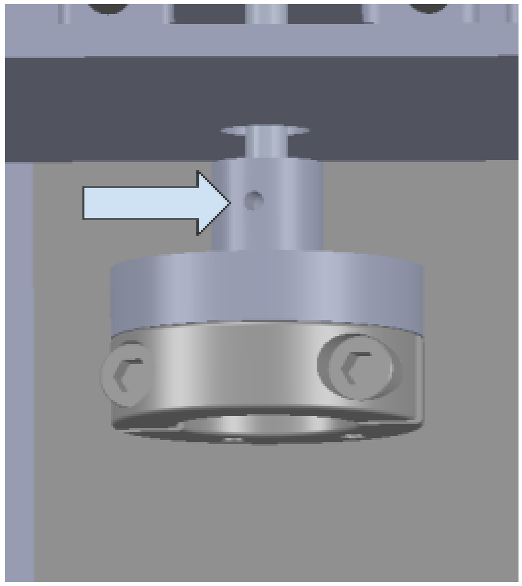


Figure 4: Two set screw locations

Troubleshooting

The major problem that the team foresees occurring is binding in the gear train. The gear train for one motor on one side of the clinostat is shown in Figure 5. As you can see, the four test tube grippers are in line while the motor gear is on top of the entire gear train. If binding occurs and there are problems with rotation, simply align the gears by unscrewing the set screw located on each gear.

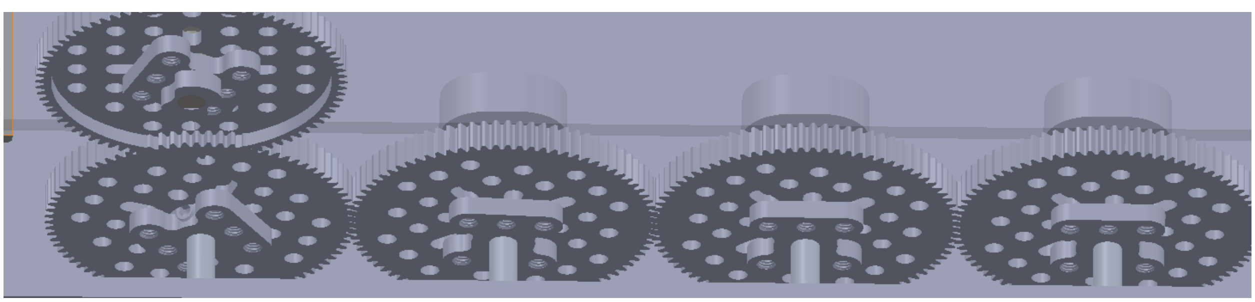


Figure 5: Gear train

If other problems occur, such as pieces break or pieces get lost, the entire design of the system and the build of materials can be found in this Google Drive:
https://drive.google.com/drive/u/1/folders/1pDhMktO6qtgT-_S753FKuocw0VWCmywE

You can also contact members of the team for additional help if there are problems.
Karthik Bijoy: kbijoy@umich.edu, (312) 622-0513
Kevin Wen: kwen@umich.edu, (631) 889 - 7556

APPENDIX H: ARDUINO CODE

```
//Arduino Code for 2D clinostat
//Version 1: 4/26/2021

//download all required libraries
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <LiquidCrystal.h>



//Set all preassigned values
bool switch1Status = 0;
bool switch2Status = 0;
bool motorL = 0;
String motor1Status = "Off";
String motor2Status = "Off";
const int enA = 3;
const int enB = 6;
const int in1 = 4;
const int in2 = 5;
const int in3 = 7;
const int in4 = 8;
const int switch1 = 11;
const int switch2 = 12;

int LeftMotorSelect = 0;
int RightMotorSelect = 0;
int SpeedUpButton = 0;
int SpeedDownButton = 0;

int speedL = 100;//Speed for the left motor
int speedR = 100;//Speed for the right motor

LiquidCrystal_I2C lcd(0x27, 16, 2);

void setup() {
 //Start the LCD screen
  lcd.init();
  lcd.backlight();

  //configure all inputs and outputs to the arduino microcontroller
  pinMode(enA, OUTPUT);
```

```
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
  pinMode(enB, OUTPUT);
  pinMode(in3, OUTPUT);
  pinMode(in4, OUTPUT);
  pinMode(switch1, INPUT);
  pinMode(switch2, INPUT);
  pinMode(13, INPUT);
  pinMode(9, INPUT);
  pinMode(10, INPUT);
  pinMode(2, INPUT);
  delay(500);
  Serial.begin(9600);
  //Configure LCD start message
  lcd.setCursor(2,0);
  lcd.print("2D CLINOSTAT");
  lcd.setCursor(2,1);
  lcd.print("Initializing");
  delay(3000);

  lcd.clear();
}

void loop() {
  Lcd();
  motorSelect();
  motorSpeed();

  //Assign the button inputs
  LeftMotorSelect = digitalRead(9);
  SpeedUpButton = digitalRead(13);
  SpeedDownButton = digitalRead(10);
  RightMotorSelect = digitalRead(2);

//Configure the motors to run when the switch is thrown
  if(digitalRead(switch1)){
  digitalWrite(in1, HIGH);

  digitalWrite(in1, HIGH);
  digitalWrite(in2, LOW);
   analogWrite(enA, speedR);

  } else {
  digitalWrite(in1, LOW);//both motors off initially
```

```
  digitalWrite(in1, LOW);
  digitalWrite(in2, LOW);

  }


  if(digitalRead(switch2)){

  digitalWrite(in3, HIGH);
  digitalWrite(in4, LOW);
   analogWrite(enB, speedL);
  } else {

  digitalWrite(in3, LOW);
  digitalWrite(in4, LOW);



  }



}


//Functions for the loop code-----------------------------------------------

void Lcd(){
//code to display the LCD messages
if(digitalRead(switch1)){
  switch1Status = 1;

} else {
  switch1Status = 0;

}

if(digitalRead(switch2)){
  switch2Status = 1;
} else {
  switch2Status = 0;
}
```

```
if (switch1Status == 0){
   motor1Status = "Off";
} else {

   motor1Status = "On ";
}

if (switch2Status == 0){
   motor2Status = "Off";
} else {

   motor2Status = "On ";
}
if(motorL == 0){
  lcd.setCursor(0,0);
  lcd.print("R: " + motor1Status + " SPD: " + speedR/10 + " *   ");
  lcd.setCursor(0,1);
  lcd.print("L: " + motor2Status + " SPD: " + speedL/10 + "     ");
}
if(motorL == 1){
  lcd.setCursor(0,0);
  lcd.print("R: " + motor1Status + " SPD: " + speedR/10 + "     ");
  lcd.setCursor(0,1);
  lcd.print("L: " + motor2Status + " SPD: " + speedL/10 + " *    ");
}

}

void motorSelect(){

//Identify which motor will run based on the buttons pressed

if(LeftMotorSelect){

  delay(1000);
  motorL = 1;
}

if(RightMotorSelect){
  delay(1000);
  motorL = 0;
}
```

```
if(motorL == 0){
Serial.println("Right Motor");

} else if(motorL == 1){
  Serial.println("Left Motor");
}


}

void motorSpeed(){
  //Set the PWM boundary for the speed
if(speedL > 255){
  speedL = 255;
}

 if(speedR > 255){
  speedR = 255;
}
if(speedL < 0){
  speedL = 0;
}

if(speedR < 0){
  speedR = 0;
}

//Increase and decrease the speed based on the selected button
if(SpeedUpButton && motorL == 1){
  delay(500);
  speedL = speedL + 10;
}
if(SpeedDownButton && motorL == 1){
  delay(500);
  speedL = speedL - 10;
}

if(SpeedUpButton && motorL == 0){
  delay(500);
  speedR = speedR + 10;
}
if(SpeedDownButton && motorL == 0){
```

```
  delay(500);
  speedR = speedR - 10;
}


}
```