University of Michigan

Mechanical Engineering 450 - Fall 2023

Sponsored by: Alex Shorter, Assistant Professor, University of Michigan Department of Mechanical Engineering and Jeffrey Koller, Lecturer, University of Michigan Department of Mechanical Engineering

Enhancing ME 240 - Final Report

Implementation of Physical Educational Devices in the Classroom

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Executive Summary

Students taking Mechanical Engineering (ME) 240 through the University of Michigan currently learn the dynamics concepts presented in the course through theoretical system analysis, leading to a lack of student understanding of real-world applications. Our task is to design a physical educational device to bridge the gap between theoretical physics principles and tangible dynamics applications. This will give students a deeper grasp of dynamics that can be used in higher level engineering courses and their engineering careers. The goal of our team is to see an increase in student comprehension and grades in ME 240, as well as advanced courses for which ME 240 serves as a foundational class.

To ensure that our final product adequately solves the issues currently faced in ME 240, our team developed a list of requirements and specifications that we used to test the success of our product. The key requirements for this project are that it is easy to transport, easy to use, capable of tracking, and effectively increases student learning in ME 240. Using these requirements as guidelines, our team generated a list of potential concepts, starting individually then compiling ideas as a group. These concepts were then categorized and subsequently evaluated against our project's requirements, at which point the best design for each topic was presented to our sponsor. The feedback from our sponsors, as well as our own evaluation of our potential concepts, led to the design of a variable ramp, which will include a student guide and tracking software to ensure that our concepts can be used by students independently to better understand engineering dynamics.

Our team manufactured a prototype of our variable ramp design, as well as developed the accompanying student guide and tracking software. Throughout our manufacturing process, our team kept a bill of materials to ensure that we did not exceed the allotted budget for our project. We also developed manufacturing plans for each of the parts required for the construction of our prototype to ensure future teams are capable of replicating our device if necessary. Engineering analysis and preliminary verification tests have shown that our product meets the majority of our specifications, including ease of transport, ease of use, and capability of tracking. We also plan to present our student guide to the Center for Research on Learning and Teaching (CRLT) to ensure it is adequate for leading students through our experiments. Future study will need to be conducted through validation testing to ensure that the product is beneficial in a classroom environment, and that students are capable of conducting the intended experiments within the time given for a lecture.

Although we feel that our work has produced a device that will be beneficial for ME 240 students, we recognize that our design process was limited in terms of student feedback, which we would encourage in the future if work on this project is continued. To continue to evaluate and improve the state of educational demonstrations in the ME 240 classroom, our team would like to see future ME 450 teams study the impact of our device on students' understanding of engineering dynamics, as well as develop additional devices to address more topics within the ME 240 curriculum.

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Revised Abstract

Implementing experimental systems in a foundational dynamics course could lead to increased student comprehension of the concepts taught within the class. The objective of this project is to develop physical educational devices to be implemented in Mechanical Engineering (ME) 240 that are transportable, durable, and more interactive than current learning methods. These devices will give students a stronger understanding of dynamics concepts that are used in higher level engineering classes and will lead these students to design better products during their engineering careers.

Problem Overview

Our team has been tasked with producing a physical educational device for students in the Mechanical Engineering (ME) 240 classroom due to the current lack of experimental and real-world applications students experience that connect to the theoretical models they are taught. Professor Alex Shorter and Lecturer Jeffrey Koller, the ME 240 professors for the Fall 2023 semester, serve as the mentors for this project. The current method of teaching in ME 240 is purely theoretical, with students learning via lectures or textbook problems that they complete during class or as part of their homework. This theory-driven teaching method has caused some students to struggle to understand and connect the dynamics principles presented in ME 240 to real-world applications, which has ramifications for their future work as engineers, both as students and as employees. Having a strong understanding of the concepts presented in ME 240 is crucial, as this class serves as a foundational course that higher level mechanical engineering courses, such as ME 350, ME 360, and ME 440, build upon. A lack of understanding in ME 240 will cause these students to struggle with these more advanced concepts, and leave them unprepared to graduate. Beyond the mechanical engineering curriculum, having a deeper understanding of system dynamics allows engineers to design more complex systems that can better address the problems they are hired to solve. Without a strong understanding of fundamental dynamics principles, engineers would not be able to produce devices that adequately meet the needs of their clients. The major objective of this project is to ensure that engineering students have a deeper understanding of the abstracted concepts that they learn about in class by creating physical devices that can be used to gain hands-on experience with the systems that students are modeling. Our sponsors want to have multiple systems produced in order to address a wide variety of topics within the ME 240 curriculum. A successful project outcome for our team would be developing one of these devices that will be implemented in ME 240 classrooms to demonstrate the material taught during lectures, and will be used by students to verify the results of the systems they model in class. The designed systems should result in an increase in student comprehension of the material presented in ME 240, leading to higher grades within the class and potentially in more advanced courses which rely on the foundational concepts presented in ME 240.

Benchmarking and Standards

Our team of students is not the first that has attempted to address the lack of experimental demonstrations within the ME 240 curriculum. In a previous semester of ME 450, a group of students was tasked with solving the same problem that our team faces now, and while they were able to produce a physical device, our sponsors stated that this previous solution did not adequately address the problem because of the overly complicated design of the product combined with a lack of student interaction with the device [16]. Our team will aim to amend this issue with our solution to this task.

There are also other existing physical devices used in an educational setting that our team looked to for inspiration, as well as for information about how current demonstrations fail to convey their intended material to students adequately. Other universities, as well as other departments within the University of Michigan, utilize physical demonstrations to convey the concepts presented in their analogous dynamics classes. Our team used these competitor demonstrations as benchmarks for our own project to understand both the strengths and flaws of systems currently in use. This helped our team to design a device that we believe will excel in the areas in which these competitors are failing to meet our stakeholders' needs. A summary of these competing physical demonstrations of kinematics and dynamics principles from other universities, as well as an evaluation of their performance, are summarized in Table 1 below:

Table 1: The benchmarking table for competitor physical engineering education systems. The topic addressed by each demonstration is listed, with an evaluation of how well each demonstration meets the key requirements of our product.

Demonstration	Principle Shown	Ease of Use	Transportability	Student Interactivity
MIT Monkey and a Gun [13]	Particle kinematics	Fair (Easy to run demo but only can run once w/out manual reset)	Poor (Large demo, requires significant time to set up)	Poor (Hard for students to run because of long reset time)
Texas A&M Galileo's Feather and Coin [14]	Gravity in a vacuum chamber	Good (Easy to drop items in a vacuum)	Poor (Large vacuum chamber, difficult to move)	Poor (Expensive vacuum chamber, requires responsible adult to use)
UM Physics Atwood's Machine [15]	Rotational & rigid body kinematics	Good (Easy to drop items in a vacuum)	Poor (Large demo, requires significant time to set up)	Poor (Large setup makes student interaction difficult)
Physics Demo YouTube Channel: Two Carts [16]	Elastic & inelastic collisions	Great (Easy to run demo multiple times)	Fair (Long track may require cart to transport)	Great (Students can easily run demo)
Physics Demo YouTube Channel: Two Spheres [17]	Rotational & rigid body kinematics	Great (Easy to roll objects)	Good (Small items, may require cart to transport)	Good (Students can run demo, although may not be as effective as professor led)
Physics Demo YouTube Channel: Hoberman Sphere [18]	Angular momentum	Great (Easy to spin object)	Great (1 person can carry easily)	Good (Students can run demo, but may be difficult to collect data)

The Massachusetts Institute of Technology uses a demonstration coined “Monkey and a Gun” in their Department of Physics, in which a professor fires a ball from a cannon at the same instant a monkey is released from a pole [14]. This demonstrates how particle kinematic equations can be used to set the cannon angle just right so the ball hits the monkey mid air. Similarly, the Texas Agricultural & Mechanical University employs a vacuum chamber in their “Galileo’s Feather and Coin” demonstration to show how two objects accelerate at the same rate regardless of mass because gravity is the only force acting on the objects [11]. The University of Michigan’s Physics Department teaches rotational kinematics through a demonstration of the classic “Atwood’s Machine” which is commonly found in textbook problems [4][8]. YouTube also offers a number of recordings of physics demonstrations which can be done in a classroom setting. The channel “Physics Demo " has various youtube videos such as “Two Carts”, where two carts on a track are pushed at each other, to explain elastic and inelastic collisions [1][5][17].

As the benchmarking table shows, many of the existing physics demonstrations are not adequately transportable, as they are often too large or include too much equipment for one person to move on their own. Many of these demonstrations are also not interactive for students, as they are either hazardous or too complex, and must be run by a professor. Our team will aim to design devices that amend both of these issues to ensure our final product can be implemented in ME 240 classrooms with student participation as the primary goal. Where competing demonstrations succeed is in their ease of use, so we will also aim to meet this standard in order to ensure that our devices do not fail to achieve what most other demonstrations are capable of.

User Requirements and Engineering Specifications

In order to determine the desired features of the final product we will create, our team contacted the current ME 240 professors, who act as our sponsors and one of our primary stakeholders, for an interview. During our meeting, the professors described the current state of the ME 240 curriculum, as well as a number of attributes that they wished to see our final product exhibit. These desired attributes became the functional requirements for our device [16]. Once we had compiled this list of requirements from our sponsors, our team began researching standards and papers relating to each requirement, and built a list of metrics with which to evaluate the characteristics of the product, creating our engineering specifications. Each specification uses an existing standard or paper to inform the objectives that we intend for our product to achieve, and has been justified within the context of the problem. The full list of functional requirements and engineering specifications is shown in Table 2 on pg. 7:

Table 2: The complete list of the functional requirements and engineering specifications relating to our project. Each requirement is matched with at least one specification, a reference to inform the connected metric, and how the requirement fits within the context of our problem. The requirements are organized in order of importance, with our key requirements listed at the top of the table.

Requirement	Specification	Reference	Design Context
Easy to transport	Lifting index $\leq$ 1.0 Width: 200mm - 500mm Length: 200mm - 500mm Height: 200mm - 500mm	Applications manual for the revised NIOSH lifting equation [2]	Must be able to move the device easily around the UM campus
Easy to use	Ready to demo in < 5 steps AND < 5 minutes Requires $\leq$ 2 tools to change configurations	Scheduling Flexible Flow Shops with Sequence-Dependent Setup Effects [18] ISO 8887 [21]	Must minimize set up time to ensure enough time is provided to conduct the demonstration itself
Capable of tracking	Must be able to track at minimum 1 of the following metrics: time, displacement, velocity, acceleration, or force	Survey of Motion Tracking Methods Based on Inertial Sensors: A Focus on Upper Limb Human Motion [20]	Students must be able to verify data collected from devices using equations taught in class for effective learning
Learning Effectiveness	Students must demonstrate increase of 5% perceived understanding of topic using Likert scale survey	A Review of Key Likert Scale Development Advances: 1995-2019 [23]	Students must have a perceived increased learning for the device to be useful
Durable	Fatigue lifetime $\geq 10^5$ cycles	Fatigue life prediction for power supporting frame of electric-driven seismic vibrator under random load [10] ASTM E1457-19e1 [19]	More cost effective, environmentally friendly, and time efficient to build a long-lasting machine rather than one that needs to be rebuilt annually
Interactive	Students must be able to independently operate device	ISO 9241 [9]	Physical interaction with the product may give students a deeper understanding of the device's physics concepts
Adjustable	Capable of $\geq$ 2 and $\leq$ 10 configurations	Creating Modular Platforms for Strategic Flexibility [6]	Need multiple configurations for a broader understanding of course material, but cannot have so many that the device becomes overly complex
Consistent	Execute models with $\leq$ 3% repeatability error	Typical errors, accuracy classes and currently expected accuracy of inertial measurement units [22]	Device should be able to exhibit ideal physical behavior and accurate tracking in order to demonstrate concurrence with theoretical behavior
Accuracy	Experimental results with $\leq$ 10% of first principle model/simulation results error	Interactive physical experiments in an advanced undergraduate structural dynamics course [24]	The physical device must match what is discussed via the theoretical model in class

As can be seen in the table, all of our functional requirements have been contextualized within the problem and translated into engineering specifications. Each of these specifications has been quantified based either on prior research published in papers or on engineering standards, which will ensure that each metric we will evaluate our product against is reasonable. For example, the professors would like our final product to be easily transported, as any device used in class cannot be left in a lecture hall and must be stored elsewhere. Based on this requirement, our team researched standards relating to the safety of lifting objects in order to determine the limits on the weight of the devices. This is intended to ensure that the devices are safe for the professors to lift, whether it be simply moving the devices from a desk to a cart, or carrying the devices around campus. This research led our team to the NIOSH lifting equation, a method of determining the maximum weight that can be safely lifted based on both the weight of the object and the positions in which the object is carried and moved [2]. This equation specifies that a lifting index larger than 1 can pose a potential risk for low back injuries, so our design will aim to keep our devices' lifting indices below this metric. In order to measure the devices' lifting indices, the team will measure each of the dimensions specified by the NIOSH lifting equation, including the horizontal distance between the object and the body, the vertical distance between the object and the floor when the object is lifted, and the amount of twist needed in the body to lift the object. These measurements can then be used in the given equation to determine the devices' lifting indices.

Our sponsors would also prefer that the devices are durable, and capable of use over a number of semesters. This longer lifetime will reduce the overall cost of the devices, as fewer materials will need to be bought to repair the products within a given time span. This will also reduce any negative environmental impact relating to the manufacturing or disposal of the materials used to build our devices, and minimize the time spent repairing and assembling the devices. In order to determine a metric with which to evaluate the longevity of the product, our team researched papers relating to typical fatigue life cycles of vibrating machines. This research indicated that typical life cycles for vibrating equipment lie somewhere between 10,000 and 10,000,000, so our designs will aim to have an expected lifespan of at least 100,000 cycles in order to surpass the minimum threshold [10]. In order to estimate the lifespan of our products, our team plans to perform a finite element analysis of the structures we produce, which can be used to determine the forces acting within the products and in turn estimate the lifespan of our project through a fatigue life cycle estimation [19].

As previously discussed, many existing demonstrations fail to meet the requirements of easy to transport and student interactivity. Often, demonstrations are either too bulky or too heavy for an individual to transport without the aid of a cart or second person. Demonstrations also tend to be led by instructors rather than students, preventing students from gaining hands-on experience with the physical systems they are modeling. Most demonstrations also do not include the capability to collect any data, opting instead to visually demonstrate dynamics concepts to students. Our team aimed to amend these issues through the development of the final product that we will deliver to our sponsors.

As our project developed, our team expanded upon our initial list of functional requirements and engineering specifications. In addition to our original functional requirements, our team included learning effectiveness and accuracy as characteristics that our device must exhibit. With the intended outcome of this project being to enhance student understanding of concepts presented in the ME 240 curriculum, we felt that it is important to consider how well our device is able to improve the grades of students who use our device as part of their ME 240 classroom experience. We also recognize, however, that this is a characteristic that is difficult to quantify prior to the implementation of the product within the ME 240 curriculum. In order to measure the success of our design in terms of improvement of student comprehension, evaluation of the product will need to be conducted in future semesters of ME 240 while using the product we deliver to our sponsors. We also feel that our device must behave similarly to the theoretical behavior that students model in ME 240, as this will ensure that comparison between analytical and real-world scenarios is possible.

The functional requirements and engineering specifications presented are listed in order of importance, with the most important requirements being listed first. Most important to our team was making sure that our final deliverable can be implemented in a classroom setting. With this in mind, we made ease of transport and ease of use our most important functional requirements. If professors are unable to move our product in and out of a lecture hall, it cannot be used for demonstrations, so ensuring that our device is transportable is key to its implementation. Also important is the product's ease of use, as we intend for students to conduct our demonstrations during a lecture period. If our device is too complex, it will take too much time for students to set up and run the demonstrations during class, and thus our device will not be used in the ME 240 curriculum. Also paramount to our device's success is how effective it is at increasing student understanding of dynamics concepts. It is for this reason that tracking capability and learning effectiveness are the next most important requirements for our product. We intend for students to compare our physical demonstration to the theoretical analysis they are conducting in class, which is not possible without experimental data. In order to collect this data, students will need some method to track the demonstrations they conduct, which is why we have made tracking capability one of our key requirements. Learning effectiveness is also a key consideration, as the ultimate goal of this project is to improve student understanding of dynamics concepts. With this in mind, we would like to see students' grades in ME 240 improve following the implementation of our device. When designing a product, we also want to ensure that it is as harmless as possible, not just to its users but to the environment as well. With this in mind, we ranked durability as one of the more important requirements, as building a product that has a long lifetime will ensure that materials are not being wasted rebuilding or repairing our device.

In addition to the functional requirements of our device, we also needed to be aware of ABET Teaching Standards and how they apply to our problem. ABET is the set of standards that all universities have to follow in order to make sure education at one university is not drastically different from that at another university. ABET accredited programs meet a set of quality requirements and teaching evaluations to ensure students are learning properly. With our devices being implemented in a ABET accredited classroom we must ensure they fit within these standards. Regarding teaching equipment and laboratory demonstrations it specifically calls out that devices must “be available, accessible, and systematically maintained and upgraded to enable students to attain the student outcomes and to support program needs” [7].

Design Process

The design problem our team faced has a wide range of possible solutions as a result of the numerous topics within the ME 240 curriculum that our project could demonstrate, as well as the different methods through which each demonstration could convey the intended topic. With such an open-ended problem, our team decided to address this challenge using a problem-oriented design process, as opposed to a more solution-oriented approach [15]. The design process that we have chosen to utilize closely resembles the mechanical engineering capstone design process introduced to the ME 450 class.

The beginning of this design process included meeting with the ME 240 professors, who act as our sponsors and stakeholders, as well as developing a survey to send to former students of ME 240 to gather their relevant opinions. Once feedback was collected from our sponsors, our team began developing a number of potential solutions to the problem being faced in ME 240. These conceptual designs took the gathered stakeholder feedback into account to ensure that the individuals most impacted by our design will be content with the final product that we produce. While we originally intended to gather student feedback through our survey, time constraints prevented us from sending the survey, and we now plan to collect student feedback through testing of our final deliverables during ME 240 lectures. After developing a number of concepts, our team began to refine this list into a smaller set of solutions that could be presented to our stakeholders, with the intent being to allow the ME 240 professors and students to select the design or designs that they feel will best address the lack of a physical device within the ME 240 classroom. This method of stakeholder concept selection was meant to ensure that our team follows a problem-oriented design process, as we feel that making a decision about our product’s design without user feedback may lead us towards a solution-oriented approach in which we focus on refining a design that we believe would best solve the challenge we face. Following the stakeholder selection of the final design, our team generated a preliminary model for this device, and built and tested a prototype of this design. This testing led to the refinement of our design into a final build design, which our team has prototyped and intends to deliver to our sponsors at the end of the semester. Our team has also conducted engineering analysis and verification testing of this final deliverable to ensure that it meets the requirements given to us by our sponsors. This testing has been largely successful, with our final deliverable meeting the majority of our engineering specifications. The next stage of our design process is to have our product implemented in ME 240 classrooms, where its effectiveness as a dynamics demonstration can be validated. A summary of our team’s design process is shown in Figure 1 on pg. 11:

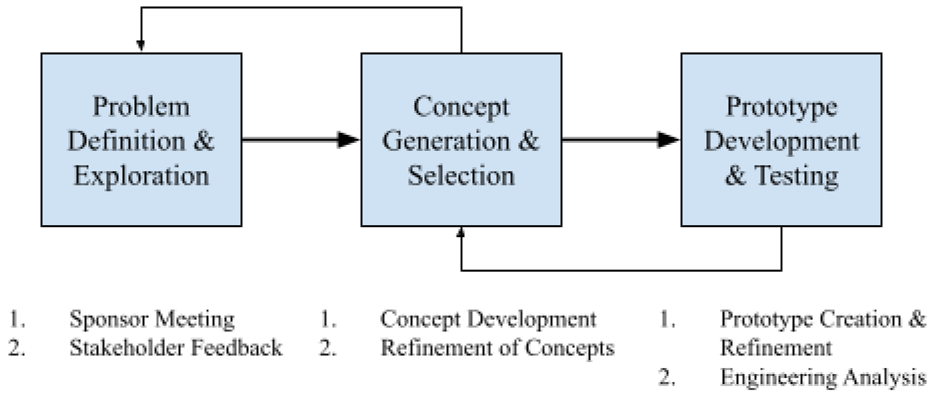


Figure 1: A diagram of our team's design process. Each of these major phases was split into smaller stages, as can be seen in the diagram. Arrows between stages indicate direction of movement, with smaller arrows included to indicate revisions that may be necessary throughout the process.

This design process was intended to closely match the process presented in ME 450, as problem-oriented design processes such as the presented process tend to rely on "logical deduction" rather than prior experience. A focus on analytical thinking rather than accumulated knowledge will be beneficial to engineering students such as ourselves, who may not have had the opportunity to complete significant engineering tasks in the working world, and thus lack the experience necessary to follow a more solution-oriented approach [15].

Stakeholders, the Design Context and Intellectual Property

To ensure that our final product has the most positive impact possible, our team analyzed the groups and individuals impacted by a solution to this problem and what form this impact would take. We also explored how the implementation of this project could affect the environment and society as a whole, the powers at play who can influence the implementation of a solution to the problem, and the property rights associated with our project.

Stakeholder Identification and Impact

The first step our team took to understand the context of our problem was to determine the individuals and groups who have a stake in our project. The individuals most affected by our project, the primary stakeholders, include the students who will take ME 240 in future semesters, and the professors teaching these ME 240 students. Secondary stakeholders, those who will be less directly affected by our final product, include higher level mechanical engineering professors within the department, manufacturers of competing engineering education equipment, and engineering simulation software developers. Tertiary stakeholders, who are far removed from our project but may have some connection to this problem, include the manufacturers of the material that we will use to build our product, customers of future ME 240 students, computer manufacturers, customers of competing educational devices, the Foundational Course Initiative which redesigns foundational courses at the University of Michigan, and the Mechanical Engineering department as a whole.

Once our team had compiled this list of stakeholders, we categorized them into one of six categories based on the type of relationship that they hold with our product. These six categories are resource providers, beneficiaries and consumers, complementary organizations and allies, affected or influential bystanders, supporters and beneficiaries of the status quo, and opponents and problem makers. Resource providers, those who will supply our team with monetary support, knowledge, technology, and other assets, include the ME 240 professors who will provide our team with information about the class's curriculum and current areas of difficulty, and manufacturers of the materials which will be used to create our final product. Beneficiaries and customers, those who will benefit from a solution to the problem at hand, include the future ME 240 students who will have an increased understanding of dynamics as a result of our product, and the customers of these ME 240 students who will purchase equipment that has been improved through this deeper understanding of dynamics. This category may also include the ME 240 professors at the completion of this project, as they may benefit from devices that more easily present dynamics concepts to students. Complementary organizations and allies, those who support our cause and may assist our team in generating a solution to the presented problem, include the professors of higher level mechanical engineering courses who stand to benefit from an increased student understanding of foundational dynamics, and the Foundational Course Initiative, a program at the University of Michigan which redesigns foundational courses, and may help in implementing our final product. The University of Michigan's mechanical engineering department, which may play a role in incorporating our final product into the ME 240 syllabus, acts as an affected or influential bystander, those who have no direct connection to the problem presently but who may influence the success of a solution. Supporters and beneficiaries of the status quo, those who would stand to benefit from the current education methods, include companies producing simulation software that is currently being used to model engineering systems in an educational setting, and the computer manufacturers on which these simulation softwares are run. Opponents and problem makers, those who would oppose our efforts to generate a new educational tool, include manufacturers of competing physical engineering education products, and customers of these competing manufacturers. The stakeholders were further categorized by the design context of the relationship between our product and our stakeholders, including social, economic, and environmental. Stakeholders categorized under the social design context include people or groups whose lives, work, or knowledge will be impacted by our product. Similarly, stakeholders categorized under the economic design context include people whose finances will be impacted by our product, while stakeholders categorized under the environmental design context will impact the environment through their involvement with our project. Finally, each stakeholder's impact was determined to be either positive or negative as it relates to their design context. A summary of these stakeholders and their relationships to our product are presented in the stakeholder map shown in Figure 2 on pg. 13:

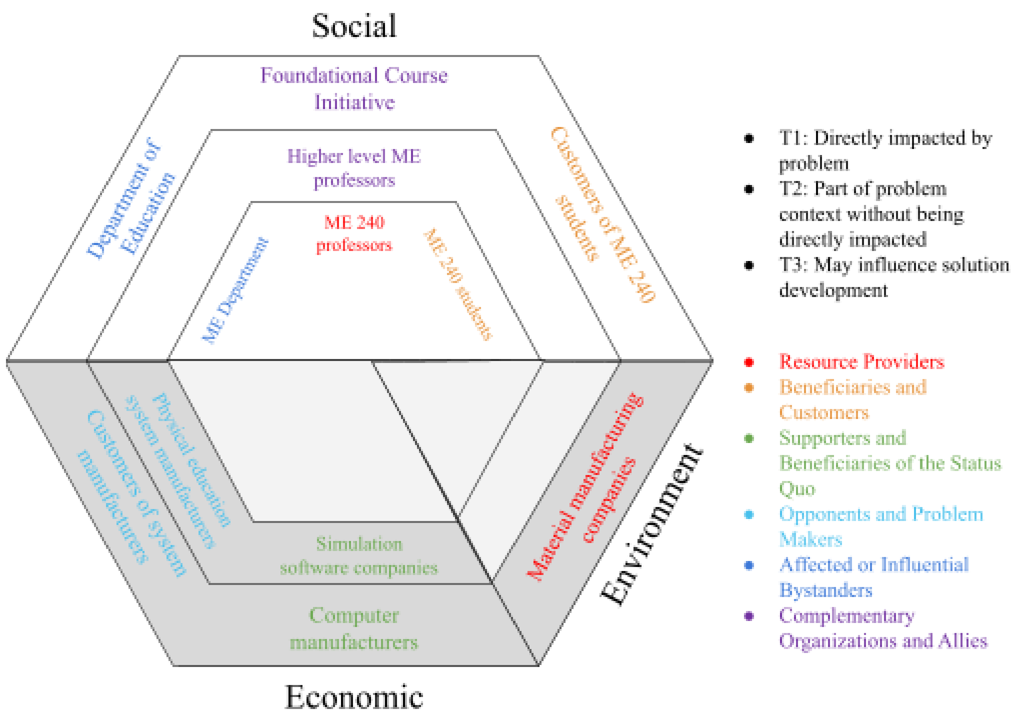


Figure 2: The stakeholder map for individuals, groups, and organizations related to our project. Stakeholders are divided into one of three tiers based on the level of connection they have to this project, as well as one of six categories based on the nature of this connection. Stakeholders affected positively by this project are highlighted in white, while stakeholders affected negatively are highlighted in gray.

The stakeholders most positively impacted by our project are the future ME 240 students. This project is intended specifically to improve student understanding of the concepts learned in ME 240, which in the short term will improve their grades within the ME 240 class. More broadly, students should also see an increase in their understanding of more advanced engineering concepts, as ME 240 acts as a foundational course for many of the subjects that students will branch out into over the course of their education at the University of Michigan. This may also help them when they enter the workforce, as having a more in-depth understanding of engineering concepts will make graduates more appealing candidates to their potential employers. While the project is primarily focused on helping students, it will also help the professors of ME 240. This project will make teaching the concepts presented in ME 240 easier to understand, giving professors more time to focus on topics that students struggle with and improve their understanding of topics outside of the scope of this project. Other stakeholders who may benefit from the production and implementation of this product may be higher level mechanical engineering professors who may find it easier to teach students who have a stronger understanding of foundational concepts, customers of future ME 240 students who may purchase products designed with a better understanding of dynamics, and material manufacturers who may profit from our use of their materials in the product our team designs. Successfully implementing our product within the ME 240 curriculum may also lead to more physical devices being developed for higher level classes such as ME 360 and ME 440, which in turn would increase student understanding of the material presented in these advanced courses.

Stakeholders who might be affected negatively by implementing our product include manufacturers of competing engineering education equipment, engineering simulation software developers, computer manufacturers, and customers of competing engineering education equipment. Each of these stakeholders could potentially see a decrease in business if our product is successful enough to push the university's engineering department, and possibly other colleges, to develop physical engineering education devices like our product. We also expect the material manufacturing companies involved with making the products necessary to create our final deliverable to negatively impact the environment through the gathering of raw material and pollution. This stakeholder analysis provides a deeper understanding of who our design impacts and who impacts our design, which allowed the team to make more conscious design decisions. Understanding both the positive and negative impacts our product will have on various stakeholders and the world as a whole allowed the team to make more conscious design decisions that improved the performance of our final product.

Social Context

Beyond the ME 240 classroom, a lack of understanding of dynamic systems may lead engineers to design products that do not achieve their goals or cannot address problems adequately, which in turn may lead to social or societal issues going unaddressed or unsolved. Ensuring that engineering students have a strong understanding of the principles presented in ME 240 will ensure that these future engineers are able to design products that make significant headway towards addressing the problems faced by our society, which in turn will improve the lives of those beyond engineering students. In the context of this problem, our sponsors likely rank societal impact lower than education in terms of the importance of the outcomes of this project. Our sponsors, Professor Alex Shorter and Lecturer Jeffrey Koller, are primarily concerned with improving mechanical engineering students' understanding of dynamic systems. While this will impact how engineering students are able to apply this knowledge to the products they design, and thus how they affect society as a whole, this societal impact is too far removed from the current scope of this problem to be considered by our sponsors. This educational priority is likely to affect the design of our final product. In order to best educate the users of our device, we will need to design our product for ease of use and robustness, instead of designing with the intention of guiding engineering students to design their own products with societal impacts in mind. While this educational focus may not have a direct negative social impact, our product may not achieve the full societal benefit that it would be capable of if it were designed to have a greater social impact. Despite this, educating engineering students on dynamic systems is likely to have a positive impact on their ability to analyze and design real-world systems, which in turn will benefit society as a whole [12].

Sustainability

The sustainability of our design was heavily influenced by the manufacturing of our device, specifically by the materials we used to create our final product. We had initially planned to use milled or lathed aluminum or steel as the main material of our device, both of which are finite resources which produce significant amounts of pollutants [13]. In order to mitigate the negative environmental impact of our product, and make the manufacturing of our device simpler, our team changed both the material and manufacturing process for the most significant parts of our final design. We elected to use acrylic rather than sheet metal when manufacturing the larger parts of our final design, and while plastics tend to be more difficult to recycle than metal and still create some pollution during production, they tend to be more resistant to chemical weathering like rust, and can be more beneficial to the environment than some single-use glasses and metals. Our team also considered the forces acting on our final device to ensure that our product will not break under normal operations, meaning that recycling the material used for our product will not play a significant role in polluting the environment due to our final deliverable's long expected life cycle. Our team also chose to laser cut our acrylic parts rather than machine these parts for our final product, which will produce less material waste than more traditional machining methods. Processes like milling, lathing, or computer numerical controlled machining tend to produce a significant amount of waste material, so our team avoided these sustainability losses by buying parts that were already manufactured according to our design. Beyond the manufacturing of our product, the use of our project is unlikely to have a significant impact on its sustainability. However, we limited the use of motors and electronic components in our design in favor of using human interaction to ensure that excess electricity isn't wasted by our product. This will also ensure that more of our product can be recycled when failure does occur, as recycling electronic components is a lengthy and complex process [3]. We did include smaller metal parts in our product, and while the manufacturing of these parts may have been environmentally detrimental, these parts will be recyclable and thus more sustainable at the end of their life. While using metal made the upfront cost of the device more expensive, in the long run the reduced number of necessary replacement parts will offset the initial materials cost.

Ethical Concerns

A significant ethical dilemma relating to the design of our project is the impact it will have on students who struggle with standard teaching methods. Neurodivergent students, such as those with ADHD, dyslexia, or autism, often learn differently and require different teaching methods than other students. A device that is designed to improve the understanding of the majority of students may overlook a minority of students who are struggling the most. We want our project to improve the understanding of all students, and to ensure that this is achieved we intend to contact ME 240 students following the implementation of our final product to evaluate whether it is beneficial to all students or just a select group. We also recognize that a single device is unlikely to meet the needs of every ME 240 student, which is why we would encourage future ME 450 students to develop additional devices to address more of the ME 240 curriculum. As engineering students at the University of Michigan, we are expected to abide by both the university's Code of Conduct and the College of Engineering's Honor Code. These codes require that we must submit only original work, or credit others when their work is referenced. We must also ensure the safety of the public who will come into contact with our work. As a team, our personal ethics are similar to those of the University of Michigan, as we will submit only the work that we have produced as part of this project, along with references to the works of others which our project builds upon. We also have produced a final design that is safe both environmentally and in use to ensure that our work is only beneficial to its users and society as a whole. Beyond the university's standards of ethics, to meet the standards of our personal ethics, we believe we have designed a product that will help those who struggle the most with the concepts presented in ME 240, rather than simply the vast majority of students who do not have such difficulties. This may differ from our future employers, who may only consider the benefit of the products that we as engineers design for their customers, rather than the impact these products may have on more marginalized groups or broader audiences.

Visible, Invisible, and Hidden Powers

A number of different power dynamics have shaped the design of our final product. Our team had power over both the project sponsor and the end users of our product in that we decided how often to interact with these stakeholders, as well as how much we employed their advice or desires in the design of our product. While our project sponsors had some power over our team in terms of what information we were given in order to solve the problem, our end users had little control over the design of our product naturally. In order to give power back to our end users, our team intends to create an invited space for ME 240 students to comment on the benefits and drawbacks of using our device once it is implemented in the classroom, as well as to inform future ME 450 teams about which topics they believe would most benefit from a physical educational device, and what form that device should take. These power dynamics are both forms of visible power. The design choices we made, however, may have more invisible power over our stakeholders. If we were unable to design a product that takes into account marginalized groups like neurodivergent students, it may subtly reinforce the idea that the needs of neurodivergent students are not as important as those of the larger student body, which is why we will ensure that minority groups are given a voice in the evaluation of our product, as well as the design of any future devices. There were also power dynamics between our team's members. Each of our backgrounds informed how experienced we are with certain aspects of the design process, and this played a significant role in which group members were deferred to for specific stages of the development of our product. While we were wary of these dynamics within our team, we also leveraged these to our advantage by utilizing each individual's expertise within the design process to create the best possible product for our end users. The strategy that our team employed in order to address inclusivity problems that we were not able to initially identify was to keep consistent contact with some of our most important stakeholders. Our team wanted to ensure that the people who will be impacted by our product had a say in its design throughout its development, as we felt that this would lead to a device that best fits our stakeholders' needs. This would ensure that any inclusivity issues that arise in the middle of the design process will not go unaddressed, and our end users would receive a product that they are happy with.

Intellectual Property

Intellectual property did not play a significant role in this project. Our team did not need to rely on any existing devices while designing our product, and thus has designed a wholly original product to educate engineering students on dynamic systems. Intellectual property protections did limit the designs our project was allowed to take on, as we did not want to mimic other educational devices with our design in case these competitor devices were protected by intellectual property rights. This means, however, that the product we present to our sponsors will be entirely our own work, and therefore the design may be protected by intellectual property rights of our own.. Our team has not been asked to waive our intellectual property rights for this project, nor are we required to sign a non-disclosure agreement, making the individuals composing this team the owners of any intellectual property that will be created in our project.

Sources of Information

In order to gather information regarding the standards relating to our engineering specifications, as well as prior solutions and currently implemented educational devices, our team met with the engineering department's librarian, Ms. Sarah Barbrow. During this meeting, our team discussed the search engines and methods that would be best for gathering this information. We also discussed the sources of information that would be most applicable to our project, as well as how patents may apply to our final product. Our team found that the best approach for gathering information was to utilize databases to search for standards and papers relating to each of the specifications of our product, then compare different articles to determine a consensus on what metrics our device should be able to meet. Where our team struggled was in gathering information about the competing educational devices that are currently available. We wanted to ensure that the product we designed was not derivative of another educational tool, especially if that tool was protected by intellectual property rights or a patent. We found, however, that many of the educational devices used as demonstrations are not usually patented, and thus it was not clear which devices were protected and which could be replicated. Our team worked around this lack of information by designing a unique device, as far as our research indicates.

Concept Generation

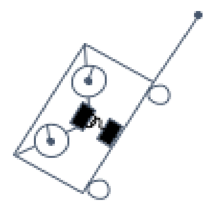
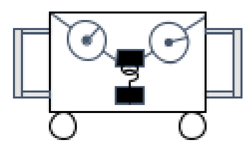
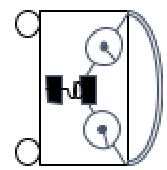
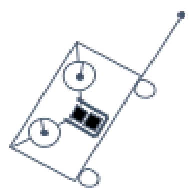
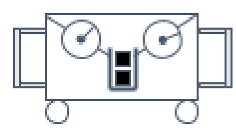
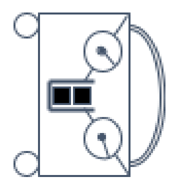
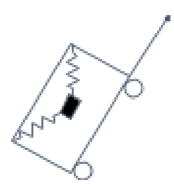
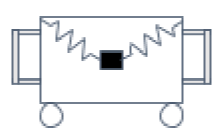
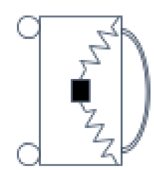
To begin to develop a final product to implement in ME 240, our team began generating potential concepts that could be used to demonstrate dynamics principles. Our concept generation process began by designing various solutions to our given problem as individuals. Each member of the team spent time coming up with a list of potential concepts that could be used to demonstrate various topics within the ME 240 curriculum. In starting our concept generation process individually, our team hoped to encourage each member to come up with unconventional designs to the problem we are tasked with solving. Working on our own would protect each member from any scrutiny or perceived judgment from other members of the team, allowing them the freedom to explore more unique and potentially unorthodox ideas. We also wanted to give each member enough time to come up with a large number of ideas to ensure that we did not fixate on a single topic, and could bring a variety of designs to discuss as a group. This would also give individuals time to create drawings of each idea they came up with, which we felt would be the best way to convey the concepts that we had generated. Within this individual concept generation phase, each member used a morphological chart to further develop the initial ideas they created. While morphological charts are typically used to address various subfunctions of a concept, it was difficult to decompose this project into subfunctions due to the unrestricted nature of the problem we were tasked with solving. While we are required to present a physical device at the end of the semester, our sponsors largely left any decisions regarding the functions of our final product up to our team. Without having any specific topics chosen to demonstrate, it was challenging to outline general subfunctions of the product that our sponsors would like us to create. Instead, each member of the team used the morphological chart to address different requirements that our sponsors would like our final product to meet. In using morphological charts, our team hoped to generate designs that were capable of meeting all of the functional requirements that the team set for the project, and thus could theoretically be used to address the given problem. An example of one of these morphological charts is shown in Table 3 below:

Table 3: A morphological chart used to develop the initial concepts generated by the team. Functional requirements of the device are presented on the left, with potential designs to address each requirement shown on the right.

Functions	Option A	Option B	Option C	Option D
Carrying Mechanism	Handles	Wheels	Straps	
Easy to Use	Few Components	Automated	Limited Enclosures	
Material Durability	Metal	Plastic	F Small Forces	Few Mechanical Parts
Adjustable Parameters	Differing Springs	Attachable Mass	Nesting Mass	

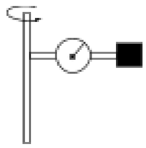
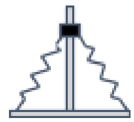
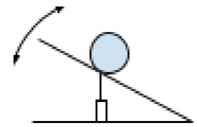
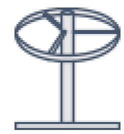
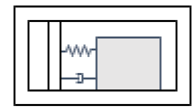
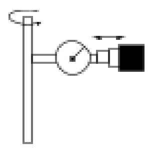
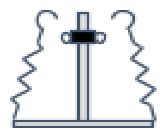
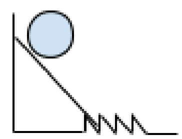
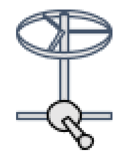
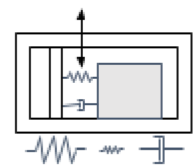
As can be seen in the morphological chart, some of the most important functional requirements of this project were considered when generating concepts for this project. These morphological charts describing different methods of meeting our sponsors' functional requirements were used to improve upon the initial concepts that were generated by each member of the team. One of the designs from each category in the morphological chart was added to the initial concepts, generating a number of designs that did not vary in terms of the conveyed concept, but instead in terms of the functionality of the devices. One of the concepts that was expanded upon through the use of the morphological chart is shown in Table 4 below:

Table 4: Variations of a "mass in a moving box" concept using a morphological chart. Each concept in this table shows the basic "mass in a moving box concept", but utilizes different methods of addressing the transportability and adjustability requirements that were generated using the morphological chart shown in Table 3 on pg. 18.

		Transportability		
		Wheels	**Handles**	**Straps**
Adjustability	**Attachable Mass**			
	Stackable Mass			
	Springs			

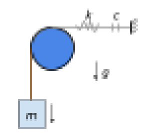
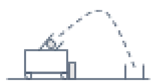
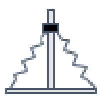
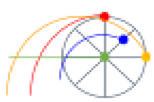
Following the individual concept generation phase, our team reconvened to present the concepts we had generated to each other. The goal of doing this was to have members of the team expand upon the ideas that others had generated, and in doing so foster more unique solutions that the team was unable to come up with individually. Our team wanted to ensure that various backgrounds and experiences were taken into consideration with each of the designs, as our product is intended to be used by a vast audience of different engineers, rather than a single individual. We also wanted to step away from any fixation that might have occurred during the individual generation phase by exposing each team member to different concepts generated by different lines of thinking. To further develop the designs generated by individual members, the team focused on utilizing design heuristics as a group. This was intended to expand upon the ideas individuals were able to generate into more unique solutions to the problem at hand. Some of the design heuristics used are shown in Table 5 on pg. 20:

Table 5: Design heuristics used to develop concepts within the team concept generation phase of our design process. The original and developed concepts are shown, along with the design heuristic categories used to adapt the original designs.

Original Concept	 1a. Mass on a force gauge	 2a. Spring acceleration demonstration	 3a. Adjustable ramp	 4a. Adjustable flywheel	 5a. Shock absorber in a box
Design Heuristic Used	Telescope	Make components detachable	Substitute way of achieving function	Incorporate user input	Allow user to rearrange
New Concept	 1b. Telescoping mass on a force gauge	 2b.Adjustable spring acceleration demonstration	 3b. Adjustable sawtooth ramp	 4b. Hand-operated flywheel	 5b. Adjustable shock absorber

These two phases of concept development led to a significant number of potential designs, many of which were very unique from each other. Five of the most unique concepts are shown in Table 6 on pg. 21, while a full set of the concepts generated by our team are shown in Appendix A, Table A1 on pg. 67:

Table 6: The five most unique designs generated by our team. Designs are shown alongside their description, as well as the concepts within the ME 240 curriculum they are meant to demonstrate and the functional requirements they meet.

ME 240 Concept	Design Illustration	Concepts Demonstrated	Requirements Met
Mass-Spring-Damper System	 1. Controlled Pulley	• Second Order Systems • Spring and Damper Forces	• Durable • Easy to Use
Collisions	 2. Cart Cannon	• Conservation of Momentum • Elastic and Inelastic Collisions	• Interactive
Pendulum/Mass -Spring System	 3. Spring Accelerator	• Spring Energy • Conservation of Energy	• Easy to Use • Interactive
Wheel Motion & Friction	 4. Wheel Tracker	• Wheel Position • Wheel Velocity	• Durable • Easy to Use • Interactive
Rotational Inertia	 5. Hoberman Sphere	• Conservation of Angular Momentum	• Easy to Transport • Easy to Use • Adjustable

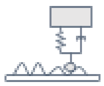
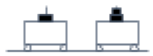
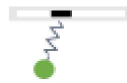
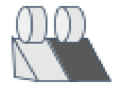
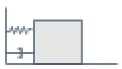
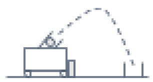
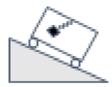
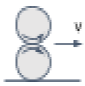
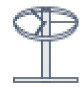
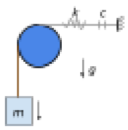
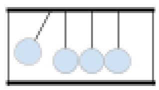
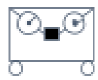
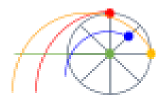
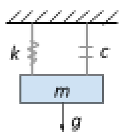
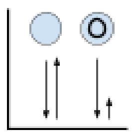
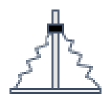
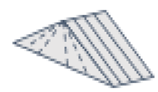
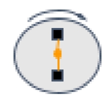
Each of these concepts are the basic designs that were generated by individual members of the team during the first phase of the concept generation process. The first three designs were generated by examining the typical problems that students examine and solve within the ME 240 curriculum, while the remaining designs were generated using inspiration from other existing dynamics demonstrations. As can be seen, the concepts generated throughout this phase of the design process varied wildly, both in terms of the topic within the ME 240 curriculum that they aimed to address, and the methods in which each device intended to convey that topic. The controlled pulley concept is intended to address both string tension and mass-spring damper systems. It is largely meant to replicate one of the typical textbook problems that students will solve during their time in ME 240, and thus can be used to compare the theoretical behavior of this system to its actual characteristics. The cart cannon, on the other hand, is meant to address collisions and particle trajectory. While this does not come directly from the textbook problems solved in class, it does draw upon multiple topics within the curriculum to complete the demonstration. The spring accelerator is meant to demonstrate principles of energy, both its different forms and its conservation. Like the controlled pulley, this demonstration draws on one of the textbook problems students are expected to solve, and can be compared to this ideal behavior. The wheel tracker, on the other hand, does not come from textbook problems, but instead draws inspiration from other dynamics demonstrations, as well as one of the more conceptual topics presented in ME 240. The intent of this demonstration is to showcase how the velocity of points on a wheel vary with respect to position relative to the ground and the wheel itself. This is a topic that tends to be presented in a more conceptual manner within the ME 240 curriculum, so the goal of this topic is to connect these dynamics principles to a real world example. Similarly, the Hoberman sphere demonstration is intended to demonstrate a more theoretical concept of angular momentum conservation. This design also draws from existing dynamics demonstrations, and is intended to present this concept in a visual setting to enhance student understanding. While these concepts generally address the issue of a lack of student interaction in the ME 240 classroom in similar ways, it is clear that these demonstrations are distinct from each other in terms of what they are intended to convey to the students.

Once our team had presented each of the concepts that we were able to generate, and expanded upon those that required more development, we moved on to organizing each of these concepts, which was the first stage in selecting our final concept for this project.

Concept Selection

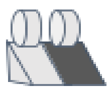
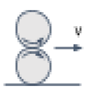
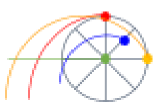
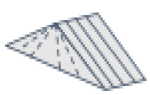
In order to organize our concepts, our team began by classifying each potential design based on the topic within the ME 240 curriculum that the design was meant to address. These topics included: Mass-Spring-Damper Systems, Collisions Demonstrations, Pendulum & Mass-Spring Systems, Wheel Motion & Friction Demonstrations, and Rotational Inertia Demonstrations. The concepts were then sorted into one of the five categories based on the topic they addressed, an abbreviation of which is shown in Table 7 on pg. 23, with the full list shown in Appendix A, Table A1 on pg. 67:

Table 7: The five categories of the ME 240 curriculum into which all of our team's designs were sorted. An abbreviated list of designs within each category is shown.

Mass-Spring-Damper System	Collisions	Pendulum/Mass-Spring System	Wheel Motion & Friction	Rotational Inertia
 Road Simulation	 Cart Collisions	 Pendulum Track	 Friction Ramp	 Hoberman Sphere
 Sideways Shock Absorber	 Cart Cannon	 Pendulum Cart	 Linked Wheels	 Adjustable Flywheel
 Controlled Pulley	 Newton's Cradle	 Tension Cart	 Wheel Tracker	 Parallel Axis Proof
 Hanging Mass	 Elastic vs. Inelastic	 Spring Accelerator	 Variable Ramp	 Rotating Mass on String

Once our concepts were categorized, our team developed a method of evaluating each potential design against the others. We chose to weigh five of the factors that would influence the design of our project based on how they would impact our final product. These five factors included: ease of use, effectiveness, transportability, cost, and assembly and manufacturability. We felt that ease of use and effectiveness were most important to our design, as these are the characteristics that will impact how well our final product is able to convey dynamics principles to ME 240 students. The impact of these categories on our primary stakeholders is the reason they were weighted highly at a 5. The next most important characteristics of our device are transportability and cost. These are two categories that will need to be taken into consideration when designing our final product, and while they may not directly impact our stakeholders, they will constrain the designs we consider; thus, these categories were given a weight of 3. Lastly, the assembly and manufacturability category was given a weight of 2 as this characteristic largely impacts how easy it will be for our team to create the design we settle on. While this may affect the completeness of our device by the end of the semester, it will not be as important to the overall success of the device, resulting in a lower weight than the other categories. Once we weighed each category, all of the generated concepts were scored based on how well they met each characteristic. The score the designs received in each category was multiplied by the weight of the category, and the sum of these products was taken as the total score of each design. These total scores were then compared within each of the ME 240 curriculum categories to determine the best design concept for each topic. An example of the comparisons within one of these curriculum categories is shown in Table 8 on pg. 24:

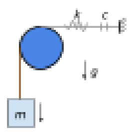
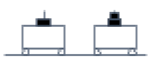
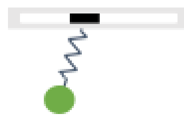
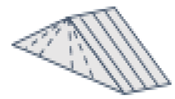
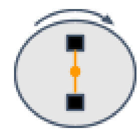
Table 8: A comparison of each of the designs within the wheel motion & friction curriculum category. The score each design received for each requirement category is listed, as well as the total score each design received. The variable ramp received the highest total score, which is distinguished within the table.

Wheel Motion & Friction	Ease of Use (5)	Effectiveness (5)	Transportability (3)	Cost (3)	Assembly & Manufacturability (2)	Total
 Friction Ramp	5	1	5	5	5	70
 Linked Wheels	5	3	3	5	2	68
 Wheel Tracker	5	3	4	5	5	77
 Variable Ramp	5	3	5	5	5	**80**

As can be seen in the comparison table, these designs all scored similarly in the ease of use and cost categories. Our team felt that all of these designs could be created in such a way that it would be possible for the user to take one or two simple actions to operate the device, satisfying the ease of use requirement from Table 2 on pg. 7. The simplicity of these devices also led us to believe that it would be fairly cheap to produce these designs, as none of them require expensive equipment such as motors or a computer, leading to a high cost score. In terms of the transportability of these designs, the variable and friction ramps scored the highest due to the fact that these are very simple designs and could be made fairly small to allow users to carry them in their hands. The wheel tracker ranked slightly lower as bike wheels, the intended frame of this design, are large and slightly bulky though still lightweight enough for one person to carry. The linked wheels demonstration ranked the lowest in this category as the team felt that a frame of some sort would be needed to support the wheels, making this a heavier and bulkier design than the others in this category. All of the designs ranked highly in the assembly and manufacturability category due to their simplicity, with the exception of the linked wheels demonstration, whose score was lower due to the need for larger framing to support the wheels. Finally, for the effectiveness category, we felt that none of these designs would be ideal for presenting their intended topics, as there is no immediate method of data comparison involved in the demonstrations. This resulted in all of these concepts ranking lower in the effectiveness category. The friction ramp ranked especially low in this category due to the typically nonlinear behavior of friction, which we felt would make it difficult to convey ideal friction behavior to this foundational dynamics course. The results of these rankings led to the variable ramp being determined the best design to present wheel motion to ME 240 students, which will be discussed in more detail later in this report.

This design comparison process was conducted for each potential topic within the ME 240 curriculum, allowing the team to determine the best designs for each principle based on the highest score. The results of this comparison are shown below in Table 9:

Table 9: The highest scoring designs for each topic within the ME 240 curriculum. The total score each design received is listed alongside its description.

Mass-Spring-Damper System	Collisions	Pendulum/Mass-Spring System	Wheel Motion & Friction	Rotational Inertia
 Controlled Pulley (51)	 Cart Collisions (72)	 Pendulum Track (75)	 Variable Ramp (80)	 Rotating Mass on String (72)

As can be seen, design scores varied significantly between different categories, with the mass-spring-damper demonstration scoring the lowest and the wheel motion and friction design scoring the highest. While these designs scored the highest in each of their respective categories, the team compared the benefits and drawbacks of each of these designs to determine which design would be best to pursue as our final product.

The Controlled Pulley's best characteristics are its ease of use and its transportability, in which the design scored a 3 in both categories. The team believed that this design can be mostly automated, leaving the user with minimal inputs to operate the device properly. Additionally, this device can be designed to be well contained and relatively small, helping the user to be able to easily transport the device. The team does expect the design to be a bit heavy due to the automation just mentioned, which is why the transportability score is lowered. This design consists of a straightforward path of operation, with a force being exerted next to a spring and damper, having a result on a pulley and mass. Because of this, and the relatively few parts involved, the assembly and manufacturing score was rated as a 3. Finally, for the remaining categories of effectiveness and cost, a ranking of 3 and 2 were given. The team felt that since the system may be heavily automated with little user input, then there may not be much student interactiveness. The demonstrated concepts in the curriculum may be easy to see, but the lack of interactiveness with students drags the design down. Additionally, because of the heavy mechatronic influence, the cost will be higher with this design than what will be discussed in the future, leaving with this design as a 2.

The Cart Collisions's best features are its ease of use and its cost, which scored this design a 5 in both categories. There is very little setup required for this design, as well as very few components, making it fairly simple for a user to test the collision behavior of the two carts. This simplicity of its design will also keep the cost of this design low, as complex and expensive equipment like motors are not required. This design also scored fairly high in the assembly and manufacturability category, receiving a 4, as the simplicity of the design will require very little machining. The only difficulty our team perceives in the manufacturing of this design would be the rail system, as machining long parts may pose a challenge. In effectiveness and transportability, this design scored a 3. We felt that this design would do a decent job conveying the idea of energy conservation during collisions; though this may be difficult to convey without an accompanying simulation, resulting in an average effectiveness score. We also felt that this design would not be too cumbersome to transport, though the length of the track used in this demonstration would heavily influence a user's ability to carry it by hand, making it somewhat more difficult to move this design.

The pendulum track demonstration scored highly in most categories, earning a 5 in ease of use, transportability, cost, and assembly and manufacturability. We felt that we could easily put together a swinging pendulum guided by rails, and that this design was simple enough to be run with little human input. We also felt that this design could be made fairly portable depending on the size of the final product, and with a lack of complex mechanical parts like motors, the cost of the device could also be kept fairly low. Where this design did not score highly is in the effectiveness category, earning only a 2. Our team felt that this design would need to rely heavily on a simulation component in order to convey the intended material, as there is very little visual comparison that could be made with this device; the lack of human interactiveness mentioned above does not help the score either. Additionally, measurements of the angles and speed of the pendulum would need to be taken, which would then require some sort of simulation to show the behavior of the device relative to its theoretical results.

The variable ramp demonstration also scored highly in most categories, earning a 5 in the same categories as the pendulum track design. This design should prove very simple to set up, and the user should only need to place objects on the ramp as part of the demonstration, making this a very easy device to use. This device should also be very easy to transport, as it could potentially be folded up and flattened for a user to carry by hand. The simplicity of the device, as well as the lack of any motors or complex machinery, ensures that this will be a very cheap design to produce, as well as fairly simple to manufacture and assemble. This design does improve in the effectiveness category, however, scoring a 3. While this design would likely still be aided by the use of an accompanying simulation, our team feels that it would be possible to convey some dynamics principles with this device without the use of data collection, such as differences in moments of inertia. This possibility for pure physical demonstration is why our team ranked the effectiveness of this design higher than the pendulum track demonstration.

The rotating mass on a string scored similarly to the pendulum track demonstration, earning a 5 in ease of use, cost, and assembly and manufacturability. This design is intended to only require the user to pull a string to change the angular momentum of the device, and with very little required to set up the demonstration, this device should be very easy for students to use. The device also does not have many parts, leading to a low cost and easy manufacturability. This design scored slightly lower in transportability, earning a 4. We felt that this design would likely be bulky or heavy, and thus might be somewhat difficult for one person to transport by hand. Where this design struggled was in the effectiveness category. We felt that, without the use of tracking software, it would be difficult to convey precisely how rotational inertia changes as a result of mass positioning, which would decrease the effectiveness of this design.

The results of this concept selection process led our team to pursue the variable ramp design. We felt that this device could be designed to be easily transported, possibly by folding the design to be carried under arm or through the addition of a handle. This design could also be manufactured to be very lightweight, which would ensure that this device does not exceed the safe NIOSH lifting metric. With few moving parts and only small forces involved in its operation, this device would likely last multiple semesters, and would be unlikely to reach the endurance limit required for fracture to occur. The simplicity of the device would ensure that it will be easy to use, and should be capable of setting up within 5 minutes and potentially without the use of any tools. This device was intended to be adjustable with different ramp angles, and could be used for multiple demonstrations, which meets the adjustable functional requirement. The device's simplicity would also ensure that students could use this device without instructor aid. While the initial design did not require a tracking component to demonstrate the intended material, it would be possible to integrate such a component into the activities. Finally, the accuracy and consistency of this design would be adjusted as the prototype was developed in order to ensure that our device was meeting our engineering specifications.

The final design we settled on varied significantly from the first concepts our team designed in the concept generation process. Five of these early-stage concepts are shown below in Figure 3:

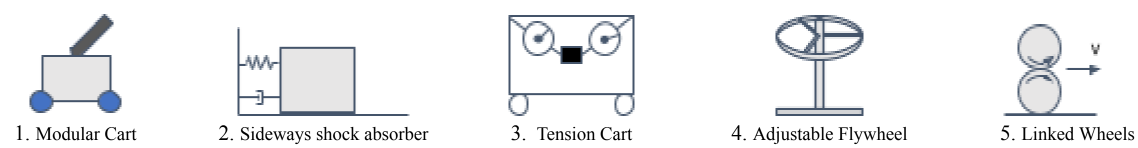


Figure 3: Five of the first designs developed as part of the concept generation process.

The first of these designs is the modular cart demonstration. This design was intended to cover multiple concepts within the ME 240 curriculum, such as rigid body kinematics or conservation of energy and inertia. The second of these designs is the shock absorber, which was intended to demonstrate vibrational dynamics through the use of a mass-spring-damper system. The third design is the tension cart, intended to show how forces are distributed within a suspension system in a moving object. The fourth demonstration is the adjustable flywheel, which would showcase conservation of angular momentum through a variable flywheel radius, changing the angular speed of the device. Finally, the fifth design is the linked wheels demonstration, which would show the behavior of wheels which roll without slipping.

As can be seen, none of these early designs resemble the variable ramp design that our team chose to pursue. Through our concept selection process, these designs that had initially seemed like viable demonstrations to our team members were determined to be unsatisfactory for solving the challenge of implementing a physical system in the ME 240 curriculum. Our team's selection process ensured that we did not fixate on our initial solutions to this design problem and instead focused on finding the demonstration that would best convey dynamics principles to engineering students.

Alpha Design

For our alpha design, our team chose to pursue the variable ramp demonstration, as this design had the highest overall score of any of our generated concepts. A diagram of our alpha design is shown in Figure 4 below:

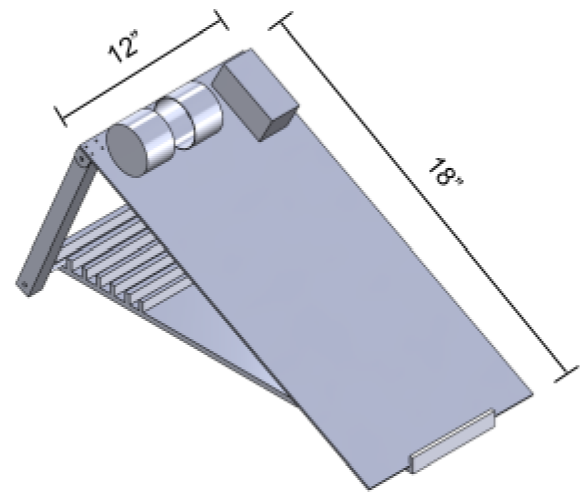


Figure 4: Isometric view of the alpha design of the variable ramp CAD model.

The roll surface of the alpha ramp was 12” by 18” with an incline range of 22° to 33°, which could be extended with additions to the base. This design also included three different types of objects to study: a hollow hoop, a solid cylinder, and a solid box. We chose these objects due to their occurrence in many dynamics problems as well as their common moments of inertia. The inclusion of multiple objects with the variable ramp was intended to make our final product more robust and interactive, as the major objective of this project is to deepen students’ understanding of dynamics concepts as much as possible. This design incorporated a number of different dynamics principles, such as rolling without slip, moments of inertia, and differences between static and kinetic coefficients of friction. We also believed that this design would be capable of satisfying each of our functional requirements, such as transportability due to the design’s ability to fold flat, and ease of use with setup only requiring the placement of the ramp’s legs within the supporting baseplate’s ribs. These initial beliefs would later be proven incorrect through prototyping, which is discussed later in this report. Our initial plan was to manufacture this device using aluminum stock to create the ramp and the legs, and 3D printed material to create the baseplate, though this was subject to change as our prototype developed. This initial design required about 10 fasteners, which were planned to be standardized in order to simplify any potential repairs. We also planned to include methods to track the demonstration, such as using stopwatches, inertial measurement units (IMUs), and video cameras to document the time, speed, and position of objects on the ramp. Data from these tracking devices would have been used by students to compare the demonstrations to the ideal behavior calculated in the ME 240 classroom. Figures B1 and B2 on pg. 70 and 71 in Appendix B show two example models that students could derive in class to validate the demonstration's behavior.

This alpha design was selected with approval from our sponsors, the ME 240 professors; however, this consent did not unfairly influence this choice. Our team had already evaluated all of our generated concepts prior to seeking approval from our sponsors and only presented concepts that would best meet the requirements of this challenge. Our sponsors did not insist on this design and communicated to our team that any of the designs we presented to them would be satisfactory demonstrations in the ME 240 curriculum. This impartiality as to our final chosen concept ensures that this design was not selected due to heavy sponsor influence and will be the best demonstration to implement in the ME 240 curriculum. Although the initial design was simplistic, through prototyping and engineering analysis, our team refined our design to ensure that our product would perform adequately and meet the requirements of this project.

Build Design

In order to further validate the success of our product in meeting the requirements of our sponsors, our team constructed a prototype of our alpha design. This alpha prototype is shown below in Figure 5:

Figure 5: The alpha prototype of the variable ramp.

The purpose of this prototype was to determine whether our initial design was robust enough to meet the specifications our team created to evaluate our final product. With the goal of evaluating our initial design in mind, our team ran experiments using the prototype we constructed, and collected both quantitative and qualitative information about its performance. Our team first conducted an analysis of the accuracy and repeatability of our alpha prototype by recording objects rolling down the ramp while simultaneously measuring the amount of time needed for the objects to roll down the ramp. The time rolling for the objects was then compared to their theoretical behavior using concepts learned through the ME 240 curriculum. Our team found that the roll times of these objects were fairly repeatable, generating similar results for each roll, and were accurate to the expected roll time based on theory. During this testing, however, we also found that our device struggled to meet more qualitative metrics, which we felt would need to be refined through a second iteration of our build design. The qualities which our design failed to exhibit and our planned changes based on the results of our alpha prototype's evaluation are shown below in Table 10:

Table 10: The areas of improvement identified in initial testing of the alpha prototype. Planned design changes are listed alongside the reasons improvement is needed for each functional requirement.

Requirement	Ability to Meet Specification	Feedback	Design Change
Transportability	Fair	• Large base makes ramp awkward to carry, especially for smaller people • Hinge location prevents ramp for folding flat	1) Amend design so it can fold to 0° 2) Add carrying handle 3) Design way to secure loose parts
Ease of Use	Fair	• Easy to adjust angle • Intuitive to use ramp • No guide to operate ramp	1) Increase detail on guide student guide to walk 2) Have accompany tutorial video in addition to student guide
Repeatability	Poor	• No way to align objects so they roll straight • No way to align multiple objects	1) Create alignment system for objects
Capable of Tracking	Fair	• Can only measuring time it takes for objects to roll down • Difficult to track position of object center or edge points by manually looking through video	1) Use computer visions (CV) tracker to tracker objects to get position and/or velocity and acceleration data
Learning Effectiveness	Poor	• Need lab guide to walk through activities • Incorporate lab type structure • Need change inclination variance to 0-50°	1) Amend student guide to be more ME395 lab style to cover various learning activities on ramp 2) Have multiple learning activities that cover multiple topics to increase learning effectiveness of ramp

As can be seen in the table, our initial prototype struggled to meet the functional requirements of transportability, ease of use, repeatability, capability of tracking, and learning effectiveness. While moving and using the alpha prototype, our team felt that the large base made it difficult to carry the ramp comfortably, especially for the smaller members of our team. In our alpha design, the hinge allowing motion of the ramp was attached to the baseplate. This design choice, however, prevented the alpha prototype from folding completely flat, as the ramp plate would come into contact with the legs prior to laying flat on the base plate. With these flaws in mind, our team felt that adding a component for carrying the device, as well as changing the location of the hinge to allow the ramp to fold flat, would make our product more transportable. We also recognized that our alpha design did not account for transporting the objects being rolled down the ramp, which we also aimed to amend in future iterations of our device. The alpha prototype also struggled in its ease of use. Though adjusting the angle of the ramp was easy and it was fairly intuitive to use, there was little direction as to how the ramp should be used. To better direct student focus on the intended course concepts, our team felt that the development of a student guide would be beneficial, though this would be developed separately from our ramp prototypes. The testing of the prototype also made it clear that some form of release mechanism would be required to keep the demonstrations consistent. During testing, a ruler was used to control the release of the device, which we found was a fairly uncontrolled and inconsistent method. We felt that this would introduce too much human error into the demonstrations, and would make rolling multiple objects down the ramp simultaneously difficult. With these considerations in mind, our team planned to incorporate a release mechanism into future iterations of the prototype. The importance of tracking capabilities was increased after testing the device as well. While we were able to measure the time required for objects to roll down the ramp, this was the only data we were able to collect, which we felt would not be enough for students to have an increase in understanding of dynamics concepts. It was also difficult to track the position of the object through the videos taken alone. With this in mind, our team decided to separately develop tracking software that would be capable of recording the position, velocity, and acceleration of the objects rolling down the ramp. Finally, we felt that the lack of a student guide would limit the improvement of student comprehension of the topics presented by our product, which further reinforced the need to develop a student guide alongside the physical prototype.

Taking into consideration the insights gained from the testing of our alpha prototype, our team began refining our initial decisions to create a more robust and useful prototype. This build design made a number of improvements to our alpha design, better meeting the requirements that our sponsors had laid out at the beginning of the semester. This beta build design is shown below in Figure 6:

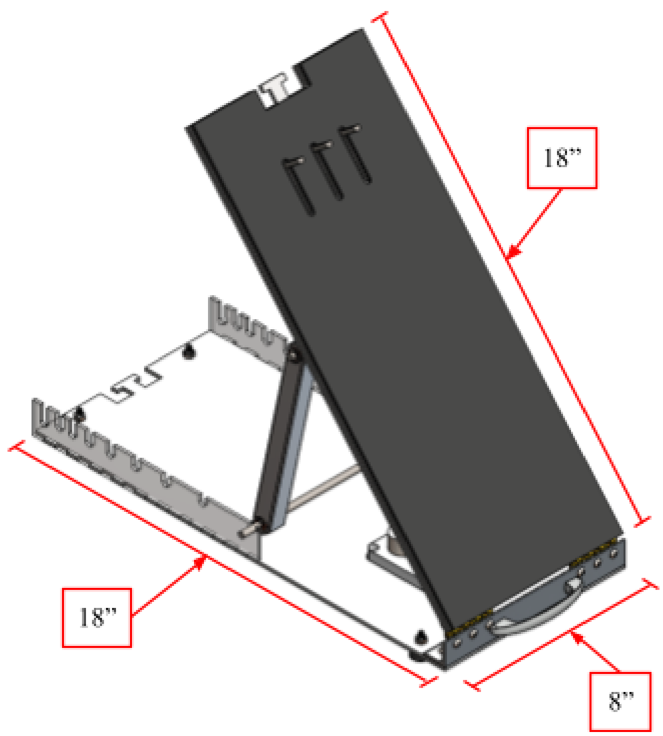


Figure 6: Isometric view of the beta design of the variable ramp CAD model.

This beta build design takes into account each of the flaws our team identified in the testing of our alpha prototype. To improve the transportability, the hinge of the ramp was raised, allowing the ramp to fold completely flat, and a handle was added for easier carrying. A part rack was also added to organize the parts required as part of the demonstrations. A release mechanism using pins protruding from the ramp's surface was also added in order to better control the rolling of the objects during the demonstrations. Though not part of the build design, development of the student guide and tracking software was also started at this time. A summary of the design changes to the prototype is shown below in Figure 7:

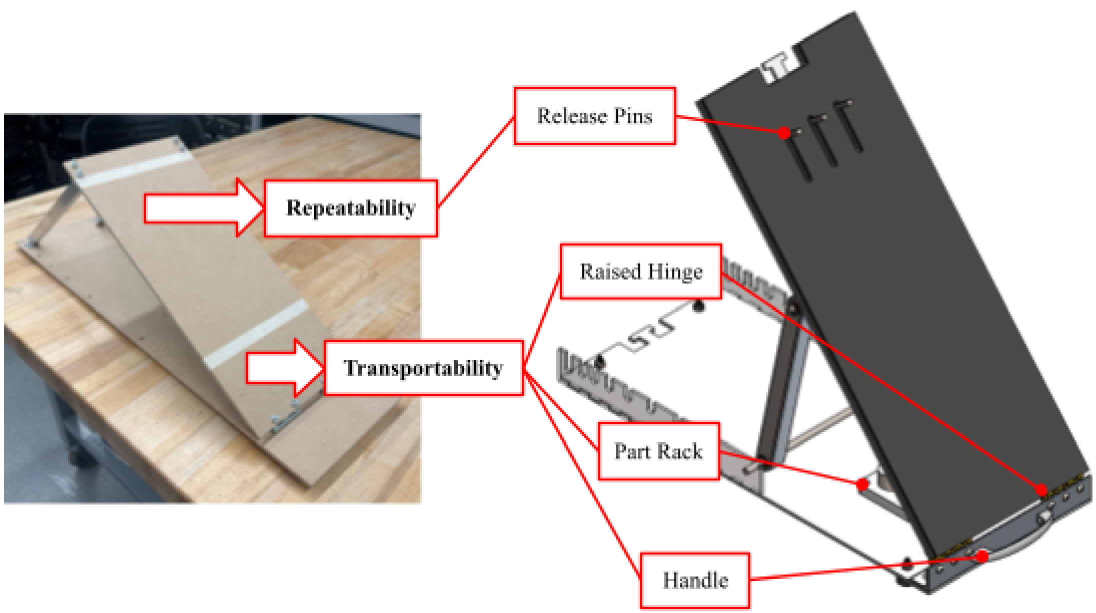


Figure 7: The improvements made from the alpha prototype to the beta build design.

To organize the construction and assembly of this beta build design, the components of the design were labeled according to their function within the assembly. Figure 8 on pg. 33 highlights the key components of the beta build design:

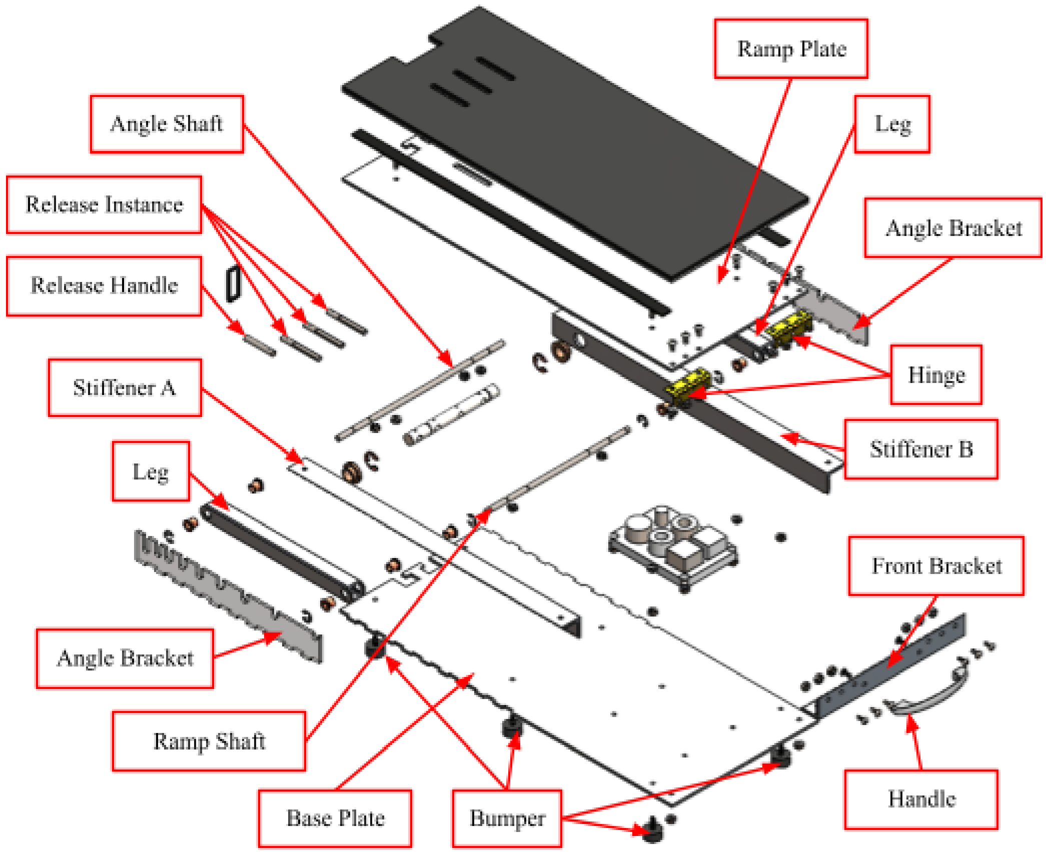


Figure 8: The key components of the variable ramp's beta build design.

The components highlighted in Figure 8 can be organized into two subsystems of the variable ramp: the base and the ramp. These subsystems are shown in Figures 9a and 9b below:

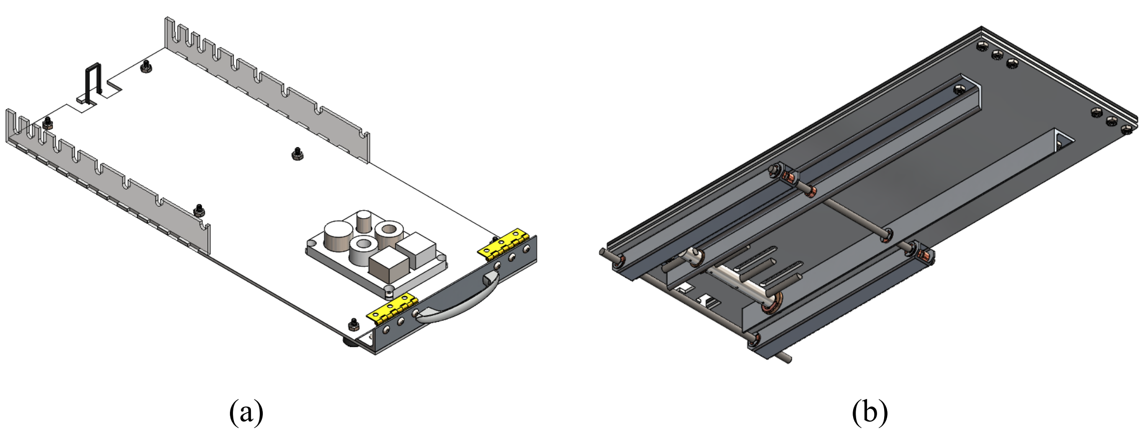


Figure 9: (a) The base subsystem of the variable ramp design. **(b)** The ramp subsystem of the variable ramp design.

The base subsystem of the ramp is meant to provide a stable surface to mount the stationary components of the ramp, and is meant to be placed on a flat surface. The ramp system is the moving component of the variable ramp design. The ramp rotates about the hinges attached to the base, while the legs attached to the ramp via the ramp and angle shafts are allowed to rotate freely. To lock the ramp into a specific angle configuration, the angle shaft is placed within one of the slots cut into the angle brackets attached to the base. This allows the ramp to be placed at angles from 15° to 50° in increments of 5°. The release master also rotates, allowing the release instances to protrude from the ramp plate to create a stop for any objects placed on the ramp. These motions are shown in Figure 10 below:

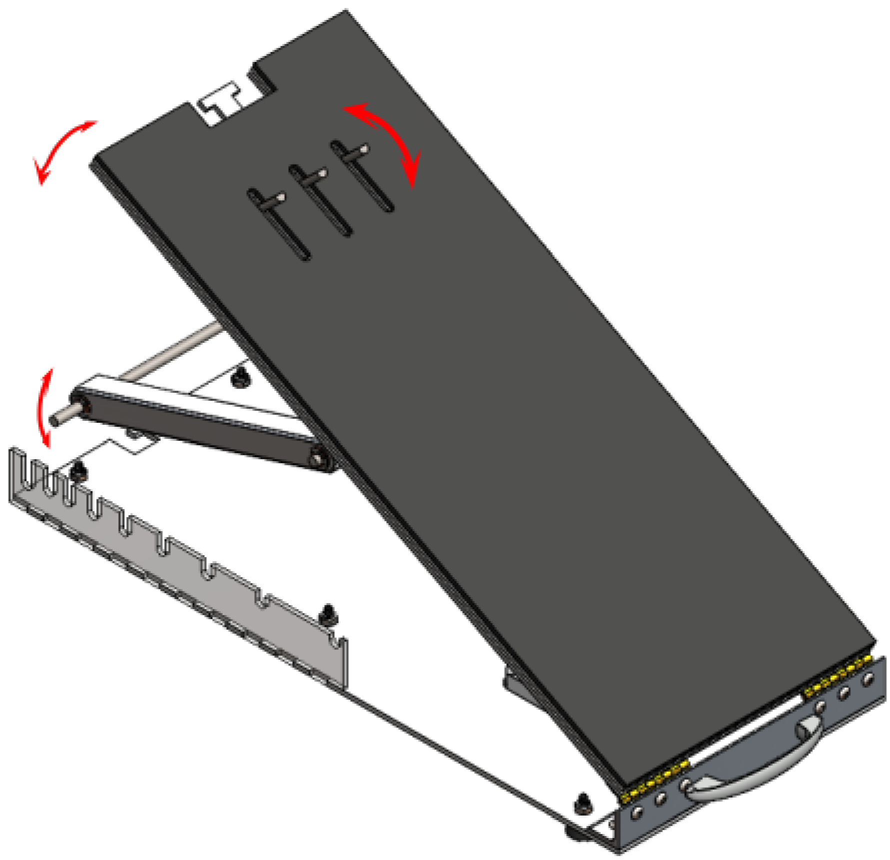


Figure 10: The motions allowed within the variable ramp design.

With the goal of completing construction of the beta build design by the end of the semester, our team developed a bill of materials. This was done in order to ensure that we purchased the materials necessary for our design in a timely manner, and that our final product would not exceed the budget allotted to completing this project. The full bill of materials for the beta build design is shown in Table 11 on pg. 35, as well as in Appendix C, Table C1 on pg. 72:

Table 11: The complete bill of materials for our beta build design. The manufacturer, part number, and cost of each item is listed, as well as the parts that will be made from stock materials.

Item	Quantity Purchased	Supplier	Catalog Number	Cost	Contact	Part(s) Created
12"x24"x1/8" Acrylic Sheet	3	McMaster	8505K722	$46.20	mcmaster.com	Base Plate, Ramp Plate, Rubber Plate
12"x24"x1/8" Rubber	1	McMaster	1370N55	$29.13	mcmaster.com	Rubber Sheet
12"x24"x1/8" Garolite Sheet	1	McMaster	8491K13	$28.19	mcmaster.com	Plastic Plate
3/4"x3/4"x1/16" Square Tube	2 ft.	McMaster	6546K52	$12.66	mcmaster.com	Leg
L-Channel	4 ft.	McMaster	8982K4	$13.33	mcmaster.com	Front Bracket, Stiffener A, Stiffener B
1/4"x36" Shaft	1	McMaster	1886K4	$13.98	mcmaster.com	Ramp Shaft, Angle Shaft, Release Handle, Release Instances
1/2"x6" Shaft	1	McMaster	6061K13	$6.35	mcmaster.com	Release Master
6"x12"x1/8" Acrylic Sheet	1	McMaster	8560K199	$4.87	mcmaster.com	Angle Bracket
1"x1" Aluminum Bar	1/2 ft.	McMaster	9008K14	$7.67	mcmaster.com	Aluminum Block
1" Aluminum Rod	1/2 ft.	McMaster	89535K37	$16.15	mcmaster.com	Aluminum Tube, Large Aluminum Disk, Small Aluminum Disk
1" Plastic Tube	1 ft.	McMaster	8627K629	$9.91	mcmaster.com	Plastic Tube
1"x1" Plastic Bar	1 ft.	McMaster	8739K92	$18.11	mcmaster.com	Plastic Block
Handle	1	McMaster	1786A11	$4.83	mcmaster.com	N/A
1/4" Bushing	10	McMaster	2938T2	$7.60	mcmaster.com	N/A
1/2" Bushing	2	McMaster	1677K338	$3.04	mcmaster.com	N/A
1/4" Retaining Ring	1 (100 pack)	McMaster	97431A300	$6.93	mcmaster.com	N/A
1/2" Retaining Ring	2	McMaster	92725A560	$4.90	mcmaster.com	N/A
Hinge	2	McMaster	1603A7	$9.08	mcmaster.com	N/A
1/16" Spring Pin	1 (250 pack)	McMaster	98296A027	$7.90	mcmaster.com	N/A
8-32 x 3/8" Button Head Screws	1 (100 pack)	McMaster	97763A177	$5.05	mcmaster.com	N/A
8-32 x 1/2" Button Head Screws	1 (50 pack)	McMaster	97763A178	$5.68	mcmaster.com	N/A
Bumpers	1 (10 pack)	McMaster	9541K24	$8.79	mcmaster.com	N/A
8-32 Nylon Locknut	1 (100 pack)	McMaster	90101A009	$8.99	mcmaster.com	N/A
Velcro	1	McMaster	9273K11	$7.17	mcmaster.com	N/A
Rubber Bands	1 (2675 pack)	McMaster	12205T74	$11.78	mcmaster.com	N/A
Total	N/A	N/A	N/A	$298.29	N/A	N/A

As can be seen in the table above, each component of our build design was taken into consideration in our bill of materials. Stock sizes for each component were identified, as well as a provider from which our team could purchase these materials. The listed cost of each required purchase was tallied, resulting in an overall material cost of about $300 for our build design, or about $100 under our $400 budget limit. This spare budget was allocated to any additional material our team needed to purchase in the event that our design needed to be refined a second time or if parts needed to be replaced.

In addition to the bill of materials, our team developed engineering drawings for each part that would require machining for the completion of our build design. These drawings ensured that our team accurately and efficiently created the parts necessary for the assembly of our beta build design. Figure 11 below shows one of the engineering drawings that was used in manufacturing our final product, with our complete set of engineering drawings provided in Appendix E starting on pg. 117.

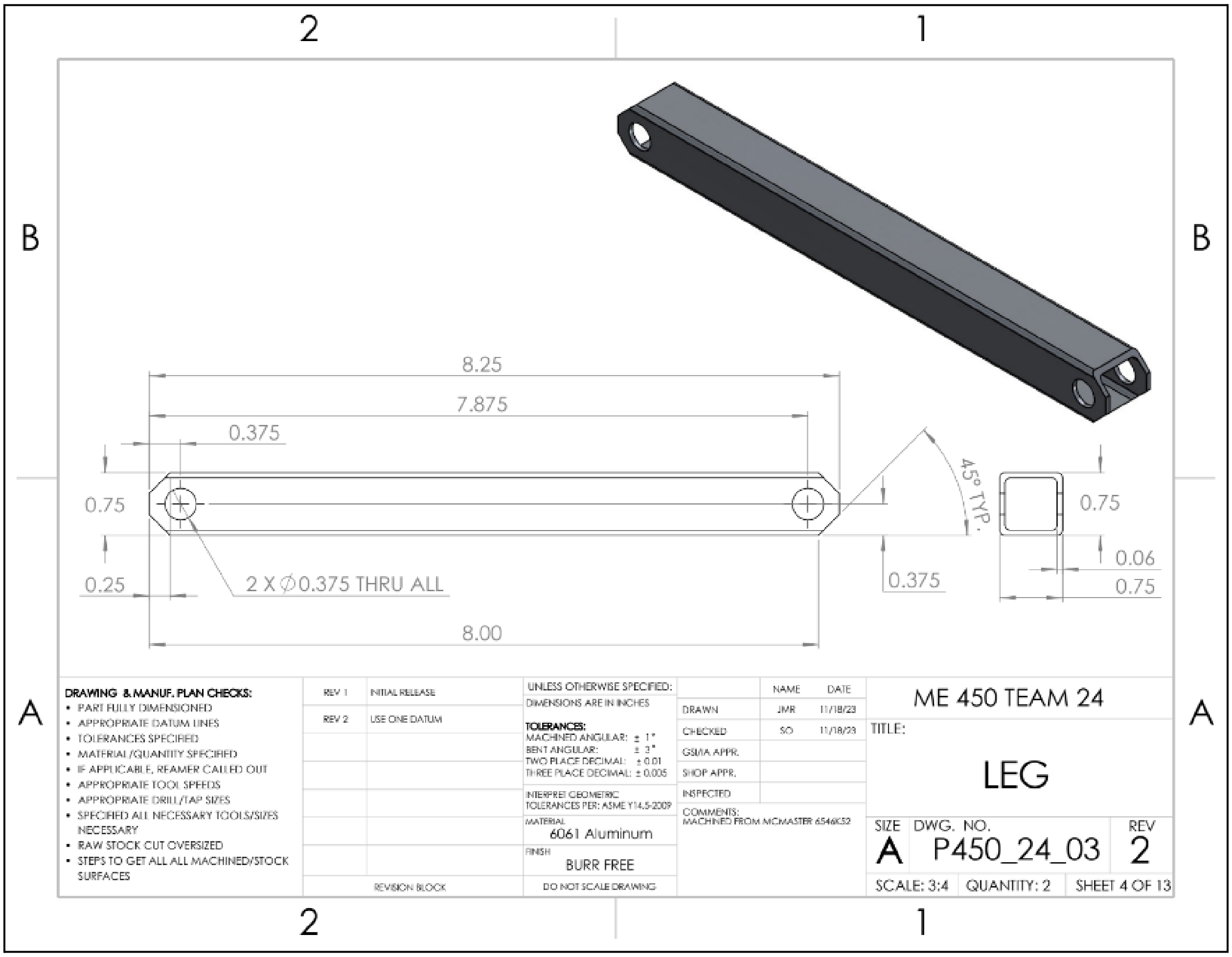


Figure 11: Manufacturing drawing for the leg components of the beta design.

Each of the parts that required machining for the assembly of our build design also required a manufacturing plan. These manufacturing plans ensured that our team knew what devices and tools were required for the machining of each part. They also ensured that the proper methods and speeds were used when manufacturing our project, which both made the machining process more efficient and protected the devices that were used from wear and damage. Figure 12 on pg. 37 shows one of the manufacturing plans that was used in machining the parts for our final product, with our complete set of manufacturing plans provided in Appendix F starting on pg. 129.

Manufacturing Plan

Part Number: P450_24_03 Revision Date: 11/18/2023
Part Name: Leg
Team Name: ME 450 Team 24

Raw Material Stock: Aluminum Square Tube, 3/4 x 3/4 x 24 x 1/16

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed (RPM)
1	Cut raw stock to 8.375 length	Horizontal Band Saw			
2	Hold part in vise.	Mill	Vise		
3	Mill one end of part, just enough to provide a fully machined surface.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
4	Remove part from vise. Break all edges by hand.			File	
5	Place part in vise to machine other end of part. Mill the part to 8.25 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	Vise	Drill Chuck	
8	Find datum lines for X and Y.	Mill	Vise	edge finder, drill chuck	1000
9	Centerdrill and drill the first hole.	Mill	Vise	Center drill, 23/64 drill bit, drill chuck	1200, 1400
10	Ream the hole.	Mill	Vise	3/8 reamer, drill chuck	100
11	Find datum lines for X and Y.	Mill	Vise	edge finder, drill chuck	1000
12	Centerdrill and drill second hole.	Mill	Vise	Center drill, 23/64 drill bit, drill chuck	1200, 1400
13	Ream the hole.	Mill	Vise	3/8 reamer, drill chuck	100
14	Remove part from vise. Break all edges by hand.			File	

Figure 12: Manufacturing plan for the leg components of the beta design.

To complete the manufacturing of our beta prototype, our team utilized the university's Undergraduate Machine Shop and a number of its machines. In our manufacturing plans, our team outlines the use of a mill, a lathe, a horizontal band saw, and a laser cutter in the machining of our prototype's parts. On the mill, we identified the need to use vices, collets, a drill chuck, an edge finder, end mills, center drills, drill bits, reamers, and a file. On the lathe, we planned to use collets, a turning and facing tool, grooving tools, and a file. Each of these tools and their uses are specified within our complete set of manufacturing plans. Beyond the manufacturing plans for the parts of our build design that needed machining, our team used a manufacturing guidebook to assemble our final prototype. These manufacturing instructions are listed in Appendix D, with references to the specific manufacturing drawings and plans used in each step, as well as diagrams of the assembly process.

The tolerances of the parts within our beta prototype vary in terms of their importance. Less important tolerances of our design include the length and width of both the base plate and the ramp plate. These dimensions are not critical, as the overall area of the ramp will not have any significant impact on the performance of our final product. The length of the slots in the ramp plate, as well as the total length of each of the shafts and components of the release mechanism are also relatively trivial to the product's performance. The slots in the ramp only need to be long enough to allow the release mechanism to fit through them without interference. Similarly, the length of each shaft only needs to be long enough to ensure that parts can be mounted to them; any excess material beyond the fastening points on the shafts will not be detrimental to the performance of the prototype. The tolerances that are more important to the design of the device are the locations where parts meet. The holes required for mounting the shafts to the stiffener brackets and legs of the prototype will need to be precisely machined in order to ensure that the shafts are not misaligned, and will be able to rotate to allow motion of the legs. Similarly, the holes for mounting the hinges, as well as the holes and slots on the release mechanism, will need to be precise in order to ensure that parts will fit together without interference. Most critical to the success of our beta prototype is the machining of the slots on the angle brackets. The positions of these slots will ensure that the ramp will lie as close to the intended angle as possible in each of its configurations. If the angle brackets' slots are slightly misaligned, the angle of the ramp could be affected by degrees, which would change the results of any experiments students would conduct using our product. It is for this reason that the angle brackets for the beta prototype were laser cut. This is a more automated and controlled process, and taking the human error out of the machining of these parts ensured that our beta prototype functions as close to ideally as possible.

We expect that this beta build design that we will pass on to our sponsors will closely reflect the final iteration of the product that will be used in the ME 240 classroom. However, we also recognize that any testing that our team has conducted will not exactly match the behavior of our design in its intended environment. It is likely that once our product is implemented in classrooms, issues will be identified that will have to be addressed with future iterations of this design. This beta prototype is not meant to be the final iteration of our design, but instead a product that our team used for testing against the majority of our engineering specifications, and that can be used in the next semester in order to evaluate its performance and its effect on student understanding of dynamics concepts. We have analyzed the behavior of this beta prototype using the engineering test plans outlined in Appendix B, Table B2 on pg. 69, which will be discussed in more detail in later sections of this report. The only specification that our team was unable to measure is the learning effectiveness of our device. This specification must be measured through the implementation of our device in the ME 240 classroom, which will need to be conducted over at least the next semester of the class. With this in mind, our beta prototype is designed to be as accurate to what we expect the final iteration of this project to be, as we aim to prove that a ramp demonstration is capable of improving the student understanding of dynamics concepts, while still recognizing that the general design of the ramp is likely to change throughout its implementation in the classroom. This build also demonstrates the engineering knowledge our group has utilized in the completion of this project. Our knowledge of statics, fracture behavior, and manufacturing methods informed our choices in terms of the materials used in this build design, as well as the possible dimensions for each part within our final product. Our experience with engineering dynamics also informed our build design, as we took into consideration how to best simplify our device's demonstrations in order to provide accurate dynamic behavior that students can use to collect data and compare to theoretical motion. This knowledge of engineering dynamics not only informed the build design that we will present to our sponsors, but the entirety of the final product that we intend to be implemented in the ME 240 classroom.

Engineering Analysis

In order to confirm the feasibility of this beta build design, our team developed plans to analyze the design's characteristics using engineering principles. Each of these analysis principles was connected to one of the functional requirements of the device in order to ensure that our preliminary design fulfills the expectations of our sponsors and meets the needs of the students who will be using our product in future semesters of ME 240. A summary of the key engineering analysis methods is shown in Table 12 below, with the full list of analyses provided in Appendix B, Table B1 on pg. 68:

Table 12: Engineering analysis methods used to evaluate the beta build prototype. Justifications for each analysis method are provided.

Requirement	Specification	Engineering Analysis	Justification
Easy to transport	Lifting index ≤ 1.0 Width: 200mm-500mm Length: 200mm-500mm Height: 200mm-500mm	1) Use CAD to estimate design mass; ensure mass ≤ 16 kg for lifting index ≤ 1.0 2) Kinematic calculations to ensure device is stable on flat surface	1) CAD can provide estimation of actual mass prior to prototype construction
Easy to use	Ready to demo in < 5 steps AND < 5 minutes Requires ≤ 2 tool to change configurations	1) Ensure bolts are uniform 2) Calculate number of steps needed to set up and operate demonstration to ensure under 5 steps	1) Bolt uniformity will ensure number of tools needed to repair product is minimized
Capable of tracking	Must be able to track at minimum 1 of the following metrics: time, displacement, velocity, acceleration, or force	1) Ensure tracking devices can be secured for reliable data collection. 2) Ensure selected measurement devices have minimum 2 decimal points for measurement.	1) Based on prior experiments in ME 395, 2 decimal point round off is high enough fidelity for given experiments
Learning Effectiveness	Students must demonstrate increase of 5% perceived understanding of topic using Likert scale survey	1) Develop Likert scale to access before and after student understanding of topic	1) Student understanding is subjective. Likert scale best way to rate subjective view on topic comprehension

To determine whether this beta design was easy to transport, the CAD model of the beta design constructed in SolidWorks was used to provide an estimate of the mass and geometric dimensions of the product. While the NIOSH lifting equation provides a more accurate estimate of the maximum weight of an object if it is to be safely lifted, it is largely dependent on the method used to carry the object, which could only be determined after the assembly of our build design. To analyze our beta design prior to its construction, therefore, our team turned to existing research. Based on experimentation and guidelines from the Spinal Institute at the University of Ohio[25], the maximum recommended weight limit for low-risk single handed carrying is 16 lb, or 7.26 kg. With this in mind, our team used our existing CAD model to conduct a mass evaluation of our beta design. In SolidWorks, the material of each part was specified based on the intended build material, at which point the software was used to estimate the total weight of the beta design. The width, length, and height of the ramp at the largest open angle of 50° were also evaluated in Solidworks using the measure tool. The total mass and maximum dimensions of the beta design estimated in Solidworks can be seen below in Figures 13a and 13b, respectively:

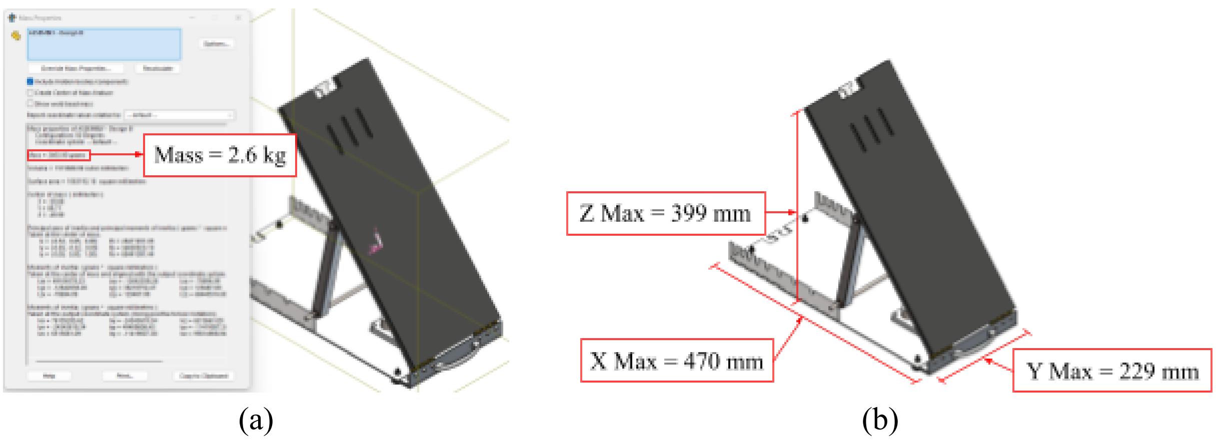


Figure 13: **(a)** Mass evaluation of the beta build design. **(b)** Measurements of the maximum length, width, and height of the beta build design.

As Figure 10a shows, the total estimated mass of the beta design was 2.6 kg, which is less than 7.26 kg, indicating that the beta design's weight is safe to lift. Figure 10b shows that the total width, length and height at the maximum open angle were estimated to be 229 mm, 470 mm, and 399 mm respectively, all falling within the required 200 - 500 mm range. Thus, the Solidworks mass and dimension analysis predicted that the beta design should meet the ease of transport requirement.

Our team also considered how easy this beta design was to use. The ease of use requirement specified the ramp design should be set up in under five steps for a demonstration. With this in mind, the CAD model of the beta design was used to simulate the process of setting up the device from the closed 0° configuration to any of the open angle configurations from 15° to 50°, and the number of steps taken for each configuration were counted. One of these simulations is shown in Figure 14 on pg. 41:

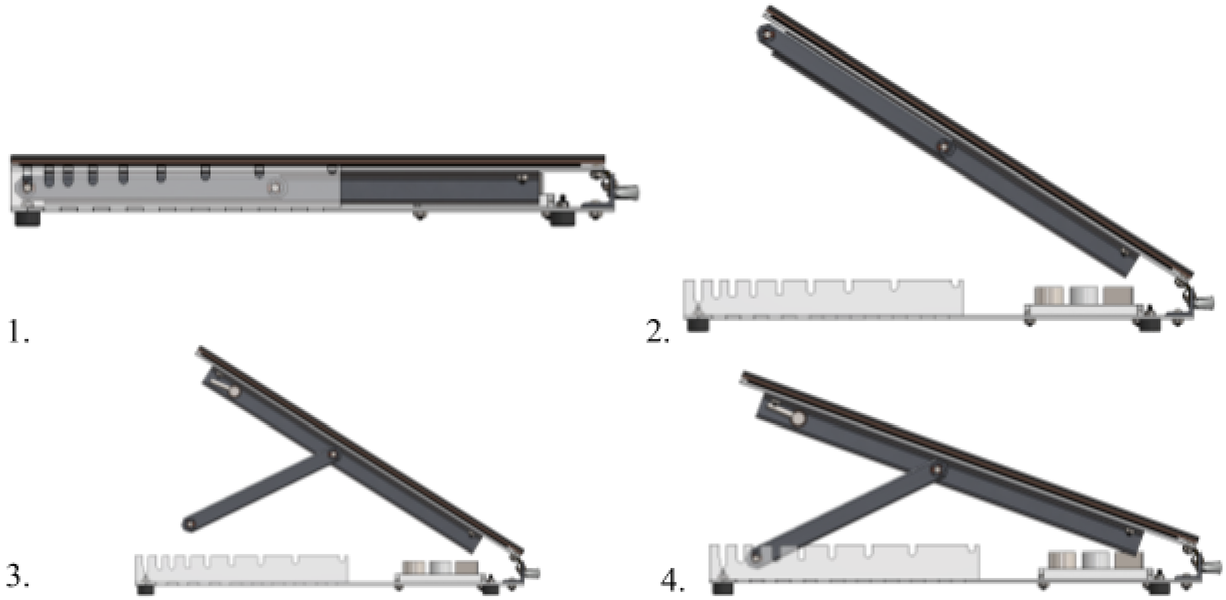


Figure 14: The simulated steps necessary to set the beta build design in the 20° configuration.

As can be seen, the CAD simulation indicated that setting up the beta design in the 20° configuration would require four steps, which is less than the five step limit, satisfying the ease of use requirement. The remaining configurations all had the same result, taking less than five steps to set up, indicating that the beta design should meet the ease of use requirement.

Our team not only needed to consider the safety and usability of our device, but also its longevity. One of the scientific fields most involved in the development of this design is solid mechanics. While manufacturing this device, our team needed to ensure that the product that we have now created is capable of being used as intended without breaking. To accomplish this, our team used principles of solid mechanics to analyze the forces acting on our device and any associated fracture modes to determine when our device is likely to fail if we were unable to design the device to resist fracture. An example of the calculations used to analyze the failure of our device are shown in Figure 15 on pg. 42:

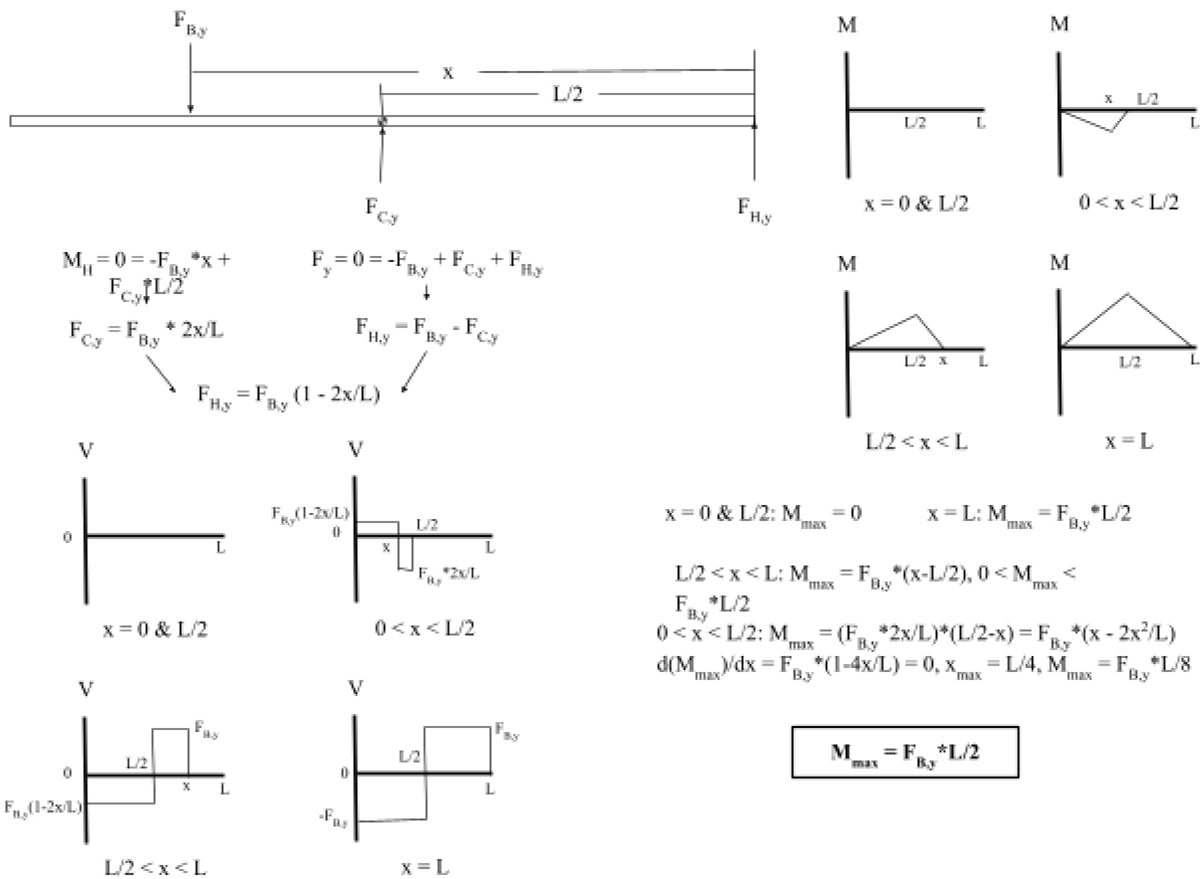


Figure 15: The calculations for the maximum moment that will be exerted on the variable ramp by an object placed on its surface.

The above figure shows the calculation of the maximum moment that will be exerted on the ramp during the conducted demonstrations. This maximum moment was then used to calculate the maximum bending stress, σ_{max}, in the ramp over the course of a demonstration, which is shown in Equation 1 below:

$$\sigma_{max} = \frac{M*y}{I} = \frac{\left(F_{B,y}*L/2\right)*h/2}{1/12*wh^3} = \frac{3F_{B,y}L}{wh^2} \quad (1)$$

where $F_{B,y}$ is the force exerted on the ramp by the object placed on its surface, L is the length of the ramp, w is the width of the ramp, and h is the thickness of the ramp. This equation was used to solve for the minimum tensile strength that the material chosen for the ramp must exhibit based on the weight of the object being placed on the ramp, as well as the ramp's dimensions. These calculations were used to justify the use of acrylic as the material of the ramp.

As this device is intended to demonstrate dynamics principles, our team also needed to conduct analyses of the dynamics involved in the device. We needed to derive the dynamics models relating to the demonstrations that our device is capable of to ensure that its actual performance matches its theoretical behavior. These derivations should match those that will be completed by students in the ME 240 curriculum to ensure that our ramp design is capable of comparison to the concepts learned in this class. Examples of these dynamics calculations are shown in Appendix B, Figures B1 and B2 on pg. 70 and 71.

To ensure the tracking software will be useful for students while conducting the demonstrations, our team conducted extensive engineering and user testing. The engineering analysis that can be completed on the tracking software is rather limited, but our team has ensured that the tracking software we have developed is capable of at least two decimal points of precision. Based on our individual experiences in ME 395, a two decimal point round off is an estimation of high enough fidelity to provide accurate data on the experiments we intend for students to conduct.

Our team also needs to ensure that the final deliverables we pass on to our sponsors will have a positive impact on student comprehension of engineering dynamics. However, the best method of testing the learning effectiveness of our deliverables will be to conduct extensive user testing with ME 240 students, which is not a metric that can be easily analyzed prior to the completion of our final product. In lieu of engineering analysis on our deliverables, our team has created a feedback survey for our sponsors to give to individuals who test the effectiveness of our device. This survey consists of a number of questions graded based on a Likert scale, as the effectiveness of an experiment in improving comprehension of a concept is rather subjective.

Final Design

Our initial engineering analysis and alpha design prototype led to our team's final deliverables, which include a variable ramp, a student guide, and tracking software. Each of these deliverables is shown in Figure 16 below:

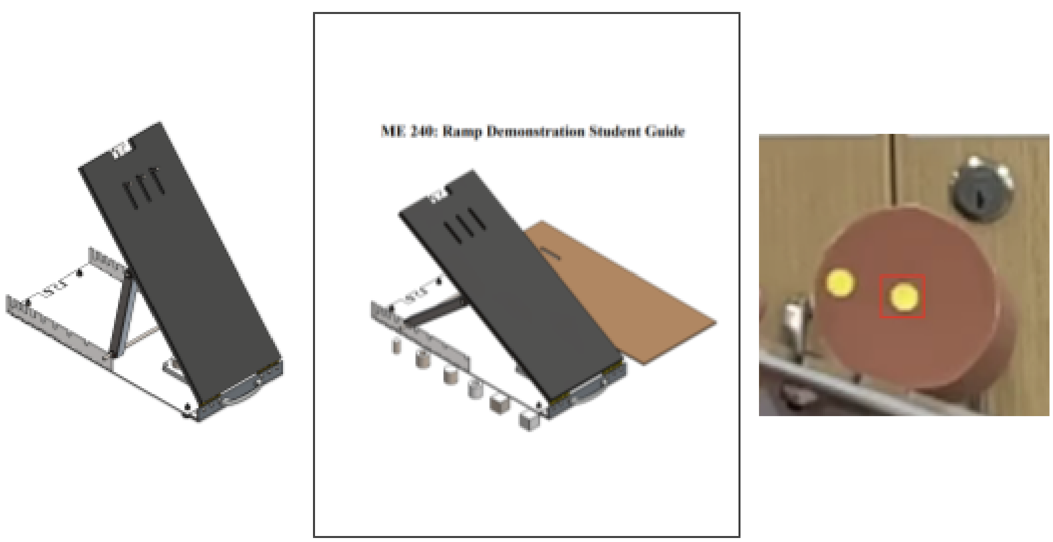
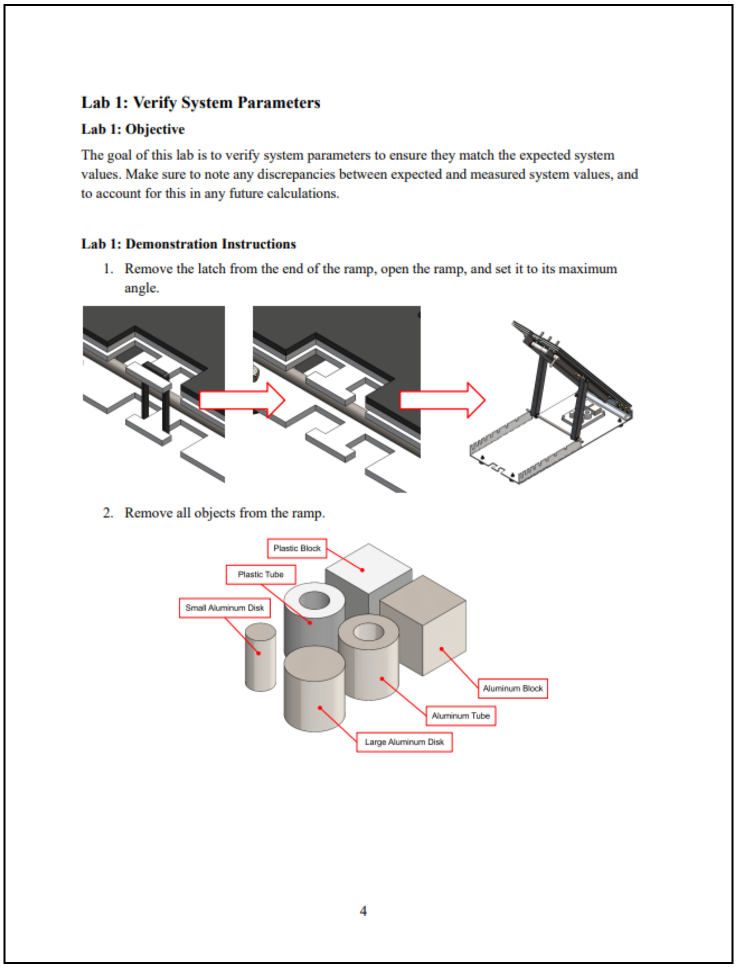


Figure 16: The final deliverables for this project.

As discussed in the build design section, issues with our alpha build design discovered during the preliminary analysis and prototyping phase led to the refinement of the variable ramp design, shown on the left of Figure 16. This variable ramp is meant to address the majority of our functional requirements, as well as many of the issues discovered during the testing of the alpha prototype. The final ramp deliverable will be easy to transport due to its attached carrying handle, durable due to the selection of acrylic and aluminum for the majority of the body, adjustable via the different angle configurations, and interactive due to the hands-on nature of the demonstrations. It has been improved from the alpha build design in terms of its transportability, ease of use, and repeatability. The primary objective of the ramp deliverable is to provide students with a physical device that they can interact with to simulate the dynamics problems that they will be challenged to solve in the ME 240 classroom, controlling the parameters of the ramp and the objects they use in the demonstrations.

The issues found through testing the alpha prototype also led to the creation of a student guide. The team felt that while the alpha prototype made it easy to conduct demonstrations relating to ME 240 concepts, it was not made clear how these demonstrations should be conducted. This led to the need for a guide which students could follow to collect meaningful data about the experiments they would conduct. To maximize the effectiveness of this student guide, our team outlined multiple demonstrations covering various dynamics concepts that will be conducted using our ramp. This will ensure that students will not be limited to one topic when using our product, but can instead use the device to address any lack of understanding that they have within the ME 240 curriculum. This student guide currently introduces the students to five different activities: measuring system properties, coefficient of friction calculations, comparisons and calculations of simple dynamic rolling, and calculations of eccentric object rolling. Each of these activities is meant to introduce students to different concepts within the ME 240 curriculum, slowly building knowledge to address more challenging problems. Each activity will include step-by-step instructions guiding students through the intended demonstration, as well as pictures and diagrams of the ramp to indicate which items and configurations will be used. An example of one of the activities is shown in Figure 17 on pg. 45:



Lab 1: Verify System Parameters

Lab 1: Objective

The goal of this lab is to verify system parameters to ensure they match the expected system values. Make sure to note any discrepancies between expected and measured system values, and to account for this in any future calculations.

Lab 1: Demonstration Instructions

1. Remove the latch from the end of the ramp, open the ramp, and set it to its maximum angle.

2. Remove all objects from the ramp.

Plastic Block
Plastic Tube
Small Aluminum Disk
Aluminum Block
Aluminum Tube
Large Aluminum Disk

4

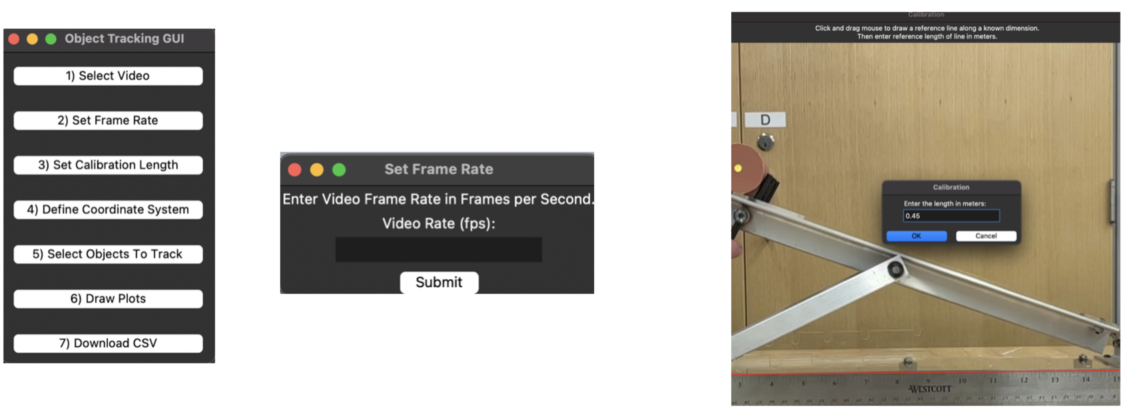
Figure 17: One page of the student guide. Instructions are given step-by-step with attached diagrams.

The purpose of this student guide is to ensure that students accurately and purposefully use the ramp to enhance their understanding of dynamics principles, rather than simply running experiments with no direction. The guide is meant to increase our final product's ease of use and learning effectiveness by instructing students on how to use the ramp for meaningful experiments, as well as increase its consistency and accuracy by ensuring that students run the demonstrations in a way that they will gather useful data that can be compared to their theoretical analysis. This design guide will likely be both a physical packet and a virtual document, so students will be able to follow instructions to run the demonstration, then review the questions in their own time.

The last deliverable that became relevant following the alpha prototype testing was the tracking software. While testing the alpha prototype's behavior, our team used a simple camera as well as a stopwatch to record the position and time of objects being rolled down the ramp. We found that this method of data collection was too rudimentary, and did not provide accurate enough information to collect meaningful data about the system. The inclusion of tracking software as one of our final deliverables is meant to address this issue, fulfilling the functional requirements of ease of use and learning effectiveness by providing a simple way for students to collect data relating to the demonstration, as well as fulfilling the capability of tracking and accuracy requirements by increasing the reliability of the tracking system.

We chose to pursue camera tracking methods to collect experimental data rather than embedding IMUs or other sensors within the demonstrations' objects because we felt that the latter could impact the kinematics of the experiments. With mass distribution playing a significant role in the kinematics of our intended demonstrations, it was imperative that we kept the ramp's accompanying objects as simple as possible, which embedded trackers would not allow. Tracker IO, a software used in the University of Michigan's Physics 140 class, as well as an open source tracking software created in MATLAB, were evaluated as potential options for the tracking software. When tested with a sample video taken of a cylinder rolling down the tramp, the automatic tracking feature in Tracker IO failed to track the center of mass of the cylinder, making it unsuitable software for our purposes. The open source MATLAB code faced similar issues, and frequently crashed due to the high power consumption of the application. Rather than use these unsatisfactory programs, our team developed a tracking software program in Python that uses the Channel and Spatial Reliability Tracker (CSRT) software from OpenCV to track points on the objects during experiments. To ensure that our final deliverables truly meet the requirements and specifications laid out for this project, our team conducted tests on each of these products.

The tracking software features simple graphical user interfaces (GUIs) to guide students through the process of tracking objects used in the demonstrations. Command lines are used to prompt the user for any necessary information, elements of which are seen in Figure 18 below:



(a) (b) (c)

Figure 18: (a) The main GUI for the tracking software. **(b)** An example of the prompt requests for which users will need to enter information. **(c)** The prompt request to set the calibration length.

Figure 18a shows the main GUI of the tracking software, in which the user will click each button in order, starting with the "1) Select video" button. Once a button is clicked, a second window will appear prompting the user for information, including numerical values such as those requested in Figure 18b, which shows the prompt request for the user to enter the frame rate after the button "2) Set Frame Rate" is pressed. The user also interacts with various windows for buttons 3 through 5 to define locations or object information. Figure 18c shows the prompt after selecting the button “3) Set Calibration Length”, which asks the user to draw a line and define its length in meters. Through the buttons and prompts of the tracking software, the user is able to select a video to analyze, set the frame rate of the video, determine a reference length, define the origin of the system and its vector orientations, and identify the objects to be tracked. After following prompts 1 through 5, users can download the data they collect as a .csv file by pressing the button “7) Download csv” so they can plot the data in MATLAB or other softwares preferred for data analysis.

Verification & Validation

Following the completion of the assembly of our final deliverable, our team conducted a number of verification and validation tests building off of our initial engineering analysis to confirm that the product we will present to our sponsors will meet their expectations. To accomplish this, our team outlined verification and validation tests for each of the engineering specifications that our product is required to meet. Table 13 below shows the most important verification and validation tests, while the full list of tests is shown in Appendix B, Table B2 on pg. 69:

Table 13: A list of the key engineering analysis performed on the build design to estimate if specifications were met. Each requirement is matched with an analysis plan with justifications provided for said plans.

Requirement	Specification	Verification Plan	Validation Plan	Justification
Easy to transport	Lifting index ≤ 1.0 Width: 200mm-500mm Length: 200mm-500mm Height: 200mm-500mm	1) Use mass scale to confirm mass ≤ 16 kg 2) Measure maximum dimensions of prototype using ruler	1) Carry object from 3rd floor of GGBL to 1st floor, subjective carrying rating must be “easy”	1) 1st floor to 3rd floor, approximate distances the device will need to be hand carried
Easy to use	Ready to demo in < 5 steps AND < 5 minutes Requires ≤ 2 tool to change configurations	1) Run demonstration 10 times number of steps needed for setup is < 5, amount of time needed for setup is < 5 minutes, and number of tools needed for changing configurations is ≤ 2 2) Amount of time needed to complete data collection for each activity ≤ 45 mins	1) Record number of steps and time taken for in-class setup 2) Ensure demonstration can be completed within a class period	1) Assuming 10 runs per semester, shows consistent use for entire semester 2) 90 minute block, students will take longer to run activity. If team team members can complete in ½ time, students highly to complete by end of 90 min block
Capable of tracking	Must be able to track at minimum 1 of the following metrics: time, displacement, velocity, acceleration, or force	1) Run demo 5 times. Successful runs if data collection was able to be completed as intended with meaningful data, and data tracking devices remain in intended locations	1) Have students conduct demonstration and record. Ensure students are capable of extracting data from tracking software	1) Students need to have access to usable system information to compare data to theoretical analysis
Learning Effectiveness	Students must demonstrate increase of 5% perceived understanding of topic using Likert scale survey	1) Have Center for Research on Learning and Teaching review student guide to ensure it is adequate for guiding students	1) Conduct testing with ≥ 5 students. Perceived understanding of topic should increase by 5% using Likert survey	1) Student understanding is subjective. Likert scale best way to rate subjective view on topic comprehension

The most important requirement that our team verified was our product's transportability, as this characteristic dictates whether our product can be implemented in a classroom setting, and whether it will be safe for students and professors to move. To verify this requirement, our team first used a mass scale to confirm that our product does not exceed the specified limit of 16 kg. With a weight of 1.98 kg, our design easily meets this specification. This verification method was intentionally rather simple, as our team only aimed to determine whether it is possible to lift our product. To provide a more reliable verification of how safe it is to lift our device, our team used the NIOSH lifting equation shown below in Equation 2:

$$Lifting\ Index = \frac{Load\ Weight}{Recommended\ Weight\ Limit} \tag{2}$$

This equation specifies that an object is safe to lift if its lifting index is less than or equal to 1. The load weight is simply the mass of the object being lifted, while the recommended weight limit is determined by a number of factors dependent on the position of the body while carrying the object, shown below in Equation 3:

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \tag{3}$$

where *RWL* is the recommended weight limit, *LC* is the load constant, *HM* is the horizontal multiplier, *VM* is the vertical multiplier, *DM* is the distance multiplier, *AM* is the asymmetric multiplier, *FM* is the frequency multiplier, and *CM* is the coupling multiplier. The load constant is always set to 23 kg, while the remaining variables on the right-hand side of Equation 3 are determined using measurements of the object while it is being carried. In order to calculate the lifting index of our device, each team member held the device as though carrying it, and measurements were taken according to the NIOSH lifting equation to determine the recommended weight limit for each member of the team. The results of these measurements are shown in Table 14 below:

Table 14: The metrics of the NIOSH lifting equation based on measurements taken of each member of our team while carrying the variable ramp. Each of these metrics, along with the load constant of 23 kg, was used to calculate the recommended weight limit shown in the rightmost column.

Individual	HM	VM	DM	AM	FM	CM	RWL
Christian Nunez	1	0.992	0.880	1	1	0.95	19.07 kg
Sneha Ojha	1	0.976	0.878	1	1	0.95	**18.72 kg**
Adam Rajner	1	0.992	0.882	1	1	0.95	19.12 kg
James Ryan	1	0.984	0.874	1	1	0.95	18.79 kg

As shown in Table 14, the lowest recorded recommended weight limit amongst the four members of our team was 18.72 kg. A lower recommended weight limit will result in a higher lifting index, so this value of 18.72 kg was used to estimate the maximum lifting index of our device. The mass of the device measured by the mass scale was used as the load weight, resulting in an estimated maximum lifting index of 0.1057. This value falls well below our specified lifting index limit of 1, meaning our device also meets this specification. This analysis of the weight of our product using a more complex equation is an intentional choice, as user safety is one of our primary concerns when interacting with our device, and thus should be analyzed more rigorously. While we recognize that measurements based only on the members of this team may not reflect the true distribution of NIOSH lifting indexes for all of our end users, we believe that such a small estimated lifting index indicates that our device will not exceed the safe lifting index limit of 1 for any of our end users. Our team also measured the maximum dimensions of our device, which resulted in a length of 480 mm, a width of 228 mm, and a height of 394 mm, each of which falls within the specified limits of 200-500 mm. This confirms that our device was able to meet all of the specifications connected to the transportability requirement, but our team also plans to have this characteristic validated to ensure that our end users feel the same way. This will be done by having users carry the device from the third floor of the G.G. Brown Laboratory to the first floor, after which users will be asked to rate how easy it was to carry the device using a Likert scale. This will have to be done in the upcoming winter semester, but should provide a more accurate reflection of how transportable our device is, as the physical features of each user impact the NIOSH equation's lifting index, and thus gathering a larger data set will provide better information about our device's performance.

Our team has also verified that our product is easy to use according to our engineering specifications. This was done by having each member of the team conduct the intended demonstrations using our student guide, and record the amount of time it took to complete said demonstrations. This demonstration time was split into two phases: set up of the demonstration, and conducting the demonstration. The results of these time recordings are shown below in Table 15:

Table 15: The time each member of our team took to conduct one of the demonstrations listed in the student guide. This time is split into set up and conducting phases to ensure the time spent setting up the demonstrations does not exceed 5 minutes.

Individual	Set Up	Conducting	Total
Christian Nunez	27 s	17 min 30 s	17 min 57 s
Sneha Ojha	21 s	15 min 12 s	15 min 33 s
Adam Rajner	24 s	16 min 59 s	17 min 23 s
James Ryan	32 s	18 min 47 s	19 min 19 s

As shown in the table, each member of the team was able to set up the demonstrations in well under one minute, and completed the demonstrations in under 20 minutes. With specifications requiring the demonstration to be set up in under 5 minutes, and completed in under 45 minutes, our device easily meets these ease of use specifications. These metrics were put in place because we believe that, with our knowledge of both the engineering concepts demonstrated by the device and the device itself, our team should have been able to complete the demonstrations in half of the time students will take to complete them. Assuming that students are given an entire 90 minute class period to conduct the demonstrations, this would require all members of our team to complete the demonstrations in under 45 minutes, which we were all more than capable of. Even assuming that students take four times longer than our team did to set up and conduct the demonstrations, they should be capable of completing the intended experiments within the time given for a lecture. Our team also recorded the number of steps necessary to set up the demonstration according to the student guide, and found that all of our demonstrations were capable of being set up in less than 5 steps. Additionally, none of our device's configuration changes requires any tools, which means that our device was able to fulfill all of the specifications for the ease of use requirement. A similar method to these verification tests can also be used to validate the success of our product with respect to this specification. Once the device has been implemented in the ME 240 classroom, the amount of time students take to complete the demonstration can be measured to ensure that it falls below the 90 minutes given for a class period. This is an intentionally simple analysis method, as the ease with which users can use the device does not pose any health or safety risks, but instead only dictates how quickly students will be able to conduct the demonstration, which is not a critical concern.

Our team also wanted to verify that the tracking software we have developed for our product would be useful for the demonstrations students will conduct. We felt that the tracking software should be both reliable and comparable to theoretical behavior to ensure that students could compare the experimental data they collect to the analysis they will complete as part of the ME 240 class. To ensure that the experiment produced results similar to those predicted by theoretical models, our team plotted data collected using the tracking software against a plot of the expected behavior of the system based on dynamic analysis techniques. An example of these comparisons is shown in Figure 19 below:

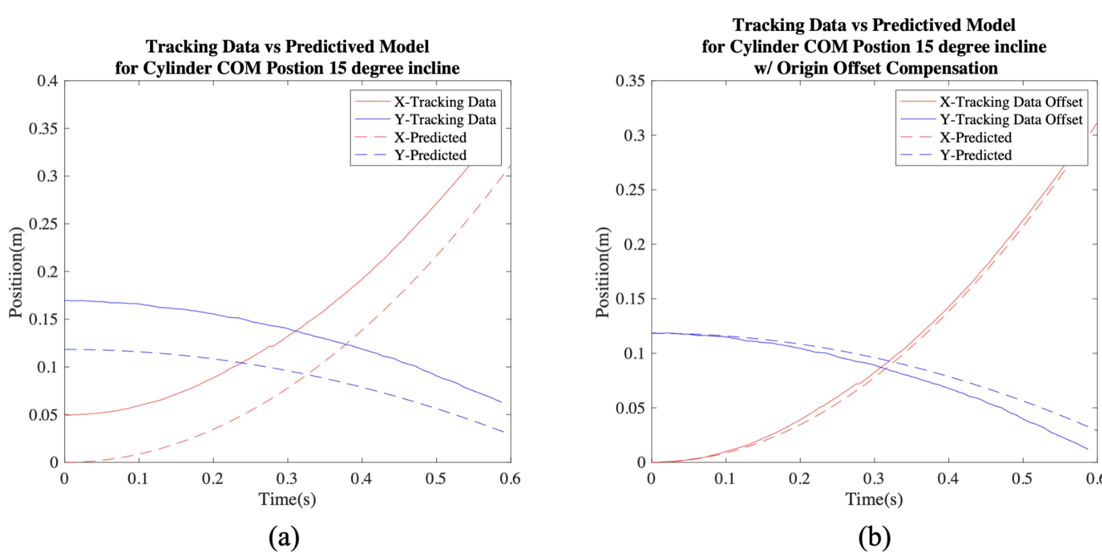
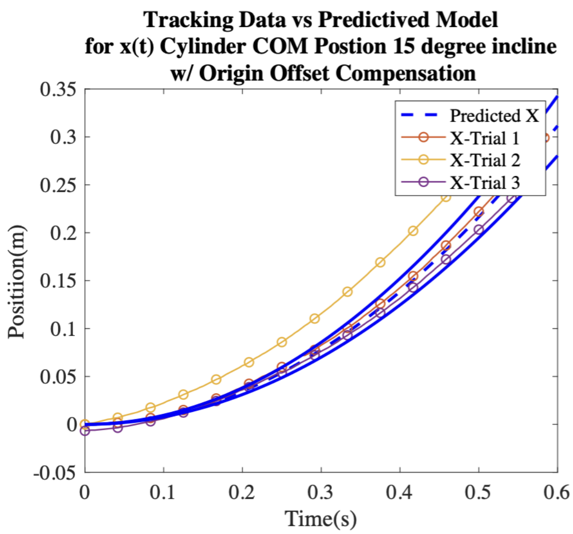


Figure 19: (a) The raw tracking software data output for *x* and *y* positions over time plotted versus results front the predicted position model derived from the equations of motion for a cylinder rolling down a 15° ramp incline. **(b)** The tracking data with an offset origin for compensation compared against the predicted model.

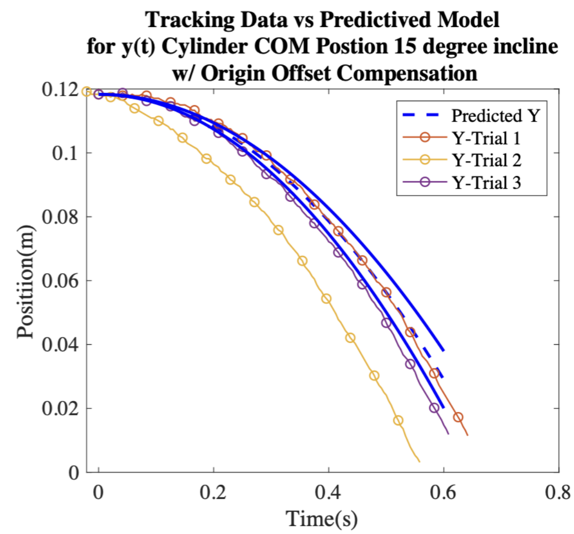
Figure 19a shows a comparison between the position data extracted directly from the tracking software and the theoretical predictions for the motion of a cylinder's center of mass on a 15° incline. The solid lines represent the position of the cylinder's center of mass with respect to the x and y axes as recorded by the tracking software, while the dotted lines show the predicted data. As the graph shows, there is a noticeable offset between the initial starting position for the cylinder in both the x and y directions, which is attributed to the placement of the origin within the tracking software. Accurately placing the coordinate system's origin in the tracking software is challenging due to the high variability in the accuracy of a user's clicks with a cursor and the difficulty in precisely aligning the clicked point with the exact intended origin location, such as the one defined for the theoretical data. Rather than put the burden of precisely identifying the tracking software's origin on our users, we instead will simply compensate for the offset by shifting the data.

The raw tracking data was adjusted for an offset to ensure that the initial positions *x(0)* and *y(0)* corresponded with the predicted positions, compensating for the difference between the origin defined in the theoretical model and the user-defined origin in the tracking software. This is shown in Figure 19b. As can be seen in the figure, after compensating for the offset, the tracking data closely aligns with the predicted x and y positions, providing an early indication that the tracking software will accurately track points for the demonstrations. It is important to note, however, that Figures 19a and 19b demonstrate how the alignment of the collected data with the predicted equations could be misrepresented without proper post-processing of the data. Despite this, Figure 19b shows that the experimental data collected with the tracking software closely matches the theoretical behavior of the system.

To quantify the accuracy of the software, the positional data collected by the tracking software from rolling a cylinder down a ramp was compared against the predicted position based on theoretical models to see if the data aligned within 10% of the predicted behavior as specified in the accuracy requirement. This comparison is shown in Figure 20 on pg. 52:



(a)



(b)

Figure 20: (a) The post-processed tracking software data output for the *x* position over time plotted against the results of the predicted position model derived from the equations of motion for a cylinder rolling down a 15° ramp incline. **(b)** The post-processed tracking software data output for the *y* position over time plotted against the results of the predicted position model derived from the equations of motion for a cylinder rolling down a 15° ramp incline.

As can be seen in Figure 20a, the *x* position of the cylinder's center of gravity on a 15° incline according to the tracking software was somewhat accurate to the theoretical behavior. Trials 1 and 3 fall within the ±10% tolerance bands outlined by the dark blue lines, indicating a successful alignment with the predicted horizontal behavior of the cylinder. Trial 2, however, fell outside of these tolerance bands. The maximum error between the expected and collected data for this trial was calculated to be 12.9%, exceeding the 10% maximum error criteria outlined in our specifications for the accuracy requirement.

As can be seen in Figure 20b, the *y* position of the cylinder's center of gravity on a 15° incline according to the tracking software was less accurate to the theoretical behavior than the *x* position. The data collected for trial 1 closely adhered to the theoretical model, falling well within the ±10% tolerance bands, while the results from trials 2 and 3 fell outside of these tolerance bands. The *y* position recorded in trial 2 was significantly lower than expected, with a maximum observed error of 79% seen at 0.55 s. While the data from trial 3 was much closer to the lower edge of the 10% error band, both trial 2 and trial 3 failed to meet the 10% maximum error specification for the accuracy requirement.

The results of the accuracy verification test shown in Figure 20 demonstrate that the tracking software fails to meet the accuracy requirement based on the 10% maximum error specification. While the software does appear capable of tracking data in a pattern close to the theoretical behavior, it does so with significant error, which may make the data collected in these experiments unreliable for the students to use. This also impacted the reliability of the tracking software.

To assess the repeatability of the tracking software, the mean and standard deviation of the *x* and *y* positions of the three trials seen in Figure 20 were calculated. The standard deviation at each time was then averaged to estimate the typical variation of the data, which was compared to the maximum 3% variation required to meet the reliability requirement. The average standard deviation for the *x* position of the three trials was 14.6%, while the average standard deviation in *y* positions was 32.4%, both of which fail to fall below the 3% threshold. Inaccuracies in the positional data collected by the tracking software are directly related to variability in how the user defines the reference length for the tracking software. The reference length is used to convert the pixels of the video into units of meters, so slight variations in how the reference length is defined can account for vast differences between the measured positional data and the theoretical model. This would explain why the average standard deviation exceeds the 3% threshold. With this in mind, alternate tracking methods to computer vision tracking software should be explored to determine if it is possible to meet the 3% variation specification for the consistency requirement. The current tracking software, however, fails to meet the reliability requirement in the same way it fails to meet the accuracy requirement.

The other requirement that our final deliverables failed to meet was the durability criteria. While our engineering analysis indicated that the ramp would not break under normal use, cracks appeared in the slots ramp plate and one of the slots in one of the angle brackets shortly after the assembly of the beta prototype. We believe that this is due to the interference of these acrylic parts with the aluminum angle shaft and release instances, which are much harder and liable to damage the plastic components of the ramp. In the case of the ramp plate, the cracking could also be attributed to stresses placed on the plate as a result of any small misalignment of the release master or ramp shaft in the stiffeners, which are attached to the ramp plate and can put shear stress on the acrylic sheet. This was an oversight in our engineering analysis, one that we would like to see corrected by future ME 450 teams to ensure that our device has a high life cycle, and will result in little wasted material.

Finally, our team would like to confirm that this device is capable of enhancing student understanding of the concepts presented in ME 240. This is a difficult metric to measure, however, especially prior to the implementation of the device in the class. We feel that the best method of verifying that our product will help students is to present our student guide to the Center for Research on Learning and Teaching (CRLT). The CRLT aims to ensure that any material presented to students in an evidence-based fashion will be robust enough for students to use and understand. With this in mind, our team would like to submit our student guide to the CRLT to ensure that the way in which we guide students through the intended demonstrations will be beneficial to their understanding of the demonstration's concepts, as well as to gather advice as to how the student guide can be improved. Howevermhis was not something our team was able to complete within the scope of the semester, and will need to be completed by our sponsors or a future ME 450 team. While this will give a general idea of how beneficial our student guide will be, the success of our deliverables in meeting this requirement will mostly be proven through the validation of student use. Once our deliverables are implemented in the ME

240 curriculum, the benefit of our product can be validated by measuring the increase in student understanding following the product's use. This can be measured by comparing the average test scores prior to and following the implementation of the device, and observing whether test scores increase by the intended 5% specification for the learning effectiveness requirement. This cannot be done within the remaining part of this semester, however, and thus is outside of the scope of our team's testing. This metric can instead be validated by future ME 450 teams, who can refine our final deliverable if necessary. This metric is also somewhat limited in terms of how accurately it can be measured. ME 240 students taking the class at different times may simply have different understandings of dynamics coming into the class, rather than the use of the device impacting their comprehension skills. It is unreasonable, however, to ask students to repeat ME 240 to show an improvement of understanding after using the device, so this method of analysis will be adequate for measuring changes in comprehension.

It is possible that, following the implementation of our deliverables in the ME 240 classroom, the professors may change the requirements they have for these educational devices. We found that, over the course of this semester, our sponsors placed more emphasis on developing the student guide and tracking software than on the variable ramp prototype, which our team did not anticipate at the beginning of this project. This could also happen following the implementation of the deliverables, as our stakeholders find issues with our product that weren't identified over the course of this semester. This is an expected part of the validation process, and can be corrected through the work of future ME 450 teams, both through revisions to the products we will pass off to our sponsors, and in changes made to any future educational devices that are created.

Discussion

While our team feels that we were able to produce final deliverables that will improve the educational experience of ME 240 students, there were some flaws in our design process that we would address if we were able to repeat this project. Early in our design process, our team planned to send a survey intended for current and past ME 240 students with the intention of informing our team of what topics have been found most difficult within the ME 240 curriculum. This would allow our team to focus on generating concepts that directly addressed the dynamics concepts found to be the most challenging, and in doing so, we would likely design a device that would show the most improvement of student understanding. However, during this stage of our design process, we found that we did not have enough time to develop a survey that we felt was adequate for gathering student feedback, and thus focused instead on the instruction we received from our sponsors. If we had more time, our team would have spent a significant portion of our project gathering input from students to ensure that the stakeholders who would interact with our product the most were happy with our final deliverables. This could be accomplished using a survey sent out to ME 240 students, or we could have attended ME 240 lectures to directly ask students what topics they were struggling with. We would also likely spend more time talking to our sponsors, despite having gathered their feedback early in the process. During the problem definition phase of our design process, we only met with our sponsors a handful of times. While these meetings were informative, it would have been beneficial to discuss what concepts students struggled with in more depth, as this would have allowed us to narrow our focus during the concept generation phase of the design process.

The biggest strength of our design is that it is not limited to one product. Our final design incorporates a physical educational device, tracking software, and a student guide. If we were to only deliver one of these products to our sponsors, the impact of this project on engineering students would be significantly reduced. The physical device ensures that students can gain visual and hands-on experience with the dynamics problems they analyze in class, the tracking software allows them to collect meaningful data to compare real-world systems to their theoretical knowledge, and the student guide lets students effectively teach themselves how to conduct and analyze experiments, rather than having to listen to a professor simply teach the material. Where our design is weak is that it only addresses a handful of concepts within the ME 240 curriculum. Our student guide currently only addresses static friction, rolling kinematics, and moments of inertia of simple objects. This can be improved by having future student teams focus on adding more demonstrations to our current student guide so ME 240 students can compare more theoretical scenarios to real-world data. This would also benefit from the creation of additional devices aimed at other dynamics concepts, as this would allow ME 240 students to physically demonstrate more than just rolling motion problems. Another weakness of our design is the material of the ramp plate. We found that, following the assembly of the variable ramp, cracks formed in the acrylic ramp plate, likely due to stresses from the mounting of the stiffeners and release mechanism. This can be improved by changing the material used for the ramp and base plates, such as some form of sheet aluminum to preserve the lightweight design of the ramp.

The most significant challenge our team encountered in our design process was deciding which concept within the ME 240 curriculum to demonstrate. The scope of this project was only limited to the ME 240 curriculum, not any specific topic within the course. With ME 240 covering a wide range of dynamics topics, and recognizing that presenting multiple concepts would be difficult within the scope of the semester, it was difficult for us to choose one concept to demonstrate with our final deliverables. We recognize that not all students will find the same concepts within the course challenging, and in being limited to one section of the curriculum, we would likely be unable to improve the understanding of all ME 240 students. The risk inherent in this challenge is that we would choose to demonstrate a topic that no students find difficult, and in doing so fail to help students understand the course's dynamics concepts. In order to address this risk, our team turned to our project's sponsors. During the concept selection process, our team presented a list of potential concepts to our sponsor. The primary objective of doing so was to ensure that the device we chose to develop would be of use in the ME 240 classroom, and would help students to better understand the course material. The risk remains with our end-users, however, that our device may not help every student taking ME 240. Every student has their own challenges, and our device may not address the needs of everyone. While we were unable to address this challenge within the scope of this semester, we have encouraged our sponsors to have future ME 450 teams work on additional devices to demonstrate a larger portion of the course curriculum.

Reflections

With the completion of our final deliverables, our team has reflected on the potential impacts of our project, how culture and identity have shaped our design process, how inclusion and equity played a role in developing our deliverables, and the ethical issues relating to our project. These reflections are discussed in the following sections.

Potential Impacts

Our final deliverables are unlikely to have a significant impact on the public unless it becomes used beyond the University of Michigan. Public health was not of significant relevance to this project, because it is only intended to be used in the ME 240 classroom. While the use of our product on a larger scale could have an impact on public health, in its current state our product is only likely to impact ME 240 students and professors. If our project does become more widespread, it may become more important to consider the materials that our deliverables use, as we would like to ensure that the large-scale production of this device does not contribute significant amounts of pollution to the environment. Similarly, public safety was not of significant importance to this project due to the restricted use of our device. If our project were used on a larger scale, it would be important to consider how the use of our device could prove dangerous, such as through moving parts or sharp surfaces, and amend these design flaws or ensure proper safety measures are put in place. Finally, public welfare was not a significant concern regarding our device, again due to the limited use of our device. In the event that our device becomes used at colleges beyond the University of Michigan, it will be important to ensure that our device is affordable and benefits all users equally. The goal of this project is to further the education of all engineering students, not a select group, so it is important to assess which students continue to struggle following the implementation of our deliverables to ensure that all students find equal benefit from our device prior to their widespread use.

If our design proves to be successful in the ME 240 classroom, it would likely be of benefit in a global marketplace. Our deliverables are intended to improve student understanding of engineering dynamics, a topic not unique to the University of Michigan. Assuming that students in ME 240 find our device to be helpful in improving their knowledge of dynamics, students at other universities would likely also benefit from using the device. With this in mind, it would likely be beneficial to provide other schools with access to the design, whether that be through assembly plans or prefabricated duplicates of our design. This would give a larger number of engineering students access to a device that would improve their understanding of engineering concepts, and in doing so would allow future engineers to design better products for their customers and society as a whole.

The most significant social impacts associated with our final deliverables will be connected to our device's use. At the beginning of our design process, we identified that the current lack of a connection between theoretical dynamic systems and physical applications could lead engineers to design products that were incapable of addressing their customers' needs adequately, which we felt could lead to social issues going unaddressed. With the development of our product, however, we feel that we have bridged the gap between theoretical and practical applications in engineering dynamics, which should give students a better understanding of how to design products that adequately address problems currently being faced by society. While our primary goal was to enhance student understanding of engineering concepts, we believe that doing so will also have a positive impact on students' capability to design systems that can benefit society as a whole. The manufacture and disposal of our device will not have nearly as significant an impact on society as its use, we expect that these phases of our product's life cycle will have a more significant impact on the environment. With our product being primarily made of metals and plastics, a significant amount of machining was required to create our final deliverables, which could have a detrimental impact on the environment through pollution if the manufacturing of our product becomes widespread. The use of plastic will also impact the environment at the end of our product's life, as plastic is typically difficult to efficiently recycle. With this in mind, we aimed to design our product to maximize its lifetime and ensure that materials aren't being wasted due to constant repairs.

Unless the use of our device becomes widespread, it is unlikely that our product will have any significant economic impact. The purchasing of materials and machining of our final product cost less than $400, and only uses electricity as part of the tracking of the demonstrations. These will not have a significant economic impact assuming that our final deliverable is the only version that is used in classrooms. This also applies to the disposal of our device, as our device can simply be disassembled to replace any parts as they fail, rather than replacing the entire device. However, this economic impact could be more significant if our product becomes more widespread. In the event that other colleges adopt our educational device design, the mass manufacturing of the device, and potentially its sale, would have a significant economic impact. While the use of our device would still be unlikely to have an economic impact, its disposal would likely be more significant, as the creation of multiple devices would also necessitate the repair and replacement of said devices. However, we would expect that any significant economic impact of our device would come well after its implementation, as time will be necessary to implement our deliverables and determine if they are truly beneficial.

In order to ensure that our team considered all of the potential societal impacts of our design, we primarily relied on a stakeholder map, shown in Figure 2 on pg. 13. This map allowed us to identify all of the most significant stakeholders related to our project, and ensure that the majority of the impact of our device will be positive. As can be seen in the stakeholder map, we categorized each stakeholder by the significance of our device's impact, the type of relationship they share with our project, the societal context of said relationship, and whether our product will be beneficial or detrimental. All of these categorizations ensured that our team took every aspect of this project into consideration when designing a solution to the problem we were tasked with solving.

Cultural, Privilege, Identity, and Stylistic Effects

Identity and stylistic differences had the largest influence on the approaches our team took throughout the course of the semester. Each member of this team comes from a different background, and as such has a unique perspective and experience in the engineering field. Some members of our team had significant experience working with machining and manufacturing, in some cases owning personal manufacturing equipment. Others had more experience working with engineering software, writing programs or analyzing systems through finite element analysis. While this did influence which deliverables of the project each member considered to be most important, this did not have a negative impact on the final product we will deliver to our sponsors. Instead, our team took the approach of leveraging the expertise of each member of the team to complete various tasks within our project. The members of our team most experienced with product manufacturing were tasked with the overview and completion of the machining and assembly of the variable ramp deliverable, while those more experienced with engineering software took responsibility for the development of the tracking software. Rather than leading to disagreements and delays in the design process, the unique identities and styles of each member of the team allowed us to focus our best efforts towards the aspects of this project that we were the most familiar with. This in turn allowed us to produce final deliverables that we are proud of, and are satisfied with passing off to our sponsors.

Identity, style and power played a large role in influencing the interactions our team had with our sponsors regarding the design process and final design. Initially, our team felt that focusing on the completion and refinement of our variable ramp build design would be most beneficial to ME 240 students, as this experimental aspect is largely missing from the ME 240 curriculum. Our intent was to ensure that students were able to visualize the effects of changing system parameters, as well as give them multiple ways to physically change the parameters of the demonstrations they would conduct. Our sponsors, however, felt that focusing on the development of the tracking software and student guide was more important to the success of this project in the ME 240 classroom. They felt that the demonstrations that students would conduct using our variable ramp should be similar to those that are conducted in classes like ME 395, which see students following a guided demonstration and collecting data to be analyzed at a later point in time. For our product to match this format, we would have to put aside some of our focus on refining our variable ramp design and instead develop instructions for students to follow to run the intended demonstrations and provide a method for collecting data on these demonstrations. With our sponsors having significant experience with instructing students, as well as the power dynamic between them and our team, we felt that it would be beneficial to defer to them, as they would likely better understand how to make concepts easier to understand for students than we would. It was also their feedback that encouraged us to pursue the variable ramp design, however, as we presented our initial design to them prior to moving forward with prototyping the concept. They felt that the device we had designed was similar to what they had envisioned for this project, and encouraged us to move forward with our variable ramp design.

Inclusion and Equity

Throughout our design process, our team held most of the power over our stakeholders in a number of ways. Our team was largely responsible for contacting our stakeholders for any information or input regarding our project, which included our project sponsors. This meant that it was largely our team's decision of how often we would interact with our stakeholders, as well as what direction we decided to pursue for our final deliverables. While our project's sponsors had some control in terms of the information they gave to our team, they largely gave us the power to decide what topics to pursue within the ME 240 curriculum and how to design a device that would address these concepts. These power dynamics also apply to our end users, the ME 240 students, who were not given any direct power over the execution of this project. The identities and experiences of the members of our team had a significant impact on our perspective of this project, which may potentially contradict the perspectives of our end users. When we took ME 240, we found rolling motion to be one of the more challenging aspects of the course's curriculum, which is why we felt the variable ramp design would be beneficial for students taking the course. Every student is an individual, however, and may not have trouble with the concepts that we found challenging. This may mean that our product will not be as beneficial to some students as others, which is why the construction of additional educational devices may be necessary in order to address other challenging dynamics concepts.

Each member of this team has a unique identity as well, which shaped each of our perspectives in different ways. The members of this team had experience with a wide range of engineering experience, with some of us more familiar with manufacturing and machining processes, and others more knowledgeable of coding and simulations. This informed what each member felt was the most important aspect of our project to focus on completing by key deadlines throughout the semester, but was also something our team leveraged to our advantage. With our deliverables relating to different areas of engineering, the members of our team were able to focus on the completion of the deliverables that most related to the engineering experience each had, allowing us to make significant progress towards refining each deliverable before the end of the semester.

In order to include diverse viewpoints of both stakeholders and team members in our project work, our team met with our sponsors, the ME 240 professors, as often as possible to gather their insight on our project. This was done by meeting our professors in person and presenting the state of our deliverables, following which the professors would give us feedback as to the direction we should take the project moving forward. We felt that this was the best method for including the views of our stakeholders with the given time to complete this project. We had originally wanted to contact ME 240 students to gather their input as well, but found that we did not have enough time to do so. We hope to amend this through our recommendations for future validation for our deliverables.

Our team primarily looked to our sponsors for their input regarding the direction we took the project. While we had primary control over what shape our final deliverables would take, we felt that the ME 240 professors should have the most say in the final design of our product for two reasons. Firstly, the ME 240 professors will be some of the individuals using our device, while our team will not. We felt that, in designing a device to be used by another group, we should primarily consider what form the users would want the product to take, rather than the opinions of our team's members. Secondly, the ME 240 professors have much more experience in teaching students dynamics concepts than the members of this team. The professors both have a better understanding of the course material, and of the best methods for increasing student understanding of said material. With this being the case, our team looked to the ME 240 professors to ensure that the deliverables we developed would be beneficial in a classroom setting. While the team looked to the professors for information regarding what form our deliverables would take, we largely made decisions regarding the physical design and material choices for this project, as we felt that these decisions could be made independently based on the general feedback our sponsors gave us.

Ethics

The most significant ethical dilemma that our team considered during the design of this project was the impact our product could have on students who struggle with standard teaching methods. We recognized that students can require various teaching methods, and traditional lectures may not benefit all students equally. This is why we aimed to design a device that did not rely on traditional teaching methods to convey dynamics concepts to students, instead incorporating more physical aspects so that students could change the systems they worked with themselves. We had initially intended to contact ME 240 students to gather information about what topics certain students struggled with, potentially organizing their responses by which students had learning disabilities to prioritize the benefit of our device to these marginalized students. We were limited in time, however, and now intend to gather student feedback on our final deliverables to gain insight as to how our device was beneficial for these neurodivergent students. This would also be applicable if our products were to enter the marketplace, as they would likely be used by a larger number of neurodivergent students. It would be beneficial to gather feedback from struggling students at the University of Michigan prior to the product entering the marketplace, as this would allow any issues with the current iteration of our deliverables to be corrected before being used by more neurodivergent students. The price of our deliverables would also be a significant ethical dilemma to address prior to implementing them in the marketplace. Beyond ensuring that neurodivergent students are able to use our devices, we want to ensure that the use of our product is not limited to the affluent. Making our device affordable for all schools would ensure that all students can experience the benefits of using the device. This should be addressed by reconsidering the materials used in our variable ramp to determine if a cheaper iteration of the device would be viable.

Throughout the course of this semester, our team was expected to abide by both the university's Code of Conduct and the College of Engineering's Honor Code. These require the submission of original work, or the credit of others when referencing their material, as well as the guarantee of the safety of those who come in contact with our products. The morals of this team closely match those of the university, as we aim to produce work that is entirely our own, and will ensure that the devices that we produce will not only be safe and beneficial for those using our device, but for society and the environment as well. This is reflected in the deliverables that we have produced for this class. To further meet our personal ethics, our team has designed our final deliverables to be beneficial to those who struggle the most with ME 240 concepts and the manner in which they are presented, rather than the student body as a whole. While we believe our future employers will have similar ethics, they may be more lenient about designing products that benefit the end users in favor of products that primarily benefit the company. We will work to ensure that all devices we design in the future are meant to benefit their users and society first and foremost, as the ultimate goal of engineering should be to improve lives globally through the products we design.

Recommendations

Following the completion of this semester, our team would recommend that our sponsors evaluate the effectiveness of our device in a classroom setting. While we believe that our product is capable of enhancing student understanding of dynamics concepts based on its success in meeting our functional requirements, it would be beneficial to implement our variable ramp in one of the upcoming semester's ME 240 lectures. This direct method of evaluating our product would allow our sponsors to determine whether our device is capable of improving students' grades, and whether additional educational devices should be implemented in the classroom. We would recommend evaluating each of our deliverables separately, rather than as a comprehensive product, as students may find our student guide or tracking software to be more beneficial than the variable ramp itself. These products can be implemented as one lecture demonstration, but be sure to gather feedback on each aspect of our deliverables, not just the variable ramp. We would also recommend that our sponsors encourage future teams to develop additional devices that address other topics within the ME 240 curriculum if our device is found to be successful. We recognize that our final deliverable is limited in scope, and will only be capable of addressing a handful of ME 240 concepts, so we would like to see future teams develop more educational devices to improve student understanding of engineering dynamics. To the teams exploring the development of additional devices, we would recommend reaching out to ME 240 students very early in the design process to ensure that their feedback is taken into consideration. While we felt that time was a limiting factor in not being able to reach out to these students, we also spent the majority of the first phase in our design process simply defining the problem, so we believe it should be possible for future ME 450 teams to reach out to ME 240 students prior to concept development with this information.

Our team also recognizes that our final deliverables are unlikely to be the final product implemented in ME 240 classrooms, and would like to make recommendations for improvements to these final deliverables. Firstly, we would recommend that both the base plate and the ramp plate of the variable ramp be replaced following a material assessment. After assembly of our ramp, our team found that while the ramp was sturdy enough to hold all of the intended objects, the stresses put on the ramp plate due to the mounting of the release mechanism caused cracks in the slots machined out of the acrylic ramp plate. This should be assessed and amended, as cracking could cause failure in the design over time. Our primary recommendation would be to use a thin sheet of aluminum in place of the acrylic ramp and base plates, though further research on potential materials would also be beneficial to determine the optimal material. We would also recommend that the bushings used to align the release mechanism be replaced with ball bearings, as we found that the release mechanism was fairly stiff and difficult to turn. While we expect ball bearings to be the best method to fix this problem, other potential solutions should be considered. We also recommend widening the slots for the release mechanism on the ramp plate. We found that the release mechanism tended to get stuck when moving through the ramp plate, likely due to a slight misalignment of the release mechanism. This should be a simple fix, as widening the slots in the ramp plate should prevent interference with the release mechanism. To improve the performance of the tracking software, it may be beneficial to purchase a camera capable of filming the demonstrations in slow motion. This will control the frame rate of the videos students will input into the tracking software, and thus remove an input that could contribute to the error of the collected data. A potential camera that may be of interest can be found here [26]. Additionally, we recommend using this camera with an associated stand, either purchased or 3D printed. The stand would help control the camera's height and distance from the ramp, ensuring proper recording of the experimentation. If the stand is to be 3D printed, a great example can be found here [27]. Finally, we would recommend changing the calibration of the tracking software. Currently, students set the distance reference in their videos by clicking and dragging their cursor between two dots placed on the ramp. This can be difficult, and could be made easier by changing the input to clicking on the two dots instead of dragging the cursor between them. It may also be beneficial to explore alternative methods of tracking the objects, such as embedded IMUs. We found that the tracking software did not measure the position of the objects on the ramp consistently, and that there were significant differences between the collected data and the theoretical behavior. While this may be a result of discrepancies between the tests, it is worth researching and testing other tracking methods to determine if more consistent data can be obtained.

Conclusions

Throughout this semester, our team has faced the challenge of trying to enhance students' understanding of the engineering dynamics concepts presented in Mechanical Engineering 240 through the implementation of a physical education device. Our team began this project by researching the existing educational devices and stakeholders connected to this problem, and identifying the potential impacts our solution could have. At the same time, our team met with our project's sponsors to outline a list of characteristics that our final product was intended to exhibit, including easy to transport, easy to use, capable of tracking, and educationally beneficial. From this initial research, our team generated a list of concepts using a number of brainstorming techniques, including morphological charts and design heuristics, then refined and organized these concepts based on the concepts they were intended to convey. All of these initial concepts were evaluated, and the best solutions were presented to our sponsors for feedback. The input from our sponsors led our team to pursue the development of a variable ramp design, in conjunction with a student guide and tracking software. The variable ramp will allow students to investigate the impact of changing system parameters on static friction, rolling kinematics, and moments of inertia, while the student guide will lead the students through the demonstrations intended to convey these concepts, and the tracking software will allow them to collect meaningful data that can be compared to the theoretical analysis the students conduct in class. Our team has analyzed the iteration of the variable ramp that we will pass off to our sponsors, and believes that this design is capable of meeting the majority of the identified functional requirements. We have identified some issues with our final deliverables, for which we have given our sponsors a list of recommended amendments to our design. We also encourage the validation of our design through user testing and surveys following the implementation of the variable ramp in the ME 240 classroom. Despite some small flaws, our team feels that our final deliverables are capable of improving the understanding of engineering students in the classroom, and that any issues remaining with our device can be addressed with further refinements of our design while the product is utilized in the classroom. Given the scope of the project and the limited time provided, we feel that our final deliverables have made impressive headway at solving the challenge of enhancing understanding of engineering dynamics, and hope that future ME 450 teams will add to our work through the generation of additional educational devices.

Acknowledgements

Our team would like to thank our sponsors, Professor Alex Shorter and Lecturer Jeffrey Koller, for their input and feedback on our project over the course of the semester. The information they provided us ensured that we designed a device that will be beneficial once implemented in the ME 240 curriculum. We would also like to thank our section instructor, Professor Kira Barton, for her guidance regarding the presentations and reports our team produced as part of the ME 450 course. Her feedback on our work led our team to produce comprehensive summaries of our work that we were able to present to our sponsors for further instruction. Finally, we would like to thank the engineering department's librarian, Ms. Sarah Barbrow, for her assistance with collecting standards and papers relating to our project.

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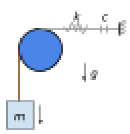
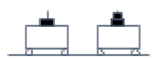
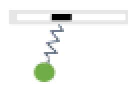
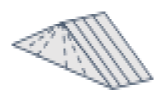
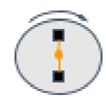
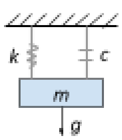
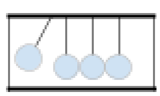
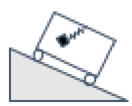
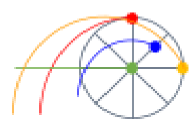
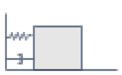
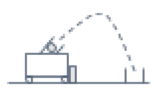
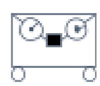
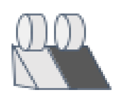
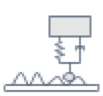
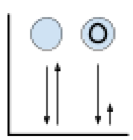
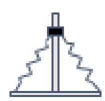
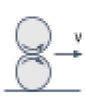
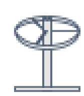
Appendix

The following appendices are meant to provide a more comprehensive summary of our team's design process and work over the course of this semester. These appendices have been organized according to the topics each addresses within our design process.

Appendix A: Concept Generation

This appendix provides an overview of the different design concepts generated during the concept generation and selection phase of our design process. Each of these designs provides a concept that could potentially be developed by future ME 450 teams into additional educational devices.

Table A1: A full list of the concepts generated by our team. Each concept is listed under one of the five categories created during the concept selection phase of our design process. The concept selection score each design received is listed alongside its description. The designs have been ordered based on their concept selection scores from highest to lowest.

Mass-Spring-Damper System	Collisions	Pendulum/Mass -Spring System	Wheel Motion & Friction	Rotational Inertia
 Controlled Pulley (51)	 Cart Collisions (72)	 Pendulum Track (75)	 Variable Ramp (80)	 Rotating Mass on String (72)
 Hanging Mass (51)	 Newton's Cradle (70)	 Pendulum Cart (75)	 Wheel Tracker (77)	 Hoberman Sphere (69)
 Sideways Shock Absorber (44)	 Cart Cannon (67)	 Tension Cart (75)	 Friction Ramp (70)	 Parallel Axis Proof (66)
 Road Simulation (36)	 Elastic vs. Inelastic (65)	 Spring Accelerator (68)	 Linked Wheels (68)	 Adjustable Flywheel (41)

Appendix B: Engineering Analysis and Testing Plans

This appendix provides a summary of the engineering analyses, as well as verification and validation plans, our team designed to evaluate the efficacy of our final product, as well as additional calculations necessary for understanding and assessing our device.

Table B1: A full list of the functional requirements and corresponding engineering analysis to perform on build design to estimate if specifications are met. Each requirement is matched with an analysis plan with justifications provided for said plans.

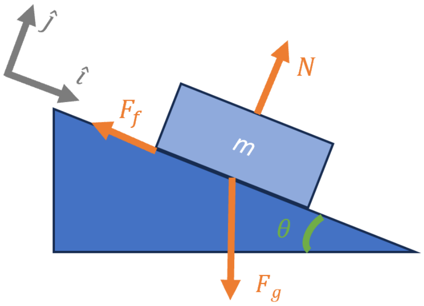
Requirement	Specification	Engineering Analysis	Justification
Easy to transport	Lifting index ≤ 1.0 Width: 200mm-500mm Length: 200mm-500mm Height: 200mm-500mm	1) Use CAD to estimate design mass; ensure mass ≤ 16 kg for lifting index ≤ 1.0 2) Kinematic calculations to ensure device is stable on flat surface	1) CAD can provide estimation of actual mass prior to prototype construction
Easy to use	Ready to demo in < 5 steps AND < 5 minutes Requires ≤ 2 tool to change configurations	1) Ensure bolts are uniform 2) Calculate number of steps needed to set up and operate demonstration to ensure under 5 steps	1) Bolt uniformity will ensure number of tools needed to repair product is minimized
Capable of tracking	Must be able to track at minimum 1 of the following metrics: time, displacement, velocity, acceleration, or force	1) Ensure tracking devices can be secured for reliable data collection. 2) Ensure selected measurement devices have minimum 2 decimal points for measurement.	1) Based on prior experiments in ME 395, 2 decimal point round off is high enough fidelity for given experiments
Learning Effectiveness	Students must demonstrate increase of 5% perceived understanding of topic using Likert scale survey	1) Develop Likert scale to access before and after student understanding of topic	1) Student understanding is subjective. Likert scale best way to rate subjective view on topic comprehension
Durable	Fatigue lifetime ≥ 10^5 cycles	1) Ensure lifetime specifications of any bearings or motors used are ≥ 10^5 cycles 2) Static hand-calculations to ensure design can withstand expected forces 3) Complete FMEA for design	1) Lifetime specifications can provide rough estimate of how long product is expect to function
Adjustable input parameters	Capable of ≥ 2 and ≤ 10 configurations	1) Use CAD to ensure different configurations are achievable 2) CAD simulations to ensure design has intended range of motion	1) CAD simulations enough simulation to understand range of motion
Interactive	Students must be able to independently operate device	N/A	N/A
Accuracy	Experimental results with ≤ 10% of first principle model or simulation results error	1) Run simulations within CAD or another CAE tool to ensure the theoretical first principle model matches the simulations.	1) If the analytical model is able to match CAE simulations, and those match the experimental results, then we can gain certainty in device accuracy.

Table B2: A full list of the functional requirements and corresponding engineering analysis to perform on build design to estimate if specifications are met. Each requirement is matched with an analysis plan with justifications provided for said plans.

Requirement	Specification	Verification Plan	Validation Plan	Justification
Easy to transport	Lifting index ≤ 1.0 Width: 200mm-500mm Length: 200mm-500mm Height: 200mm-500mm	1) Use mass scale to confirm mass ≤ 16 kg 2) Measure maximum dimensions of prototype using ruler	1) Carry object from 3rd floor of GGBL to 1st floor, subjective carrying rating must be "easy"	1) 1st floor to 3rd floor, approximate distances the device will need to be hand carried
Easy to use	Ready to demo in < 5 steps AND < 5 minutes Requires ≤ 2 tool to change configurations	1) Run demonstration 10 times number of steps needed for setup is < 5, amount of time needed for setup is < 5 minutes, and number of tools needed for changing configurations is ≤ 2 2) Amount of time needed to complete data collection for each activity ≤ 45 mins	1) Record number of steps and time taken for in-class setup 2) Ensure demonstration can be completed within a class period	1) Assuming 10 runs per semester, shows consistent use for entire semester 2) 90 minute block, students will take longer to run activity. If team team members can complete in ½ time, students highly to complete by end of 90 min block
Capable of tracking	Must be able to track at minimum 1 of the following metrics: time, displacement, velocity, acceleration, or force	1) Run demo 5 times. Successful runs if data collection was able to be completed as intended with meaningful data, and data tracking devices remain in intended locations	1) Have students conduct demonstration and record. Ensure students are capable of extracting data from tracking software	1) Students need to have access to usable system information to compare data to theoretical analysis
Learning Effectiveness	Students must demonstrate increase of 5% perceived understanding of topic using Likert scale survey	1) Have Center for Research on Learning and Teaching review student guide to ensure it is adequate for guiding students	1) Conduct testing with ≥ 5 students. Perceived understanding of topic should increase by 5% using Likert survey	1) Student understanding is subjective. Likert scale best way to rate subjective view on topic comprehension
Durable	Fatigue lifetime ≥ 10^5 cycles	1) Part cycle test of moving mechanisms 100 consecutive times to ensure reliability of components 2) Run full system demonstration 100 times in a row, all demonstration runs must work with intended user setup and operation to be successful	1) Record number of in-class demonstrations before prototype failure	1) Assume 5 year lifecycle and 10 uses per semester 2) 10 uses/semester * 2 semester/year * 5 years = 100 uses
Adjustable input parameters	Capable of ≥ 2 and ≤ 10 configurations	1) Have team test range of motion on prototype to ensure all configurations are attainable	1) Have students test range of motion on prototype to ensure all configurations are attainable	1) Final deliverable should demonstrate full promised range of motion
Interactive	Students must be able to independently operate device	1) Have team run through demonstration using student guide exactly. Ensure all necessary steps are accounted for	1) Students must be able to independently operate devices without external guidance from professors	1) Student interaction requires that students must be able to operate device when professor is away attending to other students or otherwise occupied
Accuracy	Experimental results with ≤ 10% of first principle model or simulation results error	1) Compare experimental data to theoretical model to verify data collected within 10% of model	1) Have students conduct demonstration 2) Ensure students see similarities between theory and experimental data	1) Students should be able to visually recognize similarities between theoretical and experimental behavior

Question: At what angle does the block fall?

- Assume Coefficient of Static Friction (μ_s) is known



Forces

- $\vec{F_f} = -F_f\hat{\imath} = -\mu_s N\hat{\imath}$
- $\vec{N} = N\hat{j}$
- $\vec{F_g} = mg[\sin(\theta)\,\hat{\imath} - \cos(\theta)\hat{j}]$

Acceleration

- $\vec{a} = \vec{0}$

Newton's 2nd Law

$$\sum \vec{F} = m\vec{a}, \quad \vec{a} = \vec{0}$$

$$-\mu_s N\hat{\imath} + N\hat{j} + mg[\sin(\theta)\,\hat{\imath} - \cos(\theta)\hat{j}] = 0$$

$\hat{\imath}$: $-\mu_s N + mg\,sin(\theta) = 0$ $\qquad$ $\hat{j}$: $N - mg\,cos(\theta) = 0$

$$-\mu_s(mg\,cos(\theta)) + mg\,sin(\theta) = 0 \quad \leftarrow \quad N = mg\,cos(\theta)$$

$$\sin(\theta) = \cos(\theta) \cdot \mu_s$$

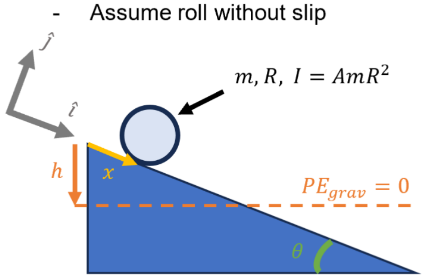
$$\tan(\theta) = \mu_s$$

$$\boxed{\theta = \tan^{-1}(\mu_s)}$$

Figure B1: A derivation of the theoretical model of the static case of the "Variable Ramp" design.

Question: How long does it take objects of *similar* Moment of Inertia to roll down the ramp?

- Given Moment of Inertia: $I = A \cdot mR^2$, where *A* is a constant determined by the object's shape
- Also given that the object starts from rest ($v(0) = 0$)
- Assume roll without slip



Conservation of Energy

$$PE_{initial} + KE_{initial} = PE_{final} + KE_{final}$$

$$PE_{grav} = KE_{trans} + KE_{rot}$$

$$\omega = \frac{v}{R} \rightarrow mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

$$mgh = \frac{1}{2}mv^2 + \frac{1}{2}\cdot AmR^2 \cdot \left(\frac{v^2}{R^2}\right)$$

$$gh = v^2\left(\frac{1+A}{2}\right)$$

$$v^2 = \frac{2gh}{1+A}$$

$$v(h) = \sqrt{\frac{2gh}{1+A}} \qquad h = x \cdot \sin(\theta)$$

$$v(x) = \sqrt{\frac{2gx \cdot \sin(\theta)}{1+A}}$$

Useful! But we're looking for how long it takes for the object to roll down the ramp

$$\frac{dx}{dt} = \sqrt{\frac{2g \cdot \sin(\theta)}{1+A}} \cdot \sqrt{x}$$

$$x^{-1/2}dx = dt\sqrt{\frac{2g \cdot \sin(\theta)}{1+A}}$$

$$\int_0^x x^{-\frac{1}{2}}dx = \int_0^t dt\sqrt{\frac{2g \cdot \sin(\theta)}{1+A}}$$

$$2\sqrt{x} = \frac{t}{2}\sqrt{\frac{2g \cdot \sin(\theta)}{1+A}}$$

$$x(t) = \frac{g \cdot \sin(\theta)}{2(1+A)} \cdot t^2$$

For total length of ramp, L, and total height, H

$$x(t_f) = L \rightarrow L = \frac{g \cdot \sin(\theta)}{2(1+A)} \cdot t_f^2$$

$$t_f = \sqrt{\frac{2L(1+A)}{g \cdot \sin(\theta)}}$$

$$L = \frac{H}{\sin(\theta)}$$

$$t_f = \sqrt{\frac{2H(1+A)}{g \cdot \sin^2(\theta)}}$$

Figure B2: A derivation of the theoretical model of the rolling case of the "Variable Ramp", demonstrating a possible effect of moment of inertia on translation.

Appendix C: Build Design Bill of Materials

This appendix gives a complete overview of the materials and parts used in the creation of our variable ramp prototype. Part descriptions are included to explain the function of each part.

Table C1: The complete bill of materials for our beta build design. The manufacturer, part number, and cost of each item is listed, as well as the parts that will be made from stock materials.

Item	Quantity Purchased	Supplier	Catalog Number	Cost	Contact	Part(s) Created
12"x24"x1/8" Acrylic Sheet	3	McMaster	8505K722	$46.20	mcmaster.com	Base Plate, Ramp Plate, Rubber Plate
12"x24"x1/8" Rubber	1	McMaster	1370N55	$29.13	mcmaster.com	Rubber Sheet
12"x24"x1/8" Garolite Sheet	1	McMaster	8491K13	$28.19	mcmaster.com	Plastic Plate
3/4"x3/4"x1/16" Square Tube	2 ft.	McMaster	6546K52	$12.66	mcmaster.com	Leg
L-Channel	4 ft.	McMaster	8982K4	$13.33	mcmaster.com	Front Bracket, Stiffener A, Stiffener B
1/4"x36" Shaft	1	McMaster	1886K4	$13.98	mcmaster.com	Ramp Shaft, Angle Shaft, Release Handle, Release Instances
1/2"x6" Shaft	1	McMaster	6061K13	$6.35	mcmaster.com	Release Master
6"x12"x1/8" Acrylic Sheet	1	McMaster	8560K199	$4.87	mcmaster.com	Angle Bracket
1"x1" Aluminum Bar	1/2 ft.	McMaster	9008K14	$7.67	mcmaster.com	Aluminum Block
1" Aluminum Rod	1/2 ft.	McMaster	89535K37	$16.15	mcmaster.com	Aluminum Tube, Large Aluminum Disk, Small Aluminum Disk
1" Plastic Tube	1 ft.	McMaster	8627K629	$9.91	mcmaster.com	Plastic Tube
1"x1" Plastic Bar	1 ft.	McMaster	8739K92	$18.11	mcmaster.com	Plastic Block
Handle	1	McMaster	1786A11	$4.83	mcmaster.com	N/A
1/4" Bushing	10	McMaster	2938T2	$7.60	mcmaster.com	N/A
1/2" Bushing	2	McMaster	1677K338	$3.04	mcmaster.com	N/A
1/4" Retaining Ring	1 (100 pack)	McMaster	97431A300	$6.93	mcmaster.com	N/A
1/2" Retaining Ring	2	McMaster	92725A560	$4.90	mcmaster.com	N/A
Hinge	2	McMaster	1603A7	$9.08	mcmaster.com	N/A
1/16" Spring Pin	1 (250 pack)	McMaster	98296A027	$7.90	mcmaster.com	N/A
8-32 x 3/8" Button Head Screws	1 (100 pack)	McMaster	97763A177	$5.05	mcmaster.com	N/A
8-32 x 1/2" Button Head Screws	1 (50 pack)	McMaster	97763A178	$5.68	mcmaster.com	N/A
Bumpers	1 (10 pack)	McMaster	9541K24	$8.79	mcmaster.com	N/A
8-32 Nylon Locknut	1 (100 pack)	McMaster	90101A009	$8.99	mcmaster.com	N/A
Velcro	1	McMaster	9273K11	$7.17	mcmaster.com	N/A
Rubber Bands	1 (2675 pack)	McMaster	12205T74	$11.78	mcmaster.com	N/A
Total	N/A	N/A	N/A	$298.29	N/A	N/A

Table C2: The list of machined parts within our beta build design. Each part is listed with the material it is machined from, how many need to be machined, and what purpose each part serves within the beta build design.

Part	Material	Quantity Needed	Purpose
Base Plate	12"x24"x1/8" Acrylic Sheet	1	Provide structure and a mounting surface to build upon
Ramp Plate	12"x24"x1/8" Acrylic Sheet	1	Provide a plate to mount ramp surfaces to
Rubber Plate	12"x24"x1/8" Acrylic Sheet	1	Provide a plate to mount rubber sheet to
Rubber Sheet	12"x24"x1/8" Rubber	1	Provide high friction surface for demonstrations
Plastic Plate	12"x24"x1/8" Garolite Sheet	1	Provide a low friction surface for demonstrations
Leg	3/4"x3/4"x1/16" Square Tube	2	Provide mechanism for propping ramp open
Front Bracket	L-Channel	1	Provide a mounting surface for hinges
Stiffener A	L-Channel	1	Provide a mounting surface for release mechanism and provide ramp plate with additional strength
Stiffener B	L-Channel	1	Provide a mounting surface for release mechanism and provide ramp plate with additional strength
Ramp Shaft	1/4"x36" Shaft	1	Provide a pivot for the legs
Angle Shaft	1/4"x36" Shaft	1	Provide a mechanism for locking the ramp into the angle brackets
Release Handle	1/4"x36" Shaft	1	Control the release mechanism
Release Instances	1/4"x36" Shaft	3	Provide surface to align objects for demonstrations
Release Master	1/2"x6" Shaft	1	Provide a place to mount release instances
Angle Bracket	6"x12"x1/8" Acrylic Sheet	2	Provide slots for different angle configurations
Aluminum Block	1"x1" Aluminum Bar	1	Provide heavy block object
Aluminum Tube	1" Aluminum Rod	1	Provide heavy tube object
Large Aluminum Disk	1" Aluminum Rod	1	Provide wide disk object
Small Aluminum Disk	1" Aluminum Rod	1	Provide skinny disk object
Plastic Tube	1" Plastic Tube	1	Provide light tube object
Plastic Block	1"x1" Plastic Bar	1	Provide light block object

Appendix D: Instructions for Manufacturing

This appendix is intended to give instructions for replicating the manufacturing of our variable ramp device, and is intended to be followed after purchasing all of the required materials listed in the bill of materials provided in Appendix C, Table C1 on pg. 72. This appendix includes instructions and diagrams relating to which parts need to be machined, and in what order the ramp should be assembled. References will be made to the manufacturing drawings and manufacturing plans in Appendices E and F, respectively, as needed.

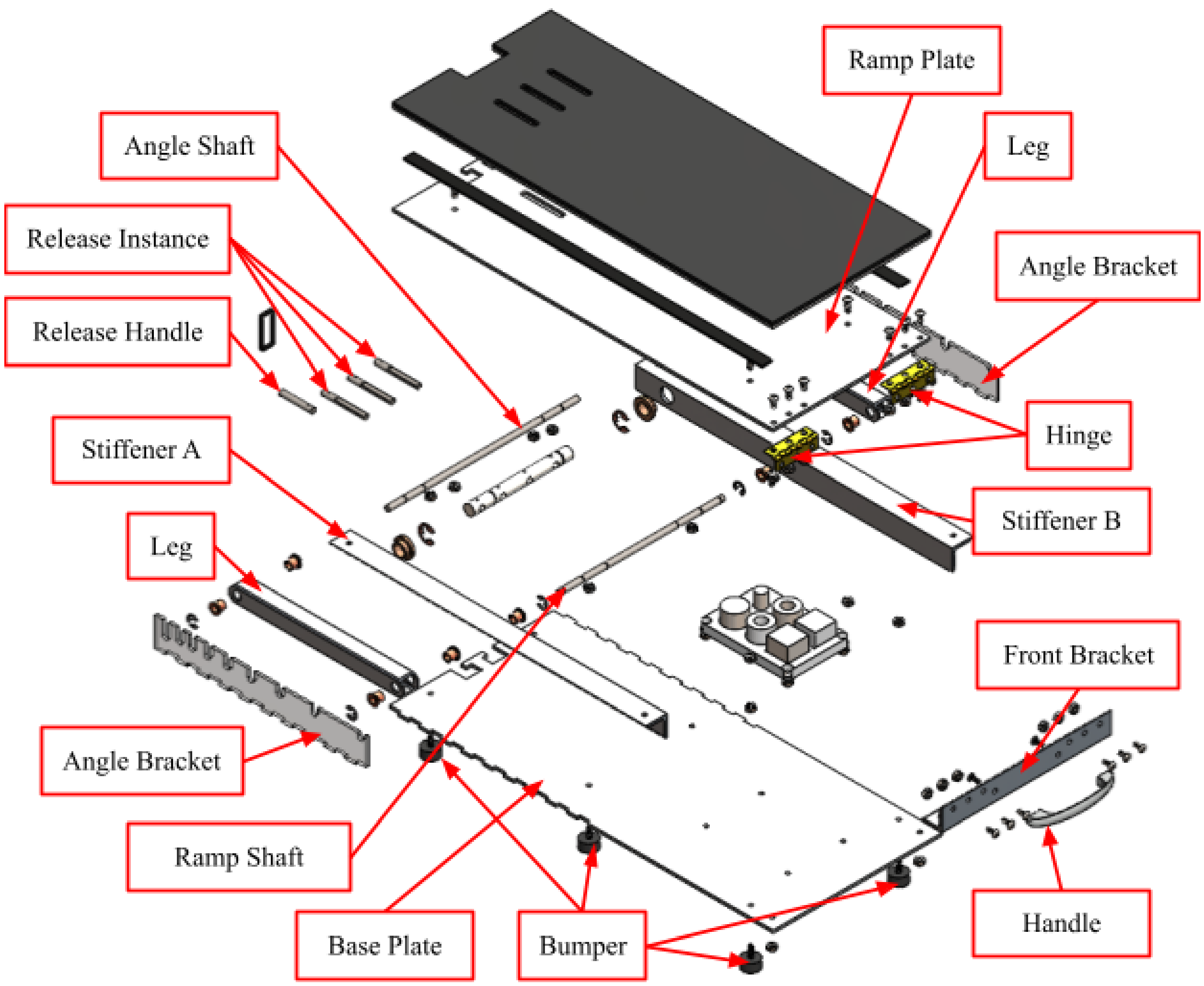


Figure D1: An exploded assembly of the variable ramp. Key components are identified.

1. Use the laser cutter provided in the undergraduate machine shop to cut the base plate. See Appendix E, Figure E1 on pg. 117 for the dimensions of the base plate. The base plate is shown below in Figure D2:

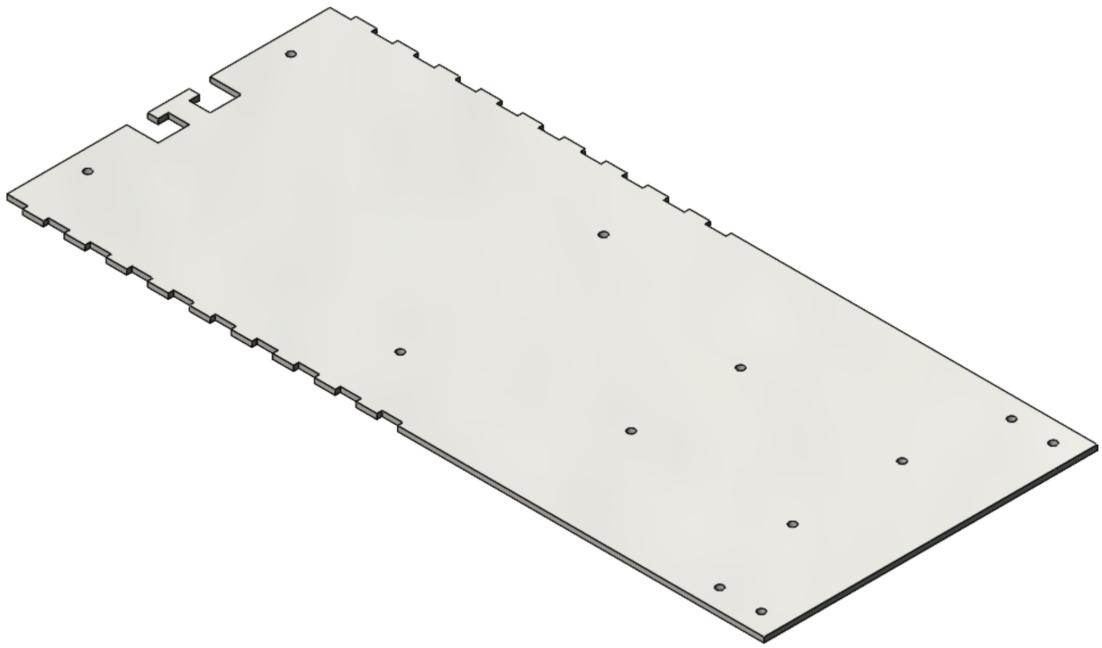


Figure D2: A CAD model of the base plate.

2. Use the laser cutter provided in the undergraduate machine shop to cut the two angle brackets. See Appendix E, Figure E7 on pg. 123 for the dimensions of the angle brackets. The angle bracket is shown below in Figure D3:

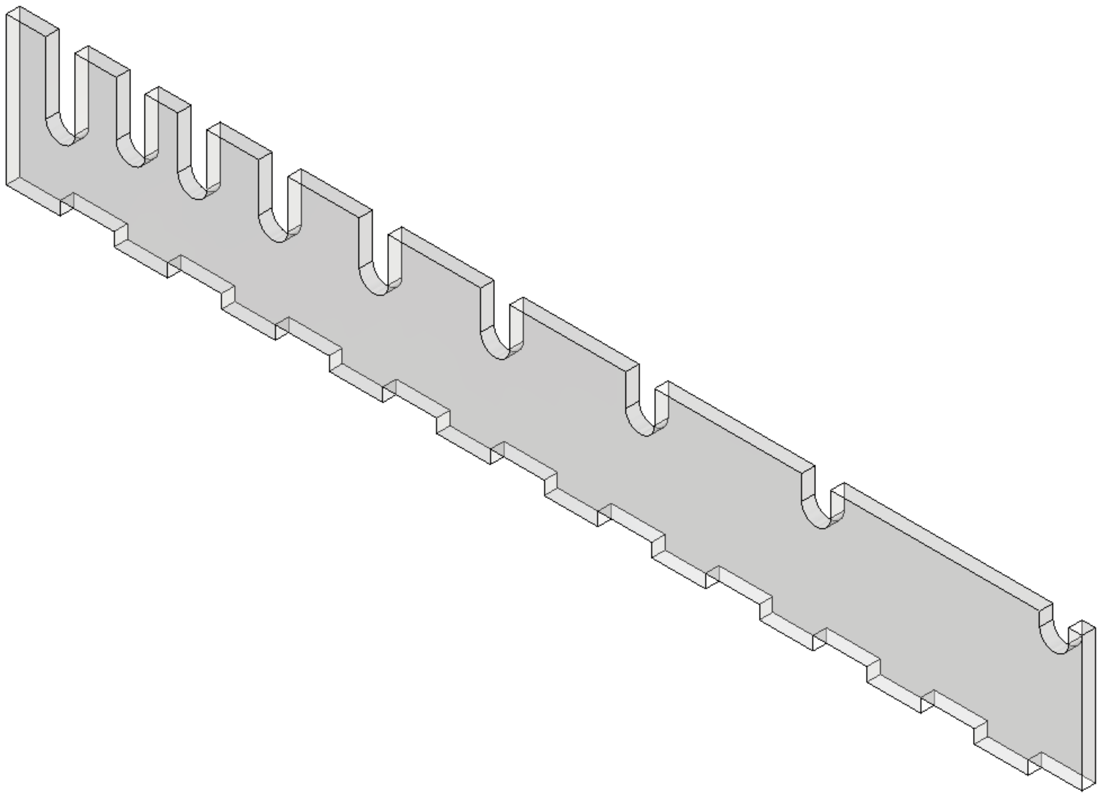


Figure D3: A CAD model of the angle brackets.

3. Use the mill provided in the undergraduate machine shop to machine the front bracket. See Appendix E, Figure E4 on pg. 120 for the dimensions of the front bracket. See Appendix F, Figure F2 on pg. 130 for the machining instructions of the front bracket. The front bracket is shown below in Figure D4:

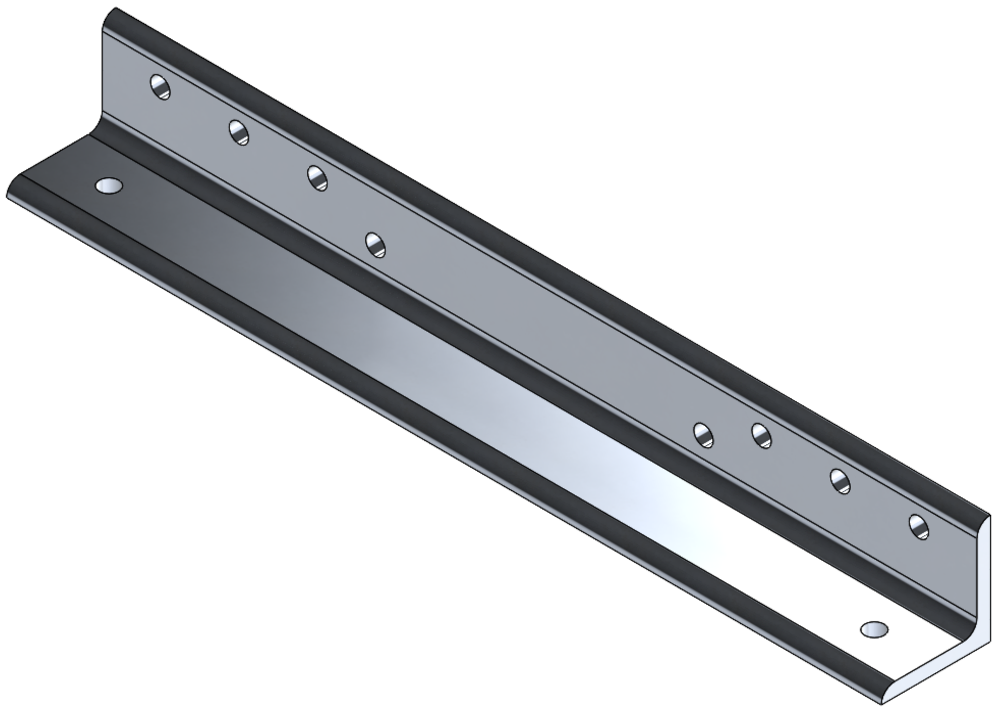


Figure D4: A CAD model of the front bracket.

4. Using an 11/32” wrench and a flat head screwdriver, assemble the six bumpers to the base plate. This will require six 8-32 locknuts. The location of the bumpers’ mounting holes in the base plate are shown in Figure D5 below, and the assembled base plate and bumpers are shown in Figure D6 below:

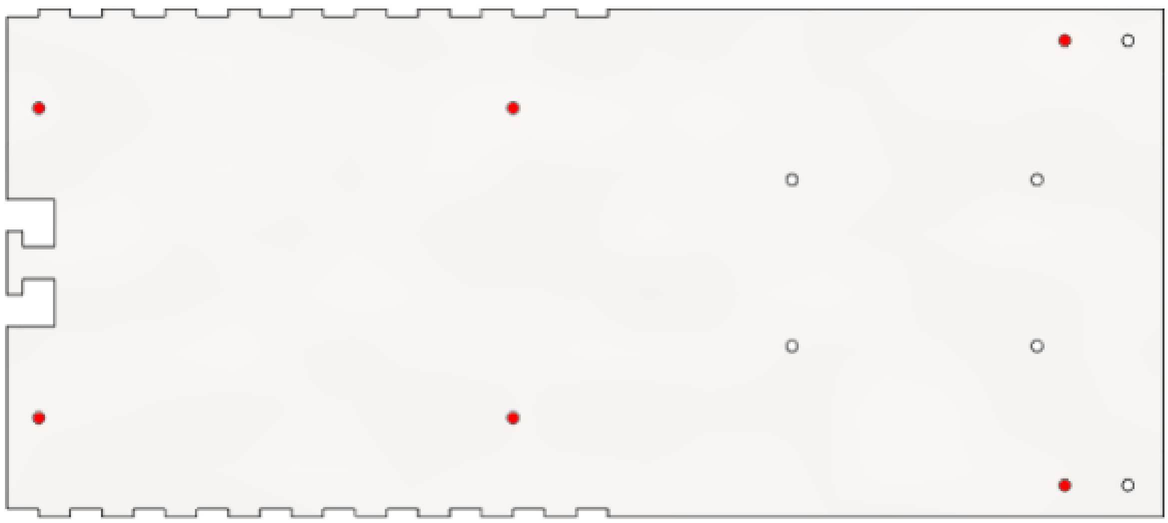


Figure D5: The mounting holes for the bumpers on the base plate, marked in red.

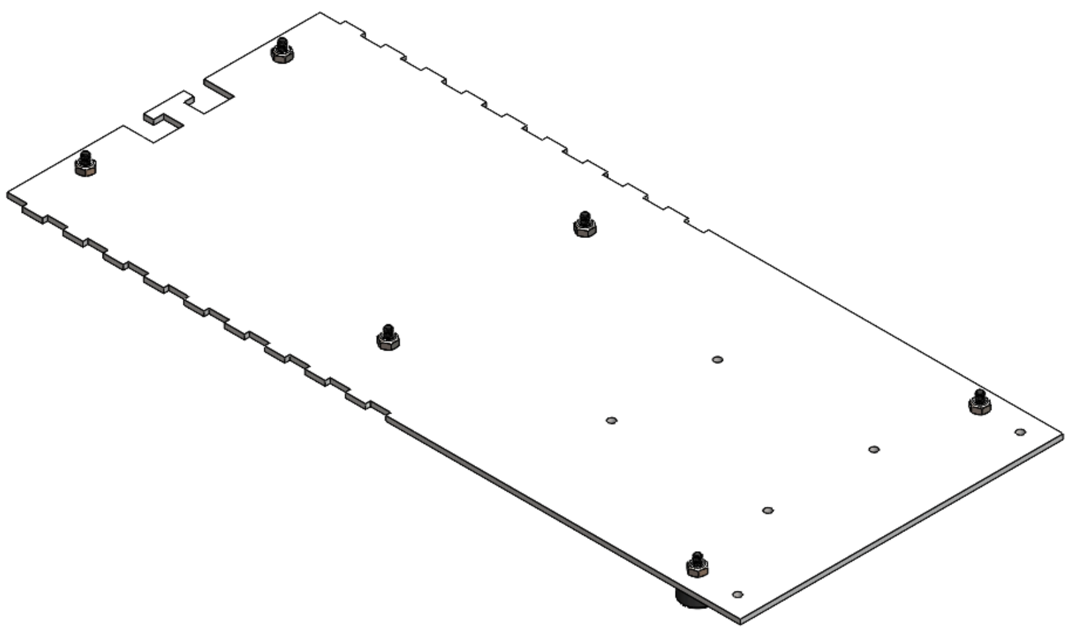


Figure D6: The bumpers assembled to the base plate.

5. Using an 11/32” wrench and a 3/32” allen wrench, assemble the front bracket to the base plate. This will require two 8-32 x 1/2” button head screws, and two 8-32 locknuts. Ensure the front bracket is placed on the opposite face of the base plate as the bumpers. Ensure the locknut is placed on the base plate face of the joint. The location of the front bracket’s mounting holes in the base plate are shown in Figure D7 below, and the assembled base plate and front bracket are shown in Figure D8 below:

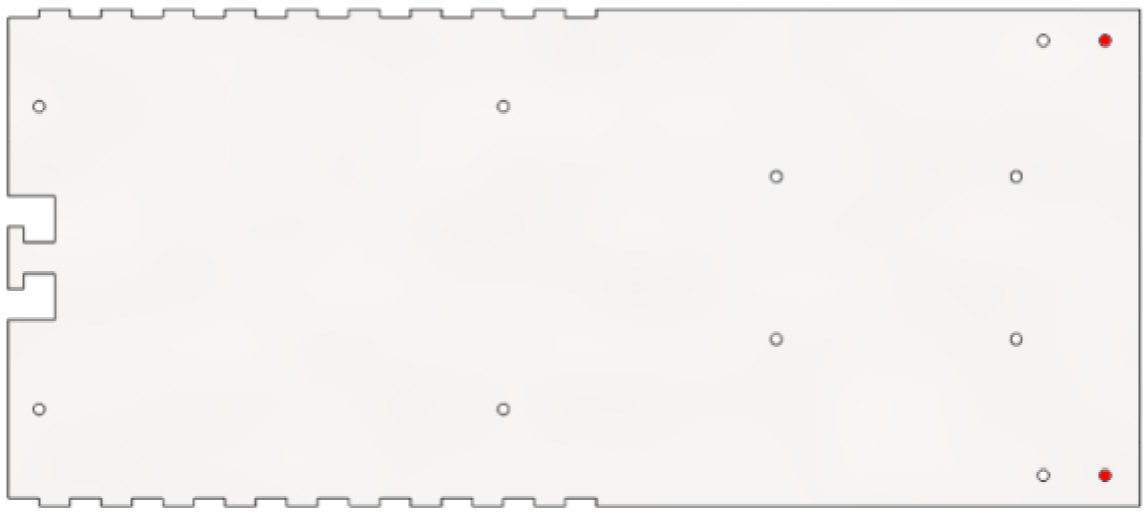


Figure D7: The mounting holes for the front bracket on the base plate, marked in red.

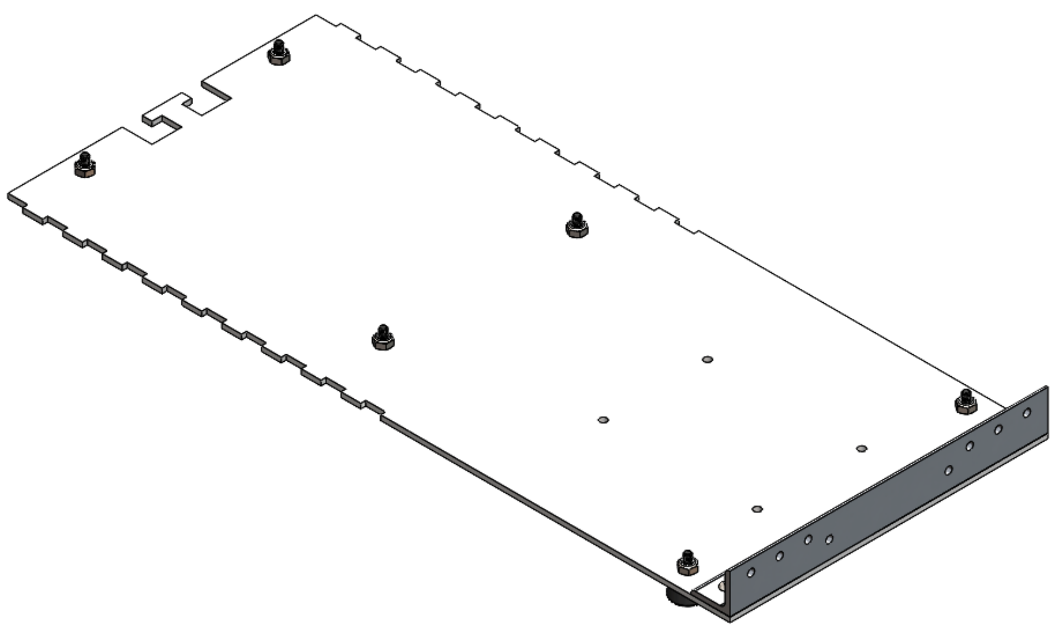


Figure D8: The front bracket assembled to the base plate.

6. Using an 11/32" wrench and a 3/32" allen wrench, assemble the two hinges to the front bracket. This will require six 8-32 x 3/8" button head screws, and six 8-32 locknuts. Ensure the hinge is placed on the inside face of the front bracket. Ensure the locknut is placed on the hinge face of the joint. The location of the hinges' mounting holes in the front bracket are shown in Figure D9 below, and the assembled hinges and front bracket are shown in Figure D10 below:

Figure D9: The mounting holes for the hinges on the front bracket, marked in red.

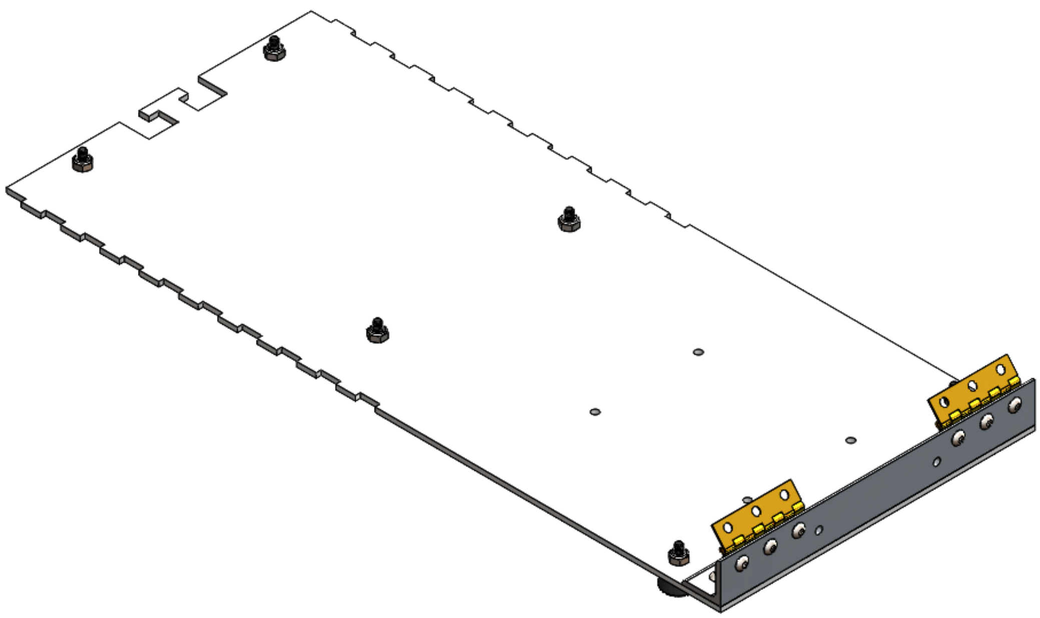


Figure D10: The hinges assembled to the front bracket.

7. Using a 3/32” allen wrench, assemble the handle to the front bracket. This will require two 8-32 x 3/8” button head screws. Ensure the handle is placed on the outside face of the front bracket. The location of the handle’s mounting holes in the front bracket are shown in Figure D11 below, and the assembled handle and front bracket are shown in Figure D12 below:

Figure D11: The mounting holes for the handle on the front bracket, marked in red.

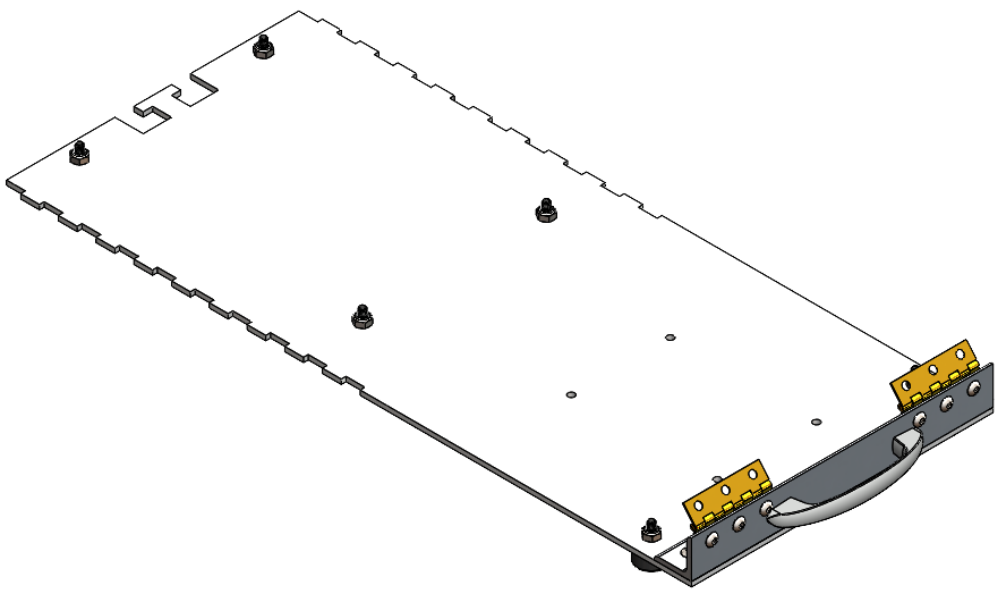


Figure D12: The handle assembled to the front bracket.

8. Using acrylic glue, assemble the angle brackets to the base plate. Follow the instructions on the acrylic glue for proper adhesion between the angle brackets and the base plate. Ensure the angle bracket is placed on the opposite face of the base plate as the bumpers. The assembled angle brackets and base plate are shown in Figure D13 below:

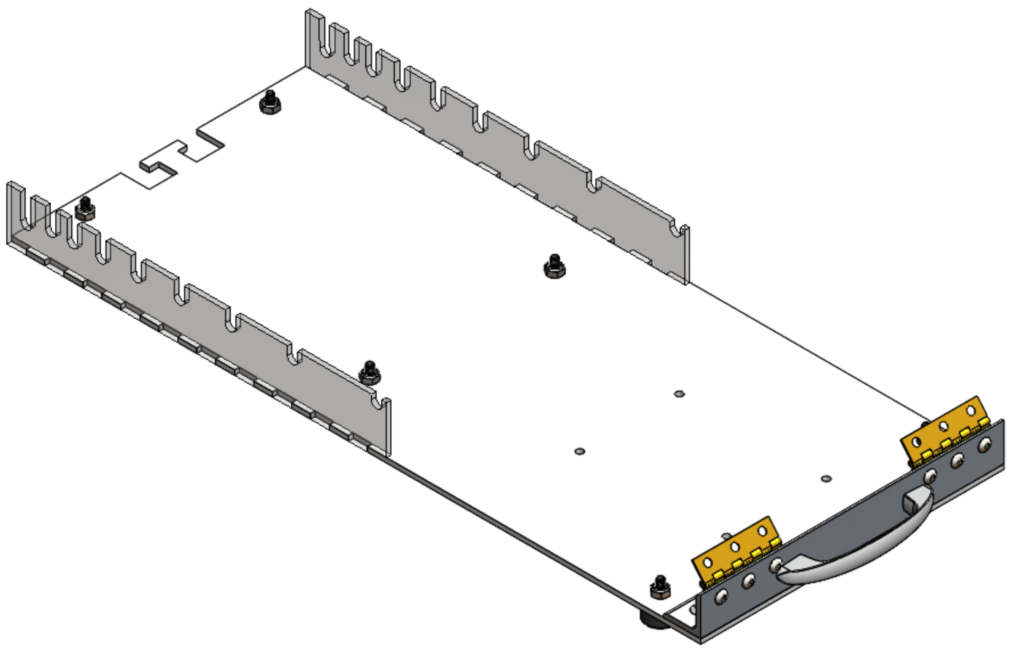


Figure D13: The angle brackets assembled to the base plate.

9. Use the laser cutter provided in the undergraduate machine shop to cut the ramp plate. See Appendix E, Figure E2 on pg. 118 for the dimensions of the ramp plate. The ramp plate is shown below in Figure D14:

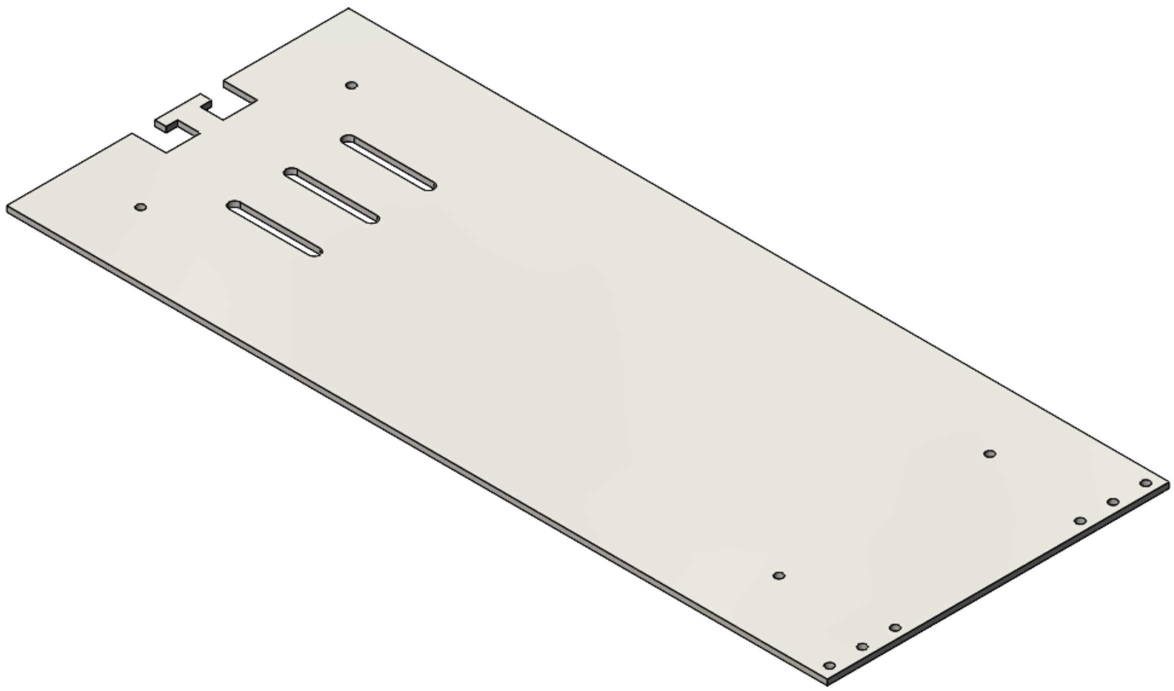


Figure D14: A CAD model of the ramp plate.

10. Use the mill provided in the undergraduate machine shop to machine stiffener A. See Appendix E, Figure E5 on pg. 121 for the dimensions of stiffener A. See Appendix F, Figure F3 on pg. 131 for the machining instructions of stiffener A. Stiffener A is shown below in Figure D15:

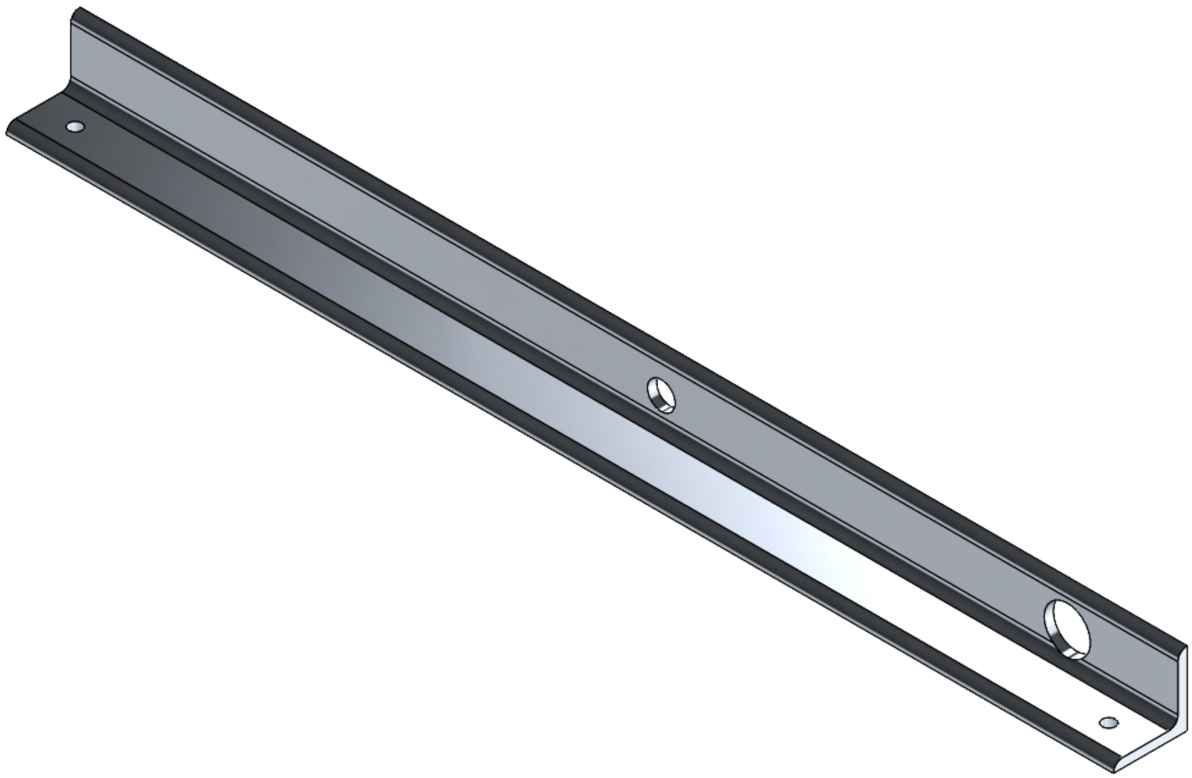


Figure D15: A CAD model of stiffener A.

11. Use the mill provided in the undergraduate machine shop to machine stiffener B. See Appendix E, Figure E6 on pg. 122 for the dimensions of stiffener B. See Appendix F, Figure F4 on pg. 132 for the machining instructions of stiffener B. Stiffener B is shown below in Figure D16:

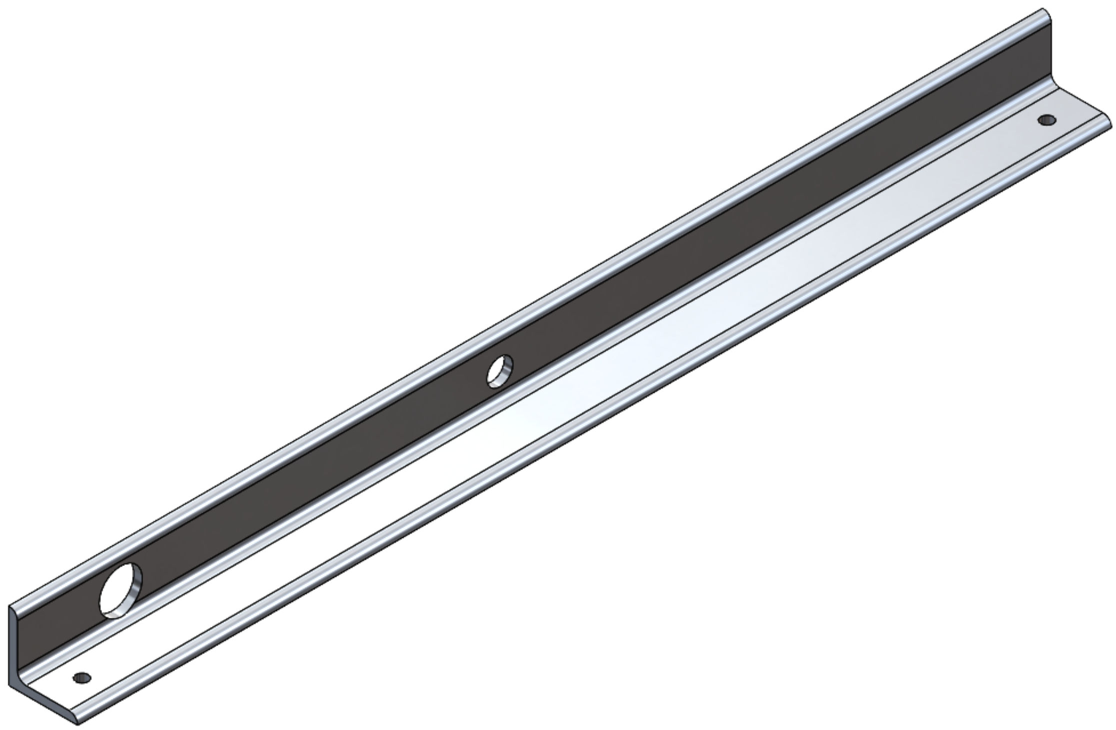


Figure D16: A CAD model of stiffener B.

12. Use the mill provided in the undergraduate machine shop to machine the two legs. See Appendix E, Figure E3 on pg. 119 for the dimensions of the legs. See Appendix F, Figure F1 on pg. 129 for the machining instructions of the legs. The leg is shown below in Figure D17:

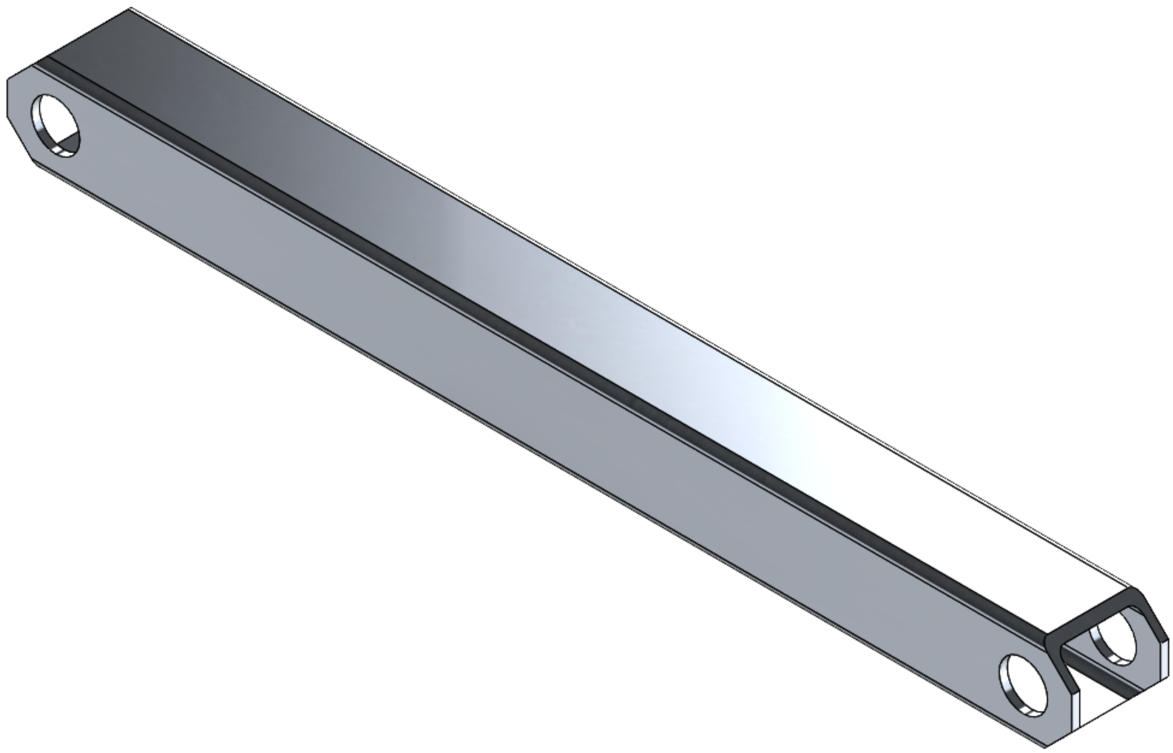


Figure D17: A CAD model of the legs.

13. Use the mill provided in the undergraduate machine shop to machine the release handle. See Appendix E, Figure E10 on pg. 126 for the dimensions of the release handle. See Appendix F, Figure F7 on pg. 135 for the machining instructions of the release handle. The release handle is shown below in Figure D18:

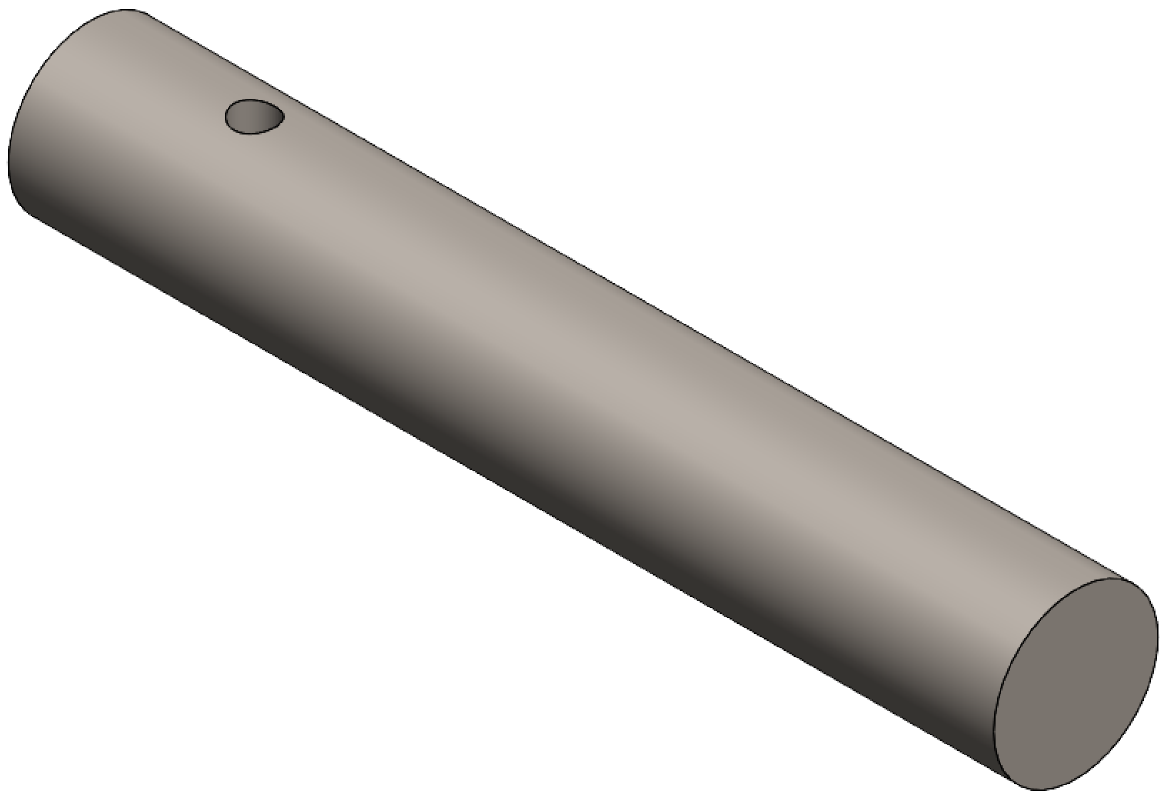


Figure D18: A CAD model of the release handle.

14. Use the mill provided in the undergraduate machine shop to machine the three release instances. See Appendix E, Figure E11 on pg. 127 for the dimensions of the release instances. See Appendix F, Figure F8 on pg. 136 for the machining instructions of the release instances. The release instance is shown below in Figure D19:

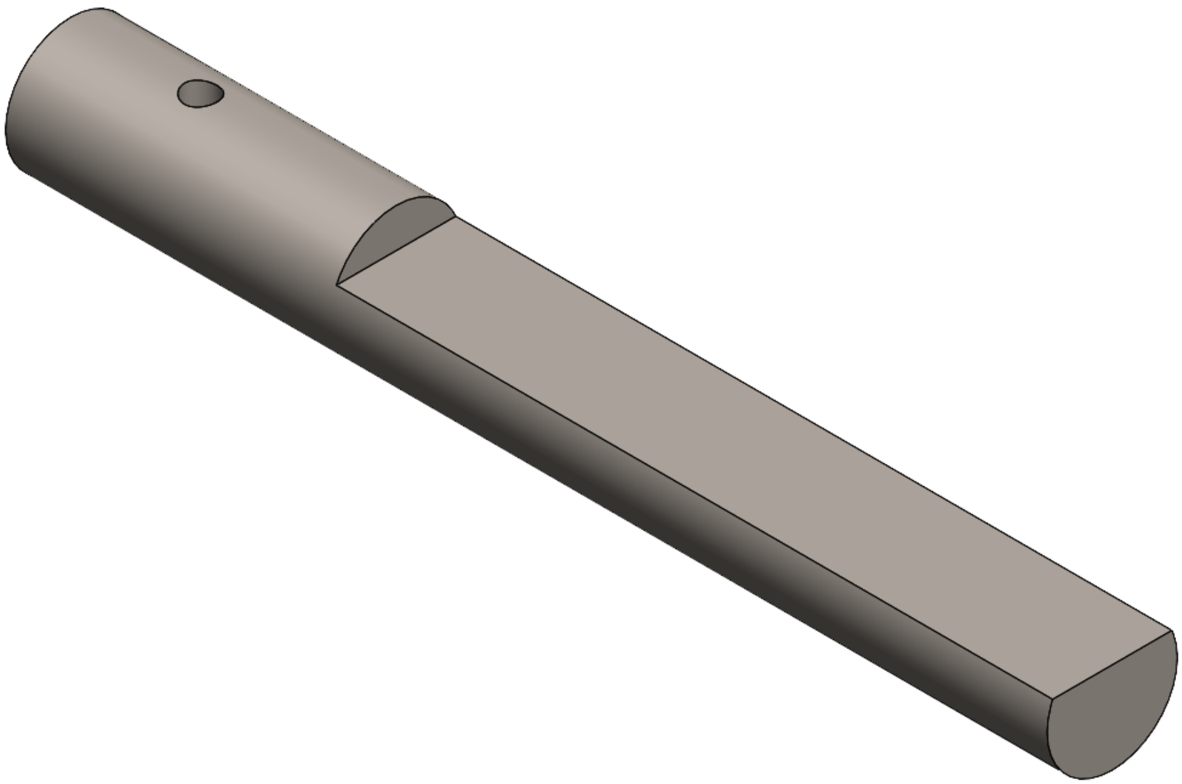


Figure D19: A CAD model of the release instances.

15. Use the lathe provided in the undergraduate machine shop to machine the ramp shaft. See Appendix E, Figure E8 on pg. 124 for the dimensions of the ramp shaft. See Appendix F, Figure F5 on pg. 133 for the machining instructions of the ramp shaft. The ramp shaft is shown below in Figure D20:

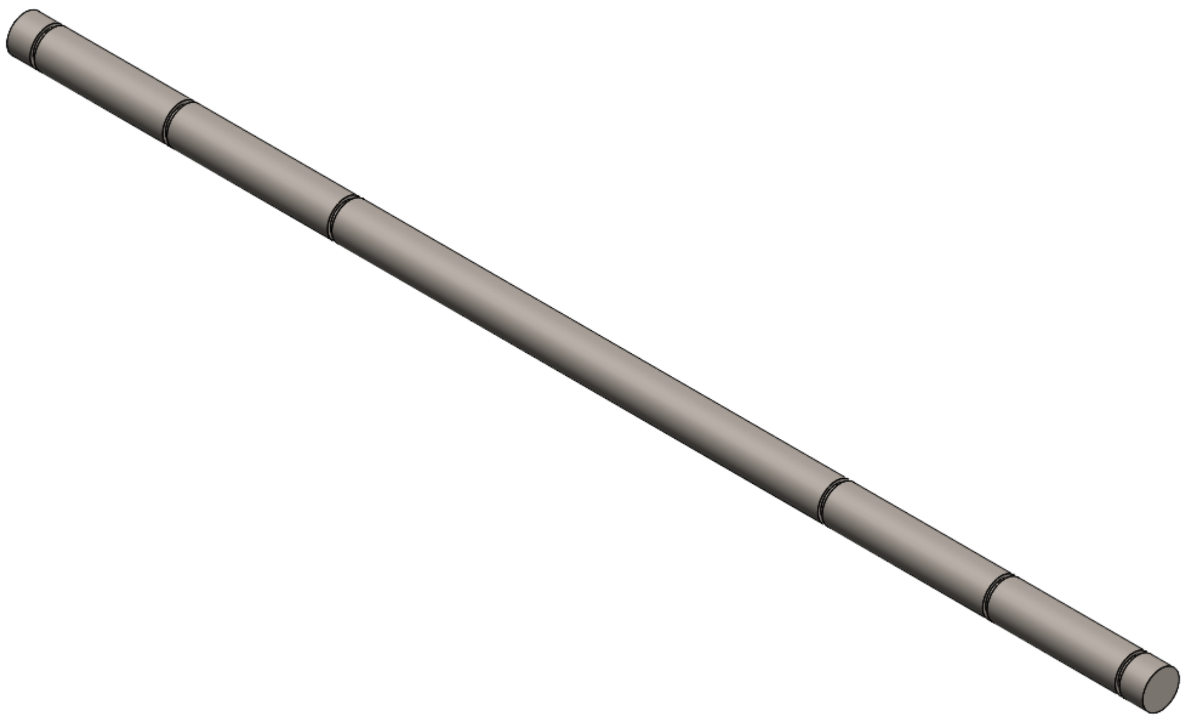


Figure D20: A CAD model of the ramp shaft.

16. Use the lathe provided in the undergraduate machine shop to machine the angle shaft. See Appendix E, Figure E9 on pg. 125 for the dimensions of the angle shaft. See Appendix F, Figure F6 on pg. 134 for the machining instructions of the angle shaft. The angle shaft is shown below in Figure D21:

Figure D21: A CAD model of the angle shaft.

17. Use the mill and the lathe provided in the undergraduate machine shop to machine the release master. See Appendix E, Figure E12 on pg. 128 for the dimensions of the release master. See Appendix F, Figure F9 on pg. 137 for the machining instructions of the release master. The release master is shown below in Figure D22:

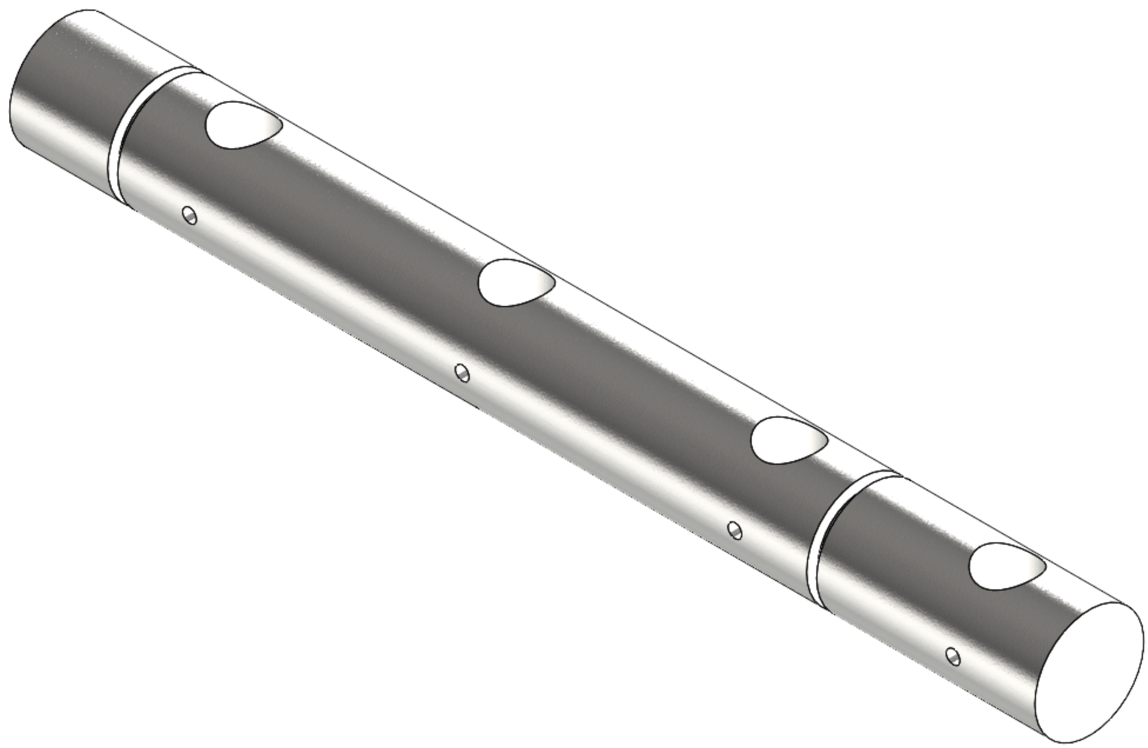


Figure D22: A CAD model of the release master.

18. Using an arbor press, assemble stiffener A and a 1/4" bushing. Ensure the 1/4" bushing is placed on the outside face of stiffener A. The location of the 1/4" bushing's mounting hole in stiffener A is shown in Figure D23 below, and the assembled stiffener A and 1/4" bushing are shown in Figure D24 below:

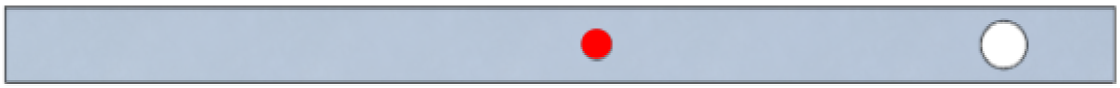


Figure D23: The mounting hole for the 1/4" bushing on stiffener A, marked in red.

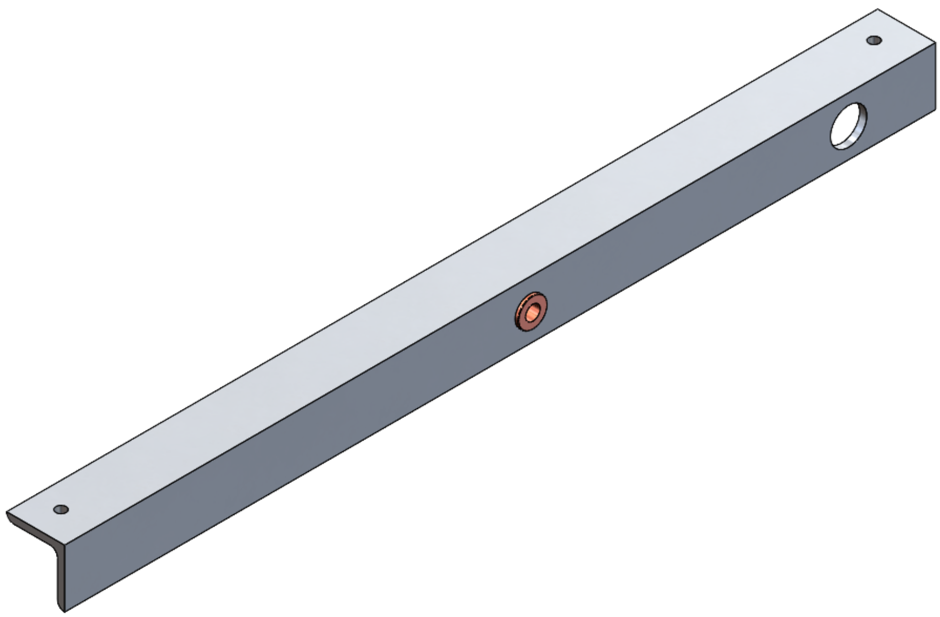


Figure D24: The 1/4" bushing assembled to stiffener A.

19. Using an arbor press, assemble stiffener A and a 1/2" bushing. Ensure the 1/2" bushing is placed on the outside face of stiffener A. The location of the 1/2" bushing's mounting hole in stiffener A is shown in Figure D25 below, and the assembled stiffener A and 1/2" bushing are shown in Figure D26 below:

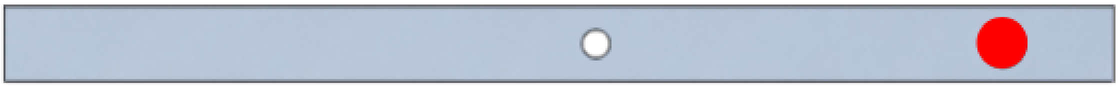


Figure D25: The mounting hole for the 1/2" bushing on stiffener A, marked in red.

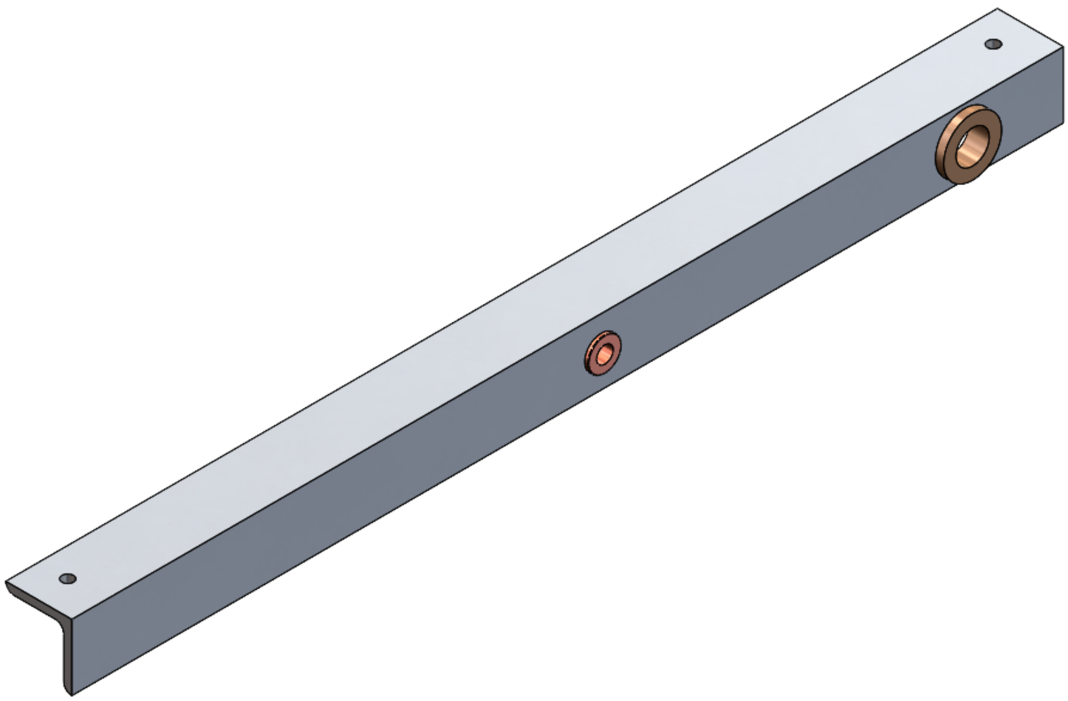


Figure D26: The 1/2" bushing assembled to stiffener A.

20. Using an arbor press, assemble stiffener B and a 1/4" bushing. Ensure the 1/4" bushing is placed on the outside face of stiffener B. The location of the 1/4" bushing's mounting hole in stiffener B is shown in Figure D27 below, and the assembled stiffener B and 1/4" bushing are shown in Figure D28 below:

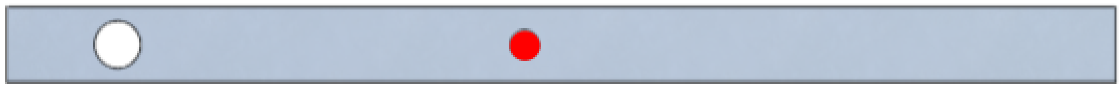


Figure D27: The mounting hole for the 1/4" bushing on stiffener B, marked in red.

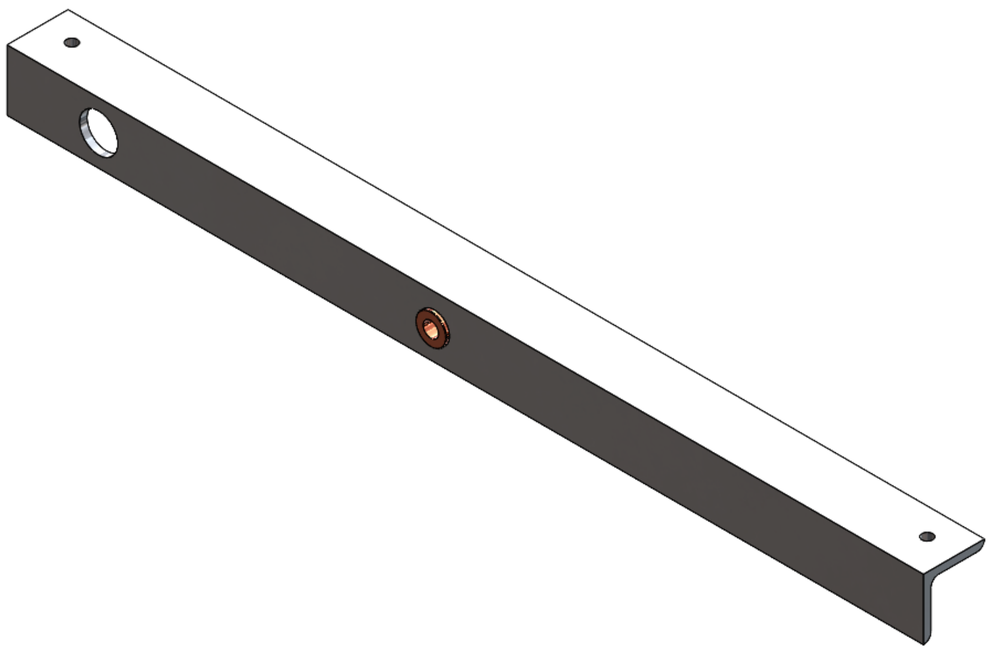


Figure D28: The 1/4" bushing assembled to stiffener B.

21. Using an arbor press, assemble stiffener B and a 1/2" bushing. Ensure the 1/2" bushing is placed on the outside face of stiffener B. The location of the 1/2" bushing's mounting hole in stiffener B is shown in Figure D29 below, and the assembled stiffener B and 1/2" bushing are shown in Figure D30 below:

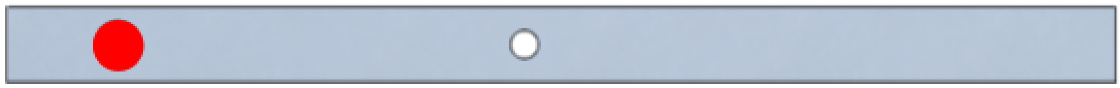


Figure D29: The mounting hole for the 1/2" bushing on stiffener B, marked in red.

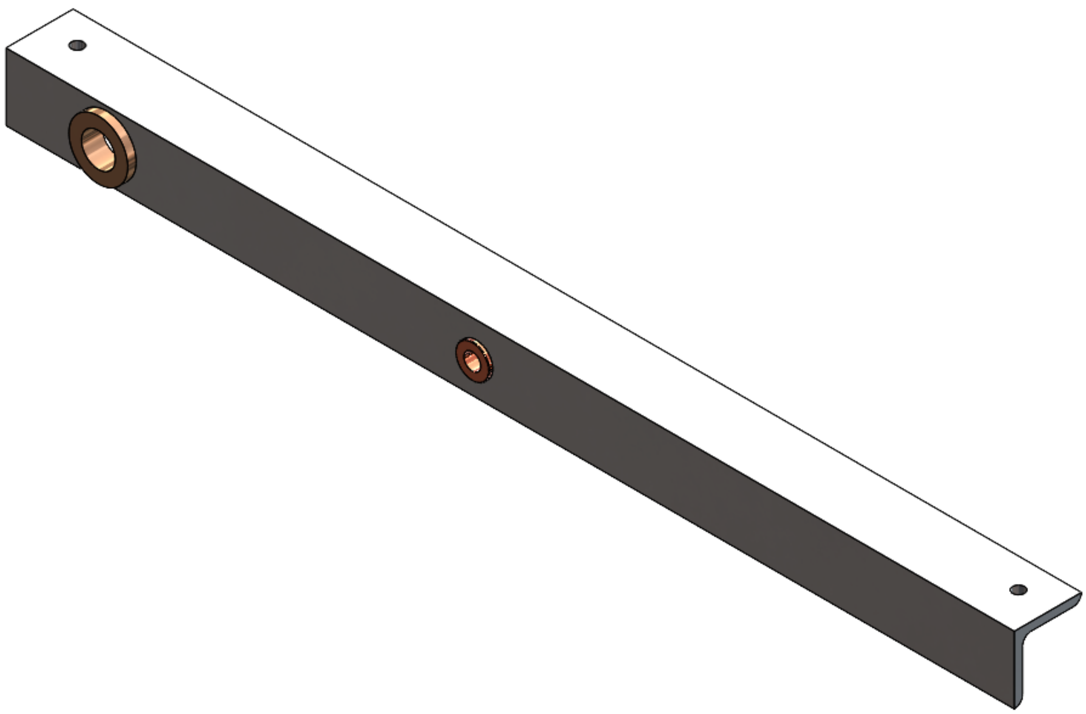


Figure D30: The 1/2" bushing assembled to stiffener B.

22. Using an arbor press, assemble the two legs and eight 1/4" bushings. The location of the 1/4" bushings' mounting holes in the leg are shown in Figure D31 below, and the assembled leg and 1/4" bushings are shown in Figure D32 below:

Figure D31: The mounting holes for the 1/4" bushings on the legs, marked in red.

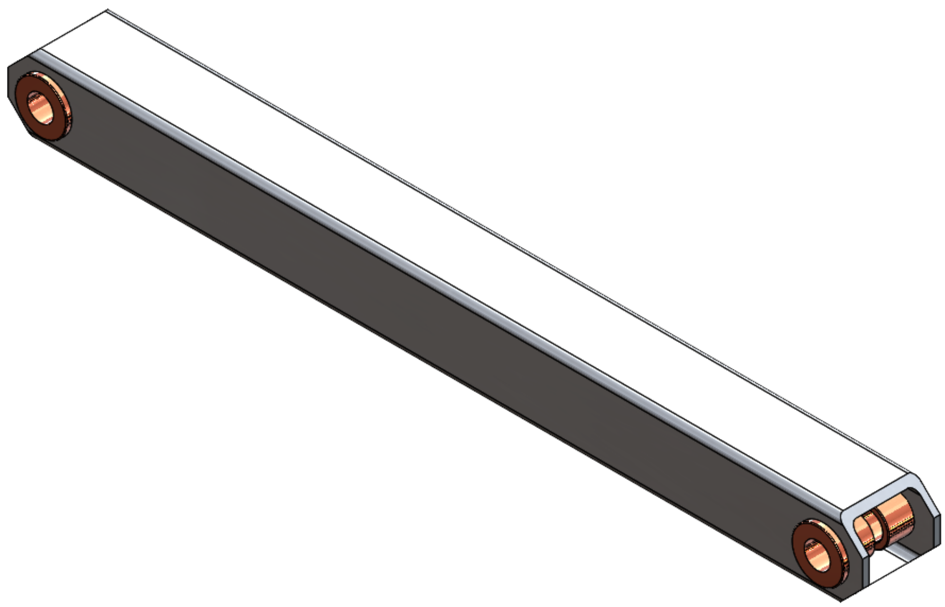


Figure D32: The 1/4" bushings assembled to the legs.

23. Assemble two of the 1/4" retaining rings to the ramp shaft. The location of the 1/4" retaining rings' mounting grooves in the ramp shaft are shown in Figure D33 below, and the assembled ramp shaft and 1/4" retaining rings are shown in Figure D34 below:

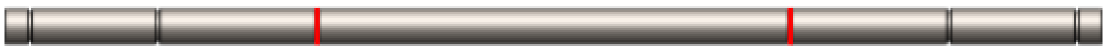


Figure D33: The mounting grooves for the 1/4" retaining rings on the ramp shaft, marked in red.

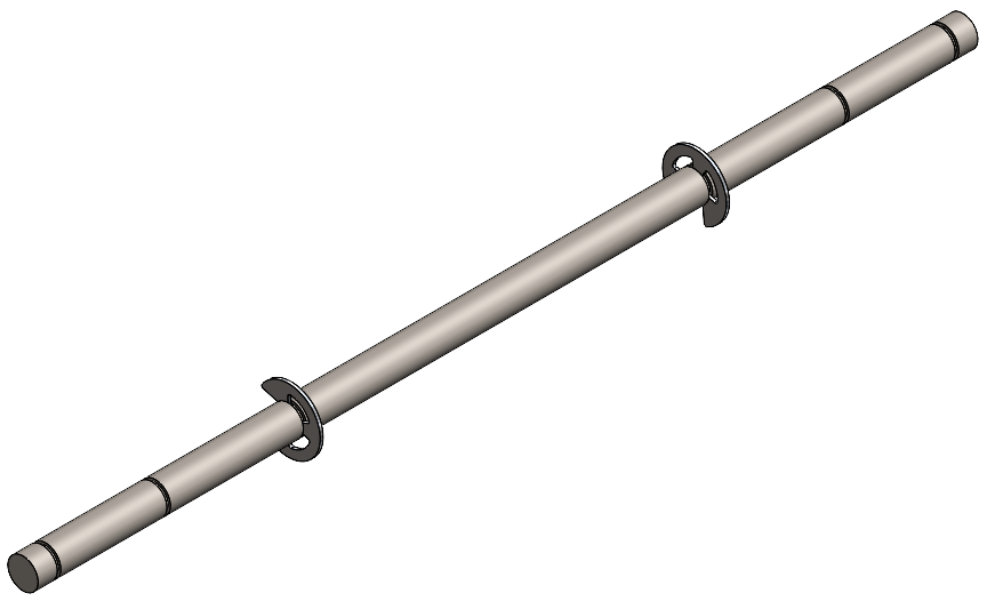


Figure D34: The 1/4" retaining rings assembled to the ramp shaft.

24. Assemble two of the 1/4" retaining rings to the angle shaft. The location of the 1/4" retaining rings' mounting grooves in the angle shaft are shown in Figure D35 below, and the assembled angle shaft and 1/4" retaining rings are shown in Figure D36 below:

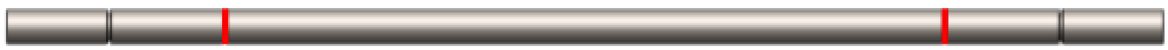


Figure D35: The mounting grooves for the 1/4" retaining rings on the angle shaft, marked in red.

Figure D36: The 1/4" retaining rings assembled to the angle shaft.

25. Using an arbor press, assemble the release master and the three release instances. This will require three 1/16” spring pins. Ensure the release instances face the same direction out of the release master. Ensure the flat faces on the release instances face the same direction. The location of the release instances’ mounting holes in the release master are shown in Figure D37 below, and the assembled release master and release instances are shown in Figure D38 below:

Figure D37: The mounting holes for the release instances on the release master, marked in red.

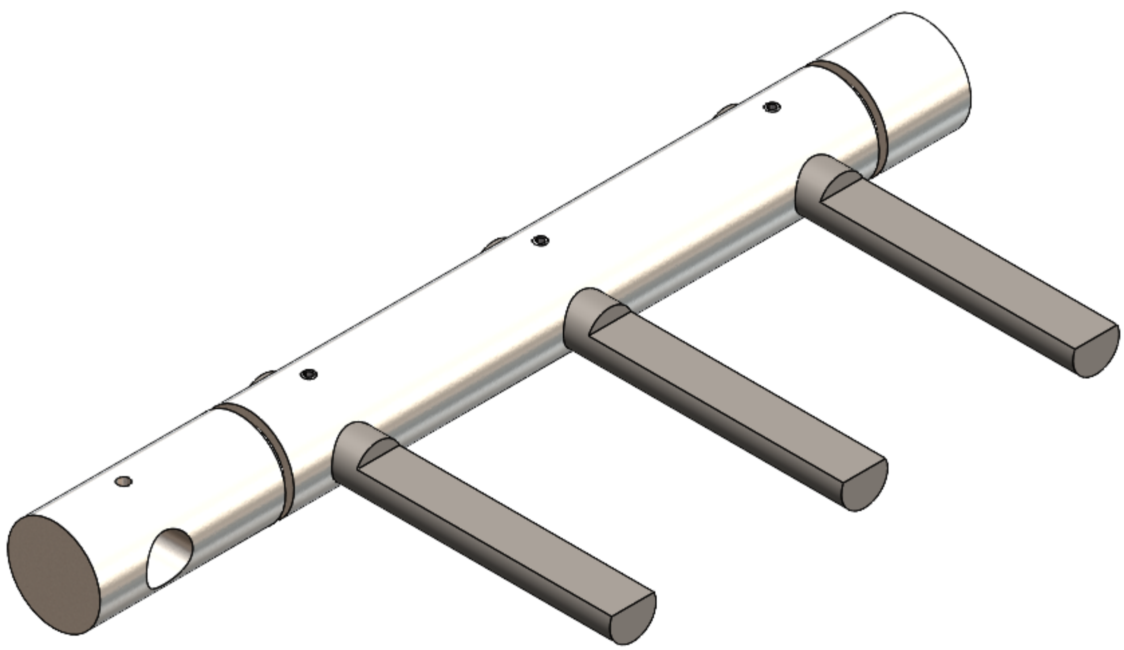


Figure D38: The release instances assembled to the release master.

26. Assemble two of the 1/2" retaining rings to the release master. The location of the 1/2" retaining rings' mounting grooves in the release master are shown in Figure D39 below, and the assembled release master and 1/2" retaining rings are shown in Figure D40 below:

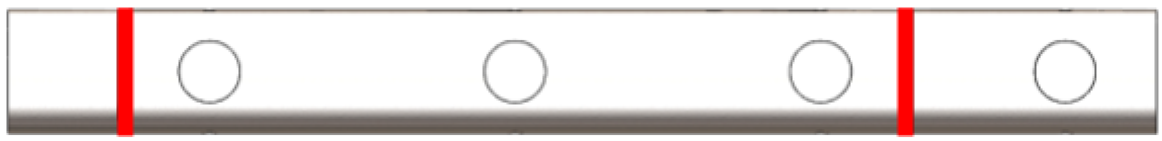


Figure D39: The mounting grooves for the 1/2" retaining rings on the release master, marked in red.

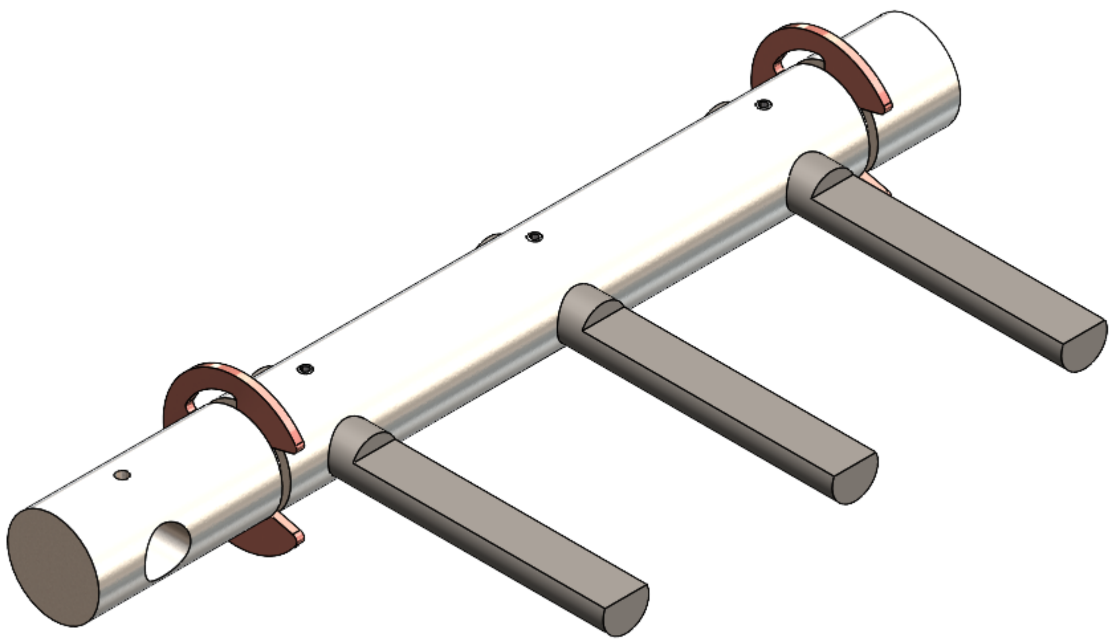


Figure D40: The 1/2" retaining rings assembled to the release master.

27. Assemble the release master to stiffener A. Ensure the 1/2" retaining ring on the release master makes contact with the larger end of the 1/2" bushing. The location of the release master in stiffener A is shown in Figure D41 below, and the assembled release master and stiffener A are shown in Figure D42 below:

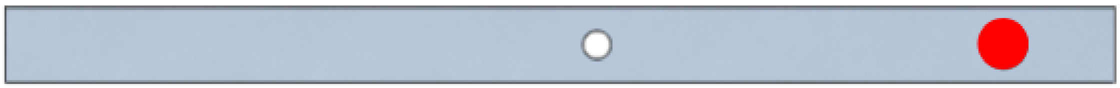


Figure D41: The location of the release master in stiffener A, marked in red.

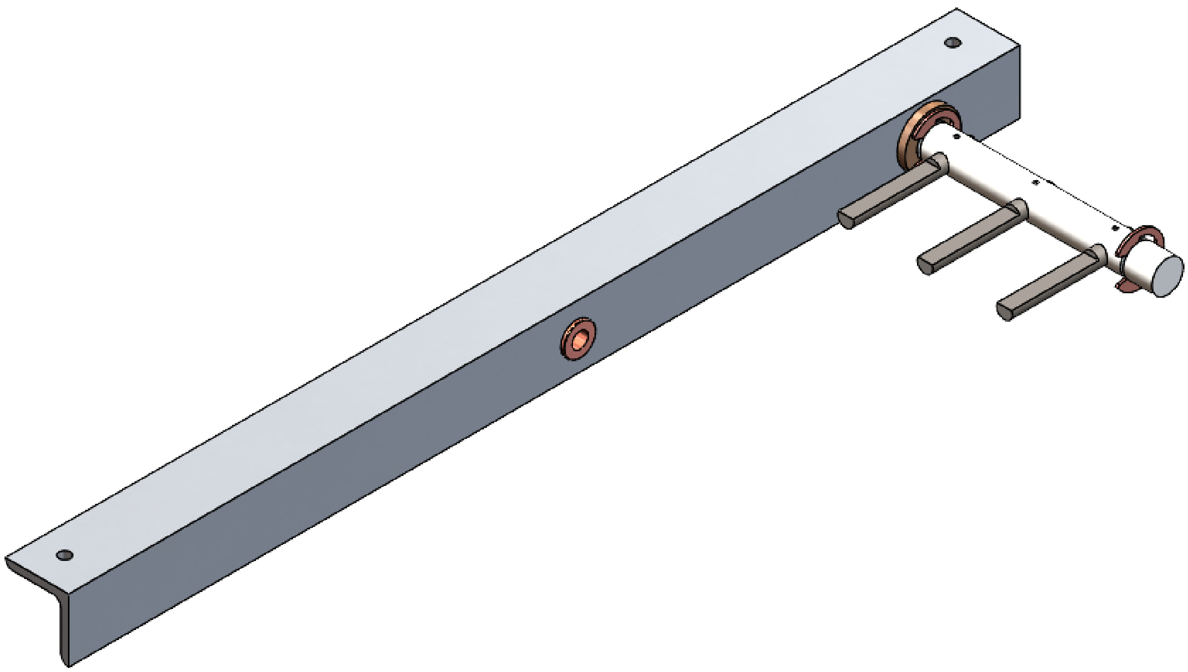


Figure D42: The release master assembled to stiffener A.

28. Assemble the ramp shaft to stiffener A. Ensure the 1/4" retaining ring on the ramp shaft makes contact with the larger end of the 1/4" bushing. The location of the ramp shaft in stiffener A is shown in Figure D43 below, and the assembled ramp shaft and stiffener A are shown in Figure D44 below:

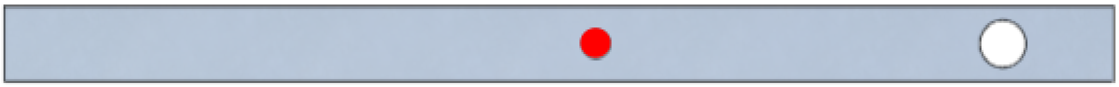


Figure D43: The location of the ramp shaft in stiffener A, marked in red.

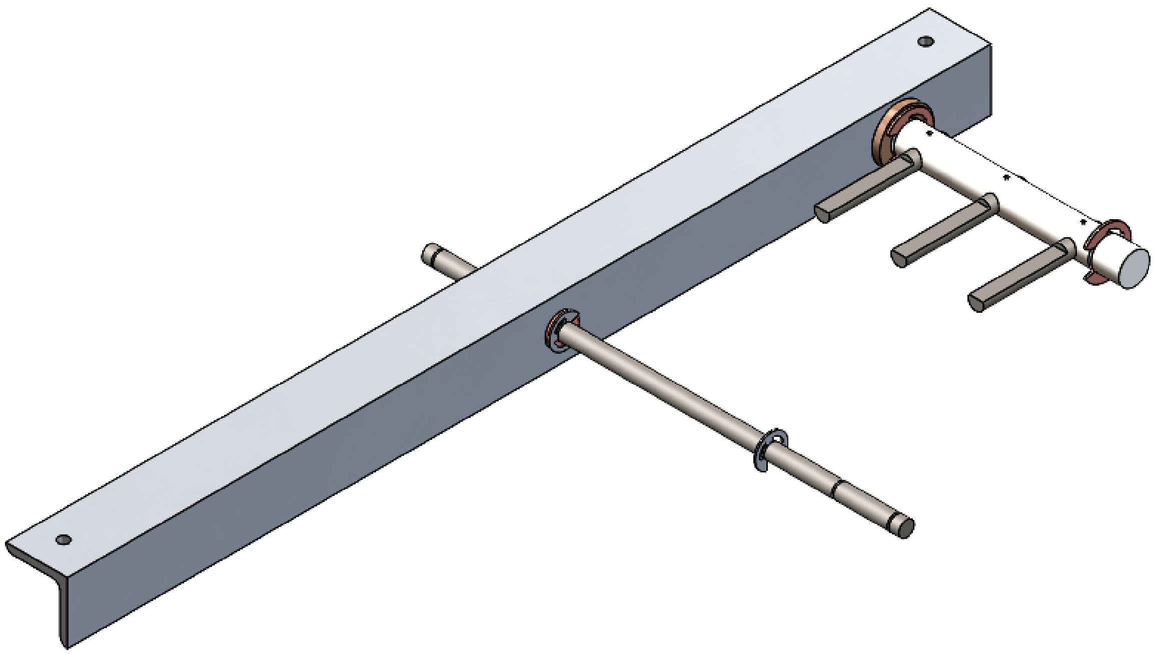


Figure D44: The ramp shaft assembled to stiffener A.

29. Assemble stiffener B to the ramp shaft. Ensure the 1/4" retaining ring on the ramp shaft makes contact with the larger end of the 1/4" bushing. The location of the ramp shaft in stiffener B is shown in Figure D45 below, and the assembled ramp shaft and stiffener B are shown in Figure D46 below:

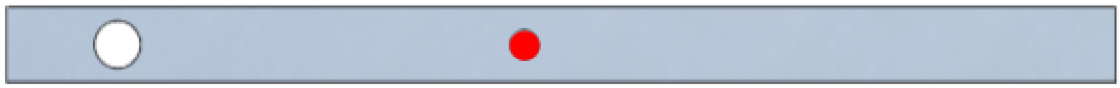


Figure D45: The location of the ramp shaft in stiffener B, marked in red.

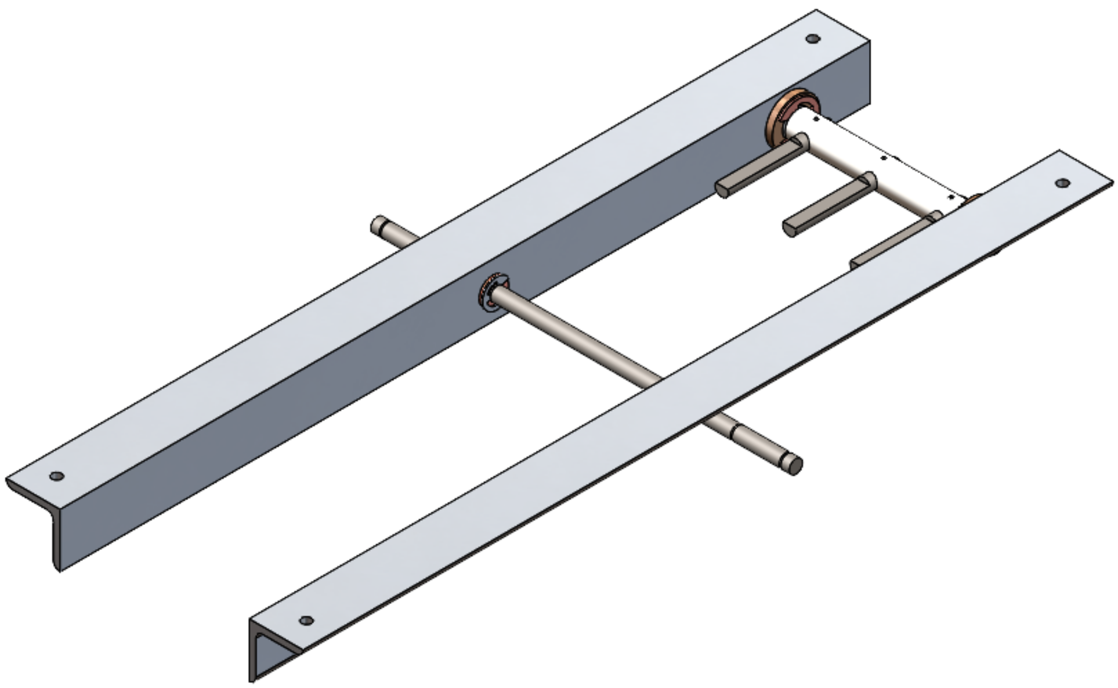


Figure D46: The ramp shaft assembled to stiffener B.

30. Assemble stiffener B to the release master. Ensure the 1/2" retaining ring on the release master makes contact with the larger end of the 1/2" bushing. The location of the release master in stiffener B is shown in Figure D47 below, and the assembled release master and stiffener B are shown in Figure D48 below:

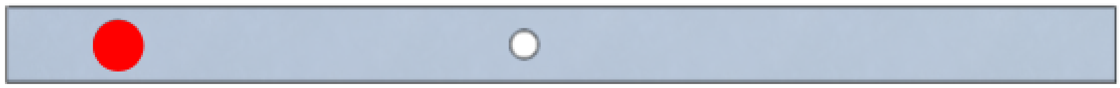


Figure D47: The location of the release master in stiffener B, marked in red.

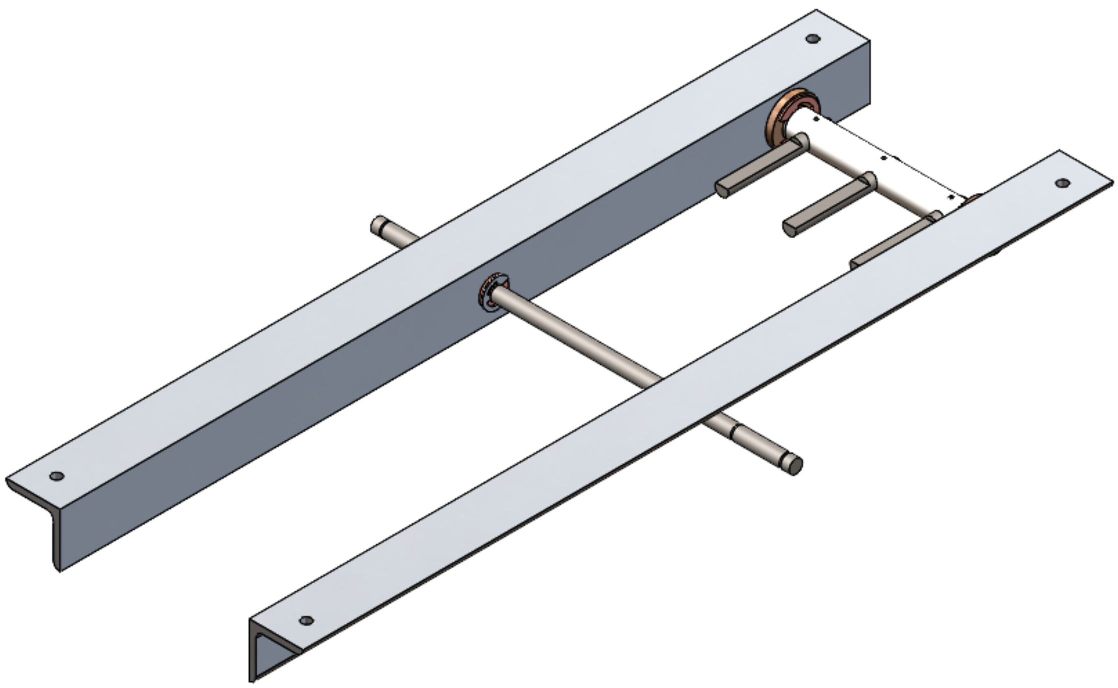


Figure D48: The release master assembled to stiffener B.

31. Using an 11/32" wrench and a 3/32" allen wrench, assemble the two stiffeners to the ramp plate. This will require four 8-32 x 1/2" button head screws, and four 8-32 locknuts. Ensure the locknut is placed on the stiffener face of the joint. The location of the stiffeners' mounting holes in the ramp plate are shown in Figure D49 below, and the assembled stiffeners and ramp plate are shown in Figure D50 below:

Figure D49: The mounting holes for the stiffeners on the ramp plate, marked in red.

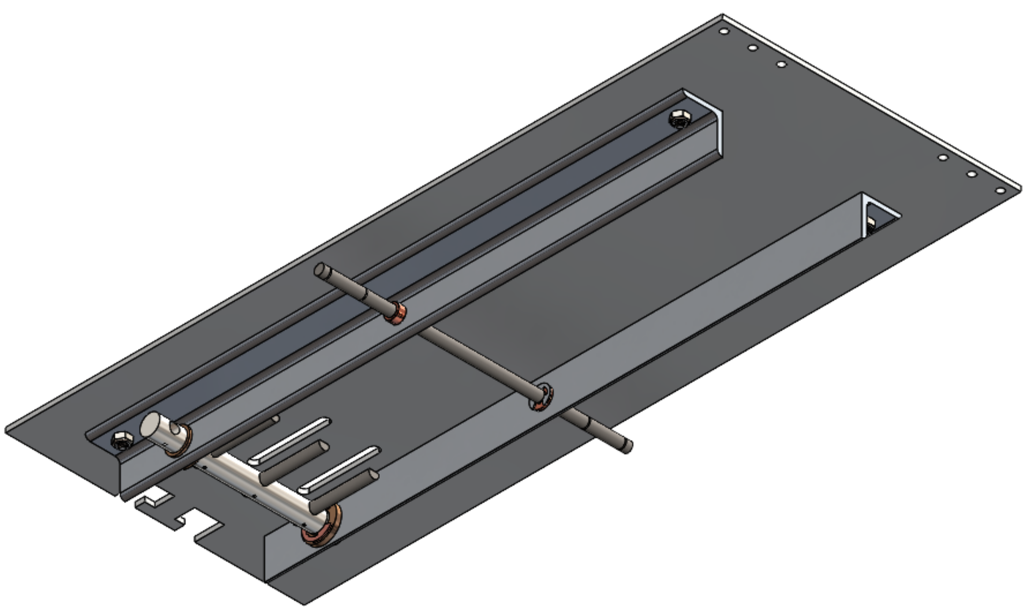


Figure D50: The stiffeners assembled to the ramp plate.

32. Assemble the release master and the release handle. This will require a 1/16” spring pin. This may require a mallet. If a mallet is used, do not swing aggressively, or you will risk breaking the ramp plate. Ensure the release handle faces the opposite direction out of the release master as the release instances. The location of the release handle’s mounting hole in the release master are shown in Figure D51 below, and the assembled release master and release handle are shown in Figure D52 below:

Figure D51: The mounting hole for the release handle on the release master, marked in red.

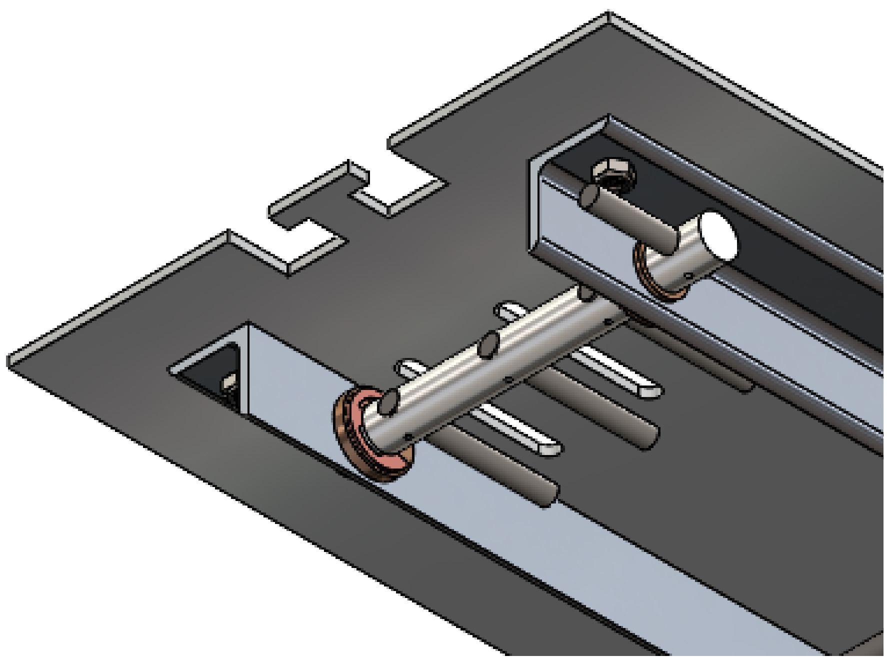


Figure D52: The release handle assembled to the release master.

33. Assemble two of the 1/4" retaining rings to the ramp shaft. The location of the 1/4" retaining rings' mounting grooves in the ramp shaft are shown in Figure D53 below, and the assembled ramp shaft and 1/4" retaining rings are shown in Figure D54 below:

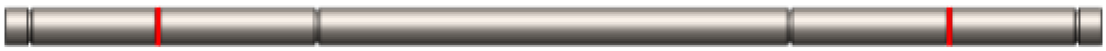


Figure D53: The mounting grooves for the 1/4" retaining rings on the ramp shaft, marked in red.

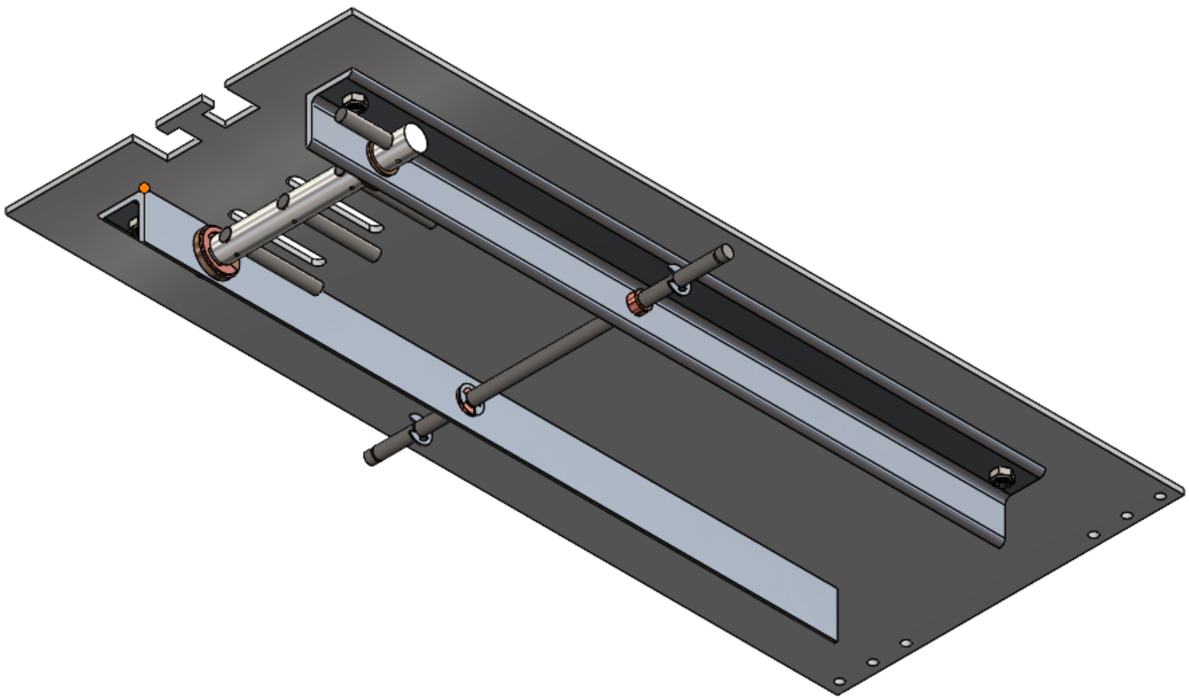


Figure D54: The 1/4" retaining rings assembled to the ramp shaft.

34. Assemble one of the legs to the ramp shaft. The location of the ramp shaft in the leg is shown in Figure D55 below, and the assembled ramp shaft and leg are shown in Figure D56 below:

Figure D55: The location of the ramp shaft in the leg, marked in red.

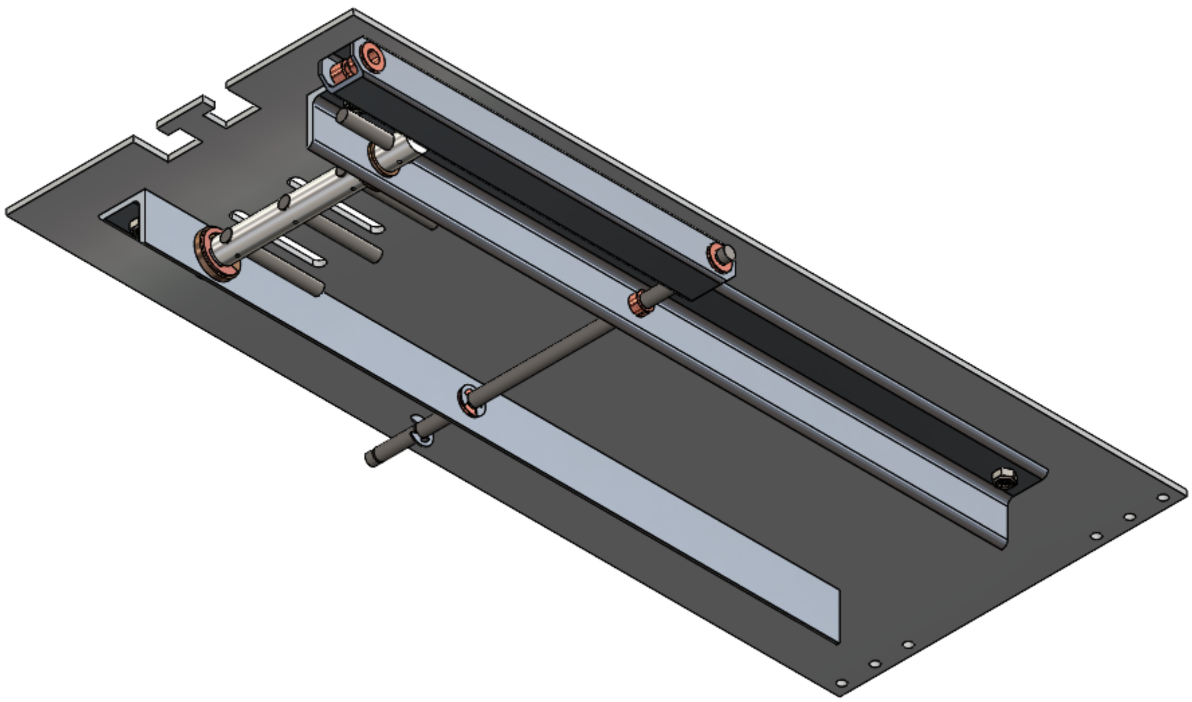


Figure D56: The leg assembled to the ramp shaft.

35. Assemble one of the 1/4" retaining rings to the ramp shaft. Ensure that this retaining ring is placed next to the leg assembled to the ramp shaft. The location of the 1/4" retaining ring's mounting groove in the ramp shaft is shown in Figure D57 below, and the assembled ramp shaft and 1/4" retaining ring are shown in Figure D58 below:

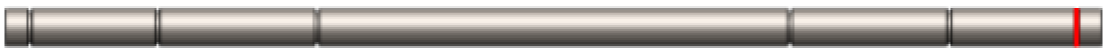


Figure D57: The mounting groove for the 1/4" retaining ring on the ramp shaft, marked in red.

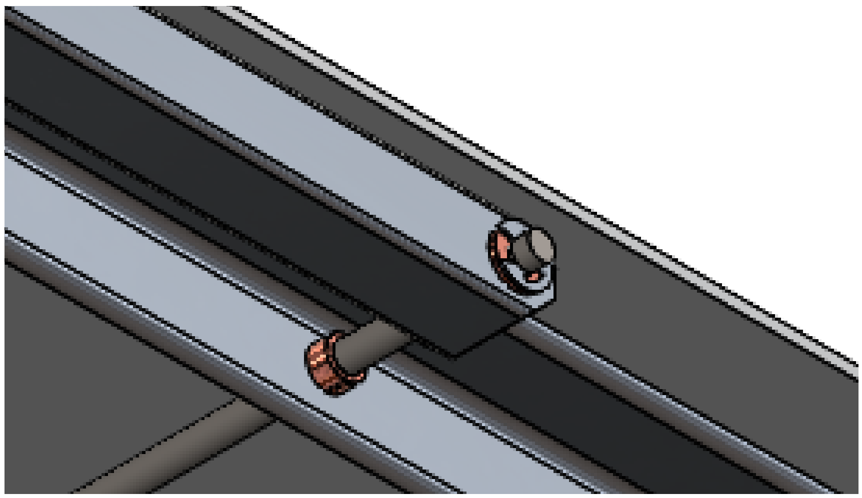


Figure D58: The 1/4" retaining ring assembled to the ramp shaft.

36. Assemble the angle shaft to the leg that has been assembled to the ramp shaft. The location of the angle shaft in the leg is shown in Figure D59 below, and the assembled angle shaft and leg are shown in Figure D60 below:

Figure D59: The location of the angle shaft in the leg, marked in red.

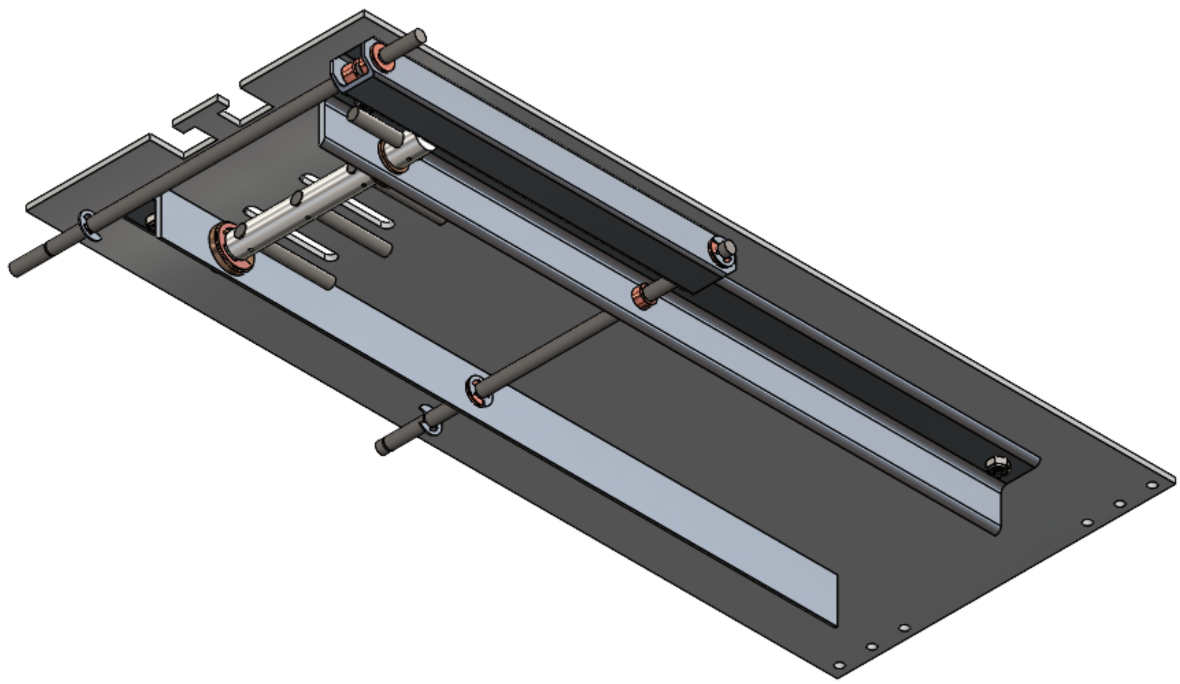


Figure D60: The angle shaft assembled to the leg.

37. Assemble one of the 1/4" retaining rings to the angle shaft. Ensure that this retaining ring is placed next to the leg assembled to the angle shaft. The location of the 1/4" retaining ring's mounting groove in the angle shaft is shown in Figure D61 below, and the assembled angle shaft and 1/4" retaining ring are shown in Figure D62 below:

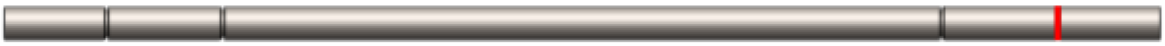


Figure D61: The mounting groove for the 1/4" retaining ring on the angle shaft, marked in red.

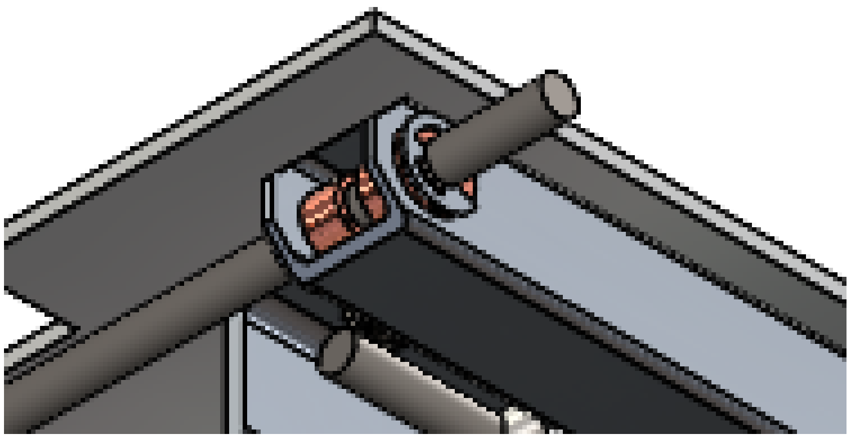


Figure D62: The 1/4" retaining ring assembled to the angle shaft.

38. Assemble the remaining leg to the angle shaft. The location of the angle shaft in the leg is shown in Figure D62 below, and the assembled angle shaft and leg are shown in Figure D64 below:

Figure D63: The location of the angle shaft in the leg, marked in red.

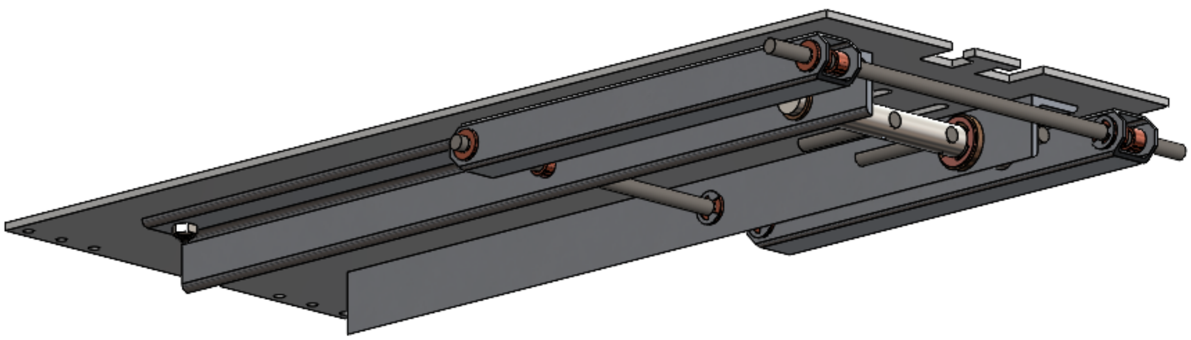


Figure D64: The leg assembled to the angle shaft.

39. Assemble the remaining leg to the ramp shaft. The location of the ramp shaft in the leg is shown in Figure D65 below, and the assembled ramp shaft and leg are shown in Figure D66 below:

Figure D65: The location of the ramp shaft in the leg, marked in red.

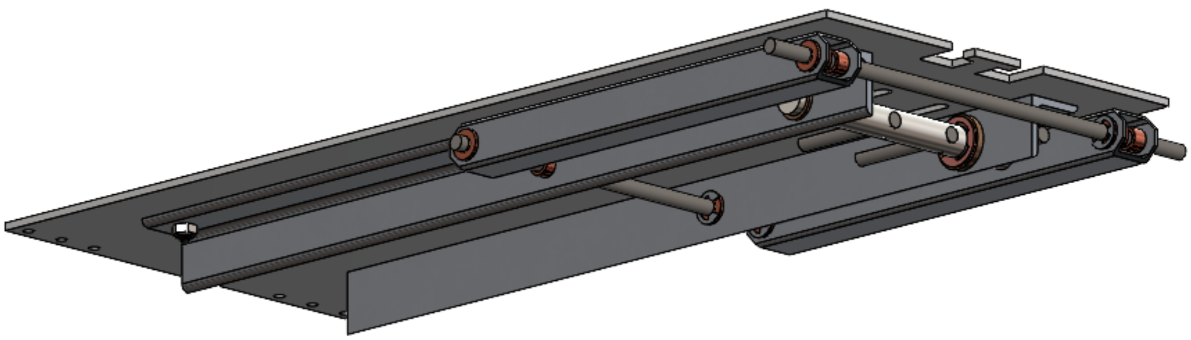


Figure D66: The leg assembled to the ramp shaft.

40. Assemble one of the 1/4" retaining rings to the angle shaft. The location of the 1/4" retaining ring's mounting groove in the angle shaft is shown in Figure D67 below, and the assembled angle shaft and 1/4" retaining ring are shown in Figure D68 below:

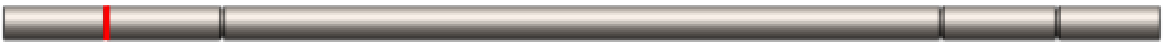


Figure D67: The mounting groove for the 1/4" retaining ring on the angle shaft, marked in red.

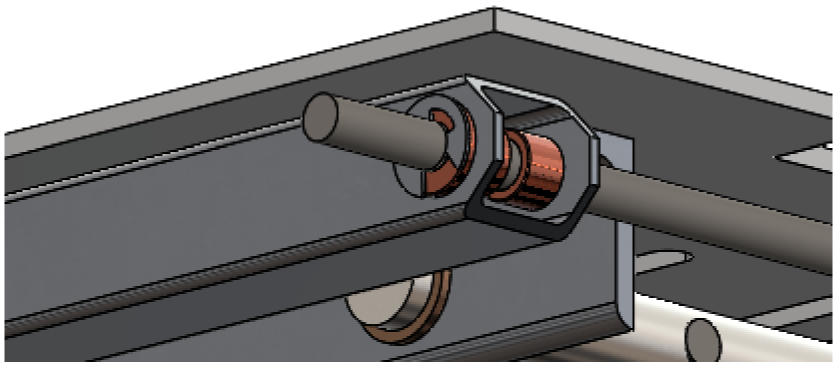


Figure D68: The 1/4" retaining ring assembled to the angle shaft.

41. Assemble one of the 1/4" retaining rings to the ramp shaft. The location of the 1/4" retaining ring's mounting groove in the ramp shaft is shown in Figure D69 below, and the assembled ramp shaft and 1/4" retaining ring are shown in Figure D70 below:

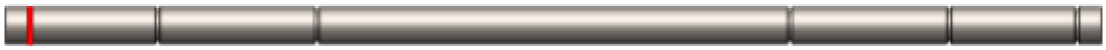


Figure D69: The mounting groove for the 1/4" retaining ring on the ramp shaft, marked in red.

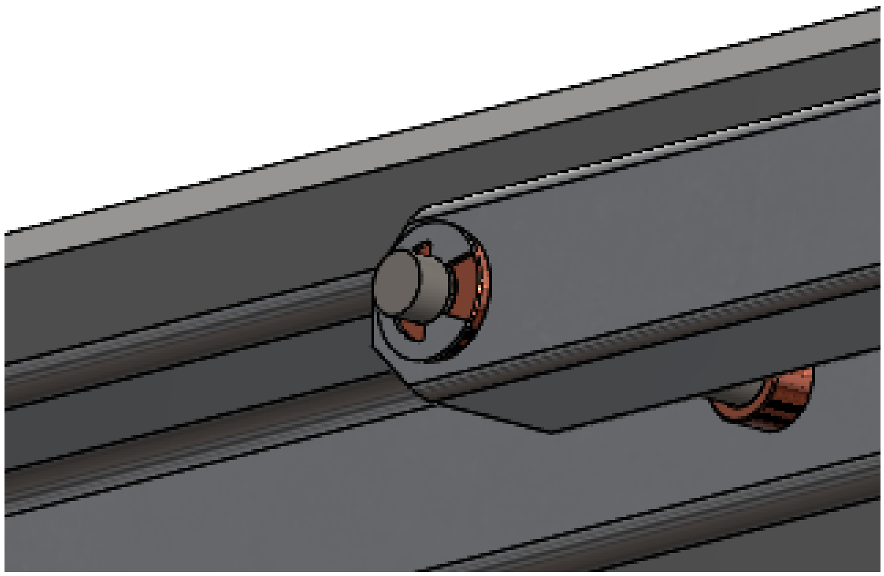


Figure D70: The 1/4" retaining ring assembled to the ramp shaft.

42. Using an 11/32” wrench and a 3/32” allen wrench, assemble the ramp plate to the two hinges. This will require six 8-32 x 3/8” button head screws, and six 8-32 locknuts. Ensure the stiffeners are placed on the inside face of the ramp plate. Ensure the hinge is placed on the inside face of the ramp plate. Ensure the locknut is placed on the hinge face of the joint. The location of the hinges’ mounting holes in the ramp plate are shown in Figure D71 below, and the assembled hinges and ramp plate are shown in Figure D72 below:

Figure D71: The mounting holes for the hinges on the ramp plate, marked in red.

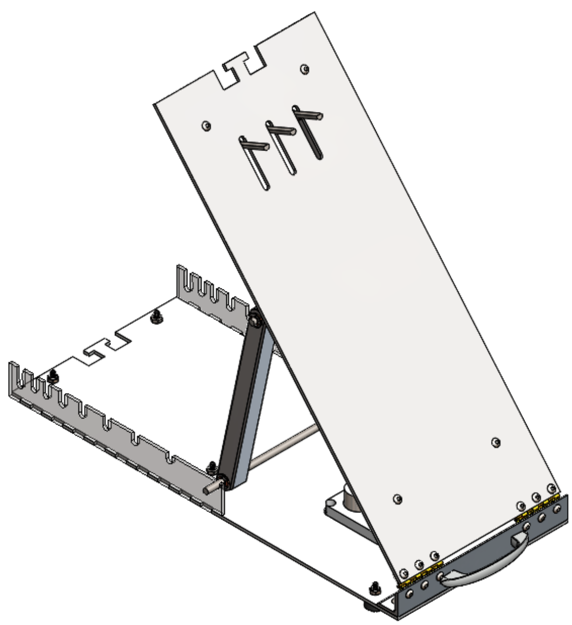


Figure D72: The hinges assembled to the ramp plate.

Appendix E: Drawings for Manufacturing

This appendix provides manufacturing drawings for each of the parts within the variable ramp assembly that will require machining. Accompanying manufacturing plans are provided in Appendix F.

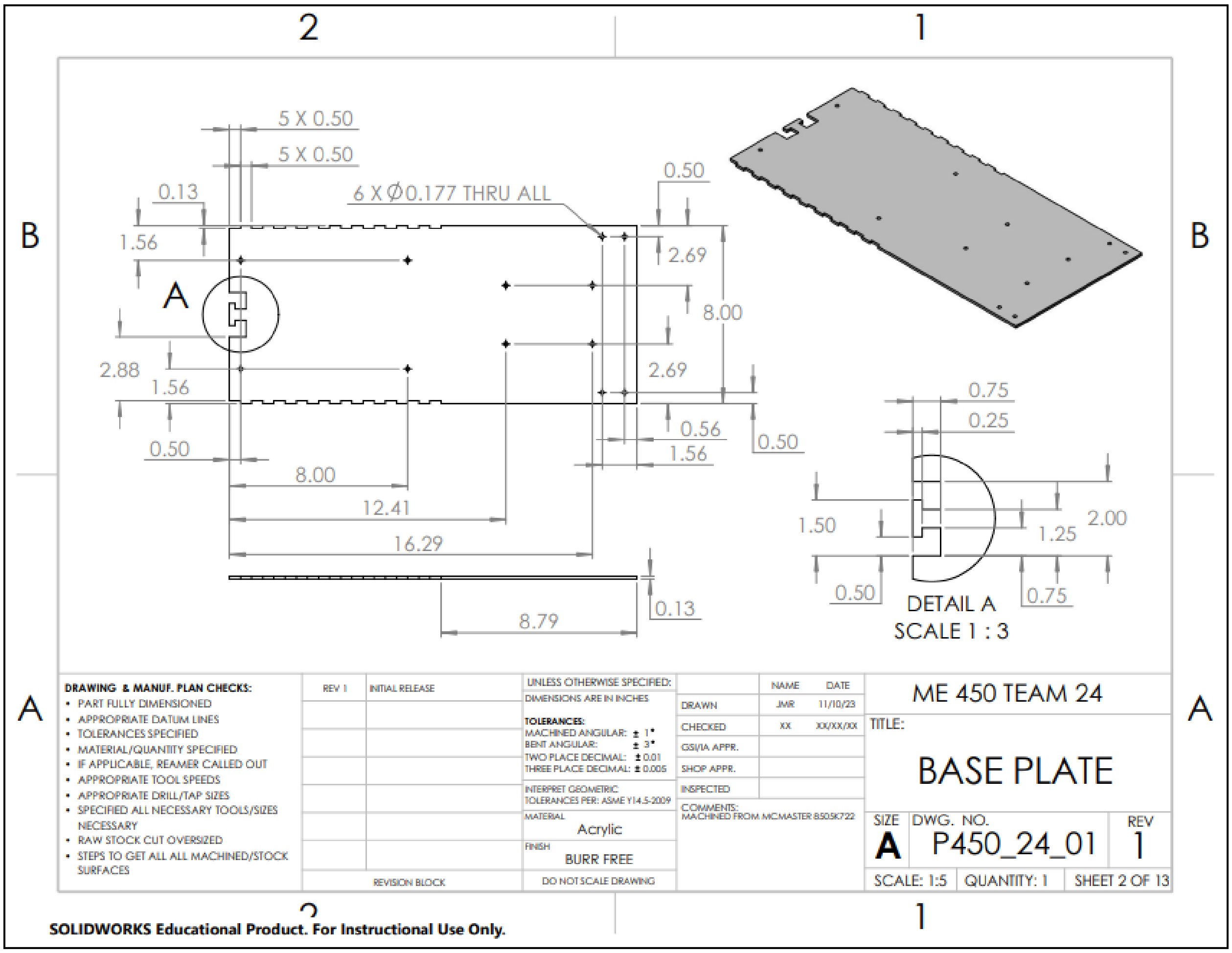


Figure E1: Manufacturing drawing for the base plate component of the beta design.

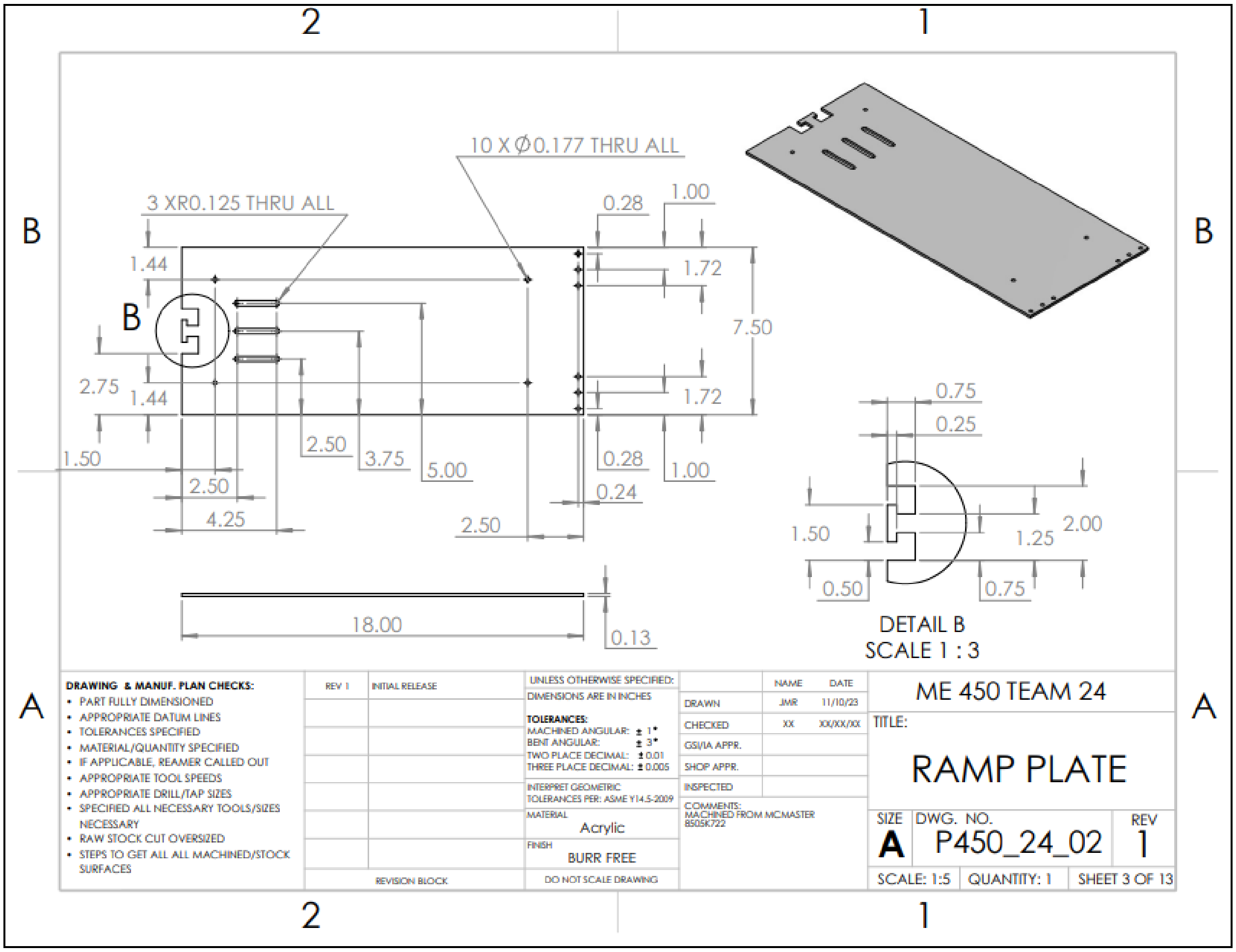


Figure E2: Manufacturing drawing for the ramp plate component of the beta design.

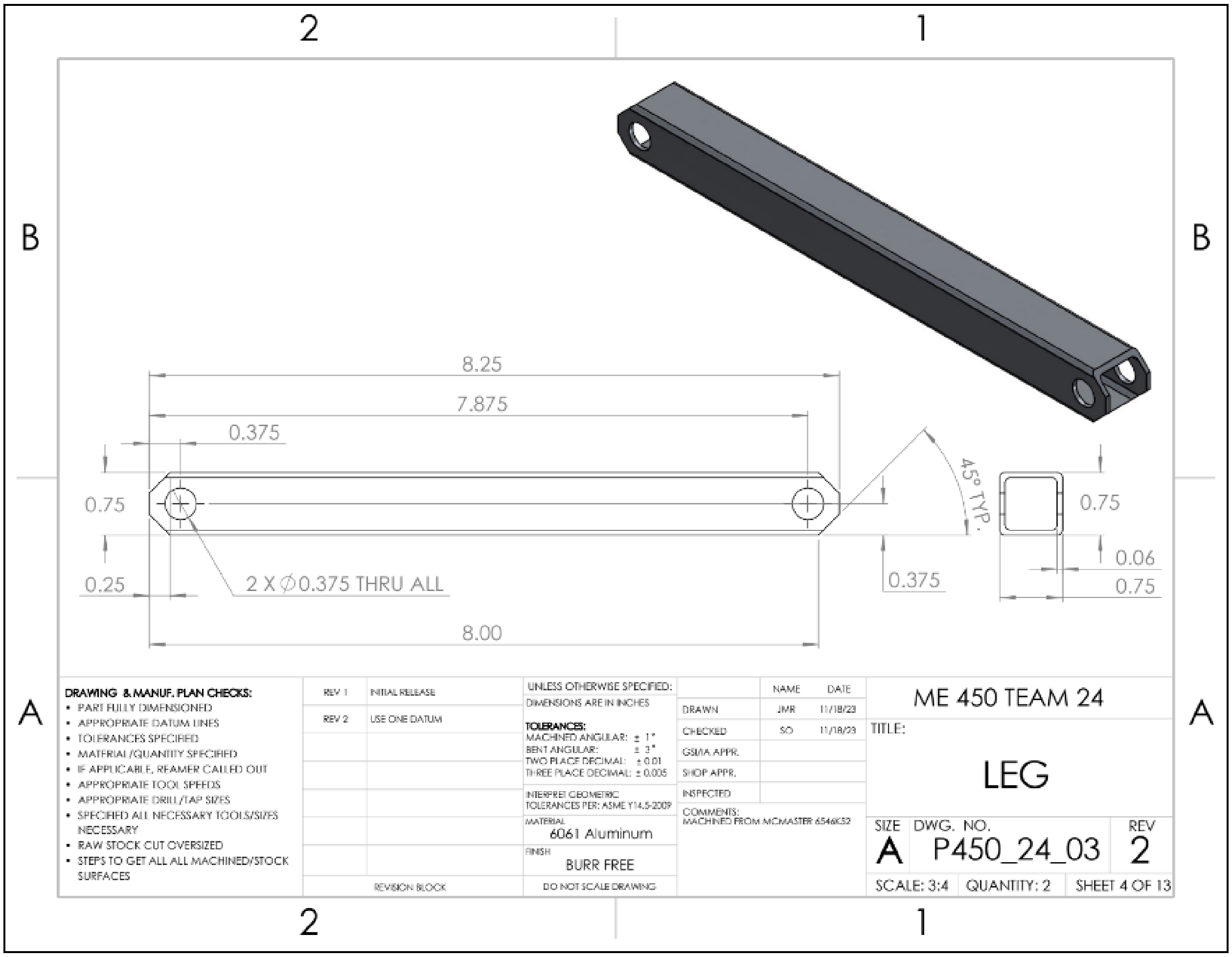


Figure E3: Manufacturing drawing for the leg components of the beta design.

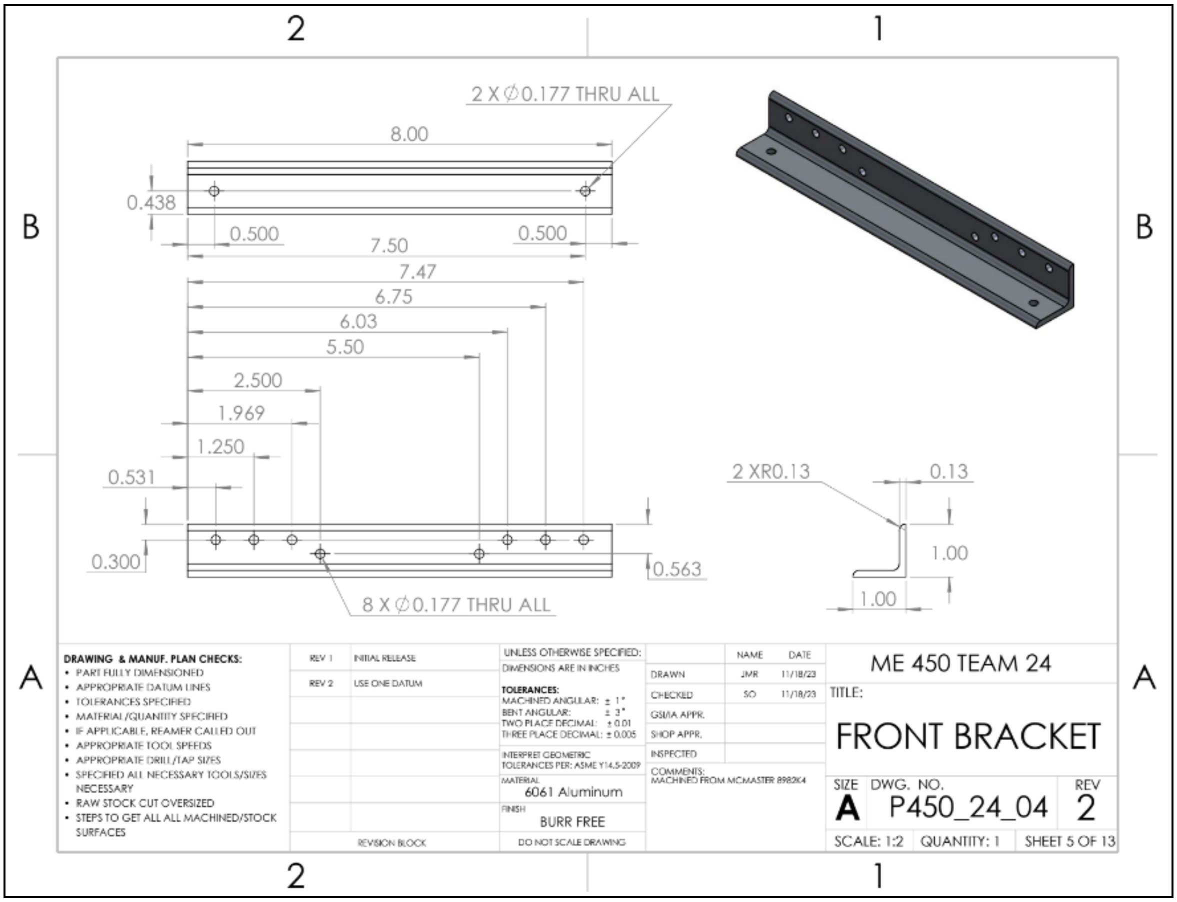


Figure E4: Manufacturing drawing for the front bracket component of the beta design.

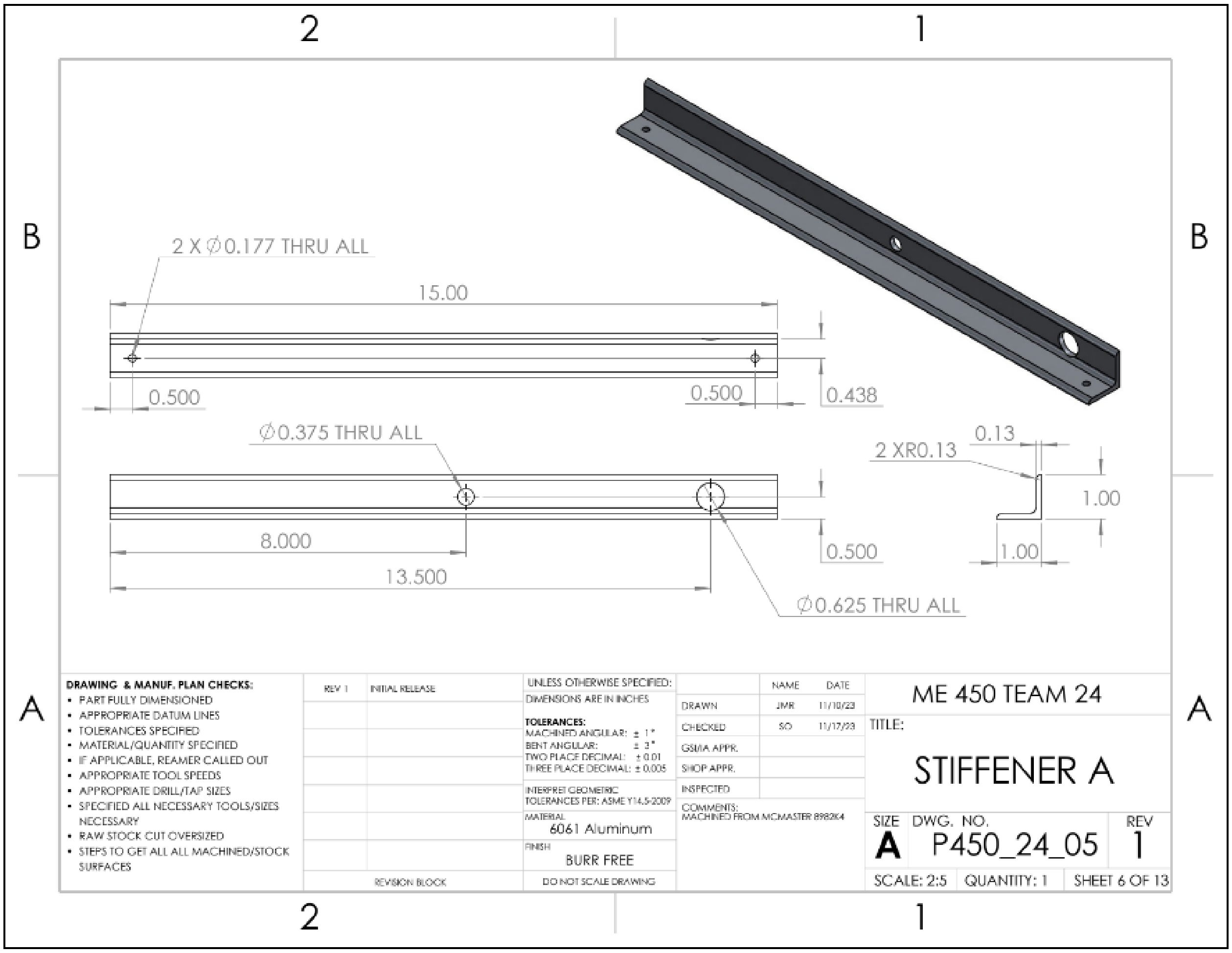


Figure E5: Manufacturing drawing for the first of the stiffener components of the beta design.

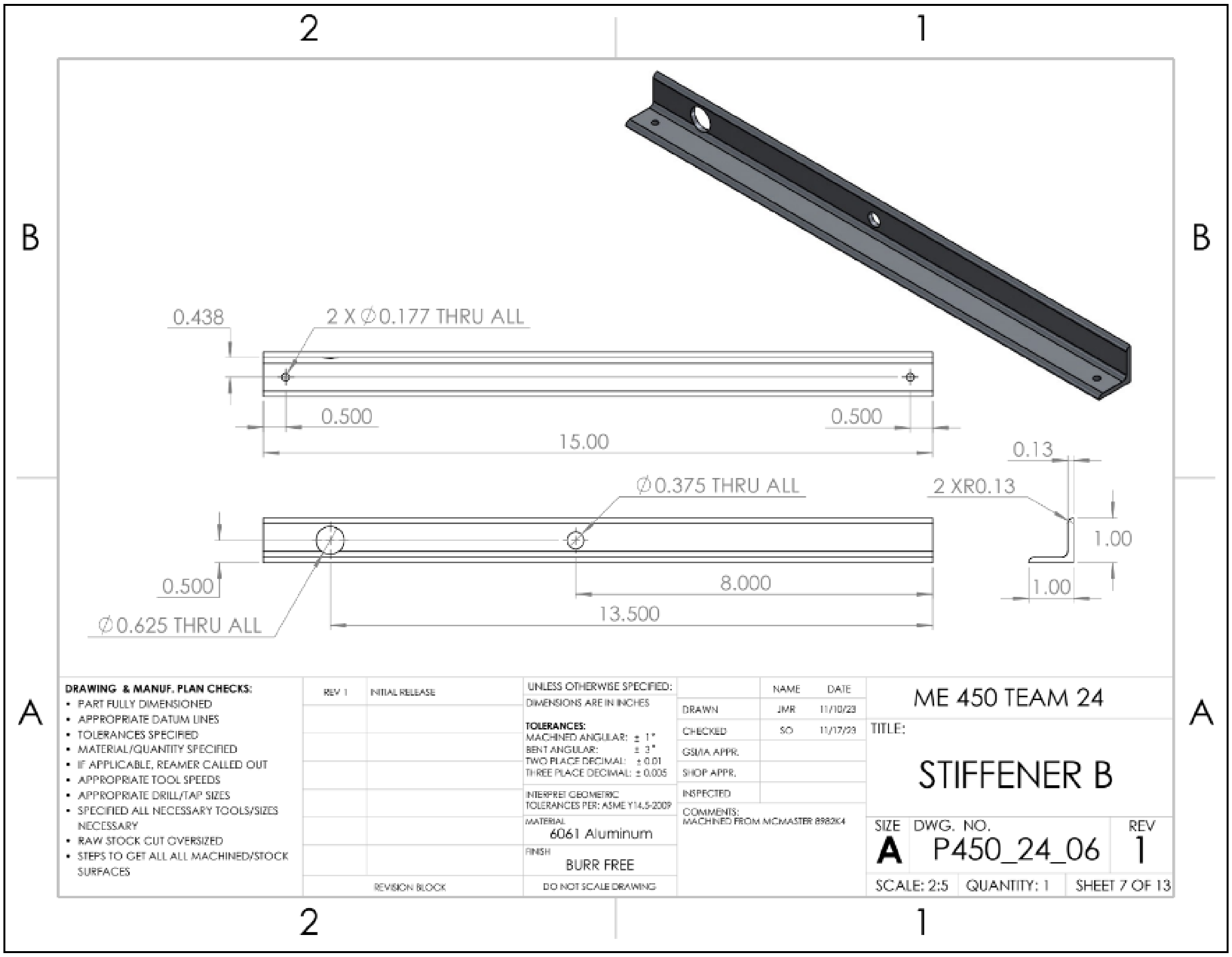


Figure E6: Manufacturing drawing for the second of the stiffener components of the beta design.

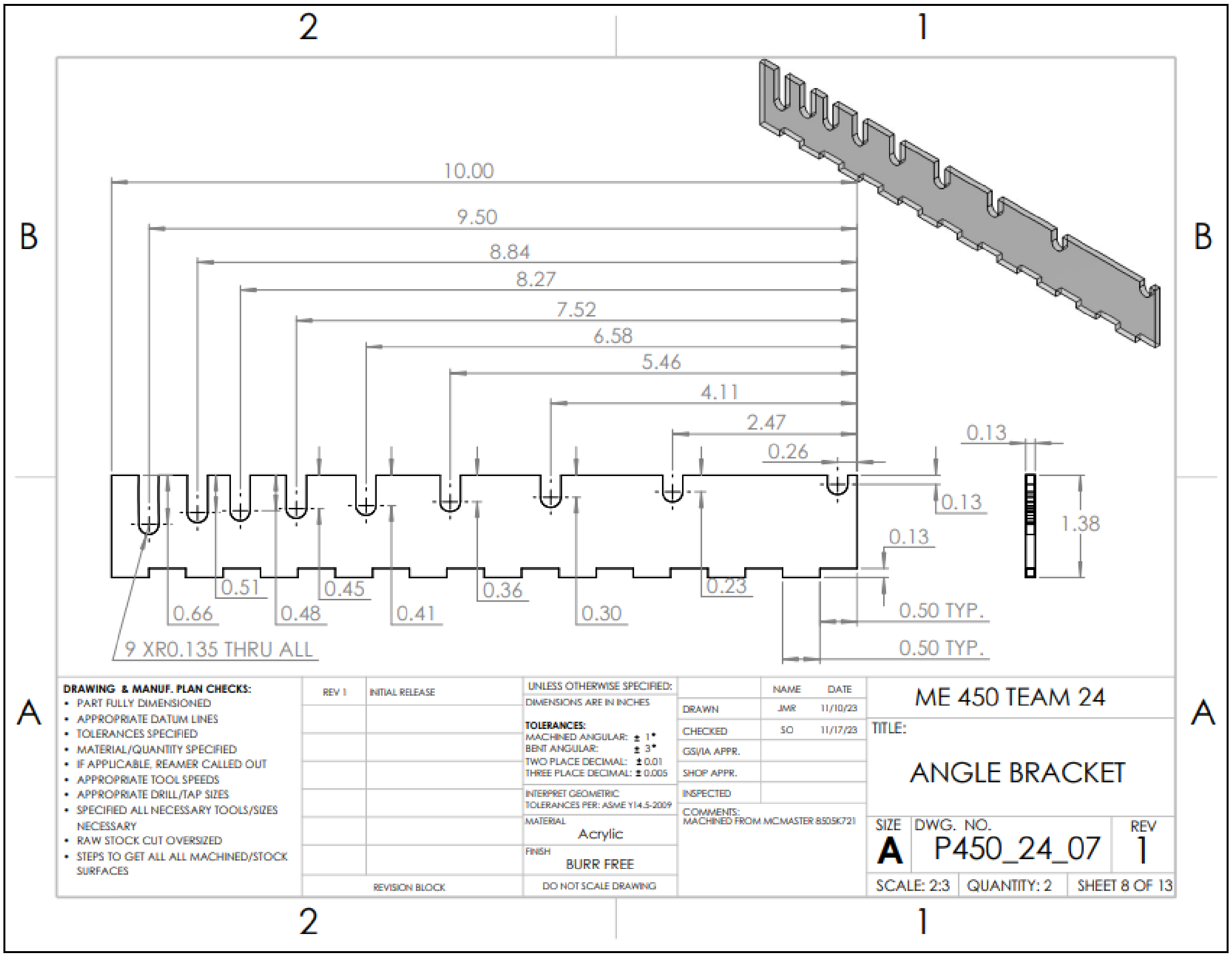


Figure E7: Manufacturing drawing for the angle bracket components of the beta design.

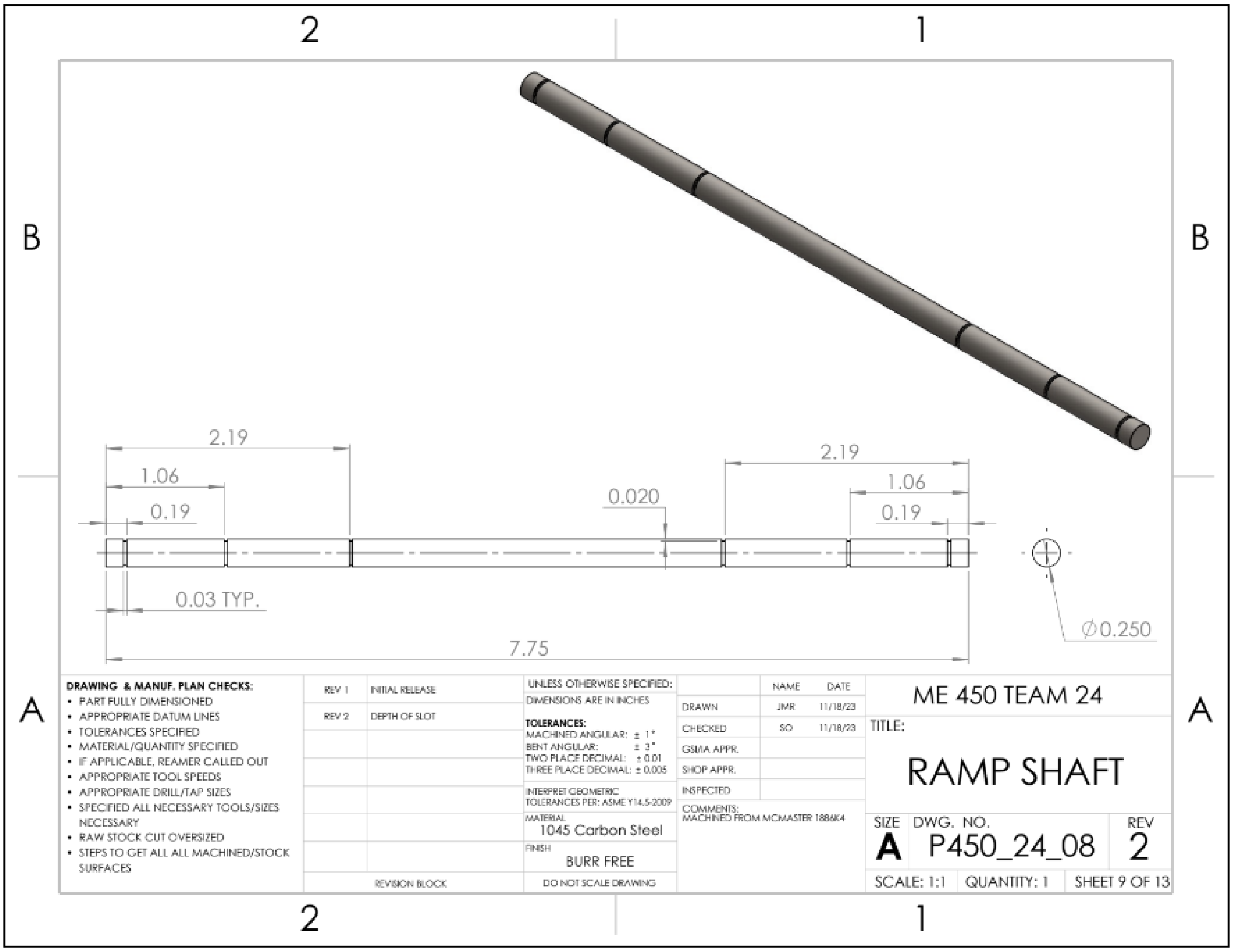


Figure E8: Manufacturing drawing for the ramp shaft component of the beta design.

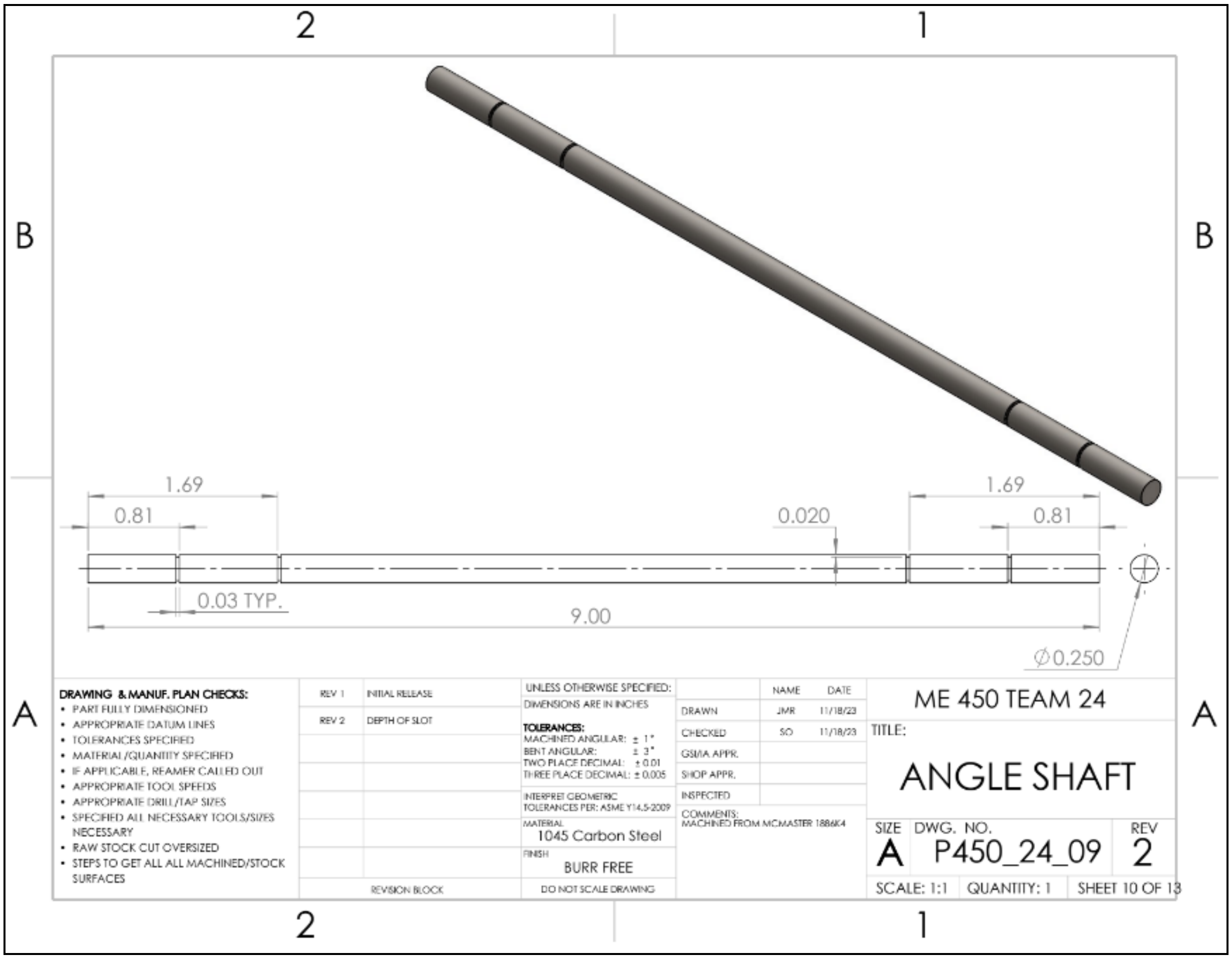


Figure E9: Manufacturing drawing for the angle shaft component of the beta design.

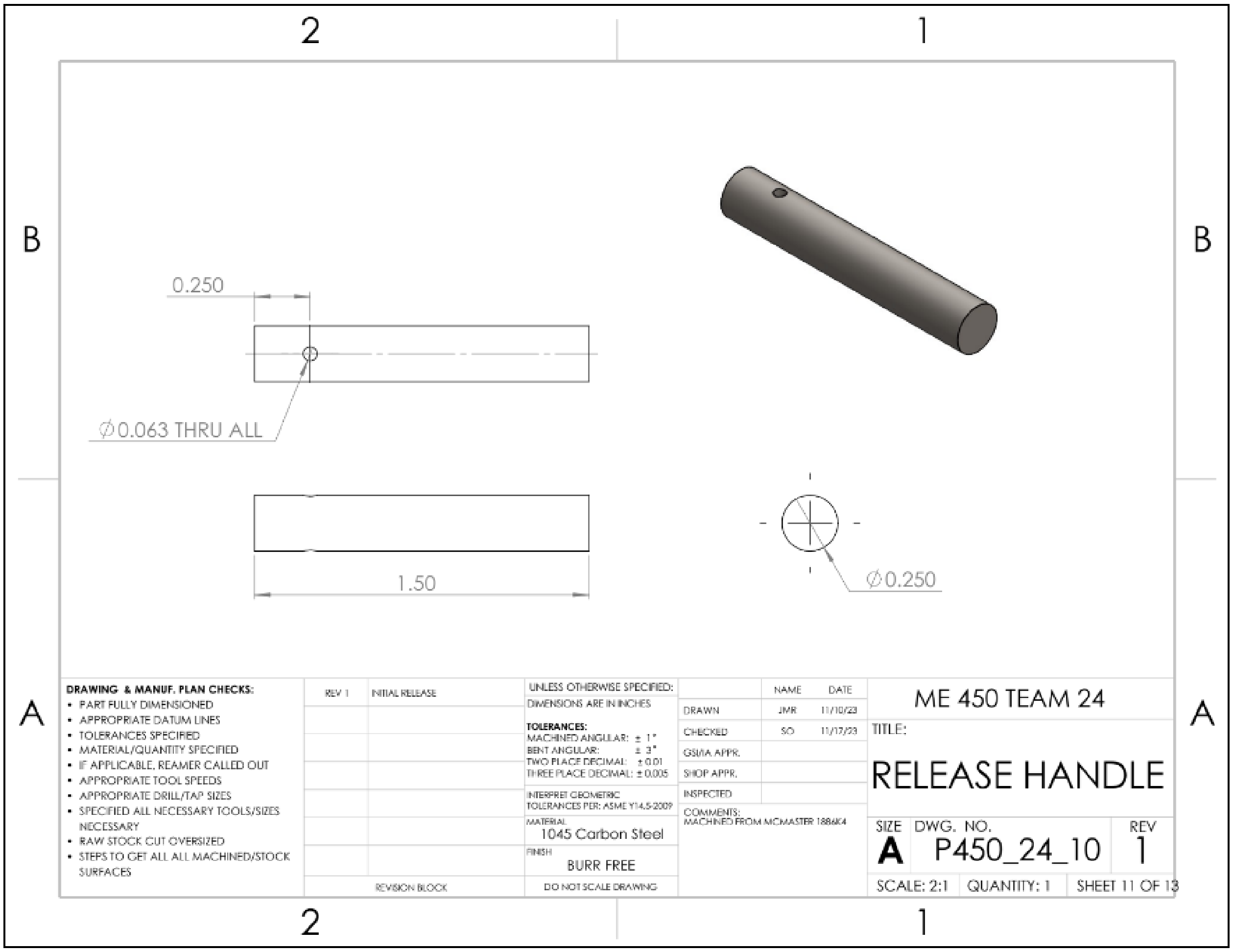


Figure E10: Manufacturing drawing for the release handle component of the beta design.

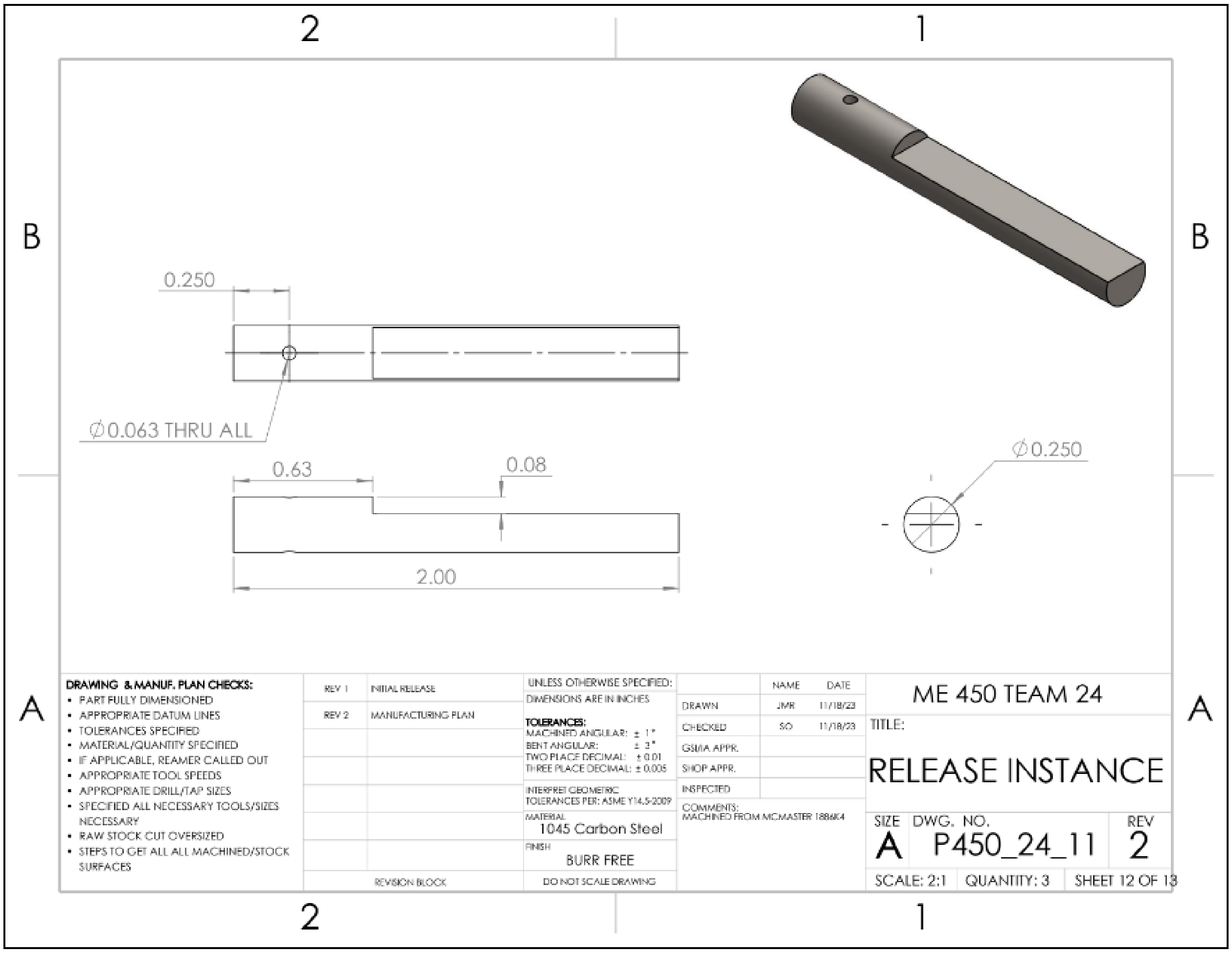


Figure E11: Manufacturing drawing for the release instance components of the beta design.

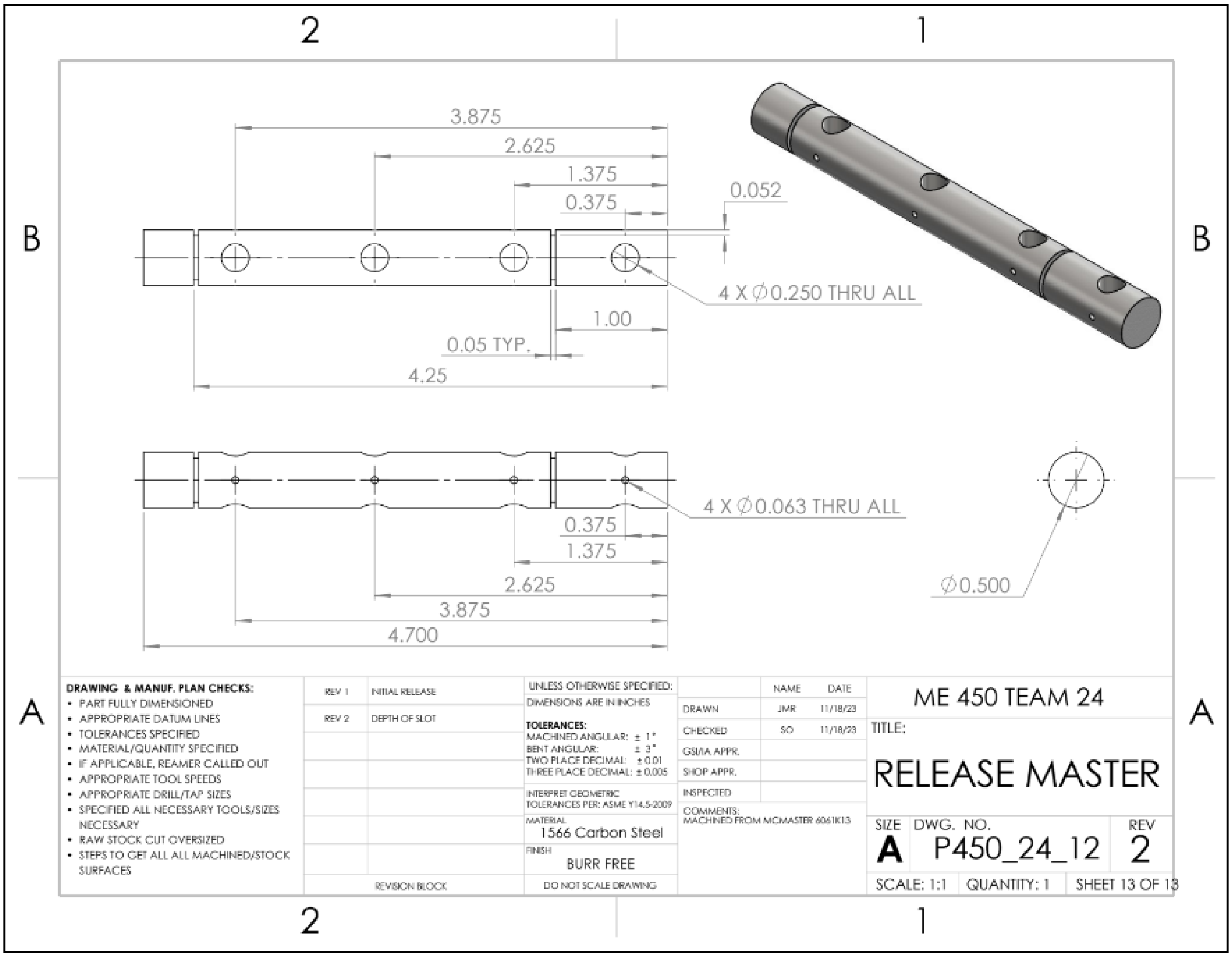


Figure E12: Manufacturing drawing for the release master component of the beta design.

Appendix F: Plans for Manufacturing

This appendix provides manufacturing plans for each of the parts within the variable ramp assembly that will require machining. Accompanying manufacturing drawings are provided in Appendix F.

Manufacturing Plan

Part Number: P450_24_03 Revision Date: 11/18/2023
Part Name: Leg
Team Name: ME 450 Team 24

Raw Material Stock: Aluminum Square Tube, 3/4 x 3/4 x 24 x 1/16

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut raw stock to 8.375 length	Horizontal Band Saw			
2	Hold part in vise.	Mill	Vise		
3	Mill one end of part, just enough to provide a fully machined surface.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
4	Remove part from vise. Break all edges by hand.			File	
5	Place part in vise to machine other end of part. Mill the part to 8.25 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Mill	Vise	3/4 inch 2-flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	Vise	Drill Chuck	
8	Find datum lines for X and Y.	Mill	Vise	edge finder, drill chuck	1000
9	Centerdrill and drill the first hole.	Mill	Vise	Center drill, 23/64 drill bit, drill chuck	1200, 1400
10	Ream the hole.	Mill	Vise	3/8 reamer, drill chuck	100
11	Find datum lines for X and Y.	Mill	Vise	edge finder, drill chuck	1000
12	Centerdrill and drill second hole.	Mill	Vise	Center drill, 23/64 drill bit, drill chuck	1200, 1400
13	Ream the hole.	Mill	Vise	3/8 reamer, drill chuck	100
14	Remove part from vise. Break all edges by hand.			File	

Figure F1: Manufacturing plan for the leg components of the beta design.

Manufacturing Plan

Part Number: P450_24_04 Revision Date: 11/18/2023
Part Name: Front Bracket
Team Name: ME 450 Team 24

Raw Material Stock: Aluminum L-Channel, 1 x 1 x 48 x 1/8

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut raw stock to 8.125 length	Horizontal Band Saw			
2	Hold part in vise.	Mill	vise		
3	Mill one end of part, just enough to provide a fully machined surface.	Mill	vise	3/4 inch 2-flute endmill, collet	500
4	Remove part from vise. Break all edges by hand.			File	
5	Place part in vise to machine other end of part. Mill the part to 8.00 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Mill	vise	3/4 inch 2-flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	Drill Chuck	
8	Find datum lines for X and Y.	Mill	vise	Edge finder, drill chuck	1000
9	Center drill hole.	Mill	vise	Center drill, drill chuck	1200
10	Drill hole.	Mill	vise	#16 drill bit, drill chuck	1400
11	Repeat steps 9 and 10 for remaining seven holes	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
12	Remove part from vise. Break all edges by hand. Reorient the part to drill on second surface.			File	
13	Find datum lines for X and Y.	Mill	vise	Edge finder, drill chuck	1000
14	Center drill hole.	Mill	vise	Center drill, drill chuck	1200
15	Drill hole.	Mill	vise	#16 drill bit, drill chuck	1200
16	Repeat steps 14 and 15 for remaining hole	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
17	Remove part from vise. Break all edges by hand.			File	

Figure F2: Manufacturing plan for the front bracket component of the beta design.

Manufacturing Plan

Part Number: P450_24_05 Revision Date: 11/11/2023
Part Name: Stiffener A
Team Name: ME 450 Team 24

Raw Material Stock: Aluminum L-Channel, 1 x 1 x 48 x 1/8

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut raw stock to 15.125 length	Horizontal Band Saw			
2	Hold part in vise.	Mill	vise		
3	Mill one end of part, just enough to provide a fully machined surface.	Mill	vise	3/4 inch 2-flute endmill, collet	500
4	Remove part from vise. Break all edges by hand.			File	
5	Place part in vise to machine other end of part. Mill the part to 15.00 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Mill	vise	3/4 inch 2-flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	Drill Chuck	
8	Find datum lines for X and Y.	Mill	vise	Edge finder, drill chuck	1000
9	Centerdrill and drill the first hole.	Mill	vise	Center drill, 3/8 drill bit, drill chuck	1200, 1400
10	Centerdrill and drill the second hole.	Mill	vise	Center drill, 5/8 drill bit, drill chuck	1200, 1400
11	Remove part from vise. Break all edges by hand. Reorient the part to drill on second surface.	Mill	Vise	File	
12	Centerdrill and drill the third hole.	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
13	Centerdrill and drill the fourth hole.	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
14	Remove and deburr	Mill		File	

Figure F3: Manufacturing plan for the first of the stiffener components of the beta design.

Manufacturing Plan

Part Number: P450_24_06 Revision Date: 11/11/2023
Part Name: Stiffener B
Team Name: ME 450 Team 24

Raw Material Stock: Aluminum L-Channel, 1 x 1 x 48 x 1/8

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut raw stock to 15.125 length	Horizontal Band Saw			
2	Hold part in vise.	Mill	vise		
3	Mill one end of part, just enough to provide a fully machined surface.	Mill	vise	3/4 inch 2-flute endmill, collet	500
4	Remove part from vise. Break all edges by hand.			File	
5	Place part in vise to machine other end of part. Mill the part to 15.00 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Mill	vise	3/4 inch 2-flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	Drill Chuck	
8	Find datum lines for X and Y.	Mill	vise	Edge finder, drill chuck	1000
9	Centerdrill and drill the first hole.	Mill	vise	Center drill, 3/8 drill bit, drill chuck	1200, 1400
10	Centerdrill and drill the second hole.	Mill	vise	Center drill, 5/8 drill bit, drill chuck	1200, 1400
11	Remove part from vise. Break all edges by hand. Reorient the part to drill on second surface.	Mill	Vise	File	
12	Centerdrill and drill the third hole.	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
13	Centerdrill and drill the fourth hole.	Mill	vise	Center drill, #16 drill bit, drill chuck	1200, 1400
14	Remove and deburr	Mill		File	

Figure F4: Manufacturing plan for the second of the stiffener components of the beta design.

Manufacturing Plan

Part Number: P450_24_09 Revision Date: 11/18/2023
Part Name: Ramp Shaft
Team Name: ME 450 Team 24

Raw Material Stock: Carbon Steel Shaft, 1/4 x 36

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut raw stock to 7.875 length	Horizontal Band Saw			
2	Hold part in collet.	Lathe		1/4 inch collet	
3	Face one end of part, just enough to provide a fully machined surface.	Lathe		1/4 inch collet, turning & facing tool	700
4	Remove part from collet. Break all edges by hand.			File	
5	Place part in collet to machine other end of part. Face the part to 7.75 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Lathe		1/4 inch collet, turning & facing tool	700
6	Remove part from collet. Break all edges by hand.			File	
7	Mark points 0.188, 1.063, and 2.188 inches from one end of the part			Marker	
8	Hold part in collet.	Lathe		1/4 inch collet	
9	Use grooving tool to cut grooves 0.020 inches deep at marks	Lathe		1/4 inch collet, 0.035 inch grooving tool	700
10	Remove part from collet. Break all edges by hand.			File	
11	Mark points 0.188, 1.063, and 2.188 inches from other end of the part			Marker	
12	Hold part in collet.	Lathe		1/4 inch collet	
13	Use grooving tool to cut grooves 0.020 inches deep at marks	Lathe		1/4 inch collet, 0.035 inch grooving tool	700
14	Remove part from collet. Break all edges by hand.			File	

Figure F5: Manufacturing plan for the ramp shaft component of the beta design.

Manufacturing Plan

Part Number: P450_24_10 Revision Date: 11/18/2023
Part Name: Angle Shaft
Team Name: ME 450 Team 24

Raw Material Stock: Carbon Steel Shaft, 1/4 x 36

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut raw stock to 9.125 length				
2	Hold part in collet.	Lathe		1/4 inch collet	
3	Face one end of part, just enough to provide a fully machined surface.	Lathe		1/4 inch collet, turning & facing tool	700
4	Remove part from collet. Break all edges by hand.			File	
5	Place part in collet to machine other end of part. Face the part to 9.00 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Lathe		1/4 inch collet, turning & facing tool	700
6	Remove part from collet. Break all edges by hand.			File	
7	Mark points 0.813 and 1.688 inches from one end of the part			Marker	
8	Hold part in collet.	Lathe		1/4 inch collet	
9	Use grooving tool to cut grooves 0.020 inches deep at marks	Lathe		1/4 inch collet, 0.035 inch grooving tool	700
10	Remove part from collet. Break all edges by hand.			File	
11	Mark points 0.813 and 1.688 inches from other end of the part			Marker	
12	Hold part in collet.	Lathe		1/4 inch collet	
13	Use grooving tool to cut grooves 0.020 inches deep at marks	Lathe		1/4 inch collet, 0.035 inch grooving tool	700
14	Remove part from collet. Break all edges by hand.			File	

Figure F6: Manufacturing plan for the angle shaft component of the beta design.

Manufacturing Plan

Part Number: P450_24_11 Revision Date: 11/11/2023
Part Name: Release Handle
Team Name: ME 450 Team 24

Raw Material Stock: Carbon Steel Shaft, 1/4 x 36

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut raw stock to 1.625 length	Horizontal Band Saw			
2	Hold part in collet.	Lathe		1/4 inch collet	
3	Face one end of part, just enough to provide a fully machined surface.	Lathe		1/4 inch collet, turning & facing tool	700
4	Remove part from collet. Break all edges by hand.			File	
5	Place part in collet to machine other end of part. Face the part to 1. 50 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Lathe		1/4 inch collet, turning & facing tool	700
6	Remove part from collet. Break all edges by hand.			File	
7	Hold part in vise. Install drill chuck.	Mill	Vise	Drill chuck	
8	Find datum lines for X and Y.	Mill	Vise	Edge finder, drill chuck	1000
9	Centerdrill and drill the hole.	Mill	Vise	Center drill, 1/16 drill bit, drill chuck	1200, 1200
10	Remove part from vice. Break all edges by hand.			File	

Figure F7: Manufacturing plan for the release handle component of the beta design.

Manufacturing Plan

Part Number: P450_24_12 Revision Date: 11/18/2023
Part Name: Release Instance
Team Name: ME 450 Team 24

Raw Material Stock: Carbon Steel Shaft, 1/4 x 36

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut stock to 2.125	band saw	vice		
2	Hold stock in Collet Block	Mill	vice, collet block		
3	Mill one end of part to provide fully machined surface	Mill	Vice, Collet block	3/4 inch 2 flute endmill, collet	500
4	remove burs and measure	Mill		File	
5	Mill part to 2 inch length in passes of .05 inches.	Mill	collet bock, vise	3/4 inch 2 flute endmill, collet	500
6	Remove part from vise. Break all edges by hand.			File	
7	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise, collet block	Drill Chuck	
8	Find datum lines for X and Y.	Mill	vise, collet block	Edge finder, drill chuck	1000
9	Centerdrill and drill the hole.	Mill	vise, collet block	Center drill, #53 drill bit, drill chuck	1200, 1800
10	remove drill and insert endmill	mill	vise collet block	3/4 inch 2 flute endmill	
11	make flat in passes of .05inches	mill	vise collet block	3/4 inch 2 flute endmill	500
12	remove part and debur			file	

Figure F8: Manufacturing plan for the release instance components of the beta design.

Manufacturing Plan

Part Number: P450_24_13 Revision Date: 11/18/2023
Part Name: Release Master
Team Name: ME 450 Team 24

Raw Material Stock: Carbon Steel Shaft, 1/2 x 6

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut raw stock to 4.875 length	Horizontal Band Saw			
2	Hold part in collet.	Lathe		1/2 inch collet	
3	Face one end of part, just enough to provide a fully machined surface.	Lathe		1/2 inch collet, turning & facing tool	700
4	Remove part from collet. Break all edges by hand.			File	
5	Place part in collet to machine other end of part. Face the part to 4.70 length, taking several passes at .05 inches per pass. Turn off the spindle, and measure part with calipers.	Lathe		1/2 inch collet, turning & facing tool	700
6	Remove part from collet. Break all edges by hand.			File	
7	Mark point 1.000 inches from one end of the part			Marker	
8	Hold part in collet.	Lathe		1/2 inch collet	
9	Use grooving tool to cut groove 0.020 inches deep at marks	Lathe		1/2 inch collet, 0.070 inch grooving tool	700
10	Remove part from collet. Break all edges by hand.			File	
11	Mark point 0.450 inches from other end of the part			Marker	
12	Hold part in collet.	Lathe		1/4 inch collet	
13	Use grooving tool to cut grooves 0.020 inches deep at marks	Lathe		1/4 inch collet, 0.070 inch grooving tool	700
14	Remove part from collet. Break all edges by hand.			File	
15	Hold part in vise. Install drill chuck.	Mill	Vise	Drill chuck	
16	Find datum lines for X and Y.	Mill	Vise	Edge finder, drill chuck	1000
17	Center drill hole.	Mill	Vise	Center drill, drill chuck	1200
18	Drill hole.	Mill	Vise	1/4 drill bit, drill chuck	1200
19	Repeat steps 17 and 18 for the remaining three holes	Mill	Vise	Center drill, 1/4 drill bit, drill chuck	1200, 1200
20	Remove part from vice. Break all edges by hand.			File	
21	Rotate part by 90 degrees, and hold part in vise.	Mill	Vise		
22	Find datum lines for X and Y.	Mill	Vise	Edge finder, drill chuck	1000
23	Center drill hole.	Mill	Vise	Center drill, drill chuck	1200
24	Drill hole.	Mill	Vise	1/4 drill bit, drill chuck	1200
25	Repeat steps 23 and 24 for the remaining three holes	Mill	Vise	Center drill, 1/4 drill bit, drill chuck	1200, 1200
26	Remove part from vice. Break all edges by hand.			File	

Figure F9: Manufacturing plan for the release master component of the beta design.

Biographies

In this section, each member of our team has included a short summary of our backgrounds in engineering.

Christian Nunez

Hi! My name is Christian Nunez (he/him/his). I'm from a small town called Grosse Ile, MI. There I grew up with my dad, mom, sister, and dog and cat. For most of my life, my dad (who majored in mechanical engineering) has worked for Ford Mo. Co.. There have been many occasions that I remember when my dad has explained to me many different parts on a car, the part he's working on, even letting me tinker with some things. To this day, I still find myself fascinated with cars and having a new passion for manufacturing. My dad has been an inspiration for me as an engineer, and I find myself running into situations that resemble lessons he taught me when I was younger. Because of this passion and inspiration, I strive to be the best mechanical engineer I can be. I find that there are many unique challenges that I run into during my college career, but I try to remember the inspiration my dad instilled with me.

As some fun facts about me, Grosse Ile is french for "Big Island" as the town is actually an island south of Detroit! Don't think it's super fancy, as it's not, but it's a cool fun fact. In college, I currently serve as a Rank Leader in the Michigan Marching Band. Being in the MMB is a separate story and dream in itself, but I find being a student leader to be one of the highest honors I've received along with some of the most difficult challenges as well. Nonetheless, I strive to be able to apply all of the lessons I've learned to the real-engineering world!

Sneha Ojha

My name is Sneha Ojha and I’m currently a 5th year in my final semester finishing my degree in mechanical engineering. I grew up in Rockville, Maryland, a city 25 minutes away from DC. I spent many of my weekends as a kid in the aerospace museum, where I fostered a love for engineering and space. I continued my STEM journey by attending a STEM high school where I was exposed to a variety of science, engineering, and mathematics concepts. I gravitated towards my physics and design classes, loving the ability to build living inventions and use physics to predict and control the way they move. This love for physics and design led me to pursue a degree in mechanical engineering at the University of Michigan. Throughout my time at Michigan I learned both in and outside the classroom. I’m currently an active member of a club called “Shift” on campus, where each member has the opportunity to create different projects. Through the club I met designers and coders, and learned how to couple my mechanical engineering skills with software and design to create new inventions. My projects outside of the classroom have fostered my love for engineering and design.

I also strived to find learning sources outside of the classroom. I took two winter semesters off to engage in full-time work. My professional work has primarily revolved around two fields: product design and aerospace. I worked six months at Northrop Grumman where I conducted loads and dynamics analysis, furthering my understanding of dynamics, modes, and resonance. I then worked the following winter semester at Apple where I honed in my prototyping and product design skills. This past summer I had the opportunity to intern to work at Humane as a product design engineer for the aipin, an AI powered device with laser projections.

Adam Rajner

I grew up in Toledo, OH, but do not worry; even though most of my family are buckeye fans I was raised a Wolverine. Growing up my uncle was an engineer for First Solar in Toledo, so I had an idea what engineering was but never knew if it was for me. After middle school I started high school at an all boys private school in Holland, a city outside of Toledo, and that is where I joined the FIRST tech challenge team and gained a real love for engineering. In that club I met some of my best friends who I still talk to on a daily basis. Through my four years our team made it to states all but one time, and always seemed to have the most fun out of all of the teams at the competitions. It was the amount of fun and passion I had on that team that made me decide I wanted to pursue engineering, but this was not the case until my senior year. Before that, I had thoughts of pursuing an art degree in film or something related, but what really made my mind was how it felt to be at those competitions and to see my work pay off. With my love of art as well is how I decided on Mechanical Engineering over other disciplines. I felt this was one where the engineer gets to be the most creative to solve problems, and use both halves of their brain to get to the best solution. After submitting my applications to college I was waitlisted here at UofM and accepted to OSU. A bit disheartened I sent in my admission fee to OSU, thinking that I would be a buckeye for four years of college. Then, the next day I got an email from UofM saying there was an update on my application, and you should have seen the look on my dad's face. These past three years have done nothing but affirm my decision to pursue mechanical engineering, and I will be working at Medtronic after graduation as a R&D engineer working on consumer diabetes products. It feels good to be confident in my career, and have the opportunity to put my education towards making people healthy.

James Ryan

I have spent my life growing up in Connecticut, though I would spend many summers in northern Michigan visiting my extended family. Though my grandfather kept an extensive number of projects in his home workshop, I will be the first in my family to pursue an engineering education. My interest in mechanical engineering goes back more than a decade, beginning with small LEGO Mindstorms competitions in primary school, then developing to more advanced projects with the FIRST Robotics Competition and engineering-related courses throughout my high school career. Engineering as a discipline, and more specifically mechanical engineering, has always appealed to me due to its connection between the theoretical analysis and practical manufacturing used to create solutions to a vast array of problems. I enjoy providing help for others, and find that I feel most successful when I am able to create tangible products for others to use for their benefit. I do, however, also enjoy having cerebral challenges to analyze, making engineering the most appealing career choice for me. In my experience engineers are both able to use their theoretical knowledge to determine a conceptual solution to a problem, and use their manufacturing expertise to help that solution come into reality. Mechanical engineering more specifically appeals to me because this field is largely unlimited in terms of the industries they work in, making job opportunities relatively abundant and keeping my options broad in terms of companies I am able to work with. To develop my mechanical engineering career I have been interning with Haydon Kerk Pittman, a manufacturing company based in Waterbury, CT for the last three summers, and I now have accepted a position at Electric Boat in New London, CT following my graduation from the University of Michigan.