NEXT GENERATION 350 PROJECT

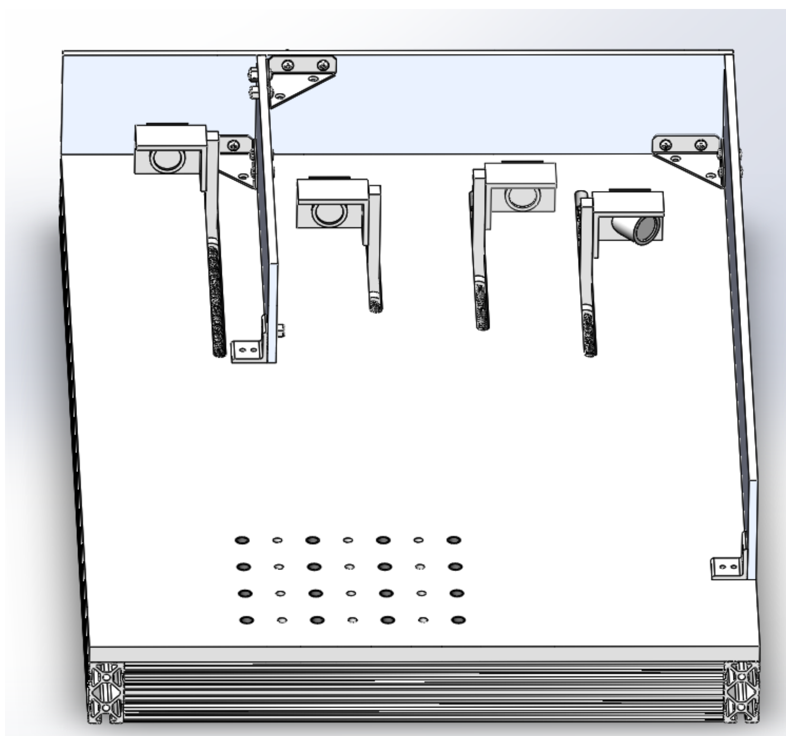


Table of Contents

Revised Abstract

The Next Generation ME 350 project is a team designed to create a new ME 350 design challenge to expand ME 350 student's mechanical engineering knowledge and create a new, unique game for students to participate in during future semesters. Specifically, a working prototype of the project, a working prototype of the playing field, and the project description document will be created. This new design will address difficulties that past ME350 students have faced, such as limited time issues and struggles with using arduino code, when participating while providing students with a unique learning experience.

Executive summary

In order to create a fun, complex, and new ME 350 design game for future semesters to compete in, this project team was established. It has been noted that past students have struggled with learning the different controls aspects of the course, especially for students who haven't taken specific classes yet like ME 360. Additionally, the previous game design was constructed with hybrid semesters in mind, removing the manufacturing component of the course. This project will take these into consideration and design a game that is accommodating for in person classes without overwhelming students to help them achieve the best possible outcome in learning the material.

In designing this project, certain requirements and specifications were needed. The project was broken down into three groups: Game Board, Game, and Mechanism. In these, the sponsor's restrictions along with stakeholders' opinions were taken into consideration. It was established that a key component to helping the students learn the material would be to have an engaging game in order to encourage students to go above and beyond when designing their mechanisms. This would be weighed by using a likert scale where the game should receive a score of at least a 3.5 out of 5. Furthermore, there were specific restraints with the required prototypes as storage and manufacturability needed to be considered in the design. The game board needed to be able to fit within a 44" by 26" by 9" cart and weigh less than 50 pounds so it could easily be transferred from the lab room to the sponsors office. Additionally, since around a dozen game boards will need to be made, the manufacture time for each game board should be under 300 hours. The mechanism created also has to follow restrictions mandated by ABET to make sure students will learn the necessary materials in the course. Specifically, this meant that the students had to design and manufacture a mechanism that used a PID controller for movement. From this, the design must include some sort of mechanism like a 4-bar linkage that would be able to have movement in two dimensions and be made with students having to spend less than 30 hours in the machine shop. All of these requirements and specifications are necessary to have a successful design that will allow students to learn the most from the project.

To determine the best possible characteristics that should be implemented with the project, past ME 350 students, GSIs, Professors, Current 350 students, past ME 450 Next Generation Project students, and the current person in charge of the Machine shop were interviewed. Besides interviews, past ME 350 game manuals and videos were reviewed as reference for analysis on what has been done in previous projects. All of these showed that the project should have a balance between manufacturing parts while not being overwhelming for the students along with encouragement from many stakeholders to help make the necessary code for the project more hand-on to help students learn more about writing arduino code. Furthermore, class modules were used to guide the design process and influence the design to be more environmentally friendly in reducing material waste.

In the design process, a divergent thinking process was used to help generate over ten concept ideas. From this, five different main concepts were selected and discussed for practicality and audience engagement. It was determined that the best possible design would be one based on a game called Plants vs Zombies and would be called Shine Your Light. This concept would have four different moving targets that move towards a four bar linkage that would have to move to shine a light on the targets. This was the superior concept as it seemed to be able to satisfy the different requirements and specifications and received an objective, positive score in a pugh chart that rated it among some of the other concepts.

To help verify the concept, manufacturing drawings were made for every part on the game board. Then, a prototype was created of one single linear target motion. In this, the proximity sensor, target, and photosensor were tested to verify everything worked and was able to be assembled. Furthermore, the mechanism was constructed and any parts that needed to be 3D printed were made. All of these components were used to help verify the deliverables that were required were able to be manufactured.

In order to complete all objectives in the time allotted, a gantt chart was created along with key milestones that need to be followed. These milestones broke up the project to specify when CAD designs would need to be completed along with the physical prototypes. These deadlines also allowed specific work to be completed for DR2, DR3, and the design expo.

Ultimately a mechanism and a prototype of a portion of the final game board were able to be completed and validated. The mechanism will be able to be used to validate the final game board once it is constructed next semester. The prototype portion of the game board was used to validate many aspects of the final game board design and generate initial code that can be modified for the final board. The final game board was not completed due to insufficient time, however, it has been communicated to the sponsor and will be completed next semester.

Project Introduction

Broadly, the goal of the team is to create a new design challenge for students in the ME 350 class at the University of Michigan to complete over the course of a semester. ME 350 is the junior level mechatronics design class that all students in the mechanical engineering undergraduate program are required to take. It builds upon some of the concepts taught in ME 250 (including motors and transmissions, general design and prototyping, and teamwork and communication) while adding more advanced concepts like detailed mechanical analysis of linkages, motor/gear torque and selection, and control system design. Students are taught these concepts in the classroom, and then apply these skills to build and program a mechanism that can accomplish a set task. This project is very important for the students' ability to competently approach design problems in a team based environment, and therefore is important for the College of Engineering to achieve its goal of producing qualified engineers that can smoothly transition to working in industry when they graduate.

The instructional team for ME 350 generally creates a “game” for students to compete in over the course of the semester. Students will then need to design and build a mechanism that can achieve the goals of the game, subject to a handful of design restrictions. The instructional team has found that changing the overall concept for the game every few semesters is helpful to keep students and instructors engaged. Each new generation of the ME 350 design challenge creates a new opportunity to identify and solve some of the problems that previous games have had. The need for a new game is higher this semester than usual, because the current version of the game was designed to be implemented virtually due to COVID-19. This comes with some drawbacks, including lack of machine shop time and manufacturing experience for students. In addition to solving some problems that were created by the current, virtual game design, the project seeks to identify and solve some of the problems that were present during previous, fully in-person semesters. The team will follow a stage based, concentric design model where they revisit the requirements throughout the semester to track the project's progress and improve upon the design at each phase of the process.

To identify problems with the current and past ME 350 design challenges, The team focused on interviewing the stakeholders for the project. A full list of these stakeholders is shown in the following table.

Table 1: Stakeholders

Stakeholder Group	**Category**	**Point of Contact Name(s)**
Past 350 Students	Secondary Allies	Abigail Overbeck, Alyssa Orlans, Joe Taylor, Dane Andrew
Machine shop	Secondary Resource Provider	Don Wirkner
ME 350 GSI	Primary Beneficiary Resource Provider	Michael Hahm, Karthik Urs
ME 350 Profs	Primary Beneficiary Resource Provider	Michael Umbriac, Shorya Awtar, Diann Brei, Chinedum Okwudire
Current 350 students	Primary Beneficiary	Emma Nigrelli, Emma DeRidder
People That Use Mechatronics Lab	Secondary Bystander	Shorya Awtar
Prof. Schwemmin	Secondary Allies	Professor Schwemmin
Past ME450 Next Gen Project	Secondary Opponents	Beth Rosenbaum, Erica Forrest, Madison Ellsworth, Mariah Hart

The project sponsor is Professor Michael Umbriac, one of the members of the ME 350 instructional team. The team interviewed him to gain an understanding of how the ME 350 design challenge fits in with the course material taught in ME 350, and to determine the essential requirements for the design from an instructional standpoint. Many of these requirements have been consistent for the past few iterations of the design challenge, so meeting these requirements does not address specific unmet needs, but they are some of the most essential for preserving the integrity of the class. Importantly, the deliverables for the semester were identified: game concept and rules with a project description document, a prototype of the playing field, and a prototype of a mechanism that could work to play the game. This project does not have IP restrictions.

To identify some of the problems that may have been present during past iterations of the ME 350 design challenge, current and past ME 350 students were interviewed. Current ME 350 students (students who are just starting the course this semester) expressed the most concern about being able to implement the coding and working with arduino for this project. In investigating further, it was found that many past ME 350 students also felt like they were not fully prepared for the coding portion of the design project, and that they didn't fully understand how to set up the control system even after completing the project. This is a difficult challenge to tackle from an instructional standpoint, because the course that teaches how to set up control systems (ME 360) is not required as a prerequisite for ME 350, so some students have very little experience with control systems when they take the class. It is therefore important to use a control system that can be adequately understood using only material taught in ME 350, so that students who haven't taken ME 360 yet are on equal footing with those who have. Past students also mentioned that it was difficult to manufacture all of their parts in the time allotted.

The team also interviewed Don Wirkner, a member of the machine shop staff, to understand what can be done to solve some of the problems with manufacturing that have been present in previous projects. The machine shop is very important for ME 350, both because future ME 350 students will be conducting their manufacturing work in the machine shop, and because the machine shop staff is primarily responsible for building the playing fields once they are designed. From this interview, requirements for the playing fields were gathered that would help the machine shop when producing them, and also got some ideas for ways that can ease the manufacturing time crunch on students.

The team interviewed two ME 350 GSIs to get another viewpoint on what aspects of the course students commonly struggle with. The GSIs felt that the amount of time required for manufacturing in the past has been achievable, which conflicts with what some of the past students reported. One GSI did mention that it would be possible to reduce the manufacturing load by encouraging the use of 3D printing as an acceptable method of creating parts. The GSIs emphasized the importance that creating a fun and engaging game could have on student engagement and performance throughout the semester. Essentially, the more the students are interested in and care about performing well on the project, the more invested they will be in their design and the better the end result will be. The GSIs identified the current software used to analyze the linkages (ADAMs) as another point of confusion and frustration for students. Lastly, another problem that they identified is that many projects produced a lot of material waste at the end of the semester. Finding a way to reuse parts, particularly if it could incorporate parts from the virtual kits, would reduce the environmental impacts and overall cost of the project.

There are no intellectual property considerations for this project. There are, however, important social contexts that need to be addressed. Specifically, public health needs to be considered as the University of Michigan Mechanical Engineering student body will be interacting with this project daily. Therefore, it is important that safety precautions are taken to ensure that students and GSIs interacting with the game board are not put in a position where they could potentially be injured.

Benchmarking

This design challenge has been an integral part of the ME 350 course for many years, so there are several previous projects to compare it to for technical benchmarking. The most recent project, The Special Pick n' Place in my Heart as shown below in Figure 1 was designed to be implemented virtually due to COVID-19. It used a paper playing field with differently colored zones. Colored washers would be placed on a ramp at the edge of the playing field, and a color sensor in the ramp would determine their color. The linkage would then swing over to the ramp, pick up the washer with an electromagnet, swing to the appropriate zone, drop the washer, and repeat until all washers were placed. While this project did not allow any machining for students due to the virtual nature (all the components used were delivered to students in a kit), it did have the strength that each student was involved in each step of the design process, because each individually got the chance to design, analyze, build, test, and code for their individual prototype.

The next Project was the High Beams and Linkage Beam as shown in Figure 2 Below. The previous project used a playing field with five flags corresponding to five photosensors. The flags were raised using servo motors, and a proximity sensor determined which flags were raised and communicated this information to the linkages. The linkage then needed to move to shine a flashlight on the photosensor corresponding to the raised flag. This project was identified by the GSIs as being less engaging for students in their sections than other projects had been.

The final project was the Ball Collection Project as shown below in Figure 3. This project featured a vertical playing field, with two tubes for balls to drop out of. The balls would be caught by a cup on the linkage, and then a color sensor in the cup would determine the color of the ball. If the ball was maize or blue, the linkage would drop the ball into a basket. If the ball was any other color, the linkage would throw the ball toward a net off the side of the playing field. This project was identified by the GSIs as being very engaging for students and very fun to watch the mechanisms run through.

Figure 1: Special Pick n' Place in my Heart

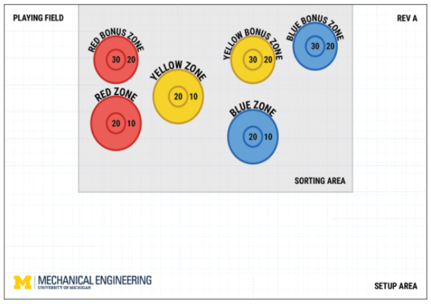


Figure 2: High Beams and Linkage Dreams

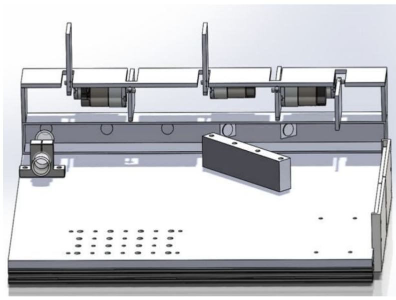
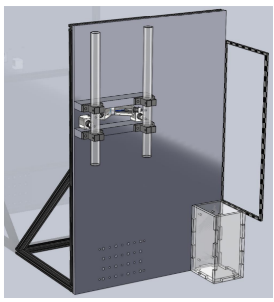


Figure 3: Ball Collection Project



To provide context on how successful previous projects were, the last three projects of the course were compared against a select few requirements. This comparison is shown below in Table 2. It was decided to include requirements from each of the three sections and choose them based on which ones could be used to differentiate them.

Table 2: Previous Project Comparison

Requirement	Weight	Ball Collection Project	High Beams and Linkage Dreams	A Special Pick n' Place in my Heart
Easy to set up Game Board	2	2	3	3
Easy to manufacture Game Board	4	3	2	5*
Use of a scoring system in Game Design	4	5	5	5
Game should be engaging and fun	4	5	2	3
Easy to manufacture Mechanism	3	3	2	3
Total	**85**	**65**	**50**	**67**

As you can see, of the previous projects the special pick ‘n place in my heart project from the hybrid semester. We believe this value is skewed because the game board was especially easy to manufacture because it was a piece of paper. Other than that, the game was still relatively engaging. The next highest performer was the ball collection project. Its main contribution was that the game itself was extremely fun and engaging for students. The lowest performer was from the high beams and linkage dreams project. This was largely due to the complexity of the game board and a lack of engagement from students.

Requirements and Engineering Specifications

Through the interviews with the professors and GSI’s for the course as well as current and former ME 350 students, characteristics of particularly successful projects were able to be identified along with what was required for the students to learn throughout the course and form them into requirements and specifications. Each of the requirements was assigned a weight (1-5) for how important it is for the project and each specification was assigned a weight (1-5) for how important it is at completing the requirement. The weights were then multiplied to find a total weight which was used to prioritize the specifications. The Team decided to split the requirements into three separate sections for clarity and organizational purposes. The first section, for the game board, is shown below in Table 3.

Table 3: Game Board Requirements and Specifications

Requirement (Weight)	Specification (Weight)	Total Weight
Inexpensive (3)	< \$700 each (5)	15
	Reduce waste and cost by using >\$100 worth of materials from COVID kits (3)	9
Easy to set up (2)	Set up in < 2 minutes (4)	8
	< 3 separate parts (2)	4
	< 5 steps to assemble (4)	8
Easy to manufacture (4)	< 300 hours to make all boards (5)	20
	≤ 2 machines to make each part of game board (3)	12
Easy to store (2)	Fits on 44” x 26” x 9” cart (5)	10
	Weighs < 50 pounds (4)	8
Game board should behave in a manner that is fair to all students (3)	Photosensors should correctly respond to presence/absence of flashlight 98% of the time (5)	15

As shown above, the requirements for the game board were that it was inexpensive and easy to set up, manufacture, and store. Easy to manufacture was determined to be the most important requirement in this section because the machine shop staff is responsible for mass producing the boards and they have been overworked with projects in the past. They said < 300 hours would be a reasonable amount of time for them to spend making all of the boards. The board also needs to be easy to store and set up because students will be operating in a space utilized by other classes, so the boards will be set up at the beginning of class and taken down and stored at the end. Specifications were completed with reference to a cart that has been used to store game boards in the past. The specification to reduce waste and cost by using greater than 100 dollars worth of materials the COVID kits was driven by one of the GSI stakeholders, Karthik Urs. In the past there has been a lot of material waste and it is a stakeholder goal to mitigate this by utilizing material that has already been bought. Another requirement is that the game board performs fairly for all students. To accomplish this the photo sensor will need to be accurate and consistently responsive.

Table 4: Game Requirements and Specifications

Requirement (Weight)	Specification (Weight)	Total Weight
Use of a scoring system (4)	1 scoring system based on machining and manufacturing (3)	12
	1 scoring category relating to linkage design (5)	20
	2 independent scoring metrics relating to performance (4)	16
Game should be engaging and fun (4)	Rating of at least 3.5 on a 5 point Likert scale (5)	20
	Game should allow multiple viable strategies to optimize performance (3)	12
Game should prevent circumvention of game rules (4)	Linkages should only able to hit one target at a time (4)	16
	Game board should require four bar linkage to complete game (4)	16

Shown above in Table 4, it was determined that the game should utilize a scoring system that measures student performance on machining and manufacturing, linkage design, and their mechanism's performance in the game. The team also emphasized the importance of the game being fun because it has been a great contributor in how much students get out of the project in the past. A Likert scale will be utilized to meet this requirement. Another specification will be allowing multiple strategies to optimize performance to help encourage design variation and creativity across teams. The requirement that the game should prevent circumvention of game rules was added because it is a design specific requirement. The students should not be able to hit multiple targets at once or be able to be successful in the game without utilizing a four bar linkage.

Table 5: Mechanism Requirements and Specifications

Requirement (Weight)	Specification (Weight)	Total Weight
Use controls taught in ME 350 (5)	Use of PID controller and Arduino microcontroller board (5) Use of Simulink/Matlab motion simulation (3) < 15 hours of manipulating code (3)	25 15 15
Use mechanism taught in ME 350 (5)	Use one or more of the following: 4 bar linkage, cam follower, rack and pinion, crank and slider, or 6 bar linkage (5) Require a transmission (5)	25 25
Use sensors taught in ME 350 (5)	At least one analog sensor, and one digital sensor (5)	25
Inexpensive design kits (3)	< $200 per kit, additional $50 per kit to spend on outside parts (3)	9
Easy to manufacture (3)	< 30 hours per group in the machine shop (5)	15
Promotes good design practices (3)	Mechanism uses two ball bearings at rotational joints (3) Mechanism properly uses shoulder screw (3)	9 9

Lastly, the team completed the requirements and specifications for the mechanism the students will be responsible for making which are shown above in Table 5. These requirements were largely determined by requirements for the course as a whole. For example, the course requires that students get experience with a PID controller and have experience designing a mechanism taught in the course. They are also required to design using feedback from an analog and digital sensor. That is why those specifications received the highest value of all at 25. Difficulties with programming were also mentioned by both GSI's and past and current me 350 students as a potential way for the course to be improved, so limitations on necessary coding time and easier to use software will be included. The team was given a budget for the design kits and wanted to limit student machining time based on feedback from the machine shop and student interviews. The requirement to promote good design practice was added because many students were not demonstrating good practice design. The team wants future ME 350 students to be shown and demonstrate good design practice.

Table 6: Summary of Requirements

Requirement (Weight)	Specification (Weight)	Total Weight
Easy to manufacture Game Board (4)	<300 hours to make all boards (5)	20
Easy to store Game board (2)	Fits on 44” x 26” x9” cart (5) Weighs < 50 pounds (4)	10 8
Game should be engaging and fun (4)	Rating of at least 3.5 on a 5 point Likert scale (5) Game should allow multiple viable strategies to optimize performance (3)	20 12
Easy to manufacture mechanism (3)	<30 hours per group in the machine shop (5)	15
Design Complexity (3)	Mechanism has motion in two dimensions (3)	9

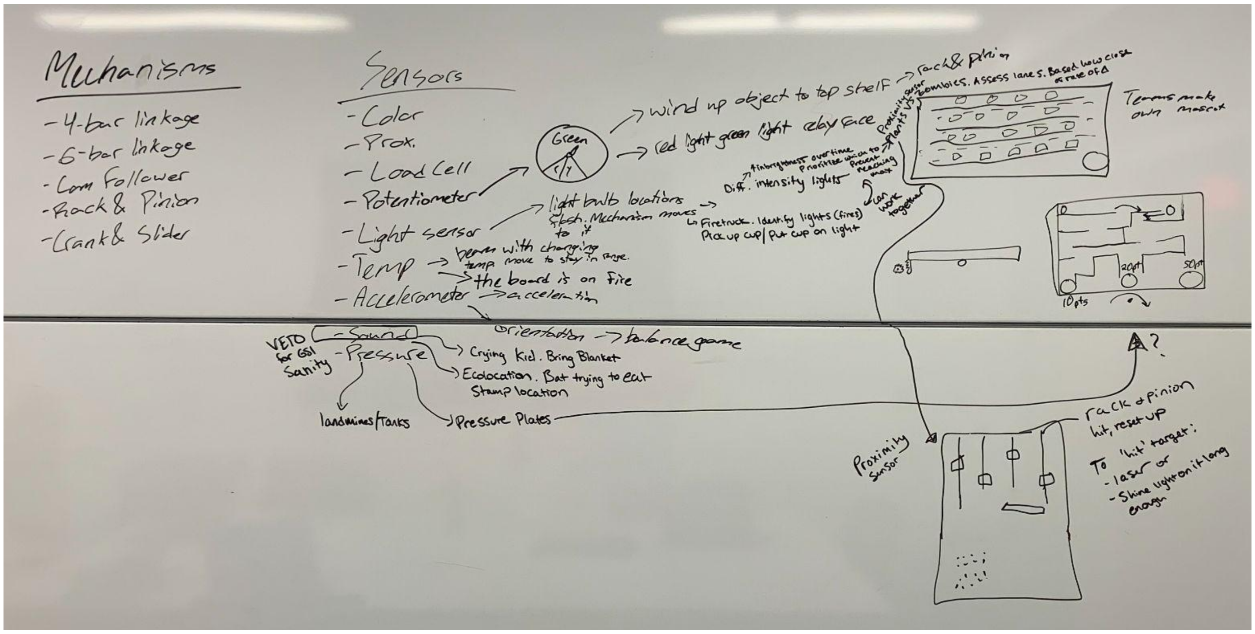
Out of all of the previously mentioned requirements and specifications, the team selected a few of the most important specifications to use to analyze future projects. Most specifications are ranked by importance according to their weights. However, not all of the high weight specifications were included for future analysis as they didn’t provide any differentiation across projects. These mainly consisted of the course requirements such as use of a PID controller, use of a mechanism taught in ME 350, use of a transmission, use of sensors, use of a scoring system and more. The most important remaining specifications included the time limit on manufacturing the game board and mechanism, size and weight limits on the game board, game engagement metrics, and mechanism design complexity.

Concept Generation

The concept generation process began with each member of the team creating their own individual game idea. The team then met to discuss each of the concepts and prepared them to be presented and graded by fellow members of the course. Following the presentation it was determined that each of the ideas were not creative enough and did not provide enough improvement to the course. Upon completion of the concept generation learning block, the team decided to host a brainstorming session with the tools the team had learned to generate more impressive concepts.

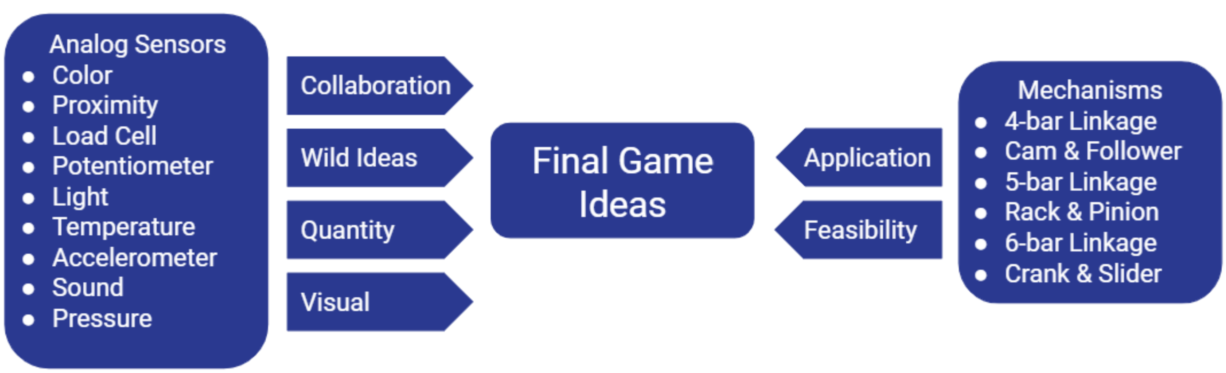
The session took place in the Findlay Learning Center with idea generation taking place on the whiteboard to encourage creativity. It began by utilizing a functional decomposition approach where the main contributors to the game were split up. Those contributors being the analog sensor that students’ mechanism will be getting values and reacting to and the overall mechanism that the students will have to design to compete in the game. A picture of the brainstorming session is shown below in Figure 4 and will be elaborated on further later.

Figure 4: Picture of Brainstorming Session



The brainstorming process began by listing each of the potential analog sensors that could be used by students. From there, a divergent thinking process was used where the team generated at least a couple of ideas for each sensor type (color and proximity sensor ideas not shown). This forced the team to get creative when thinking of potential ways to use sensors and resulted in some of the best initial ideas. The team also encouraged wild ideas. For example, a member of our team, Valerie started to talk about the game board being on fire and that led to one of our game ideas "whack-a-mole". Once the general idea of the game was generated, the team looked at all of the potential mechanisms and chose the top few options that would be most applicable and feasible for the game so far. From there, the rules and game concepts were finalized. This process helped us generate 10+ concepts of which, the top 5 were selected based on stakeholder feedback. A schematic of the process is shown below in Figure 5 and additional concepts are included in Appendix A. Further down selecting will be discussed in more detail later.

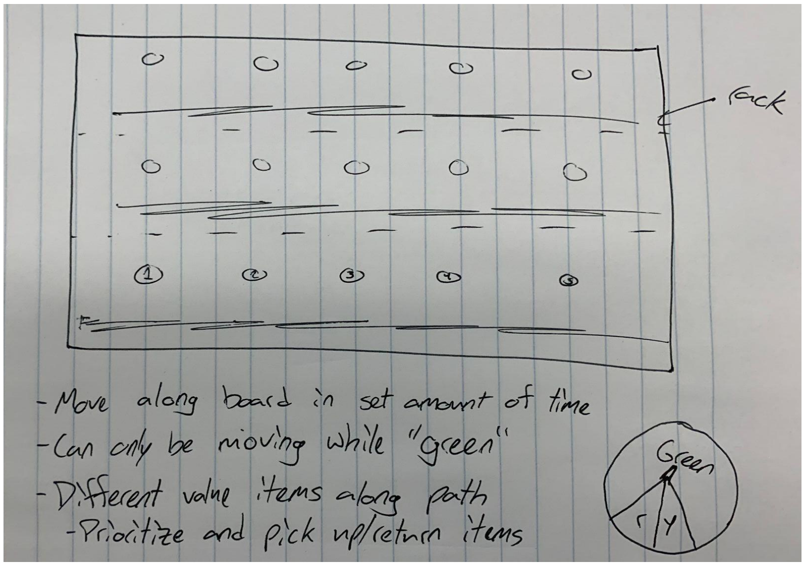
Figure 5: Concept Generation Process



The first game concept was based on the childhood game "red light green light" and utilized a potentiometer that students would get voltage readings from to determine if their mechanism was allowed to move or not.

The mechanism was a rack and pinion responsible for moving across the board and picking up objects within a set time. Teams would compete against each other on the same board. The initial concept drawing is shown below in Figure 6.

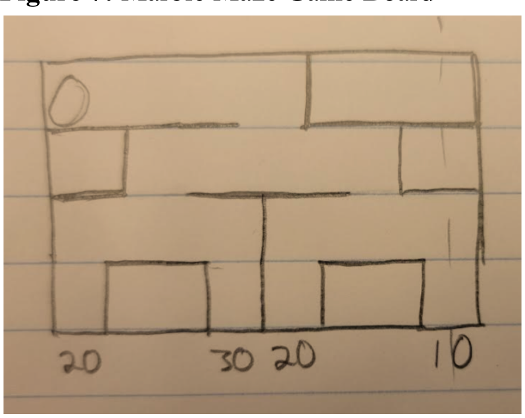
Figure 6: Red Light Green Light Game Board



The second game concept was a marble maze style game where students would be responsible for designing a cam and follower that would tilt the board of a maze. The students would have to guide a marble through the maze and attempt to score as many points as possible within the allotted time.

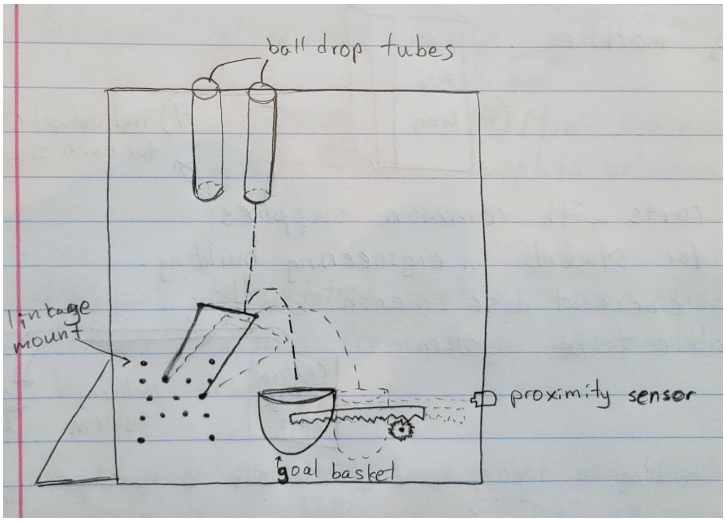
Students would get readings from several proximity sensors for their mechanism to know the position of the marble. An initial concept sketch is shown below in Figure 7.

Figure 7: Marble Maze Game Board



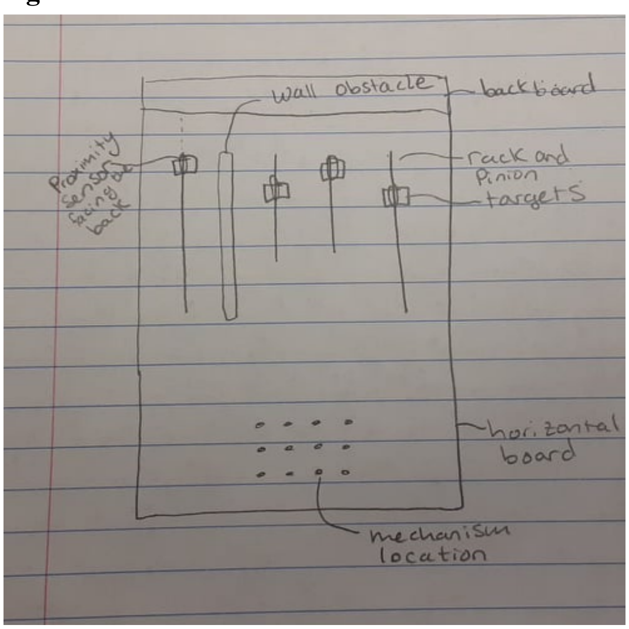
The third game concept was a moving basket bounce game. Essentially, students would design a mechanism that would be responsible for bouncing falling balls into a moving basket. Balls would fall from one of two tubes attached to the board and the basket position would be detected by a proximity sensor. The basket would likely switch between two or three positions to make design more feasible. The mechanism, a four bar linkage or crank and slider, would change angles to bounce the balls different distances. A sketch of the game board is shown below in Figure 8.

Figure 8: Moving Basket Bounce Game Board



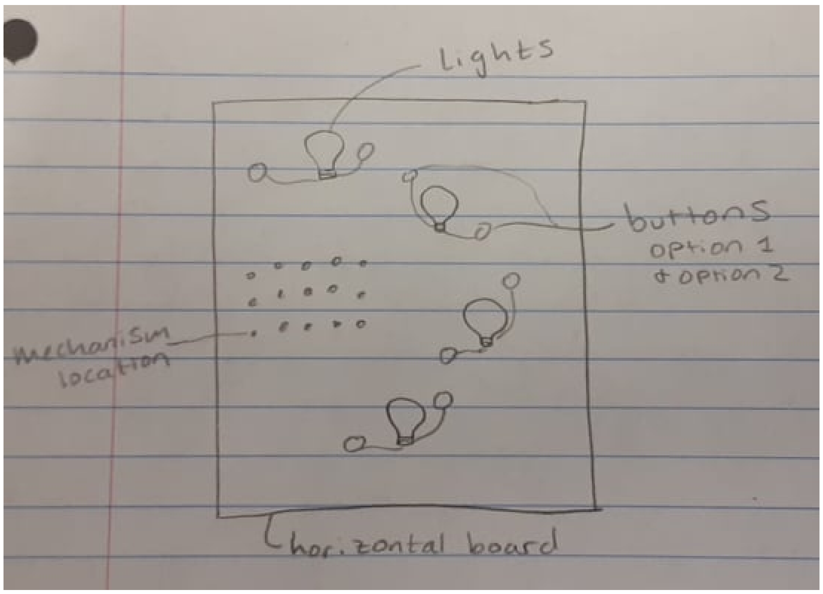
The fourth game concept was inspired by the children's game "Plants vs. Zombies' ". In this game, students would be responsible for designing a four bar linkage that must shine a light on several different targets as they move along a set path. Students must shine the light on them for a set amount of time to send the target back to the top of the board before targets reach the end of their path to avoid a scoring penalty. Points are awarded for successfully shining the flashlight on the targets. Targets would have a proximity sensor so the mechanism knows which targets are furthest along their path and they would have a photo sensor to detect the flashlight. An initial game board is shown below in Figure 9.

Figure 9: Plants vs. Zombies Game Board



The fifth and final concept was a “Whack-a-mole” style game. The board would consist of several lightbulbs that change brightness levels at different points in the game. Students’ mechanisms would take readings from a photo sensor to know which light bulbs are activated and move to the respective button to enable it. This concept was considered using a five bar linkage with light bulbs and buttons spread out or using a four bar linkage with multiple button options for each light to help encourage design variation. An initial game board is shown below in Figure 10.

Figure 10: Whack-a-mole Game Board



Concept Selection Process

To narrow down the design concept options, several tools were used. First, two likert scales were used in designing a google form in order to determine which base ideas appealed to the audience. With this, people were asked to rate each design concept on a scale of one through five on if the concept was creative and if they would like to play a game based on that concept. The first time that the likert scale was used, it was on an initial set of concepts to gauge where a student's interests were and to build more concepts based on feedback presented. Because most games from the initial set did not receive a high rating, all but one was discarded and more concepts were generated.

Before the second google form was used, many of the project stakeholders were contacted to receive their opinion on which concepts were ideal. First, the project sponsor, Professor Umbriac was contacted to show all main concepts that were drawn, as shown in Figures 6-10. From this list, Professor Umbriac was able to give feedback on which designs held merit and ideas for them to be practical for the students. This helped show where exactly the sponsor's interests were and give a more clear picture of what the sponsor would like for the project. Specifically, this showed that he would prefer if the project had the students design a four bar linkage mechanism, even though the students could design the other options like using a crank and slider or a rack and pinion. Additionally, this meeting helped debunk some of the concepts that were shown. From the discussion, the sponsor made sure to go over the downsides that some of the concepts could pose for the students. This showed that the Marble Maze Game Board concept would not necessarily be feasible for a ME350 project as it could be too complex for the students at their current level. Still, the sponsor did appreciate the ingenuity of the project and the mechanics of the game would be something that would be taught in mechatronics courses. Furthermore, it was worrying how students might not learn a lot on manufacturing and designing a mechanism as it would not use the traditional four bar linkage. Still, it was a very unique concept and would provide a different aspect in learning in ME350. Because of the cons, it was decided that that concept would be discarded in favor of the concepts that did not seem to have that issue.

Besides meeting with the sponsor, other stakeholders such as past ME350 students, current ME350 students, and ME350 GSI's were contacted to get an initial understanding of what they thought of the concepts. From this, GSI's helped go over some pros and cons for each of the concepts to help objectively look at the concepts to determine which ones would be feasible and best for the students. During these meetings, it was determined that the Red Light Green Light Game Board concept would not be one of the better concepts for the students to compete in. This design was already hesitant as the sponsor had shown his preference for using a four bar linkage as the mechanism for the project which this concept would not be using. Therefore, it was unknown if the students would be able to get the most out of designing and manufacturing a mechanism for this project. Additionally, stakeholders also feared that it would be difficult to tell if the mechanism is supposed to be moving or not at a given time, so as a game it would be more difficult to judge. The design did have the advantage of using potentiometer as its sensor which is a different sensor then the ones that are typically used. Additionally, it would have been an engaging game as it would have multiple teams competing against each other. Still, the cons were the same concerns that the stakeholders voiced when this concept was shared, so it was decided that this concept would also be discarded.

In this, the GSI's rated what they thought would be the top designs for the project which were consistently the Plants Vs Zombies, Whack-a- Mole, and Moving Basket Bounce concepts. Because of this, these concepts were then broken down and rated with a pugh chart to determine which concept would be the final concept that would be done for the Project. This pugh chart is shown in Table 7. In this, those top three designs were compared to the Ball Collection Project that was used in past semesters of ME350 and then rated against the different specifications listed. This past project was used as a standard as this project was determined by stakeholders to be one of the top projects in being engaging for the students and had a creative element in it. It was also demonstrated mathematically to be one of the best projects based on the pugh chart from Table 2.

Table 7: Concept Design Pugh Chart

Specifications	Weight	Ball Collection Project	Plants Vs Zombies	Whack-a-Mole	Moving Basket Bounce
Easy to manufacture Game Board: < 300 hours to make all boards	20	0	-1	0	-1
Easy to store: Fits on 44” x 26” x 9” cart Weighs < 50 pounds	10 8	0 0	1 -1	1 0	-1 0
Game should be engaging and fun: Rating of at least 3.5 on a 5 point Likert scale Game should allow multiple viable strategies to optimize performance	20 12	0 0	1 1	-1 0	1 0
Easy to manufacture Mechanism: < 30 hours per group in the machine shop	15	0	0	-1	-1
Design Complexity: Mechanism has motion in two dimensions	9	0	0	1	0
Total		**0**	**14**	**-16**	**-25**

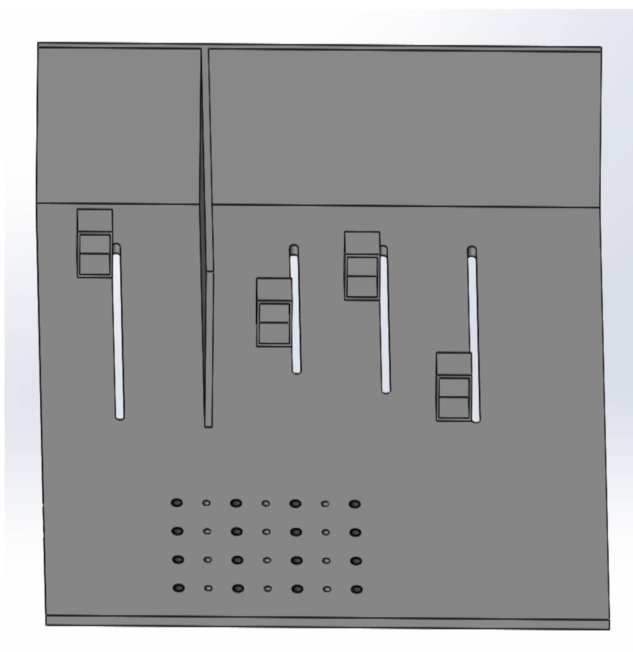
In comparing the concepts with the specifications, it was determined that the Plants Vs Zombies concept would be the best option to proceed with in designing a new ME350 game. In this comparison, it was determined that this concept, although having the potential to take longer to build the game board due to its many moving parts, would be more engaging for the students and should be easy to store. Depending on materials, it was projected that this concept could be heavier than the other two design concepts. Additionally, the concept seemed to have on par ratings for the mechanism in its manufacturability and complexity, which helped the Plants Vs Zombies concept receive a rating of 14 in the pugh chart. This was higher than the other two concepts which received negative ratings due to their mechanisms being projected to be more difficult to design, having the game board be more difficult to store, and potential in not being as engaging for the students.

It is worth noting that to determine how engaging the project would be for students, the second google form was used. In this, students were again asked to rate the top three concepts to again see if the concepts were creative and if they would like to play a game based on that concept. A likert scale was used in asking these questions so a score was able to be calculated to see if a concept fit in getting a 3.5 out of 5 for the likert scale. From this, Plants vs Zombies received a score of 4.281, Whack-a- Mole received a score of 3.322, and Moving Basket Bounce received a score of 3.410 showing that the Plants vs Zombies concept had the highest projected rating among students.

The Alpha Design

The alpha design concept was inspired by the children's game "Plants vs. Zombies' ". The students would be responsible for designing a four bar linkage that is able to maneuver across the entire game board to be able to hit the necessary targets. It also must be able to shine a light on an individual target as they move along the up and down motion. Each target will be oriented so that the linkage is not able to hit multiple targets simultaneously. The target on the farthest right side will be oriented on its right side and there will be a mirror mounted on the right. The linkage will be able to reflect the light off of the mirror and on to the furthest right target. Students must shine the light on them for a set amount of time to send the target back to the top of the board before targets reach the end of their path to avoid a scoring penalty. The linear motion of the targets are defined by a rack and carriage due to it being much simpler than a rack and pinion. In addition, linear motion is possible because of the motors that are attached to each corresponding target. The students are awarded points for successfully shining the light on an individual target for a set amount of time. Targets would have a proximity sensor so the mechanism knows which targets are furthest along their path and they would have a photo sensor to detect the flashlight.. An initial game board is shown previously in Figure 9 with an initial CAD setup shown below in Figure 11.

Figure 11: CAD of Game Board



The main subsystems of the alpha design concept consist of the mechanism, the horizontal board and the linear motion of the targets as shown in Figure 9. The mechanism is one of the main subsystems because the game would not be able to be performed with the motion of the 4 bar linkage across the entire game board. The 4 bar linkage has to be able to maneuver across the entire game board so it can shine the light on all of the targets to be successful in the game. The horizontal board and the game theme of "Plants vs.

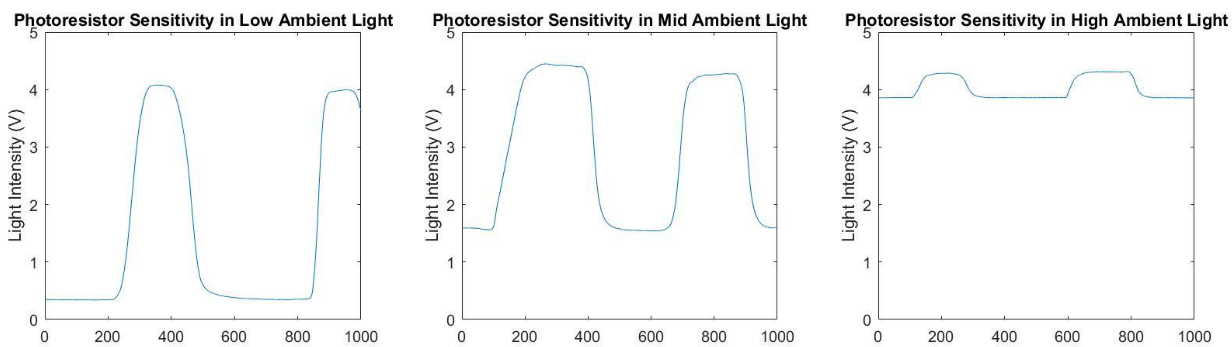
Zombies" allows for the game to be very engaging. This game theme would allow for students to be more invested in the game and enable them to get more out of the project. Lastly, the linear motion of the targets is a main subsystem because it is the main component of the game. It is the main component because the mechanism has to shine the light on the targets in order to be awarded points.

Concept Analysis and Iteration

With the alpha design selected, it is important to analyze the design for potential problems and engineering questions to be answered before prototyping begins. For the chosen design, the scoring needs to be fair for the ME 350 students who will be competing in the game, so it is necessary for the board to consistently sense when the flashlight is pointing at the targets in various levels of ambient lighting.

To answer this design question, the photosensor was tested in three different ambient light conditions for its response to a flashlight shining at it from six inches away. The photosensor was not covered from the ambient light in any of these tests, but it was bent to point sideways like it will during the actual performance of the game. The low ambient light condition was tested in a dark room with the lights turned off, the mid ambient light condition was tested in the same room with the lights turned on. The high ambient light condition was tested in a very bright room with industrial lighting. The photosensor response to the flashlight in the different environments is shown in Figure 12 below.

Figure 12: Photosensor sensitivity in different ambient light conditions



In each light condition, the difference between purely ambient light and ambient light plus the flashlight is sufficiently large, so it will be possible to use these photosensors in the final design without any cover or with only minimal cover from ambient light.

Another important question to consider is how to select an appropriate motor for the targets. The targets will each weigh up to 15 grams, and the motors will need to move them at a constant speed while the game is being played. The game will run with three rounds; the first two rounds will end after a set amount of time, and the targets will all move slowly enough for the students to be able to stop and send back each target before it reaches the end of the board. In the third round, the targets will speed up until the linkage cannot stop all of them and one target reaches the end of the board.

Each target will need to have the flashlight shining on it for one second to register, so that the students cannot just rotate the flashlight continuously through its range of motion to hit all the targets at once. In the slowest round, the students will have four seconds to hit each target (one second for the target to register the flashlight, three seconds for the linkage to identify the next target to hit and move between targets). This means each target would need to move from the start to the end of its individual path in an average of sixteen seconds, which translates to a linear speed of 1.4 cm/second.

In the fastest round, the targets potentially need to move from the start to the end of their individual paths in just under four seconds. This would force the students to ‘lose’ the round, because with a one second delay in registering the flashlight, at least one target would reach the end of its path. This means each target would need to translate at a linear speed of about 6 cm/second.

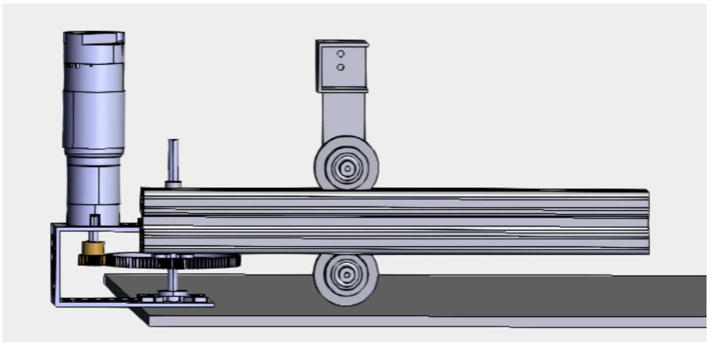
Engineering Design Parameter Analysis

Gameboard Analysis

The gameboard required different types of analysis in order to meet the requirements and specifications established by the stakeholders. The main form of analysis that was done was to use CAD modeling software to ensure that all measurements were practical and that the design was feasible. Specifically, this allowed for the design to establish overall dimensions and ensure that the design would be able to fit inside the dimensional constraints of being able to fit on a 44” x 26” x9” cart. Other forms of analysis were the Linear Motion Analysis, Lead Screw analysis, and Bill of Materials and cost analysis to ensure that the game board materials fit into the budget.
In the linear motion analysis for the target motion, the design evolved from a rack and pinion to carriage and timing belt assembly and then to a lead screw assembly. Initially, the rack and pinion designs were discarded due to the cost of the individual parts. Instead, other methods were researched at the suggestion of the stakeholders. This showed methods like scissor lifts, timing belt, and crank and slider. In order to select one of the options, a logical analysis was used to determine which method would work the best for the gameboard targets. The scissor lift method was discarded due to the many parts that it would need and the large initial force needed to start the scissor lift. Having only a small amount of parts necessary in the design was significant as two of the gameboard requirements stated that the gameboard needed to be inexpensive and easy to manufacture. Having only a few parts would help reduce costs while also helping to cut down on the amount of time it would take to manufacture all of the parts. Besides that, it would take up a lot of space under the gameboard, making it more difficult to fill the requirement of fitting on the cart.

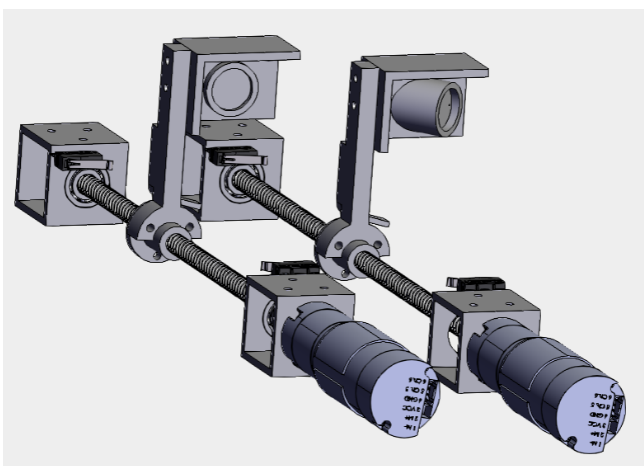
The crank and slider motion was also discarded again due to its size and its lack of ability to quickly change target direction from moving forward and backwards at anypoint on its motion. This left the timing belt option which, although it had a decent amount of parts, seemed like the best option. Upon further analysis by designing the CAD for the motion, as shown in Figure 13 along with discussion with the machine shop stakeholders, it was established that this method would also take a lot of parts to construct making the method seem overengineered along with taking up a lot of space under the board.

Figure 13: Carriage and timing belt assembly



Additionally, the timing belts would have to be constantly adjusted throughout the semester to have the correct amount of tension. This would be frustrating to the customers and make it so the game board is not as easy to assemble. Because of this, the stakeholders recommended using lead screws for the linear motion as shown in Figure 14.

Figure 14: Lead Screw Assembly with target



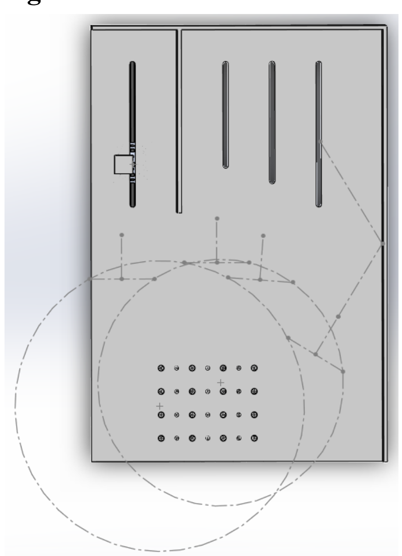
From lead screw analysis, it was decided that the game board would have a path of nine inches that the targets would move along. From this, the fastest a target would have to move would be four seconds to go from the back of the board to the front by going at a speed of 2.25in/sec. This speed was chosen based on the game rule establishing that a target would need to be shined for one second. To give motion to the targets, the planetary gear motor from the previous semesters was used to reuse parts as stated in the requirements. Based on the motor specifications established by the manufacturer, the motor had a no load speed of 12V at 435rpm. Having a goal motor speed of 350 rpm to allow for some adjustment from adding weight, a travel distance per turn needed with the lead screw of at least 0.4inches was established. From this, a lead screw that could travel 0.5 inches per turn was selected. Still, this was an estimated value, so there could be problems with this lead screw. If there are issues with the motor not being able to reach the fastest needed speed, the travel path could be reduced to seven or eight inches instead of being nine inches long. Additionally, the time it takes for the target to register the flashlight could be increased to 1.5 seconds or two seconds long. In order to test if this will be an issue, a prototype of one lead screw and its assembly will be constructed.

Mechanism Analysis

The mechanism required a variety of different analysis techniques to ensure that it was meeting the functional requirements outlined by the stakeholders. The first form of analysis was done utilizing 3D modeling software. This was primarily used to ensure that the mechanism would properly interact with the game board and that it included all of the components that the sponsors wanted to see. Other forms of analysis, such as technical analysis for the transmission ratio and a bill of materials to show costs, were also used.

To begin, a simple sketch of the mechanism consisting of the coupler link and a straight line representing the beam of the flashlight, was drawn overtop of the game board. The goal of this sketch was to ensure that the flashlight would be able to hit all four of the targets, and that the ground pivot locations fell within the designated region on the game board. To accomplish this, copies of the sketch were used to point at each of the targets. Then a circle was drawn which intersected the one end of the coupler at all four copies of the sketch. The center of this circle represents the location of the first ground pivot. This process was repeated for the other side of the coupler. A screenshot of this process is shown below in Figure 15.

Figure 15: Initial mechanism sketch with ground pivots



As shown, the center of the circles both lie within the pre-drilled holes in the game board which completes one of the goals of ensuring the holes are in a logical place. Also, the beam correctly lines up with each of the target paths proving that this design will be capable of playing the game.

Before further CAD could be completed, a necessary transmission ratio would need to be calculated. Two different methods were used to accomplish this. The first method was inertia matching. This method was selected because utilizing inertia matching allows for selection of the lowest possible start-up torque (and thus maximum mechanism speed). A full outline of the inertia matching process is shown in Appendix B. Put simply, the inertia of the linkage is calculated and used with the inertia of the motor, which is a given property, to calculate the minimum transmission ratio necessary to move the linkage. Using this method with the motor shown in Appendix C resulted in a transmission ratio of approximately 3.

The second method involved using the resolution of the encoder included with the motor. This method was chosen to ensure that the mechanism would be able to accurately hit each of the targets with the given encoder resolution. A full outline of the encoder resolution process is shown in Appendix D. Simply put, the encoder for the motor can detect a minimum change in the shaft angle. To guarantee that the linkage can hit all of the targets, there needs to be a transmission so the precise angle change in the mechanism can be detected by the encoder. Using this method with the same motor shown in Appendix C resulted in a transmission ratio of approximately 4.5.

Initially this analysis was done using a motor provided by the instructors that was used during the Winter 2020 semester and sooner (shown in Appendix E). While completing each of the inertia matching and encoder resolution calculations for this motor, the transmission ratio for each was found to be approximately 1. This was likely due to it having a much larger internal gear ratio and encoder resolution than the motor that was chosen after. The decision was made to use a different motor because the motor from the Winter 2020 semester did not necessitate a transmission as its transmission ratio was 1. This means that students could attach the motor directly to the input link which circumvents one of the requirements for the project of requiring a transmission and takes away a necessary learning point for students in the course.

The more conservative of the two previously calculated transmission ratios (4.5) was selected to ensure that the mechanism would meet the criteria of both methods of analysis and was used in the final design going forward. The remaining analysis for the mechanism, including the finalized CAD and BOM, are included in the final design section.

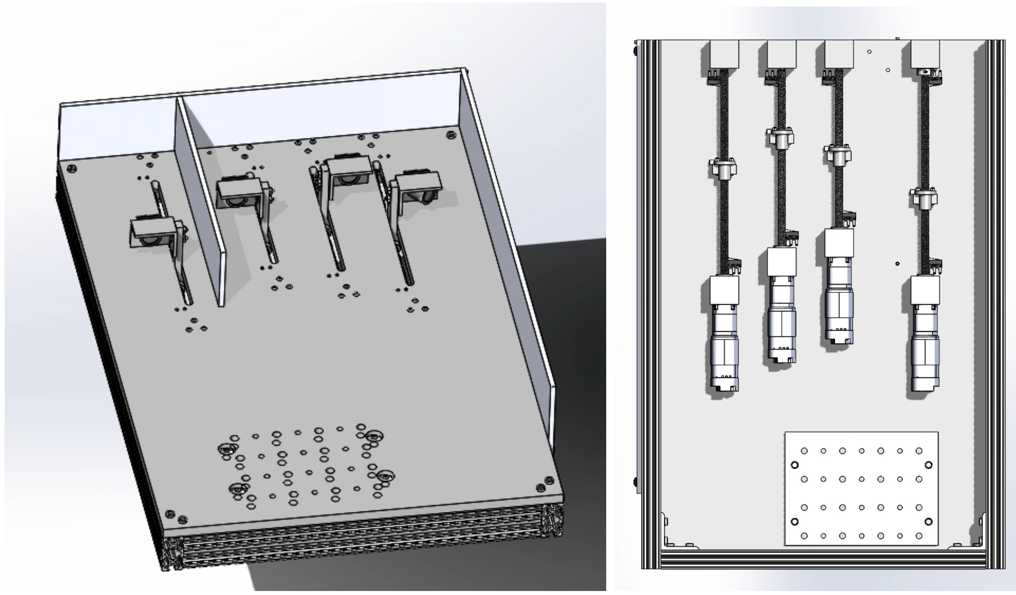
Final Design Description

CAD was used to create a design for both the game board and a sample mechanism that would be able to compete in the game.

Game Board Design

A complete CAD of the game board was constructed in order to ensure that the game would complete all requirements and be physically possible to construct. An overall version of the game board is shown in Figure 16 with the assembly order shown in Appendix G.

Figure 16: Final Game Board CAD Top and Bottom Views



As shown in Figure 15, the game board consists of a ½” delrin that is 28” by 19”. Supporting the weight and giving room underneath the game board are 80/20 aluminum V-Framing. The walls are composed of ¼” delrin where the rightmost wall will have a mirror attached to reflect the flashlight beam. Additionally, there are different mounting holes for students' mechanisms to attach to the game board. Underneath this location is a ⅜” aluminum plate attached to the baseplate designed specifically for students to secure their mechanism to through the tapped holes.

Attached to the base board are four 3D printed targets that are attached to a hub and will travel in a linear motion across the game board. Lead screws are used for this motion and it is driven by four planetary gear motors. The planetary gear motors are attached to the game board by using aluminum square channel and bearings. At the front and back of the target path, there are limit switches attached to the board. This will allow the targets to register if the targets are at the front or back of the path.

A proximity sensor is attached to the back of each target facing the back wall. There is also a photosensor in each target facing the front of the game board. There are also two aluminum corner brackets underneath the game board to provide support to the framing of the board.

The Bill of Materials, shown in Table 8, shows the parts used in the design along with if the parts will be bought or are already available.

Table 8: Game Board Bill of Materials

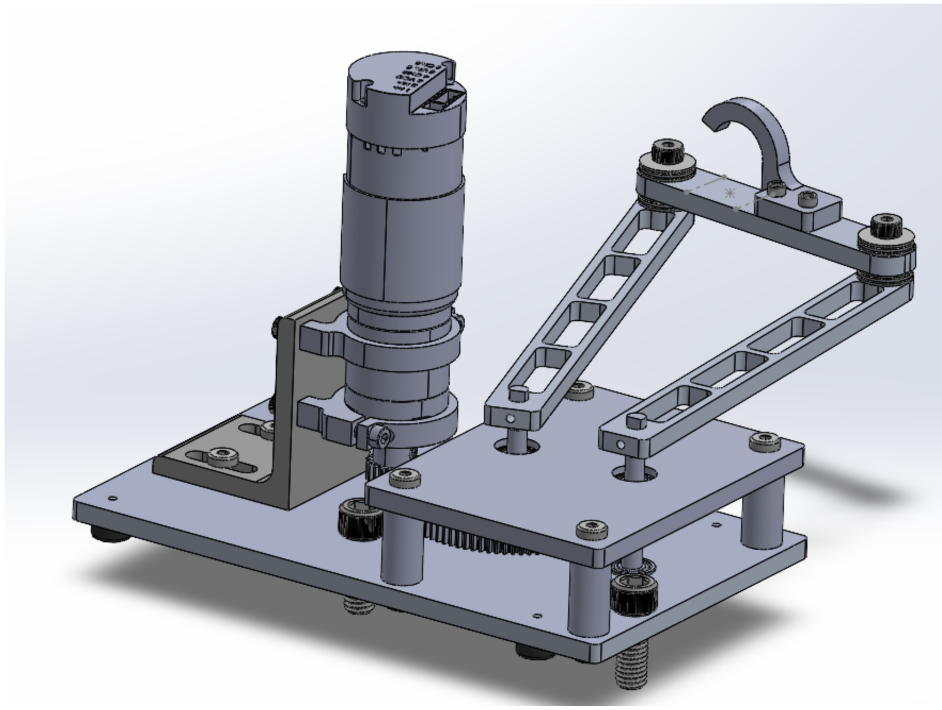
Game Board					
Part No.	Part Name	Quantity	Price (per each)	Net Price	Bought/Built
1528-2141-ND	Photosensitive Sensor	4	0.95	3.8	Bought
GP2Y0A41SK0F	Proximity Sensor	4	13.95	55.8	Bought
99030A303	Lead Screw	4	11.77	47.08	Bought
95072A125	Hub	4	20.21	80.84	Bought
60355K504	Bearings	10	1.199	11.99	Bought
H20190401BC11	Coupler (shaft to Screw)	4	4.99	19.96	Bought
5202-0002-0014	Planetary Gear Motor (13.7:1 Ratio, 435 RPM, 3.3 - 5V Encoder)	4	39.99	159.96	Have
255-6141-ND	Limit Switches	10	1.825	18.25	Have
55TF52	Base Plate (HDPE, Standard Grade, 48 in Plastic Length, 32 in Plastic Width)	1	111.92	111.92	Bought/Built
60TH62	Obstacle, Back & Side Wall (HDPE, Marine Grade, 24 in Plastic Length, 12 in Plastic Width)	1	24.94	24.94	Bought/Built
	Aluminum Plate (3/8", 8" x 1')	1		0	Bought/Built
47065T107	80/20 T Framing	1	25.59	25.59	Bought
	Target Case & Pole (3D Print)	4	0	0	Built
8982K13	Brackets (L-channel)	2	6.54		Built
1088A31	Inside-Corner Reinforcing Bracket	3	4.7	14.1	Bought
	Mirror	1	5.59	5.59	Bought
			Total price:	579.82	< 700
			Without Motors:	419.86	

This Bill of Materials shows the cost for each part along with the overall max amount which will be needed to purchase all of the parts. It was calculated that $579.82 will be needed which is under the limit of $700 as established by the sponsor. Some parts will not need to be bought. These are parts that are already available at the machine shop, like the planetary gear motor which is being recycled from last semester's project. This helped cut down costs to $419.86 which resulted in saving $159.96.

Mechanism Design

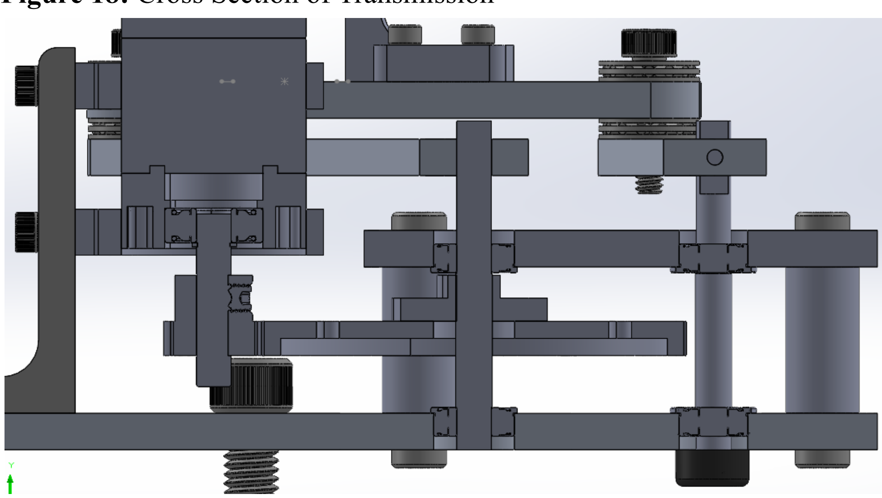
The final design of the mechanism was completed and used to ensure that it was meeting the requirements described by the stakeholders. An overall picture of the final assembly is shown below in Figure 17.

Figure 17: Final Mechanism CAD



As shown, the mechanism consists of a two part base plate, an input, follower, and coupler link, a flashlight mount, a motor/motor mount, and a transmission. The two part base plate is made of ¼" aluminum and is used to properly mount both of the ground pivots. Each of the links are also made of ¼" aluminum and include features for lightweighting. The flashlight mount is the hook-shaped piece attached to the coupler and will be 3D printed because of its complex geometry. The motor mount is made of 2.5" x 2" x ¼" aluminum angle stock and the circle mounts holding the motor are parts bought with the motor itself. The motor mount includes slots to help with transmission alignment during assembly. To better explain the transmission, a cross section view of the mechanism is shown below in Figure 18.

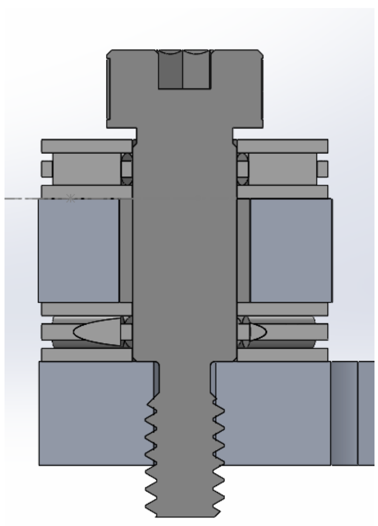
Figure 18: Cross Section of Transmission



The transmission consists of a 20 tooth pinion attached to the motor shaft using a set screw. This pinion meshes with a 90 tooth gear that is rigidly attached to the input shaft also using a set screw. This combination of gears accomplishes the 4.5 gear ratio that was calculated in previous analysis. The input shaft is held in place between two bearings by its larger outer diameter that rests on the inner race of each bearing. This design was used because it accomplishes one of our requirements of teaching good joint design practice by having the ground pivots each be supported by two ball bearings. The input link is rigidly attached to the input shaft using a set screw and the shaft is faced off at both set screw locations to allow for better grip. The follower shaft has an almost identical design.Each of the baseplates are separated using 0.5” round stock that is being used as a standoff.

The last major design feature is the rotational joint at each end of the coupler. A cross section view of the joint is shown below in Figure 19.

Figure 19: Cross Section of Coupler Joint



The joint consists of a shoulder screw, needle roller bearings, washers, and the coupler and follower link. As you can see, the shoulder screw is fully seated against the follower link (bottom). Above the follower link is a washer followed by a needle roller bearing, followed by another washer. This same style is repeated above the coupler. This design is used because it allows for the shoulder screw to be tightened down on the joint to keep it secure, but the links are still free to rotate relative to one another along the needle roller bearings. Inside the coupler is a oil-embedded bushing that is being used to align the coupler with the shoulder screw and allow it to rotate smoothly. There is also a small gap at the top of the shoulder screw to account for potential tolerance stack-up. This design was strongly recommended by the stakeholders to use as a good example of a joint for a shoulder screw that students would be able to replicate when they complete the project.

The last remaining piece of the design is the bill of materials which is shown below in Table 9.

Table 9: Mechanism Bill of Materials

Mechanism Part Category	Part Name	Quantity	Price (per each)	Net Price	Bought/Built	Link to Part
Linkage	Aluminum Plate 1/4" x 12" x 12"	1	35.61	35.61	Bought/Built	https://www.mcmaster.co
	Aluminum Angle 2.5" x 2" x 1/4" thick, 12" long	1	13.12	13.12	Bought/Built	https://www.mcmaster.co
	Aluminum round stock 1/2" diameter 6" long	1	1.45	1.45	Bought/Built	https://www.mcmaster.co
	2910 Series Aluminum Clamping Collar (6mm ID x 19mm OD, 8mm Length)	3	3	9	Bought	https://www.gobilda.com/
	1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness) - 2 Pack	4	3.49	13.96	Bought	https://www.gobilda.com/
	2100 Series Stainless Steel Round Shaft (6mm Diameter, 100mm Length)	2	1.69	3.38	Bought	https://www.gobilda.com/
	2302 Series Aluminum, MOD 0.8, Hub Mount Gear (14mm Bore, 90 Tooth)	1	12.99	12.99	Bought	https://www.gobilda.com/
	2303 Series Steel, MOD 0.8, D-Bore, Set Screw Pinion Gear (6mm D-Bore, 20 Too	1	9.99	9.99	Bought	https://www.gobilda.com/
	1308 Series Lightweight Set Screw Hub (6mm Bore)	1	5.49	5.49	Bought	https://www.gobilda.com/
	1400 Series 1-Side, 2-Post Clamping Mount (32mm Bore)	2	6.99	13.98	Bought	https://www.gobilda.com/
	Flashlight Mount	1	0	0	Bought	
Electronics	Planetary Gear Motor (13.7:1 Ratio, 435 RPM, 3.3 - 5V Encoder)	1	39.99	39.99	Bought	https://www.gobilda.com/
	Arduino Uno microcontroller board	1	21.9	21.9	Bought	https://www.digikey.com/e
	USB-A to USB-B Cable for Arduino	1	2.07	2.07	Bought	https://www.digikey.com/e
	H-bridge(L298 Motor Driver -- preassembled)	1	2.6	2.6	Bought	https://www.amazon.com
	Breadboard (30 row)	1	2.55	2.55	Bought	https://www.digikey.com/e
	Mounting Board for Arduino, H-bridge, and breadboard	1	0	0	Bought	https://www.digikey.com/e
	JUMPER WIRE M/F 6"	1	1.95	1.95	Bought	https://www.digikey.com/e
	JUMPER WIRE M/M 6"	2	1.95	3.9	Bought	https://www.digikey.com/e
	10 k-ohm resistor	10	0.01	0.1	Bought	https://www.digikey.com/e
	Toggle Switch	1	0.76	0.76	Bought	https://www.digikey.com/e
	Limit Switch	1	1.93	1.93	Bought	https://www.digikey.com/e
	Motor Wire (Bullet Lead MH-FC)	1	1.99	1.99	Bought	https://www.gobilda.com/
	Encoder Breakout Cable	1	3.99	3.99	Bought	https://www.gobilda.com/
	Power Supply (multi-voltage)	1	15.98	15.98	Bought	https://www.amazon.com
	AR-100 LED Flashlight	1	4.4	4.4	Bought	https://www.amazon.com
Fasteners	1/4-20 x 1/2" screw	10	0.09	0.9	Bought	https://www.homedepot.c
	3/8-16 x 1" screw	3	0.4	1.2	Bought	https://www.homedepot.c
	6-32 x 1/2" screw	2	0.02	0.04	Bought	https://www.homedepot.c
	M4 10mm screw	4	0.45	1.8	Bought	https://www.homedepot.c
	M5 Nylon Locknut (2 pack)	1	0.86	0.86	Bought	https://www.homedepot.c
	6mm x 20mm shoulder screw	2	1.84	3.68	Bought	https://www.mcmaster.co
	1/4" nylon spacer	4	0.12	0.48	Bought	https://www.mcmaster.co
	Threaded stud bumper	3	0.33	0.99	Bought	https://www.mcmaster.co
	Cable Ties	10	0	0	Bought	
			Total Cost	233.03		
			Adjusted Total Cost	20.32		

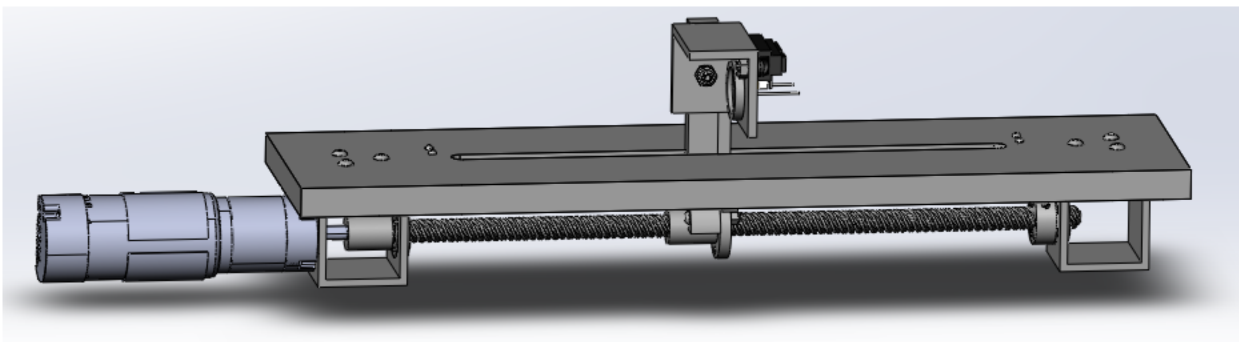
The bill of materials consists of three major categories. The first of which is the linkage category which includes all of the metal stock, bearings, motor shaft, and other physical components that will be used to make the mechanism. Most of these parts are going to be bought, but the metal stock will need to be machined into the parts shown previously in the design. The second category includes electronic components such as the motor, arduino, h-bridge, and wiring components. All of these components are going to be bought. Lastly, the third category includes all of the fasteners necessary for assembling the mechanism and all of these will be bought.

Overall, the expected total cost for the mechanism is about $230. This is above the budget of $200, but after talking with the stakeholders they are okay with that for a couple of reasons. First of all, many of the components are going to be reused from previous semester projects. This brings the cost of parts that will actually be purchased down to about $20 as it only includes a handful of specific fasteners and the supplier made motor mounts. Next, this project utilizes the motor used in previous projects and can continue to be used by students going forward. That alone brings the total cost below $200 and it is expected to drop further after ordering many parts in bulk such as the stock metal.

Prototype Description

Before machining and assembling the final game board, the linear motion assembly needed to be validated. The torque that the motor will experience is primarily due to friction between the target mount and the edges of the game board, because the targets should be moving at a constant velocity. Friction is very difficult to accurately estimate analytically; testing it empirically is a much more robust method. To do this, one modular linear motion assembly was created with a target path length of 9 inches, and the motor was tested to check that it can achieve the required maximum target speed of 2.25 in/second at 12V. CAD for this assembly is shown in Figure 20 below.

Figure 20: Linear motion prototype



If the motor was not powerful enough to actuate the target assembly at 2.25 in/sec, then there are a few steps that could be taken to still achieve the desired “endless round” behavior where the targets speed up until the linkages can’t keep up: first, the longest target path length could be shortened from 9 inches to 8 or 7 inches in the final game board prototype. An even simpler solution would be to increase the amount of time it takes for the photosensors to register the flashlight from 1 second to 1.5 or 2 seconds. Finally, the motors could be replaced with more powerful stepper motors. This solution is not preferred because without different motors, the game board would no longer meet the requirement to reuse >$100 worth of material from the COVID kits.

This initial prototype also includes an initial prototype of the target design to validate the requirement that the photosensor responds correctly to the flashlight 98% of the time. From the initial photosensor testing that has already been done, the photosensor should be sufficiently sensitive to identify when a flashlight is pointing at it even without any shield from ambient light. The purpose of testing the target shape is to validate this, and to identify the optimum target depth to reduce situations where the photosensor either identifies the presence of a flashlight when there is none, or fails to identify the flashlight when it is pointing at it. Target depth will be manipulated by adding cardboard on top of the target to determine how much shielding from ambient light the target needs.

Initial Manufacturing Plan

The manufacturing plan for the mechanism includes the following processes. First, the base plate and the links are made out of aluminum and will use a waterjet. The waterjet will be used to turn the aluminum plate that is given to into the correctly dimensioned plate and links. The holes on the links and base plate that need to be press-fit will be drilled using a mill to allow for precise location and diameter. Next, the angle and rod stock which are also made out of aluminum will be cut using a bandsaw. The holes in the angle stock will be drilled using the mill and the holes in the rod stock will be drilled using the lathe. Lastly, the flashlight component will be made out of PLA and will be 3D printed because of the complex geometry. In conclusion, all of these processes can be completed in the University of Michigan machine shop or 3D printed on campus. The main concerns in regard to manufacturing the mechanism are tolerance stack for base plate hole location and bearing locations really need to be accurate for the shafts.

The manufacturing plan for the game board includes the following processes. First, the flat stock and C channel brackets are made out of aluminum and a bandsaw will be used to obtain the correct length. The mill will be used to obtain precise holes. Next, the targets will be made out of PLA and will be made by 3D printing because of the complex geometry. Lastly, the Lead screw is made out of steel and a bandsaw will be used to cut to the correct length. In conclusion, all of the processes for the game board will be completed at the University of Michigan machine shop or 3D printed on campus. The main concerns in regard to manufacturing the game board are the tolerances with the holes because the alignment of the gameboard depends on the holes being accurate. In addition, lead screw alignment because the linear motion of the targets depends upon this being accurate.

For all parts that need to be manufactured for the game board and mechanism, a manufacturing drawing was created. These are all shown in Appendix F. For the 3D printed parts, only a STL file was needed to be submitted to the machine shop for printing.

Description of Validation Approach

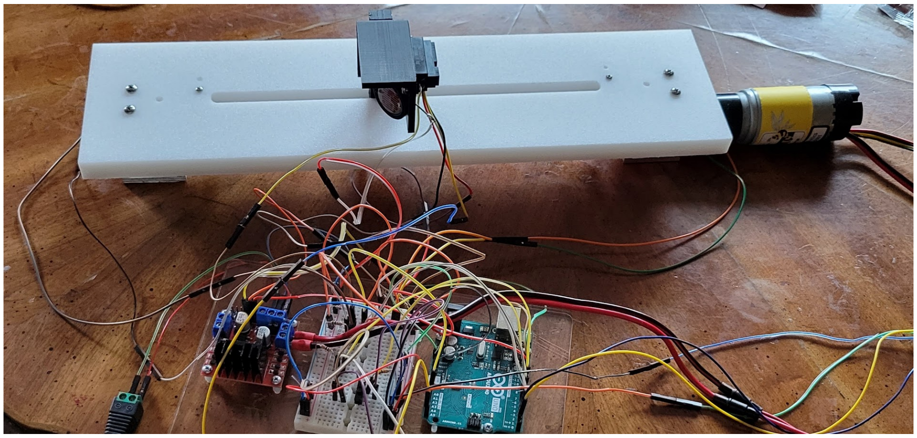
It will be necessary to verify that the final design meets all of the requirements and specifications for it. Some of these have already been checked through engineering analysis, and some of the specifications are simple yes or no checks. A list of all the specifications for the game board, game, and mechanism are shown below in Table 10, along with the method chosen to validate these specifications. Specifications that are simply checkmarks for the design are excluded from this table, as they have all been met by the final design.

Table 10: Validation of Requirements and Specifications

Specification	Validation plan	Completion date
< $700 each	Create BoM	11/3
Reduce waste and cost by using >$100 worth of materials from COVID kits	Validate COVID kit motors with initial prototype	12/10
Set up in < 2 minutes < 3 separate parts < 5 steps to assemble	Test with full board prototype	Future
< 300 hours to make all boards ≤ 2 machines to make each part of game board	Manufacturing Analysis	11/30
Fits on 44” x 26” x 9” cart Weighs < 50 pounds	Analyze in CAD	11/22
Photosensors correctly identify presence/absence of flashlight 98% of the time	Test with initial prototype	12/12
Rating of at least 3.5 on a 5 point Likert scale Game should allow multiple viable strategies to optimize performance	Test with Likert Scale with past ME 350 students	10/21
Linkages should only able to hit one target at a time Game board should require four bar linkage to complete game	Analyze in CAD Validate with full board prototype	11/16 Future
Require a transmission	Transmission analysis	11/8
< $200 per kit, additional $50 per kit to spend on outside parts	Create BoM	11/3
< 30 hours per group in the machine shop (5)	Manufacturing Analysis	11/30

To validate the motors for the linear motion of the targets, as well as to validate the photosensors, the initial prototype as shown in Figure 20 and described previously was created. A picture of this prototype is shown below in Figure 21.

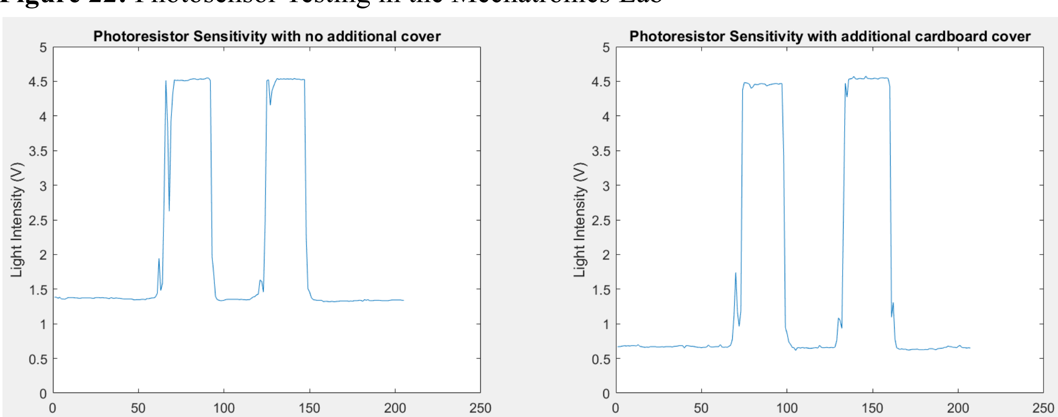
Figure 21: Constructed Linear Motion Prototype



Several things were learned from creating this linear motion prototype. First, there was some assembly difficulty attaching the fasteners inside the motor mount and lead screw mount. This will be further discussed in the discussion section on page 38. Second, more optimistically, the speed of the motors was tested, and it was found that the target could move from one limit switch to the other in 3.89 seconds. This is below the 4 second limit that is theoretically needed to force the students to “lose” in the endless round, which passes the requirement to use the motors from the COVID kits in the game board. At the same time, the prototype passed a variety of the other requirements for the linear motion (the lead screw and motor aligned using just the shaft coupler, clamping collars on the lead screw functioned as hard stops, the placement of the limit switches was appropriate to be activated at the ends of the path), which demonstrates that the design for the linear motion of the targets should work in the full game board.

The other main validation goal of the prototype was to validate the photosensor sensitivity, and to determine the optimal cover length for the 3d printed target mount piece. To test this, the photosensor was tested in the mechatronics lab with one of the flashlights that the mechanisms will use in the design project. The photosensor was tested with the 3d printed target shown in Figure 21, first with no additional cover, and then with an additional 3 inch cardboard cover. The flashlight was held 24 inches away from the photosensor. The results of these tests are shown below in Figure 22.

Figure 22: Photosensor Testing in the Mechatronics Lab



As can be seen in the graphs above, there is a large difference between the output from the photosensor when the flashlight is present and when there is only ambient light present, regardless of the length of the cover. The cardboard cover did reduce the level of ambient light present when the flashlight was not shining on the photosensor, but this reduction is clearly not necessary for the photosensor to differentiate between when the flashlight is pointing at it and when it isn't. Therefore, it is not necessary to increase the length of the cover on the 3d printed target mounts, as doing so would hurt the aesthetics of the piece without increasing the functionality of the photosensor.

Finally, code was created to control the prototype board as if it were participating in the game. This code is listed in Appendix H. The prototype board is able to start and automatically calibrate to the rear limit switch, and then move between the three rounds as timing dictates and when prompted by the GSI. Similar code would need to be developed for the full game board to incorporate four targets instead of just one.

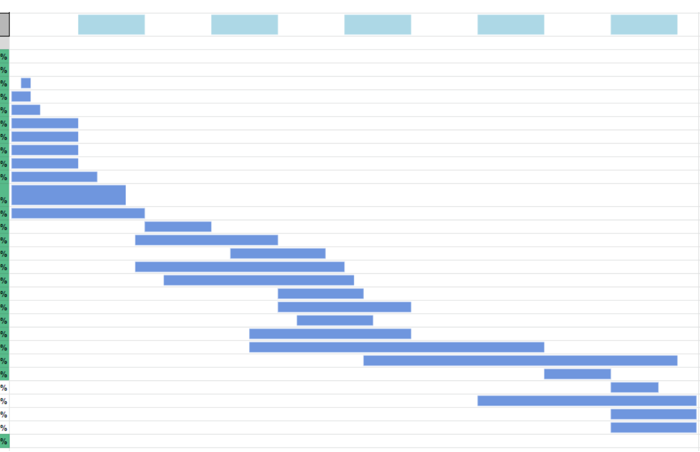
Project Plan

The most up to date project plan is shown below in Figure 23. At this point, many of the major milestones have been completed. Requirements, specifications, and initial concepts have been generated, and a final concept has been selected and designed. From this final concept, the fabrication of a mechanism and a small prototype of the final game board has been completed.

It was originally planned to have the game board constructed and validated at this point, but unfortunately the team was unable to do this on time. After speaking with the sponsor, they informed the team that this was okay and that completion of all of the deliverables was not realistic given the timeframe of the course. Instead, the team is expected to prepare the project to be continued next semester by the same or different members.

Figure 23: Project Schedule

Title	Owner	Start Date	End Date	Planned Time [Days]	% Complete
Next Gen ME350 Project					
Project Plan	All	9/21/21	9/21/21	0	100%
Problem Statement Draft	All	9/21/21	9/21/21	0	100%
Machine Shop Stakeholder Meeting	Max & Elizabeth	9/20/21	9/21/21	1	100%
Requirements/specifications draft	All	9/21/21	9/23/21	2	100%
GSI Stakeholder Meeting	All	9/21/21	9/24/21	3	100%
Have all Past ME350 Stakeholder Meetings Done	All	9/21/21	9/28/21	7	100%
5 min presentation of req./spec.	All	9/21/21	9/28/21	7	100%
Draft of req./spec.	All	9/21/21	9/28/21	7	100%
Draft of DR1 presentation	All	9/21/21	9/28/21	7	100%
Updated draft of DR1 presentation	All	9/21/21	9/30/21	9	100%
1 Design Draft Idea Each including rough rules and sketch of game board	All	9/21/21	10/3/21	12	100%
DR1 Presentation	All	9/21/21	10/5/21	14	100%
DR1 Paper	All	10/5/21	10/12/21	7	100%
Game Rules Draft	All	10/4/21	10/19/21	15	100%
Initial CAD Game Board	All	10/14/21	10/24/21	10	100%
DR2 Presentation	All	10/4/21	10/26/21	22	100%
Final Game Rules	All	10/7/21	10/27/21	20	100%
CAD Model of Design Board Prototype	All	10/19/21	10/28/21	9	100%
CAD Model of Mechanism Example	All	10/19/21	11/2/21	14	100%
Order parts for game board/mechanism	All	10/21/21	10/29/21	8	100%
DR2 Paper	All	10/16/21	11/2/21	17	100%
DR3 Presentation	All	10/16/21	11/16/21	31	100%
Prototype Mechanism	All	10/28/21	11/30/21	33	100%
DR3 Paper	All	11/16/21	11/23/21	7	100%
Fall Break	All	11/23	11/28	5	0%
Code for Mechanism	All	11/9/21	12/8/21	29	0%
Game Board Code	All	11/23/21	12/8/21	15	0%
Game Board Fabrication	All	11/23/21	12/8/21	15	0%
Design Expo	All	12/1/21	12/9/21	8	100%



Problem Analysis

Analyze the specifications and discuss the engineering fundamentals that will need to be addressed to achieve the project goals. What is difficult about the design? What are the design "drivers"? What are the major problems expected, and how will they be addressed? Is there any special equipment, technical assistance, or logistics that will be needed to solve the critical problems?Block Content.The learning blocks you conducted are relevant to the project. See the list of questions below for each block and answer all relevant questions.

There are many different engineering fundamentals required to execute the project. The design process will be followed throughout the entire project. The first step in the design process was identifying the problem for the project. This was conducted by performing several stakeholder interviews and then looking at the feedback based on several different questions. This allowed us to come up with the major issues within the ME 350 Design and Manufacturing II course. Next, the team developed the problem statement based on the major issues. Lastly, the team performed concept exploration, the team developed four different design ideas and ranked them compared to the requirements to decide which design is the most feasible. Solution development, verification, and realization are the next steps in the design process that will be utilized but have not yet been performed throughout design review 1.

The use of a 4 bar linkage, cam follower, rack and pinion, crank and slider, or 6 bar linkage will first require SolidWorks in order to create a model of what the mechanism design will look like as well as to make sure the model is a feasible design. From there SolidWorks will be used to create engineering drawings and manufacturing plans to allow for the students to manufacture their design in the machine shop. Then the students will use the mill, lathe and waterjet in order to manufacture their mechanism. The use of a PID controller and Arduino microcontroller board will be required in order for the mechanism to be able to maneuver. Matlab will be utilized for the motion simulation of the mechanism. Then the PID controller and the Arduino will then be connected to the code by the circuit and wiring. Lastly, education theory will be applied to the project in order to ensure that the material presented to the students is feasible regardless of their background in controls and manufacturing processes. This will be performed by providing the students with step by step tutorials. This will allow the students to complete each task necessary to be successful in ME 350. The instructional team will also be available to the students for more clarification which provides more support in addition to the step by step tutorials.

The most difficult part about the design is to make sure that it is an engaging game because when the game isn't engaging the students tend to be less invested in the project. The design drivers are to create an engaging game and provide students with a mechatronics project that will prepare them for their engineering career. The major problems that are expected are time, manufacturing, arduino coding, and a fun design concept. Time will be a challenge because The team has to create an entire prototype of the mechanism and game board in a short period of time. In addition, the team has little experience in manufacturing and arduino coding making the short time frame even more prominant. Each component will be addressed in the most reasonable way to ensure success of the project. Time will be closely watched by following the project plan as close as possible and holding teammates accountable. The manufacturing component will be as efficient as possible by utilizing the machine shop staff as well as working as a team. The ME 350 instructional team will be utilized throughout the process of creating the code. The past code will also be a reference. Lastly, a fun design concept will be addressed by utilizing a likert scale and having both current and past ME 350 students to take the survey.

Block Content

The following descriptions are what the team has learned about conducting engineering practices and how they can be related to the project.

Design process

The design process that the team is following is stage based and activity based. The team is following this process because the team are moving step by step through the design process but are also able to cycle back if needed to find something in an earlier stage that needs to be revisited.

Problem definition

If there was more time and resources to collect data and better define the problem for the project. The team would further investigate what students struggle with, what would make the game more engaging and education theory. The method I would conduct is a deep dive by going deeper into each issue and figuring out why it is a problem and how it can be fixed.

Social context assessment

The entire ME 350 instructional team, ME 350 students and the University of Michigan, Mechanical Engineering Department will all be affected positively by the project. The past ME 350 students that took this course during COVID-19 are indirectly affected negatively by the project because they didn't have the chance to actually manufacture their mechanism and didn't experience a more intricate game board design and project. Sponsor ranks social impact as the second most important with education being the most important. Social impact being one of the most important affects the way we are designing the project in a significant way. The project is being designed in a way for future students to be able to complete the game without any prior knowledge except the skills obtained in ME 350. This will affect social impact in a positive way because it is highly prioritized and is intended to make a friendly learning environment for students.

Library

The University College of Engineering is required to meet ABET requirements in order to be an accredited engineering school. The Design and Manufacturing II course utilizes the mechatronics project as a way to fulfill the principle of engineering application aspect.

Inclusivity

The project's sponsor is the instructor of ME 350 and has been teaching the course for many years. He has the ultimate say if the team can proceed with the main idea. This can make it hard to try new ideas and go out of the team’s comfort zone because the sponsor has many years of experience in ME 350 with how it has been done in the past. The team is all relatively the same level of experience in manufacturing, arduino coding and the design process. This makes a power dynamic not really applicable in that sense but there are stronger personalities that tend to take the lead more than others and allow for a good group dynamic. The team has a sense of power over the end users of the product. The team is designing the project and the end user will have to work within what we design. They won't be able to go too far out of the scope that we set. The team's experience with ME 350 was during the COVID-19 semester. We experience every step of the process of putting the mechanism together and performing the game because we were all given individual kits. Also, we did not experience manufacturing the mechanism and were given pre machined parts. The end users will be experiencing an in person project where they will have to manufacture the parts to make their mechanism and will not have to perform each aspect of the processes individually. They will be performing it with their team.

Ethics

The ethical dilemmas the team expects to face throughout the project include running on a time crunch to get a working prototype for the mechanism and game board. The team wants to create a good working prototype and not just get one done that is not well done. To address this the project will follow the project plan as closely as possible and hold each other accountable throughout the entire project. The team's personal ethics include honesty, integrity and hard work which transfers over to the professional ethics that are expected by the University of Michigan as well as future employers.

Environmental Context Assessment

The design will reduce material greatly by reusing the sensors and pre-machined parts from past semesters. This consumes the resources that are already available to the university and allows the project to be more sustainable. The less sustainable parts of the project could be printed using the 3D printer allowing for there to be less material wastage. This would cost an initial investment but would eventually lead to a return on investment.

Concept Exploration

The first solution concept that came to the team’s mind was very similar to the ME 350 project that was experienced during COVID-19. The team only had the visualization of a paper game board and the linkage moving in a straight across back and forth motion. After going through the steps required to reach this point in the design process. The team has started to look at past projects and visualizations have become much more broad. The game board can be much more than a piece of paper. It can have many components attached to it such as different colored baskets that correspond to the ball that is being scored and the linkage. The original solution is fairly similar to the concepts that were developing at this point besides the game board component. The mechanism still moves back and forth in motion but not in a straight direction. The concepts are still quite similar because the project has the same guidelines and components needed. The only aspect that can change is the game design within the scope of an already set project.

Discussion

The first main thing that would be explored more if there was more time is interviewing more stakeholders because there was a lot of conflicting feedback from GSI's and students. This would allow us to better understand the main issues with the project and how to really make it better. Second, the team would manufacture the whole game board because then we would be able to fully test our concept instead of just using the prototype which is only one small chunk of the game board and doesn't allow for the game to be tested with the use of the mechanism. Also, only manufacturing the prototype board doesn't give us the whole picture of whether or not the materials and components are all as functional as needed.

After testing the prototype there are many positives to the design. The linear motion works exactly as expected and the game is able to be coded to allow for all the rounds of the game to be possible. The material used was able to be manufactured well and produce the expected parts needed for the design to be functional. Lastly, the team was able to iterate on a past ME350 game and make it more engaging for the students, leading to students being more likely to dive deep into the project. Therefore, the students will get more out of the project and really learn the material.

While the prototype was being assembled a number of different issues arised. First, the main issue was that the lead screw mount and motor mount are very small and compact making it hard to assemble them to the prototype board. The solution to the motor mount and lead screw mount being so compact is to assemble them in an order that mitigates the issue. For example, attach the motor first and then attach the bearing so that the open hole for the bearing can be used to fully attach the motor using the allen wrench. Also, the holes on the lead screw mount were positioned in a way that made it very hard to attach one of the screws because it interfered with the coupler that is attached to the lead screw. The solution to this issue was to reposition the holes on both the lead screw mount and motor mount so it does not interfere with the coupler and is able to be secured to the prototype board. Lastly, the proximity sensor has more noise at higher values and this could be fixed by taking an average in the code instead of taking each input by itself. Also, the current design needs multiple Arduinos to control the game board because there aren't enough pins, this adds a lot of complications so the Arduino Mega would be a better option.

Recommendations

As discussed previously, the construction of the prototype board brought to light a few important issues with the current game board design. It is believed that the assembly difficulties for the lead screw and motor mounts have been resolved in the most recent redesign. However, it would be worthwhile to validate this by constructing the new mounts and attempting to assemble them before manufacturing the entire game board. Validating this design change should hopefully finalize the linear motion method for the target as there aren't any other known issues at this time.

The majority of the other recommendations are associated with changes to the code and hardware. First of all, the current Arduino microcontroller does not have enough pins to control all four targets on the final game board. It is recommended that the microcontroller is changed from an Arduino Uno to an Arduino Mega as it will be able to control all of the targets for the final board. Another issue that has been discovered is that the proximity sensors have a lot of noise once the target gets further along its path.

There are multiple ways that this could be potentially resolved. The first of which is changing the material of the back wall for better performance of the proximity sensor. The sensor relies on the reflection of its signal for reliable output. A different material for the back wall could better reflect the signal and decrease the noise. Another solution would be to implement a rolling average in the code so the noise is reduced overall. If absolutely necessary, the proximity sensor could be changed to a more accurate model. This is not encouraged however, as many of the current proximity sensors are already readily available.

The final and most important recommendation is, once the prototype and code have been validated, to construct the final game board, modify the code for all four targets and simulate the game using the constructed mechanism. Currently the code is set up to run with the single-target prototype and should be able to be adapted to run on all four targets once necessary. Although many measures have been taken up until this point to ensure that the game works as imagined and is engaging for students (likert scale, deep analysis of game rule, etc.), it will ultimately take the construction and playing of the final game board in order to validate that these requirements have been met.

Conclusions

Overall, this project will create a fun, complex, and new ME 350 design game for future semesters to compete in. This will address the past struggles that students have faced in learning the different controls aspects of the course, especially for students who haven't taken specific classes yet like ME 360. This project will take these into consideration and design a game that is accommodating for in person classes without overwhelming students to help them achieve the best possible outcome in learning the material.

In designing this project, certain requirements and specifications were established. The project was broken down into three groups: Game Board, Game, and Mechanism. In these, the sponsor's restrictions along with stakeholders' opinions were taken into consideration. A high priority requirement was to have an engaging game in order to encourage students to go above and beyond when designing their mechanisms and help them learn the material. Furthermore, there were specific restraints with the required prototypes as storage and manufacturability needed to be considered in the design. The mechanism created also will follow restrictions mandated by ABET to make sure students will learn the necessary materials in the course. From this, the design will include some sort of mechanism like a 4-bar linkage. Additionally, the mechanism must use a PID controller to complete the game objective. All of these requirements and specifications will help students learn the most from the project.

For guidance on the project, past ME 350 students, GSIs, Professors, Current 350 students, past ME 450 Next Generation Project students, and the current person in charge of the Machine shop were interviewed. Besides interviews, past ME 350 game manuals and videos were reviewed as reference for analysis on what has been done in previous projects. All of these showed that the project should have a balance between manufacturing parts while not being overwhelming for the students along with encouragement from many stakeholders to help make the necessary code for the project more hand-on to help students learn more about writing arduino code. Furthermore, class modules were used to guide the design process and influence the design to be more environmentally friendly in reducing material waste. Using a divergent thinking process, over ten thought out concepts were generated. From this, stakeholder feedback and a pugh chart was used to help select the final design concept which was decided to be the

Plants vs Zombies concept. This design was able to use a four bar linkage as the mechanism and had moving targets that students would have to hit with a flashlight.

In order to complete all objectives in the time allotted, a gantt chart was created along with key milestones that need to be followed. These milestones broke up the project to specify when CAD designs would need to be completed along with the physical prototypes. These deadlines will also allow specific work to be completed for DR2, DR3, and the design expo.

Overall, this project will help students explore engineering concepts in a safe environment while being able to use their creativity to accomplish a task by creating a new, unique game for students to participate in. Plus, this project will create a working prototype of the board and mechanism to fully demonstrate the concept of the created game and help see its feasibility before implementing the project as the new game challenge.

Ultimately a mechanism and a prototype of a portion of the final game board were able to be completed and validated. The mechanism will be able to be used to validate the final game board once it is constructed next semester. The prototype portion of the game board was used to validate many aspects of the final game board design and generate initial code that can be modified for the final board. The final game board was not completed due to insufficient time, however, it has been communicated to the sponsor and will be completed next semester.

Acknowledgements

This project was sponsored by Professor Umbriac and the ME 350 team. The work done would not have been possible without their support, including the ME350 GSI's, past and current students who have taken the course, and the Machine shop employees. Furthermore, Professor Schwemmin was a great help in providing bi-weekly guidance throughout the semester.

References

Andrew, Dane. Interview. By Elizabeth Ferguson. 20 September 2021.
College of Engineering Mechanical Engineering. “Project Description: High Beams and Linkage Dreams.” January 2020. University of Michigan. ME350 Project Description.
College of Engineering Mechanical Engineering. “ME350 W20 Schedule” January 2020. University of Michigan. ME350 Project Calendar.
College of Engineering Mechanical Engineering. “ME350 W19 Schedule.” January 2019. University of Michigan. ME350 Project Calendar.
Hahm, Michael. Interview. By Arianna Bressler and Valerie Smith. 24 September 2021.
Nigrelli, Emma. Interview. By Elizabeth Ferguson 21 September 2021.
DeRidder, Emaa. Interview. By Valerie Smith. 23 September 2021.
Orlans, Alyssa. Interview. By Arianna Bressler. 24 September 2021.
Overbeck, Abigail. Interview. By Arianna Bressler. 26 September 2021.
Umbriac. Michael. Interview. By Arianna Bressler, Elizabeth Ferguson, Max Kessler and Valerie Smith. 16 September 2021.
Wirkner, Don. Interview. By Elizabeth Ferguson and Max Kessler. 21 September 2021.

Biographical Sketches

Elizabeth Ferguson

My name is Elizabeth Ferguson and I am from Woodhaven, Michigan. I am a senior in Mechanical Engineering at the University of Michigan and pursuing this degree with the intent of making the world a better place. After graduation, I have accepted a job at Pratt and Whitney as a Manufacturing Engineer in Hartford, Connecticut. I am currently a Transfer Student Leader for the College of Engineering and a grader for ME 320. In my free time I enjoy spending time with family, fashion and sports.

Max Kessler

My name is Max Kessler and I am from Holland, Michigan. I chose to pursue a mechanical engineering degree because I had no idea what I wanted to do but I knew that mechanical engineering was super broad and I could go into almost any industry after I graduated. I could not be happier with my decision as I feel that I have acquired the knowledge and skills to be successful in my career going forward. Outside of school I am the Vice President of Triangle Fraternity which is a STEM fraternity on campus. I also enjoy volunteering with the Maise and Blue Cupboard, hiking and golfing. Following graduation I am hoping to pursue a career in the renewable energy industry.

Arianna Bressler

My name is Arianna Bressler and I am from Dundee, Michigan. I am a senior studying Mechanical Engineering at the University of Michigan with a minor in MultiDisciplinary Design. I was introduced to mechanical engineering from my high school's robotics team where I enjoyed the hands-on aspect that is provided along with all of the teamwork opportunities available in engineering. Outside of school, I am the Secretary of the Society of Women Engineers where I have helped encourage members to participate in events and worked on a lot of the behind the scenes information that has to be done. I also enjoy camping, playing board games, and reading in my spare time. In the future, I am hoping to pursue a career in Manufacturing and continue my education to potentially teach future engineers.

Valerie Smith

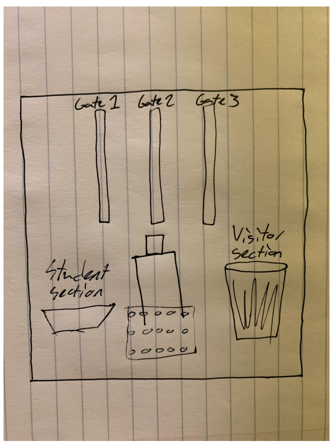
My name is Valerie Smith, and I am from Saline, Michigan. I have known I wanted to be an engineer ever since I watched Star Wars for the first time and realized that Anakin's robot hand was the coolest thing I had ever seen in my ten years of life. Eleven years and many sleepless nights desperately finishing projects later, I have no regrets. I still love learning about and working with robotics and prosthetics and I hope to attend graduate school and pursue a career in the biomedical field in the future. Before that, I will be working as a Naval Nuclear Power School Instructor in Charleston, South Carolina for five years. I am a current member of the Michigan Neuroprosthetics club, and am currently working on research with Professor Elliott Rouse and the Neurobionics Lab here on campus. When I find myself graced with spare time, I enjoy reading, hiking, and spending time with friends and family.

Appendices

Appendix A - Additional Game Concepts

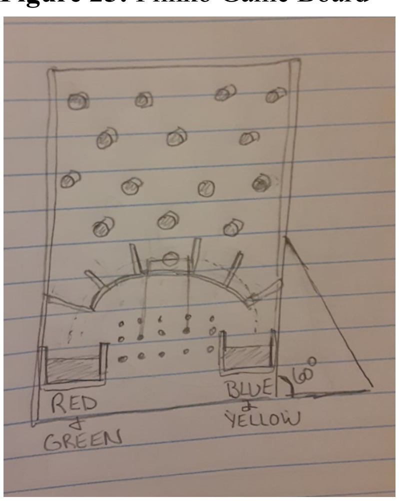
Another potential game concept was the “Mascot Sort” game where students would design a vertical four bar linkage that would utilize a load cell to read the weight of various “mascots” falling out of multiple tubes. The mechanism would then have to sort the mascots into their respective bins based on values given. Points would be assigned based on speed and correctness of the sorting. A sketch of the board is shown below in Figure 24.

Figure 24: Mascot Sort Game Board



Another concept was the plinko style game. Washers would be dropped from the top and fall randomly where the mechanism would have to detect and sort the washers by color. Students would be designing a four bar linkage and the washers would be transferred using an electromagnet. Position and color of the washer would be detected by proximity and color sensors respectively. Points are awarded based on speed and correctness. A sketch of the game board is shown below in Figure 25.

Figure 25: Plinko Game Board



The next concept was a multiple basket sorting game. Students would design a four bar linkage that would catch different colored balls falling from multiple locations. The mechanism would have a color sensor that would detect the color of the balls and the mechanism would sort them into their respective bins. Points are awarded based on speed and correctness. A sketch of the game board is shown below in Figure 26.

Figure 26: Multiple Basket Sorting Game Board

Another game concept was utilizing a temperature sensor. The premise was students would design a rack and pinion with a temperature sensor. The rack and pinion would move along a beam and attempt to position itself along the beam based on a certain temperature requirement (ex. The lowest temperature along the beam).
The next game concept was a pinball style game where students would design a four bar linkage that had to detect the motion of a falling ball and try to bounce it up, very similar to pinball. The goal of the game would be to keep the ball up as long as possible and knock it into various targets to score points.

The last game concept was very similar to the computer game pong. Students would design a four bar linkage and compete against each other. The mechanism would have to detect an oncoming ball, likely using a proximity sensor, and have to move and knock the ball back, attempting to score in the opponent's goal.

Appendix B - Inertia Matching Process
To begin the process, the equation for the torque of the mechanism was derived. This equation is shown below.

$$T = (I_m + \frac{I_L}{N^2}) \cdot N \cdot \alpha_L \quad \text{(Eq. 1)}$$

For this equation Im and IL represent the moment of inertia about the input pivot for the motor and the linkage respectively. N represents the the transmission ratio, and αL is the angular acceleration of the linkage. To minimize the torque a derivative is taken with respect to N. Then the equation is solved for N to give the transmission ratio. This equation is shown below.

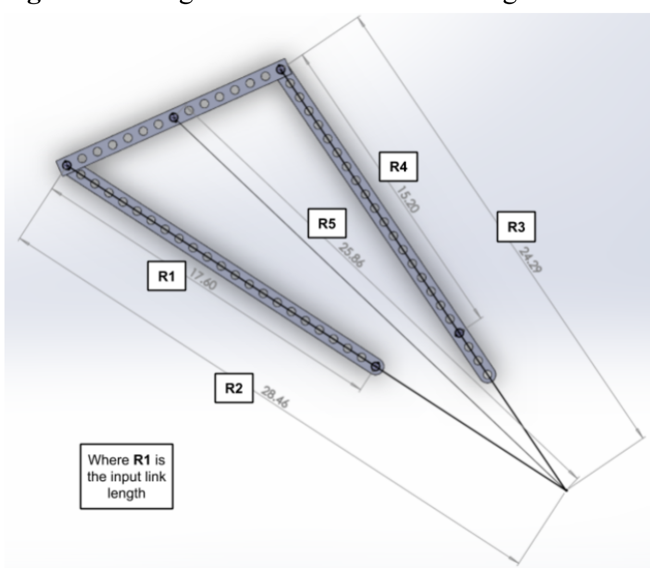
$$N = \sqrt{\frac{I_L}{I_m}} \quad \text{(Eq. 2)}$$

As you can see, the transmission ratio simplifies as a function of the inertia of the linkage and motor. The inertia of the motor is a given property included on its spec sheet, so all that is left is to calculate the inertia of the linkage.

The inertia of the linkage is calculated using the approximate weight of the links as calculated in CAD to find their inertia, and the parallel axis theorem to find it about the rotating axis. The flashlight was approximated as a point mass on the coupler to account for any added inertia effects. The equation for the inertia of the linkage (I_total) is shown below along with a diagram showing the method of finding R1, R2, R3, and R4.

$$\frac{1}{2}I_{total}\omega_{input}^{\ 2} = \frac{1}{2}I_{input}\omega_{input}^{\ 2} + \frac{1}{2}I_{coupler}\left(\frac{R_1\omega_{input}}{R_2}\right)^2 + \frac{1}{2}I_{output}\left(\frac{R_1R_3\omega_{input}}{R_2R_4}\right)^2 \quad \text{(Eq. 3)}$$

Figure 27: Diagram with method of finding R values



From there, the inertia of the linkage was calculated at each of the four locations it would move to hit targets. The maximum of these values was used to calculate the transmission ratio. A chart of this calculation is shown below.

Table 11: Inertia Matching Table

To use this spreadsheet refer to the Transmission Selection lab tutorial. Cells highlighted orange are the only cells that need an input. All of the light gray cells are automatically calculated based on the orange cells.

Your Input
Calculated Cells
Calculated Transmission Ratio

Fixed Variables		
Variable	Value	Units
m_{input}	32.37	(gram)
m_{output}	29.88	(gram)
$m_{coupler}$	112.25	(gram)
I_{input_CG}	2917.73	(gram*cm^2)
I_{output_CG}	2027.06	(gram*cm^2)
$I_{coupler\_CG}$	3001.24	(gram*cm^2)

Target One (Left)		
Geometric Variables		
Variable	Value	Units
R1 (input link)	17.66	cm
R2	33.89	cm
R3	30.27	cm
R4 (output link)	15.36	cm
R5	32.65	cm
tal Inertias of a Link (via Parallel Ax		
Variable	Value	Units
I_{input}	5441.5833	(gram*cm^2)
I_{output}	3789.4541	(gram*cm^2)
$I_{coupler}$	122662.27	(gram*cm^2)
Scale Factors		
R1/R2	0.5210977	(unitless)
(R1*R3)/(R2*R4)	1.0269288	(unitless)
Total Inertia		
I_{total}	42745.929	(gram*cm^2)

Target Two		
Geometric Variables		
Variable	Value	Units
R1	17.66	cm
R2	33.04	cm
R3	30.82	cm
R4	15.36	cm
R5	32.17	cm
tal Inertias of a Link (via Parallel Ax		
Variable	Value	Units
I_{input}	5441.5833	(gram*cm^2)
I_{output}	3789.4541	(gram*cm^2)
$I_{coupler}$	119169.76	(gram*cm^2)
Scale Factors		
R1/R2	0.5345036	(unitless)
(R1*R3)/(R2*R4)	1.0724871	(unitless)
Total Inertia		
I_{total}	43846.424	(gram*cm^2)

Target Three		
Geometric Variables		
Variable	Value	Units
R1	17.66	cm
R2	30.57	cm
R3	29.51	cm
R4	15.36	cm
R5	30	cm
Total Inertias of a Link (via Parallel Axis		
Variable	Value	Units
I_{input}	5441.5833	(gram*cm^2)
I_{output}	3789.4541	(gram*cm^2)
$I_{coupler}$	104026.24	(gram*cm^2)
Scale Factors		
R1/R2	0.5776905	(unitless)
(R1*R3)/(R2*R4)	1.1098729	(unitless)
Total Inertia		
I_{total}	44825.8	(gram*cm^2)

Target Four (Right)		
Geometric Variables		
Variable	Value	Units
R1	17.66	cm
R2	20.43	cm
R3	21.9	cm
R4	15.36	cm
R5	20.47	cm
tal Inertias of a Link (via Parallel Ax		
Variable	Value	Units
I_{input}	5441.5833	(gram*cm^2)
I_{output}	3789.4541	(gram*cm^2)
$I_{coupler}$	50036.336	(gram*cm^2)
Scale Factors		
R1/R2	0.8644151	(unitless)
(R1*R3)/(R2*R4)	1.2324668	(unitless)
Total Inertia		
I_{total}	48585.489	(gram*cm^2)

Transmission Calculations		
Variable	Value	Units
Maximum Linkage Inertia (I_L)	48585.489	(gram*cm^2)
I_{motor}	5213.61	(gram*cm^2)
Transmission Ratio (N)	3.05269924	(unitless)

Appendix C - Selected Motor Specifications

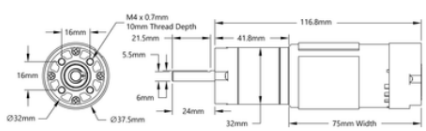
5202 Series Yellow Jacket Planetary Gear Motor (13.7:1 Ratio, 435 RPM, 3.3 - 5V Encoder)

SKU: 5202-0002-0014

$39.99

1 | Add to Cart

Add to Wish List



SPECS

Motor Size	RS-555
Motor Type	Brushed DC
Nominal Voltage	12VDC
Output Shaft	6mm D
Gearbox Style	Planetary
Gear Ratio	13.7:1
Gear Ratio Formula	(((1+(46/17))) * (1+(46/17))):1
Gear Material	Casing: Steel Ring Gear Stage 1: Steel Gear, Acetal Orbital Gears Stage 2: Steel Sun Gear, Steel Orbital Gears
No-Load Speed @ 12VDC	435 RPM
No-Load Current @12VDC	0.25A
Stall Current @12VDC	9.2A
Stall Torque @12VDC	18.7 kg.cm (260 oz-in)
Wire Length	470mm (including connectors)
Wire Gauge	16AWG
Motor Connector Type	3.5mm FH-MC Bullet Connectors
Encoder Connector Type	4-Pos JST XH [FH-MC]
Encoder Type	Relative, Quadrature
Encoder Sensor Type	Magnetic (Hall Effect)
Encoder Voltage Range	3.3 - 5VDC
Encoder Resolution	384.5 PPR at the Output Shaft
Encoder Resolution Formula	((((1+(46/17))) * (1+(46/17))) * 28)
Weight	420g

Appendix D - Encoder Resolution

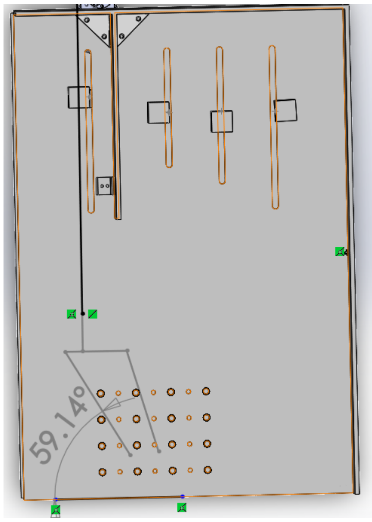
To begin this process, a CAD model was used to find the minimum change in the angle of the input link necessary to hit the entire area of each target. A table showing each of the angles as well as a screenshot of the CAD for clarity is shown below.

Table 12: Mechanism input angle chart

Resolution Analysis

Position	Minimum Angle [deg]	Maximum angle [deg]	Difference
First Target (Left)	55.52	61.7	6.18
Second Target	76	83.9	7.9
Third Target	86.6	98.3	11.7
Fourth Target (Right)	120.1	135.1	15

Figure 28: Mechanism input angle diagram



As you can see, the angle was found from the input link relative to the edge of the gameboard. As previously mentioned, the minimum and maximum angle at each target was found, and the minimum difference of 6.18 degrees was used going forward.

From there, the necessary transmission ratio can be calculated using the minimum angle difference, properties of the motor, and a desired count range that is defined by the user. For this case, to ensure the targets would be hit reliably, a desired count range of 30 counts was selected. Then, using the equation below the transmission ratio N is calculated.

$$\textit{Desired Count Range} = \left(\frac{28\ counts}{1\ rev}\right) \cdot 13.7 \cdot \left(\frac{smallest\ difference\ [deg]}{\frac{360\ degrees}{1\ rev}}\right) \cdot N \quad \text{(Eq. X)}$$

Appendix E - Winter 2020 and previous motor specs

Pololu Metal Gearmotors » 37D Metal Gearmotors » 12V 37D Metal Gearmotors »

30:1 Metal Gearmotor 37Dx68L mm 12V with 64 CPR Encoder (Helical Pinion)

Pololu item #: 4752 **105** in stock
Brand: Pololu
Status: Active and Preferred
✓ RoHS 3
Free shipping in USA

Price break	Unit price (US$)
1	39.95
10	35.96

Quantity: 1 **Add to cart**
backorders allowed **Add to wish list**

Dimensions

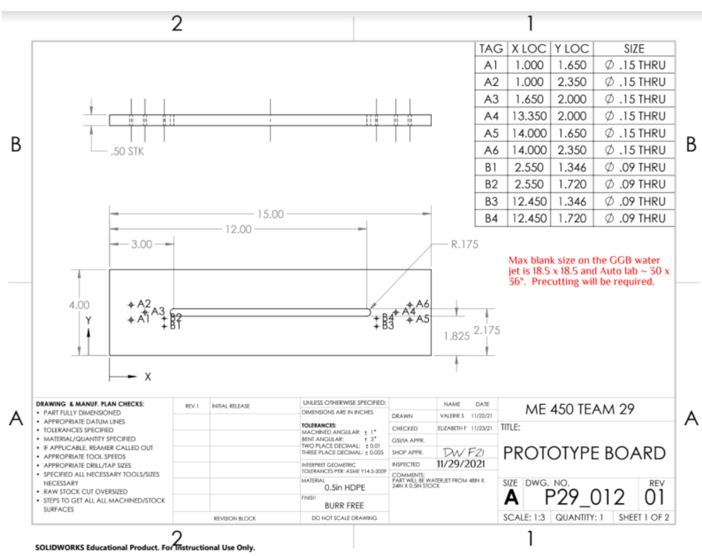
Size:	37D × 68L mm[1]
Weight:	200 g
Shaft diameter:	6 mm[2]

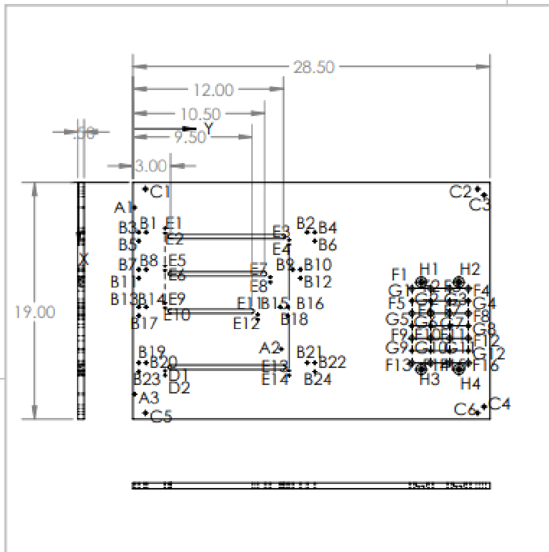
General specifications

Gear ratio:	30:1
No-load speed @ 12V:	330 rpm
No-load current @ 12V:	0.2 A
Stall current @ 12V:	5.5 A[3]
Stall torque @ 12V:	14 kg·cm[3]
Max output power @ 12V:	12 W
No-load speed @ 6V:	170 rpm[4]
No-load current @ 6V:	0.15 A[4]
Stall current @ 6V:	3.0 A[4]
Stall torque @ 6V:	7.9 kg·cm[4]
Motor type:	12V

Appendix F - Manufacturing Plans

Game Board





TAG	X LOC	Y LOC	SIZE
A1	2.00	.13	Ø.13 THRU
A2	13.38	11.84	Ø.13 THRU
A3	17.00	.13	Ø.13 THRU
B1	3.98	1.05	Ø .15 THRU
B2	3.98	13.90	Ø .15 THRU
B3	3.98	.45	Ø .15 THRU
B4	3.98	14.50	Ø .15 THRU
B5	4.68	.45	Ø .15 THRU
B6	4.68	14.50	Ø .15 THRU
B7	6.98	.45	Ø .15 THRU
B8	6.98	1.05	Ø .15 THRU
B9	6.98	12.75	Ø .15 THRU
B10	6.98	13.35	Ø .15 THRU
B11	7.68	.45	Ø .15 THRU
B12	7.68	13.35	Ø .15 THRU
B13	9.98	.45	Ø .15 THRU
B14	9.98	1.05	Ø .15 THRU
B15	9.98	11.75	Ø .15 THRU
B16	9.98	12.35	Ø .15 THRU
B17	10.68	.45	Ø .15 THRU

DRAWING & MANUF. PLAN CHECKS:

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

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

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

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL: 1/2" Delrin

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	AB	11/30/21
CHECKED	XX	XX/XX/XX
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		
COMMENTS:		

ME 450 TEAM 29

TITLE:

BASE PLATE

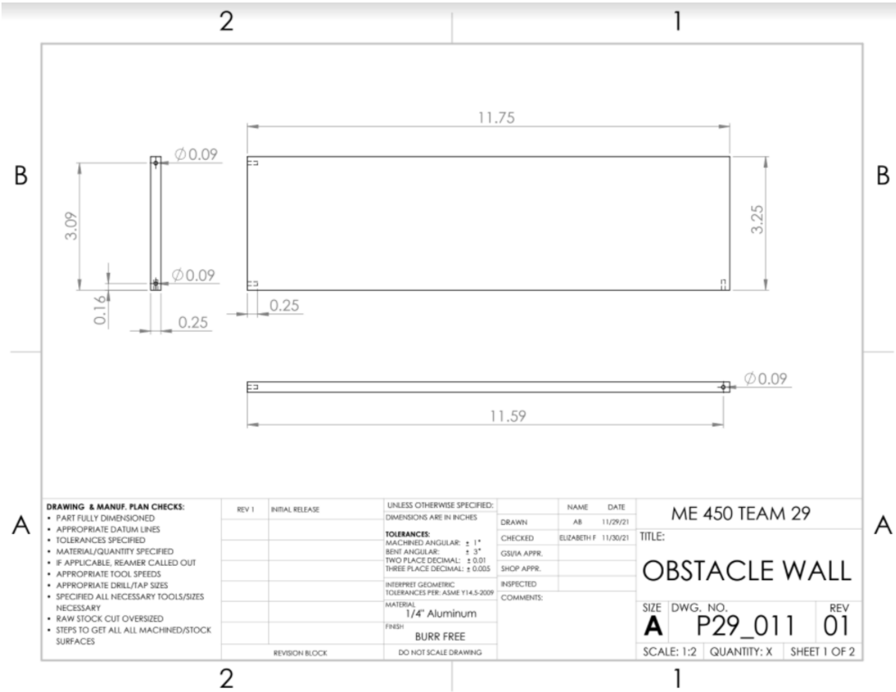
SIZE A | DWG. NO. P29_008 | REV 01

SCALE: 1:8 | QUANTITY: 1 | SHEET 1 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

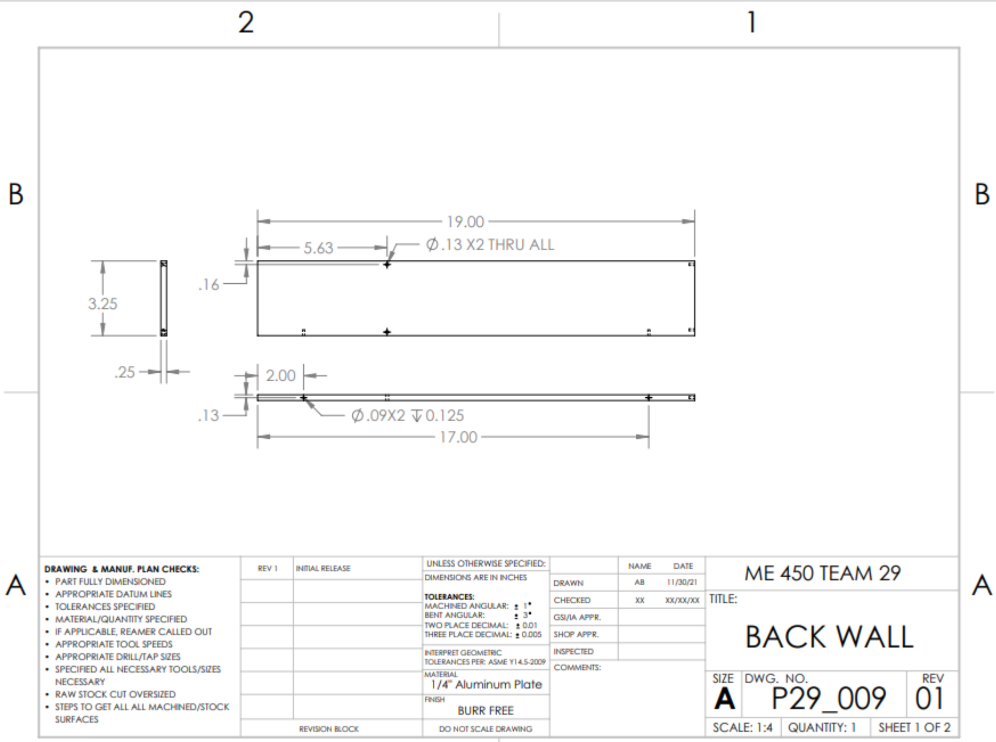
TAG	X LOC	Y LOC	SIZE
B18	10.68	12.35	Ø .15 THRU
B19	14.48	.45	Ø .15 THRU
B20	14.48	1.05	Ø .15 THRU
B21	14.48	13.90	Ø .15 THRU
B22	14.48	14.50	Ø .15 THRU
B23	15.18	.45	Ø .15 THRU
B24	15.18	14.50	Ø .15 THRU
C1	.50	1.00	Ø.26 THRU
C2	.50	27.50	Ø.26 THRU
C3	1.00	28.00	Ø.26 THRU
C4	18.00	28.00	Ø.26 THRU
C5	18.50	1.00	Ø.26 THRU
C6	18.50	27.50	Ø.26 THRU
D1	15.11	2.55	Ø.09 THRU
D2	15.48	2.55	Ø.09 THRU
E1	3.67	2.55	Ø .09 THRU
E2	4.05	2.55	Ø .09 THRU
E3	4.61	12.45	Ø .09 THRU
E4	4.98	12.45	Ø .09 THRU
E5	6.67	2.55	Ø .09 THRU
E6	7.05	2.55	Ø .09 THRU
E7	7.61	10.95	Ø .09 THRU
E8	7.98	10.95	Ø .09 THRU
E9	9.67	2.55	Ø .09 THRU
E10	10.05	2.55	Ø .09 THRU
E11	10.61	9.95	Ø .09 THRU
E12	10.98	9.95	Ø .09 THRU
E13	15.11	12.45	Ø .09 THRU

TAG	X LOC	Y LOC	SIZE
E14	15.48	12.45	Ø .09 THRU
F1	8.50	22.25	Ø .40 THRU
F2	8.50	23.75	Ø .40 THRU
F3	8.50	25.25	Ø .40 THRU
F4	8.50	26.75	Ø .40 THRU
F5	10.50	22.25	Ø .40 THRU
F6	10.50	23.75	Ø .40 THRU
F7	10.50	25.25	Ø .40 THRU
F8	10.50	26.75	Ø .40 THRU
F9	12.50	22.25	Ø .40 THRU
F10	12.50	23.75	Ø .40 THRU
F11	12.50	25.25	Ø .40 THRU
F12	12.50	26.75	Ø .40 THRU
F13	14.50	22.25	Ø .40 THRU
F14	14.50	23.75	Ø .40 THRU
F15	14.50	25.25	Ø .40 THRU
F16	14.50	26.75	Ø .40 THRU
G1	9.50	22.25	Ø .27 THRU
G2	9.50	23.75	Ø .27 THRU
G3	9.50	25.25	Ø .27 THRU
G4	9.50	26.75	Ø .27 THRU
G5	11.50	22.25	Ø .27 THRU
G6	11.50	23.75	Ø .27 THRU
G7	11.50	25.25	Ø .27 THRU
G8	11.50	26.75	Ø .27 THRU
G9	13.50	22.25	Ø .27 THRU
G10	13.50	23.75	Ø .27 THRU
G11	13.50	25.25	Ø .27 THRU
G12	13.50	26.75	Ø .27 THRU
H1	8.00	23.00	Ø .40 THRU ⌴ Ø .81 ↧ .25
H2	8.00	26.00	Ø .40 THRU ⌴ Ø .81 ↧ .25
H3	15.00	23.00	Ø .40 THRU ⌴ Ø .81 ↧ .25
H4	15.00	26.00	Ø .40 THRU ⌴ Ø .81 ↧ .25



MANUFACTURING PLAN
RAW MATERIAL STOCK: **1/4" Aluminum Plate**

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut Material to 11.75" by 3.75" long	Bandsaw		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vice	1.5" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vice, Workshop	1.5" parallels	
4	Install drill chuck	Mill	Vice, Workshop	1.5" parallels, drill chuck	
5	Find datum lines for X and Y	Mill	Vice, Workshop	1.5" parallels, drill chuck, edge finder	900
6	Center drill and drill 0.09" hole	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 3 centerdrill, Drill Bit 38	1200, 1200
7	Tap with No. 43 tap	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 43 tap and handle	
8	Center drill and drill 0.09" hole	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 3 centerdrill, Drill Bit 38	1200, 1200
9	Tap with No. 43 tap	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 43 tap and handle	
10	Remove and reinsert part with bottom facing upwards	Mill	Vice, Workshop	1.5" parallel	
11	Find datum lines for X and Y	Mill	Vice, Workshop	1.5" parallels, drill chuck, edge finder	900
12	Center drill and drill 0.09" hole	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 3 centerdrill, Drill Bit 38	1200, 1200
13	Tap with No. 43 tap	Mill	Vice, Workshop	1.5" parallels, drill chuck, No. 43 tap and handle	
14	Remove and deburr part			Deburring Tool	

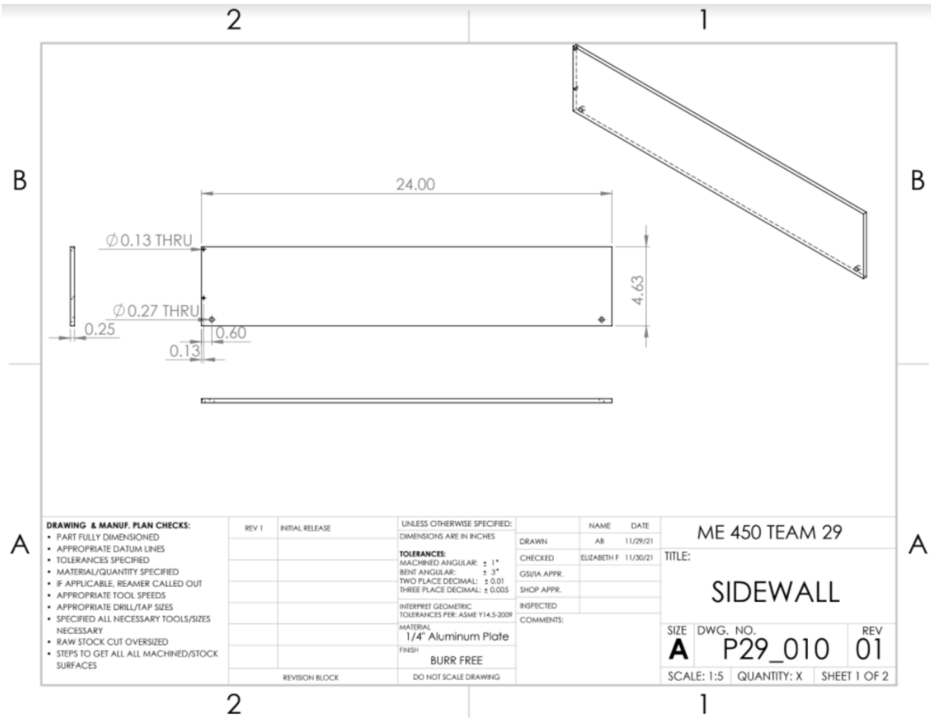


MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/4" Aluminum Plate

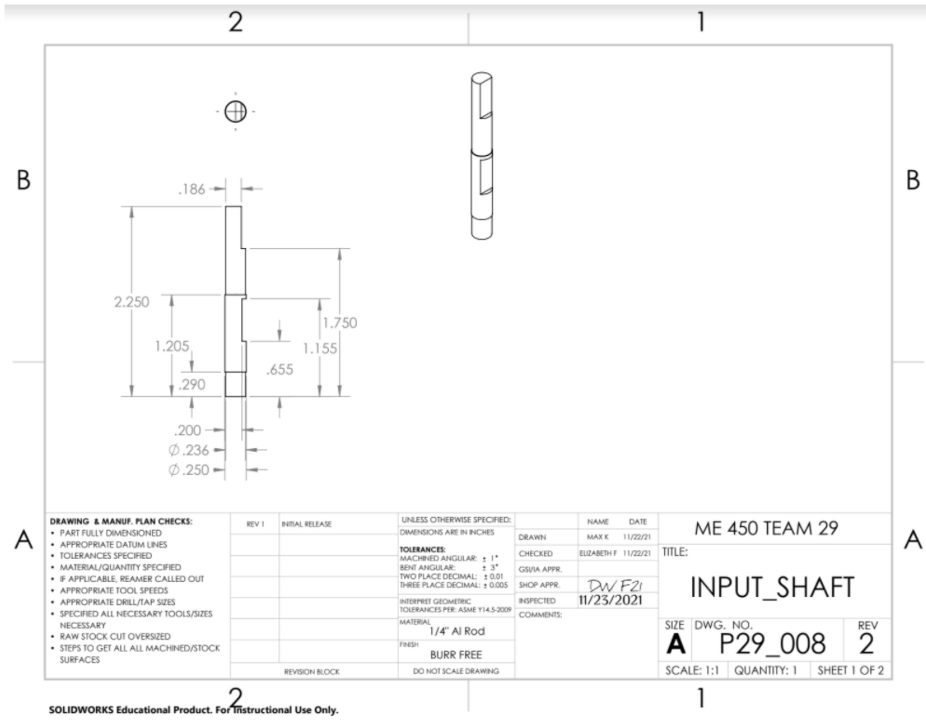
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut material to 3.25" by 19"	Bandsaw			
2	Hold part in vise	Mill	Vice		
3	Measure the part then mount on mill with parallels	Mill	Vice	1 1/2" parallels, calipers	
4	Install a workstop and zero the mill	Mill	Vise, workstop	1 1/2" parallels	
5	Install drill chuck	Mill	Vise, workstop	1 1/2" parallels, drill chuck	
6	Center drill and drill 0.13" holes	Mill	Vise, workstop	1 1/2" parallels, drill chuck, #30 drill bit	1200, 1200
7	Center drill and drill 0.08" holes	Mill	Vise, workstop	1 1/2" parallels, drill chuck, #43 drill bit	
8	Remove and deburr part	Mill	Vise, workstop		

SHEET 2 OF 2



MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" Aluminum Plate

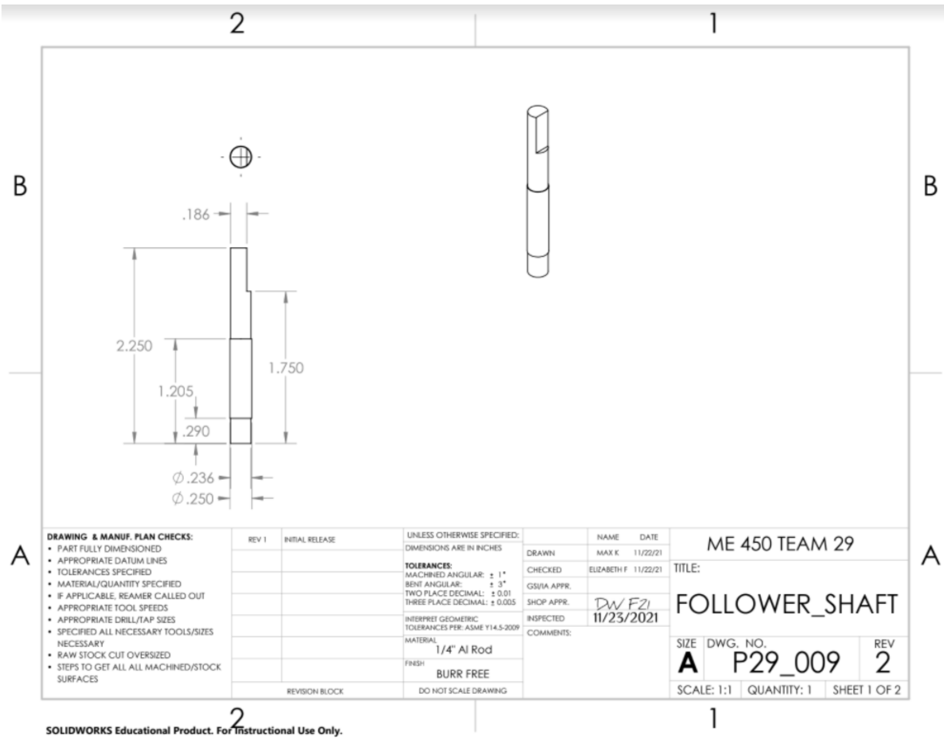
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut part to 24" by 4.63"	Bandsaw		Deburring Tool	
2	Measure the part then mount on mill with parallels	Mill	Vice	1.5" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vise, workstop	1.5" parallels	
4	Install drill chuck	Mill	Vise, workstop	1.5" parallels, drill chuck	
5	Center drill and drill 0.27" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, 17/64 drill bit	1200, 1200
6	Tap hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, #7 tap, dead center	
7	Center drill and drill 0.27" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, 17/64 drill bit	1200, 1200
8	Tap hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, #7 tap, dead center	
9	Center drill and drill 0.13" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, #30 drill bit	1200, 1200
10	Tap hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, #43 tap, dead center	
11	Center drill and drill 0.13" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, #30 drill bit	1200, 1200
12	Tap hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, #43 tap, dead center	
13	Remove and deburr part			Deburring Tool	



MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" Aluminum Rod Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock > 1.5" of final length then deburr	~~Bandsaw~~ Rod Shear	Vise	Deburring tool	300 ft/min
2	Mount with 0.5" exposed and face one end to create flat surface	Lathe	0.25" collet	Turning tool	1200 ~~750~~
3	Turn down to 0.236 diameter at specified length	Lathe Center drill and use live center on turned down section that is 1" long	0.25" collet	Turning tool	~~750~~
4	Remove, measure, and deburr part			Deburring tool	
5	Mount with opposite end exposed and face down to final length	Lathe	0.25" collet	Turning tool	~~750~~
6	Turn down to 0.236 diameter at specified length	Lathe	0.25" collet	Turning tool	~~750~~
7	Remove, measure, and deburr part			Deburring tool	
8	Mount on mill horizontally with parallels	Mill	Vise, v block with clamp		
9	Install a workstop and zero the mill	Mill	Vise, v block with clamp, workstop		
10	Face off sides to specified length	Mill	Vise, v block with clamp, workstop	1/4" endmill, 1/4" collet	1400 ~~500~~
11	Remove, measure, and deburr part			Deburring tool	

SHEET 2 OF 2



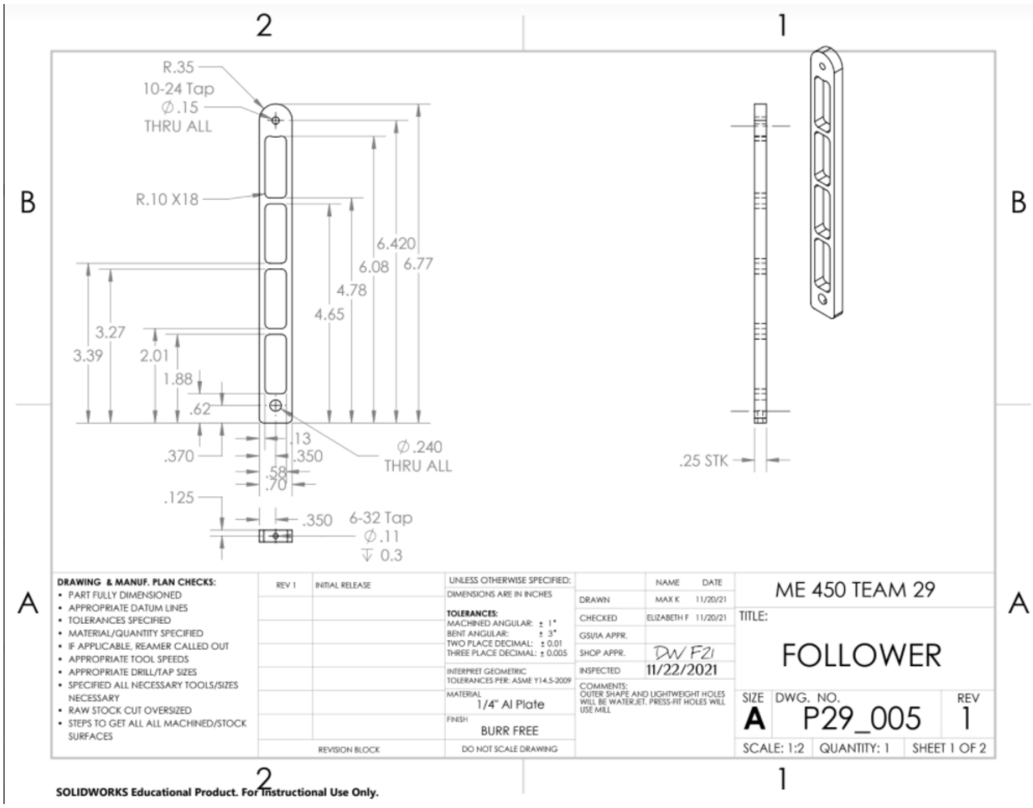
MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/4" Aluminum Rod Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock > 1.5" of final length then deburr	Bandsaw Rod Shear	Vise	Deburring tool	300 ft/min
2	Mount with 0.5" exposed and face one end to create flat surface	Lathe	0.25" collet	Turning tool	1200 750
3	Turn down to 0.236 diameter at specified length	Lathe	0.25" collet	Turning tool	750
4	Remove, measure, and deburr part	Centerdrill and use live	center for 1" long feature	Deburring tool	
5	Mount with opposite end exposed and face down to final length	Lathe	0.25" collet	Turning tool	750
6	Turn down to 0.236 diameter at specified length	Lathe	0.25" collet	Turning tool	750
7	Remove, measure, and deburr part			Deburring tool	
8	Mount on mill horizontally with parallels	Mill	Vise, v block with clamp		
9	Install a workstop and zero the mill	Mill	Vise, v block with clamp, workstop		
10	Face off sides to specified length	Mill	Vise, v block with clamp, workstop	1/4" endmill, 1/4" collet	1400 500
11	Remove, measure, and deburr part			Deburring tool	

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.



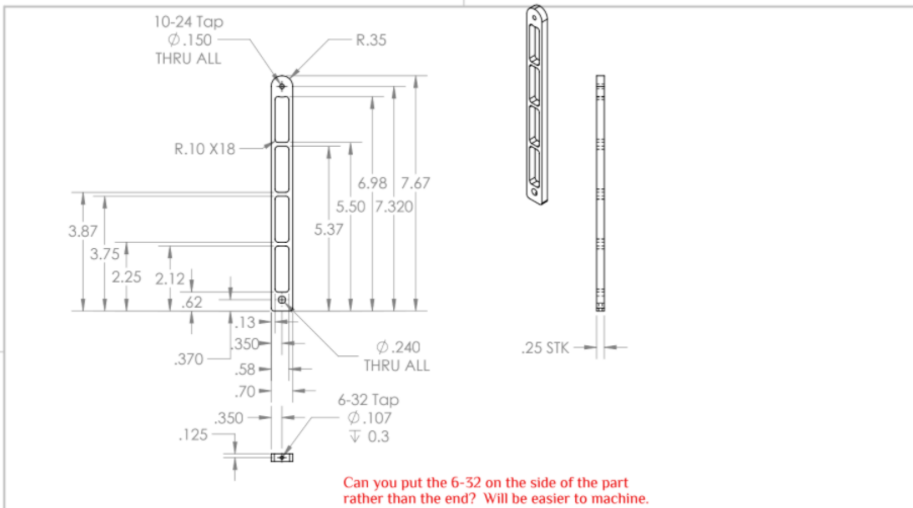
MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" Aluminum Plate

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer shape and lightweight holes then deburr	Waterjet		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vise	1.5" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vise, workstop	1.5" parallels	
4	Install drill chuck	Mill	Vise, workstop	1.5" parallels, drill chuck	
5	Center drill and drill 0.150" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, #25 drill bit	1200, 1200
6	Tap 10-24 hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, 10-24 tap, dead center	
7	Center drill and drill 0.240" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, B drill bit	1200, 1200
8	Remove and deburr part	Mill	Tall vise jaws	Deburring tool	
9	Mount in lathe with triangular vise	~~Lathe~~	~~Triangular Vise~~		
10	Center drill and drill 6-32 hole	~~Lathe~~	~~Triangular Vise~~	Drill chuck, #3 center drill, #36 drill bit	1200, 1200
11	Tap 6-32 hole	~~Lathe~~	~~Triangular Vise~~	Drill chuck, tap wrench, 6-32 tap, dead center	

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

2 1



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

REV 1 | INITIAL RELEASE

REVISION BLOCK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005
INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009
MATERIAL: 1/4" Al Plate
FINISH: BURR FREE
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MAX K	11/20/21
CHECKED	ELIZABETH F	11/20/21
GSI/IA APPR.		
SHOP APPR.	DW F21	11/22/2021
INSPECTED		

COMMENTS:
PART OUTLINE AND LIGHTWEIGHT HOLES WILL BE WATERJET. HOLES FOR PRESS-FIT WILL BE DONE ON MILL

ME 450 TEAM 29

TITLE:

INPUT

SIZE A | DWG. NO. P29_003 | REV 1

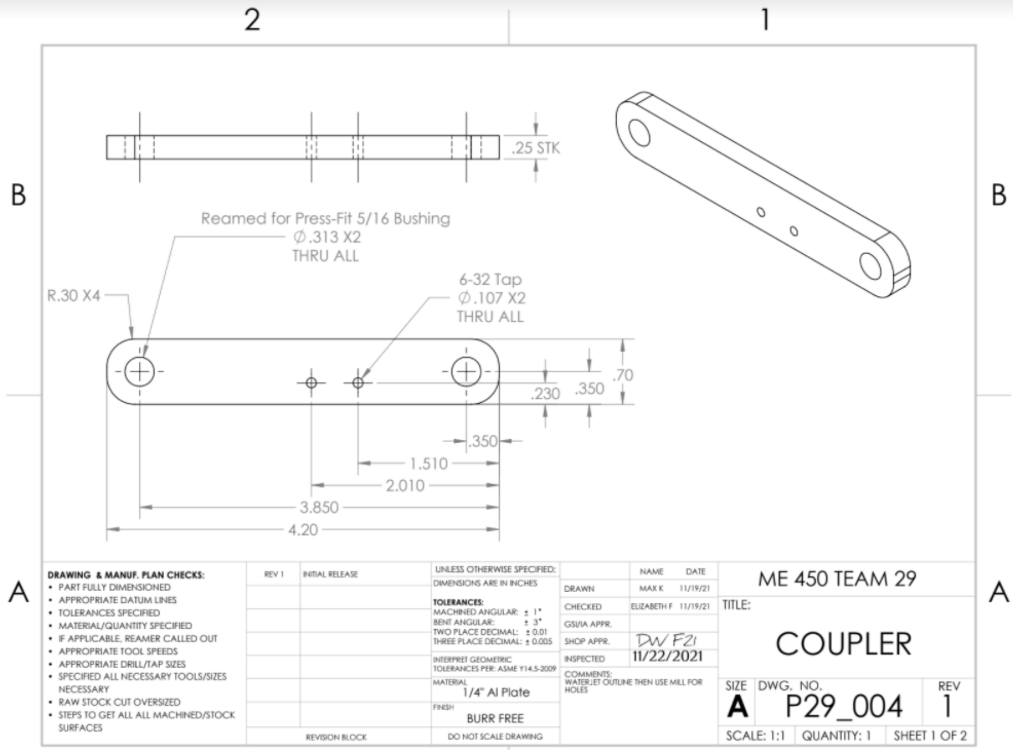
SCALE: 1:2 | QUANTITY: 1 | SHEET 1 OF 2

MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" Aluminum Plate

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer shape and lightweight holes then deburr	Waterjet		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vise	1.5" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vise, workstop	1.5" parallels	
4	Install drill chuck	Mill	Vise, workstop	1.5" parallels, drill chuck	
5	Center drill and drill 0.150" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, #25 drill bit	1200, 1200
6	Tap 10-24 hole	Mill	Vise, workstop	1.5" parallels, drill chuck, tap wrench, 10-24 tap, dead center	
7	Center drill and drill 0.240" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, B drill bit	1200, 1200
8	Remove and deburr part			Deburring tool	
9	Mount in lathe with triangular vise	~~Lathe~~ Mill	~~Triangular~~ Vise		
10	Center drill and drill 6-32 hole	~~Lathe~~	~~Triangular~~ Vise	Drill chuck, #3 center drill, #36 drill bit	1200, 1200
11	Tap 6-32 hole	~~Lathe~~	~~Triangular~~ Vise	Drill chuck, tap wrench, 6-32 tap, dead center	
12	Remove and deburr part			Deburring tool	

Use the tall vise jaws or move to side of part as suggested on print

SHEET 2 OF 2



SOLIDWORKS Educational Product. For Instructional Use Only.

MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/4" Aluminum Plate

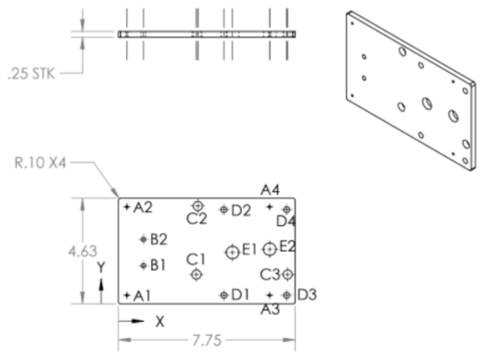
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer shape then deburr	Waterjet		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vise	1.5" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vise, workstop	1.5" parallels	
4	Install drill chuck	Mill	Vise, workstop	1.5" parallels, drill chuck	
5	Center drill and drill 5/16" hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, 19/64" N drill bit	1200, 1200
6	Ream 5/16" hole for 5/16" bushing		Vise, workstop	5/16" Reamer	100
7	Center drill and drill 6-32 hole	Mill	Vise, workstop	1.5" parallels, drill chuck, #3 center drill, #36 drill bit	1200, 1200
9	Tap 6-32 hole	Mill	Vise, workstop	1.5" parallels, drill chuck, 6-32 tap, tap wrench, dead center	
9	Remove and deburr part			Deburring tool	
10	Press-fit 5/16" bushing		Vise	Arbor press	

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

2 | 1

B | B



TAG	X LOC	Y LOC	SIZE
A1	.375	.375	6-32 Tap THRU ALL
A2	.375	4.250	6-32 Tap THRU ALL
A3	6.625	.375	6-32 Tap THRU ALL
A4	6.625	4.250	6-32 Tap THRU ALL
B1	1.100	1.675	1/4-20 Tap THRU ALL
B2	1.100	2.825	1/4-20 Tap THRU ALL
C1	3.417	1.287	∅ .40 THRU ALL
C2	3.482	4.287	∅ .40 THRU ALL
C3	7.417	1.287	∅ .40 THRU ALL
D1	4.625	.375	∅ .266 THRU ALL
D2	4.625	4.125	∅ .266 THRU ALL
D3	7.375	.375	∅ .266 THRU ALL
D4	7.375	4.125	∅ .266 THRU ALL
E1	5.000	2.250	∅ .550 THRU ALL Reamed for Bearing
E2	6.632	2.395	∅ .550 THRU ALL Reamed for Bearing

A | A

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

REV 1	INITIAL RELEASE
REVISION BLOCK	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

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

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL: 1/4" Al Plate

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MAX K	11/17/21
CHECKED	ELIZABETH F	11/17/21
GSI/IA APPR.		
SHOP APPR.	DW F21	
INSPECTED	11/18/2021	

COMMENTS:
PART OUTLINE WILL BE WATERJET. HOLES WILL BE DRILLED ON MILL

ME 450 TEAM 29

TITLE:

BOTTOM_PLATE

SIZE: A | DWG. NO. P29_002 | REV 2

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

2 | 1

2 | 1

B | B

MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/4" Aluminum Plate

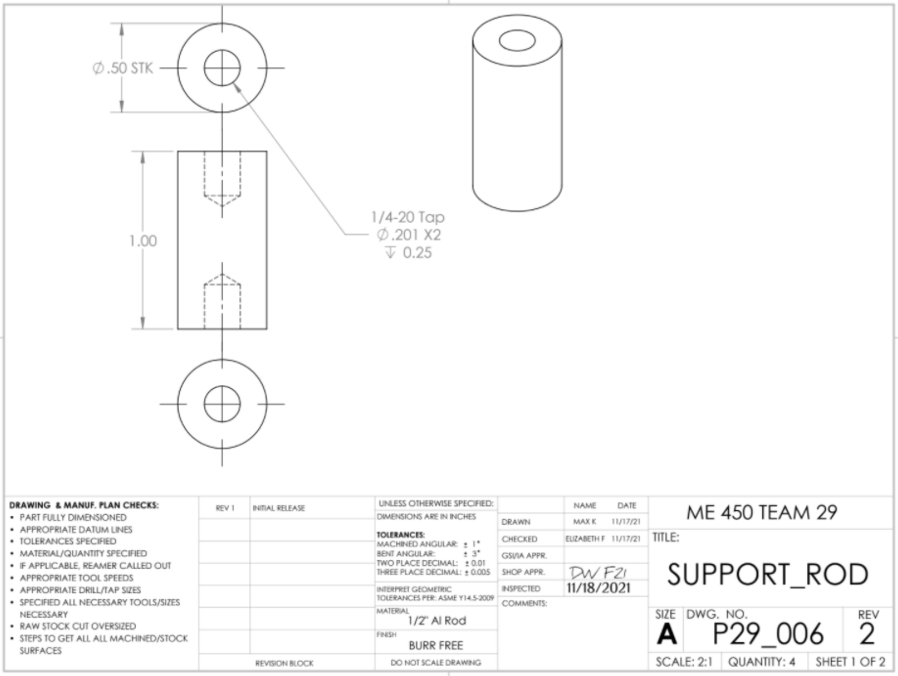
STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer shape then deburr	Waterjet		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vise	~~0.75~~" parallels, calipers 1 1/2" parallels	
3	Install a workstop and zero the mill	Mill	Vise, workstop	0.75" parallels	
4	Install drill chuck	Mill	Vise, workstop	0.75" parallels, drill chuck	
5	Center drill and drill A# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, #36 drill bit	1200, 1200
6	Center drill and drill B# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, drill bit #7	1200, 1200
7	Center drill and drill C# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, X drill bit	1200, 1200
8	Center drill and drill D# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, 17/64 drill bit	1200, 1200
9	Center drill and drill E# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, 35/64 drill bit Use 17/32" Drill	1200, 1200
10	Ream E# holes for 14mm bearings		Vise	0.550" Reamer	100
11	Tap A# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, 6-32 tap, tap wrench, dead center	
12	Tap B# holes	Mill	Vise, workstop	0.75" parallels, drill chuck, 1/4-20 tap, tap wrench, dead center	
13	Remove and deburr part			Deburring tool	
14	Press-fit 14mm bearings		Vise	Arbor press	

A and B holes can be tapped on EZ Tapper (faster)

A | A

SHEET 2 OF 2

2 | 1



SOLIDWORKS Educational Product. For Instructional Use Only.

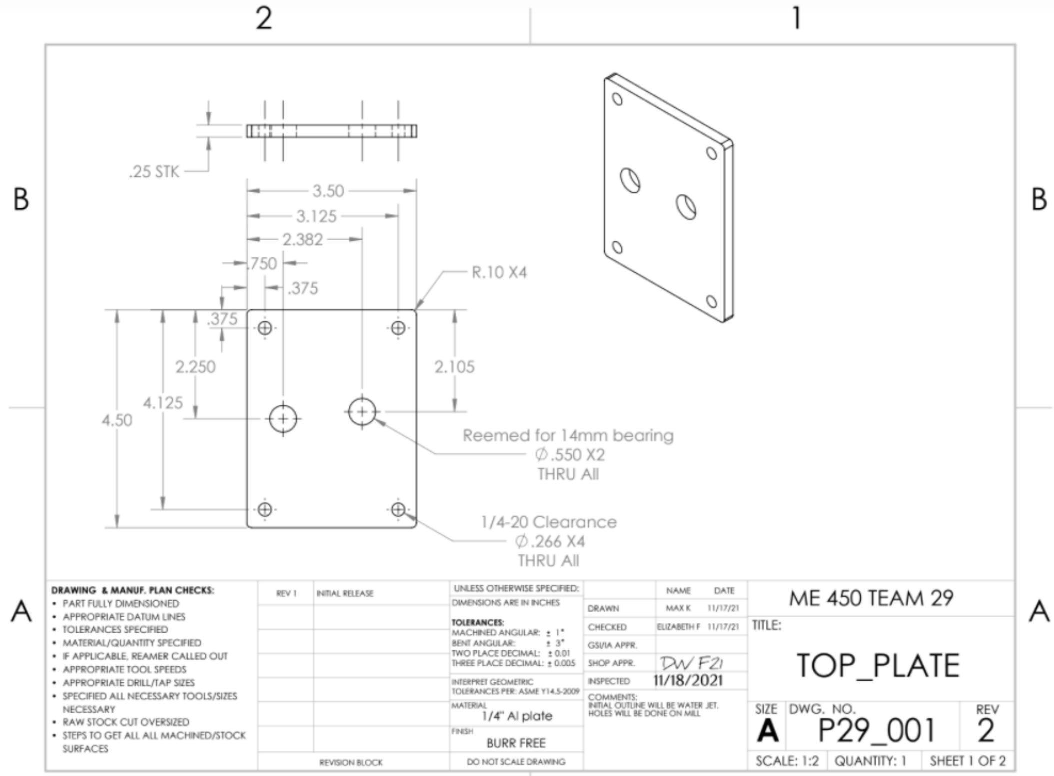
MANUFACTURING PLAN
RAW MATERIAL STOCK: 1/2" Aluminum Rod

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock > 1.5" of final length then deburr	Bandsaw	Vise	Deburring tool	300 ft/min
2	Mount with 0.5" exposed and face one end to create flat surface	Lathe	0.5" collet	Turning tool	750
3	Insert #3 center drill into drill chuck and drill a small hole in the end face	Lathe	0.5" collet	Drill chuck, #3 center drill	1200
4	Drill hole to noted depth	Lathe	0.5" collet	Drill chuck, #7 drill bit	1200
5	Tap 1/4-20 hole	Lathe	0.5" collet	Drill chuck, 1/4-20 tap, tap wrench, dead center	
6	Remove and deburr part			Deburring tool	
7	Measure then mount part with un-machined face outward	Lathe	0.5" collet		
8	Face end until final length is achieved	Lathe	0.5" collet	Turning tool	750
9	Insert ~~#3 center drill~~ into drill chuck ~~and~~ drill a small hole ~~in the end face~~	Lathe	0.5" collet	Drill chuck, #3 center drill	1200
10	~~Drill hole to noted depth~~	Lathe	0.5" collet	Drill chuck, #7 drill bit	1200
11	Tap 1/4-20 hole	Lathe	0.5" collet	Drill chuck, 1/4-20 tap, tap wrench, dead center	
12	Remove and deburr part			Deburring tool	

Drill thru the entire part, tap from each end in the lathe collet.

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

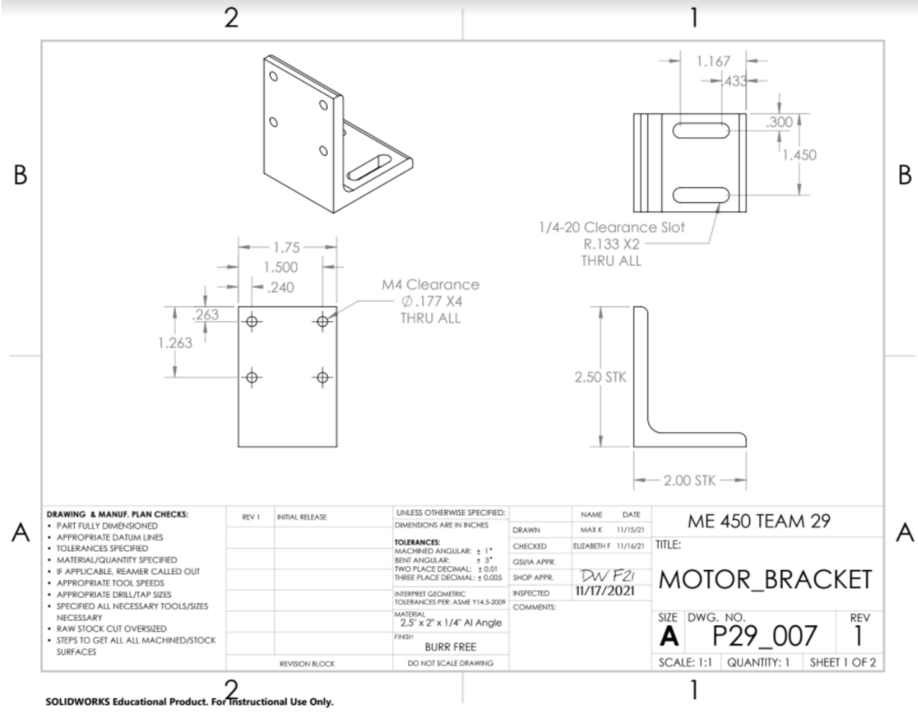


MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/4" Aluminum Plate

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Waterjet outer shape then deburr	Waterjet		Deburring tool	
2	Measure the part then mount on mill with parallels	Mill	Vise 1 1/2"	~~0.75~~" parallels, calipers	
3	Install a workstop and zero the mill	Mill	Vise, workstop	0.75" parallels	
4	Install drill chuck	Mill	Vise, workstop	0.75" parallels, drill chuck	
5	Center drill and drill outer 0.266" holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, 17/64 drill bit	1200, 1200
6	Center drill and drill inner 0.550" holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, 35/64 drill bit 17/32" drill	1200, 1200
7	Ream inner 0.550" holes for 14mm bearing		Vise	0.550" Reamer	100
8	Remove and deburr part			Deburring tool	
9	Press-fit 14mm bearings		Vise	Arbor press	

SHEET 2 OF 2



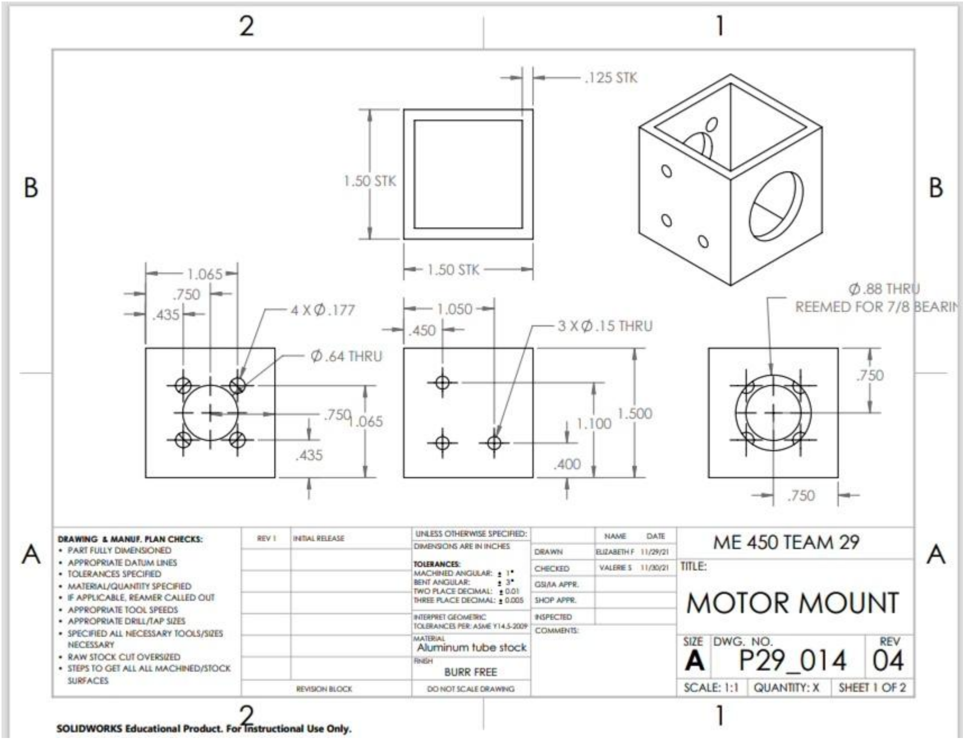
MANUFACTURING PLAN

RAW MATERIAL STOCK: 2.5" x 2" x 1/4" Aluminum Angle

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock to > 1/8" of final length then deburr	Bandsaw	Vise	Deburring tool	300 ft/min
2	Mount on mill with parallels with > 1/8" overhanging	Mill	Vise Clamp block	0.75" parallels	
3	Face off overhanging end	Mill	Vise Long 3/4" endmill from crib	3/4" two flute endmill, 3/4" collet, 0.75" parallels	500
4	Remove, measure, and deburr part. Repeat steps 2 and 3 with other side to get to final length. Remove and deburr again			Deburring tool	
5	Install a workstop and zero the mill	Mill	Vise, workstop	Let L hang outside right side of vise	
6	Mount on mill with parallels with M4 hole face upward	Mill	Vise, workstop	1 1/2" 0.75" parallels	
7	Install drill chuck	Mill	Vise, workstop	0.75" parallels, drill chuck	
8	Center drill and drill M4 holes	Mill	Vise, workstop	0.75" parallels, drill chuck, #3 center drill, #16 drill bit	1200
9	Remove and deburr part			Deburring tool	
10	Mount on mill with parallels with 1/4-20 slot facing upward	Mill	Vise, workstop	0.75" parallels	
11	Remove drill chuck and install 1/4" collet Plunge mill to rough slots at 0.25" width	Mill	Vise, workstop	0.75" parallels, 1/4" collet 2 flute endmill	
12	Use 17/64" endmill to drill slots Use clean up passes on each side of slots to bring to width	Mill	Vise, workstop	0.75" parallels, 1/4" collet, 17/64" two flute endmill	500 1400
13	Remove and deburr part			Deburring tool	

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.



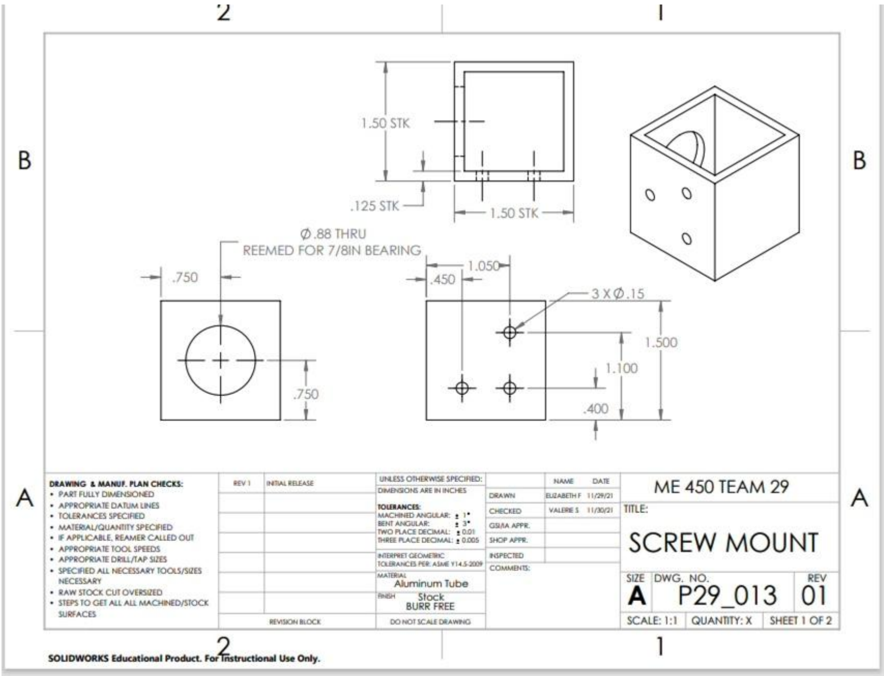
MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/8" Aluminum Tube Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut aluminum tube stock to 1.75" and deburr			Bandsaw, deburring tool	
2	Measure the part then mount on mill with parallels	mill	vise	3/8" parallels, calipers, long 3/4" endmill	500
	mill to get a flat surface	mill	vise	1.5" parallels	
	measure the part and mill to specified length	mill	vise	1.5" parallels, calipers	
3	install a workstop and zero the mill	mill	vise, workstop	1.5" parallels	
4	install drill chuck	mill	vise ,workstop	1.5" parallels, drill chuck	
5	center drill and dril 3 0.15" holes	mill	vise, workstop	1.5" parallels, drill chuck, #3 center drill, #25 drill bit	1200, 1200
6	remove part and rotate, remount, zero the mill, center drill and drill .64" hole	mill	vise, workstop	1.5" parallels, drill chuck, #3 center drill, #35/64 drill bit	1200, 1200
7	center drill and drill 4 0.177" hole	mill	vise, workstop	1.5" parallels, drill chuck, #3 center drill, #16 drill bit	1200, 1200
8	remove part and rotate, remount, zero the mill, center drill and drill .875" hole	mill	vise, workstop	1.5" parallels, drill chuck, #3 center drill, #16 drill bit	1200,1200
9	ream 0.875" hole for bearing and press in bearing with arbor press	mill	vise, workstop	0.875" reamer	100
10	Remove and deburr part			deburring tool	

SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.



MANUFACTURING PLAN

RAW MATERIAL STOCK: 1/8" Aluminum Tube Stock

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut aluminum tube stock to correct length and deburr			bandsaw and deburring tool	
2	measure the part then mount on mill with parallels	mill	vise	1.5" parallels, calipers	
3	install a workstop and zero the mill	mill	vise, workstop	1.5" parallels	
4	install drill chuck	mill	vise, workstop	1.5" parallels, drill chuck	
5	center drill and drill 3 0.15" holes	mill	vice, workstop	1.5" parallels, drill chuck, #3 center drill, #25 drill bit	1200,1200
6	center drill and drill .875" hole	mill	vice, workstop	1.5" parallels, drill chuck, #3 center drill, #13/16 drill bit	1200,1200
7	Ream 0.875" hole for bearing		vice	0.875" reamer	100
8	remove and deburr part			deburring tool	

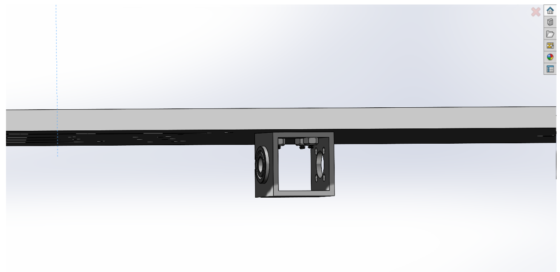
SHEET 2 OF 2

SOLIDWORKS Educational Product. For Instructional Use Only.

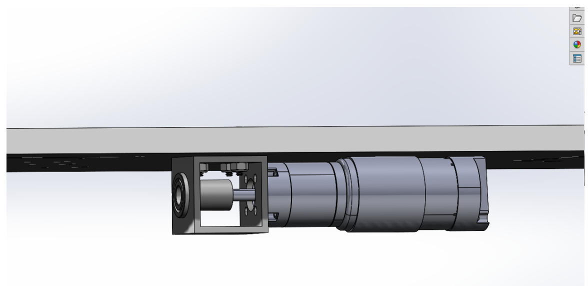
Appendix G - Game Board Assembly

Target Linear Motion Assembly

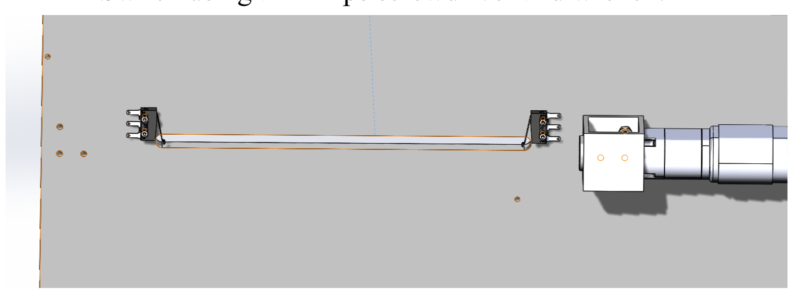
1. Fasten Motor Mounts to Game Board using three 6-32 ⅞” screws and locknuts using a wrench and Phillips screwdriver.



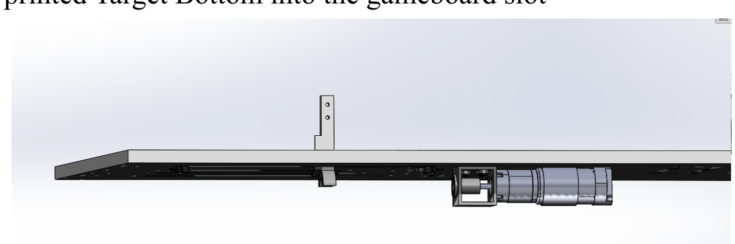
2. Attach the Coupler to the motor shaft and attach the motor to the motor mount with four set screws using an allen wrench.



3. Fasten two Limit Switches to each side of the target lane using two M2 22mm long screws and nuts for each Limit Switch using a Phillips screwdriver and wrench.

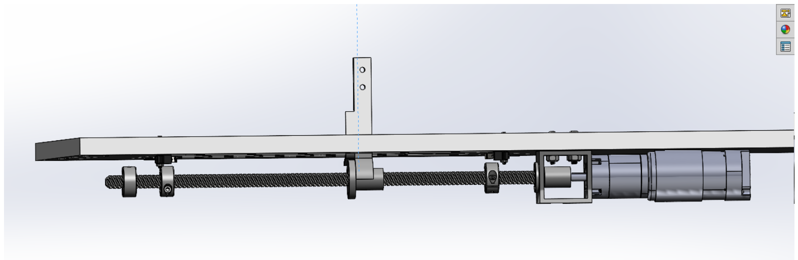


4. Insert the 3D printed Target Bottom into the gameboard slot

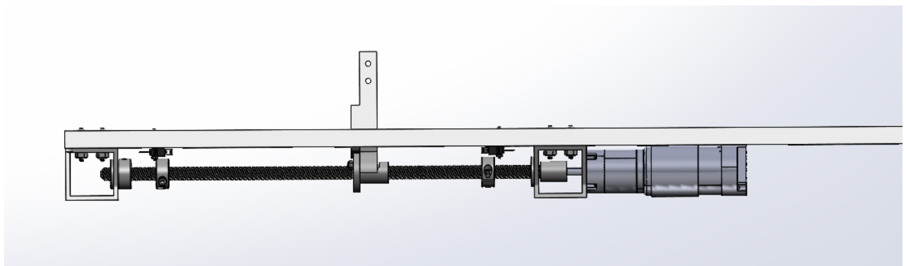


5. Attach three clamping collars to the lead screw and the Flanged nut hub.

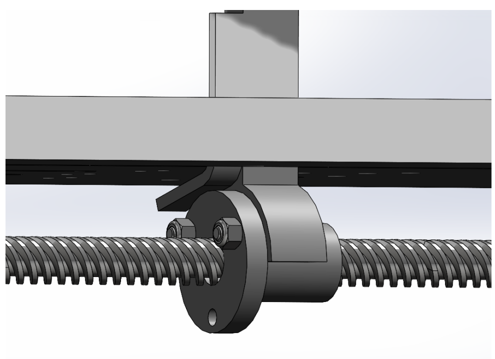
6. Attach the Lead Screw to the GameBoard using the clamping collar that is on the motor using an allen wrench.



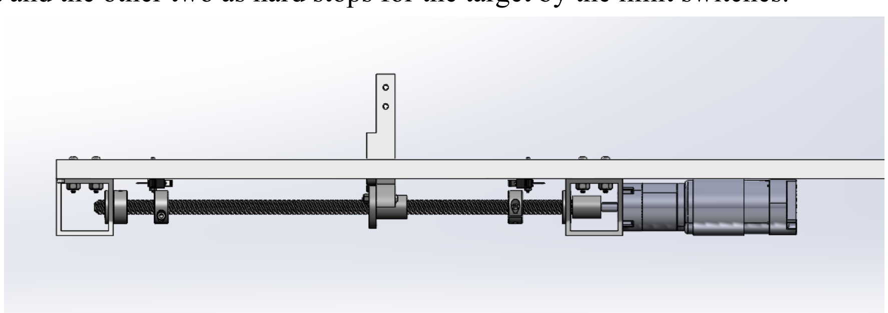
7. Slide the Aluminum Bracket into the other end of the Lead Screw and fasten the bracket to the GameBoard using three 6-32 ⅞" screws and locknuts using a wrench and phillips screwdriver.



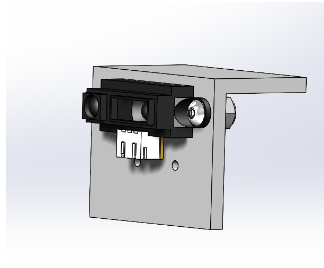
8. Fasten 3D printed Target Bottom to the Flanged nut hub using two M3 22mm screws and locknuts.



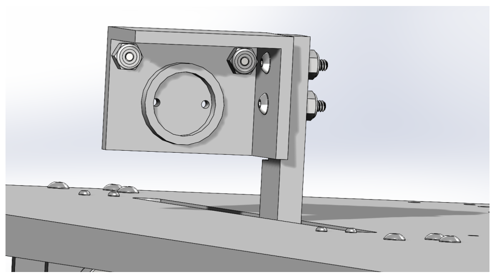
9. Tighten clamping collars to desired locations, one to secure lead screw against the aluminum bracket and the other two as hard stops for the target by the limit switches.



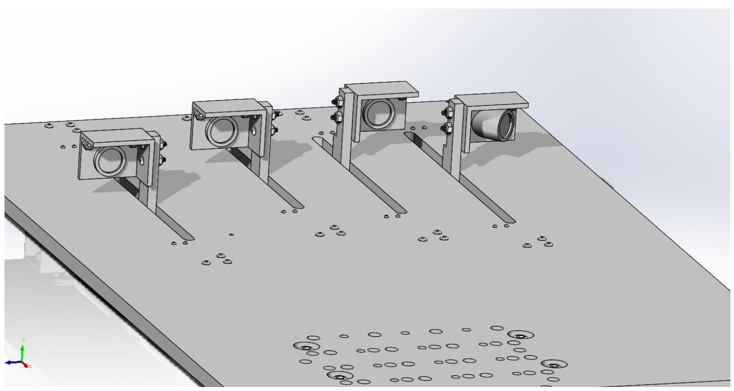
10. Fasten the Proximity Sensor to the 3D printed Target Case using two 4-40 ⅜” screws and locknuts.



11. Fasten the photosensor to Target Case using Epoxy
12. Fasten Target Case to Target Bottom using two #6 ¾” allen screws and locknuts.

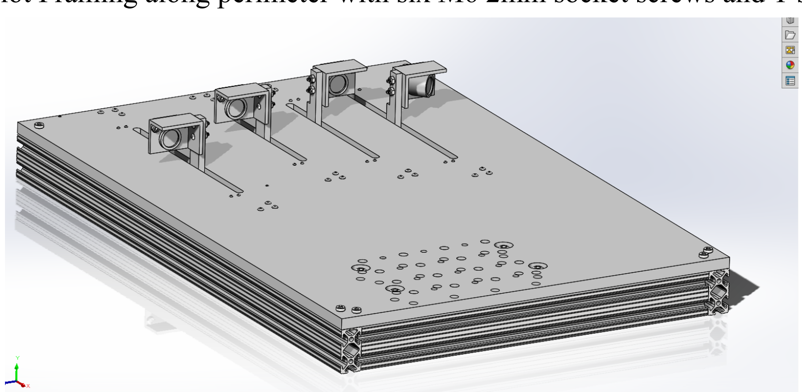


13. Repeat for each target Lane (Four Times)

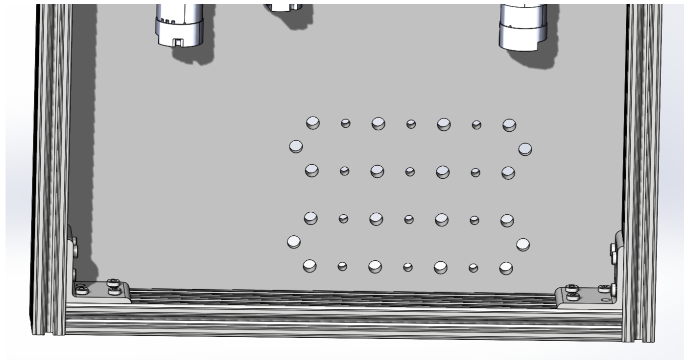


Framing Assembly

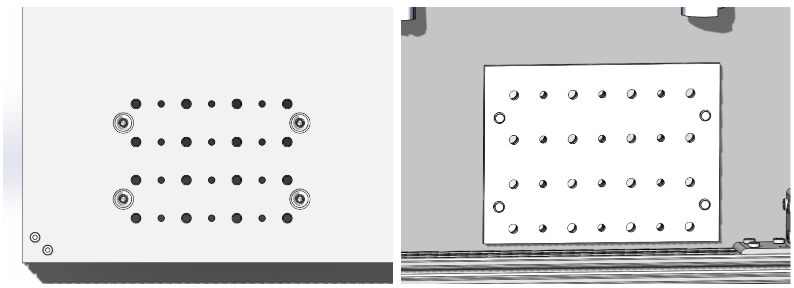
1. Attach T-Slot Framing along perimeter with six M6 2mm socket screws and T-slot framing nuts



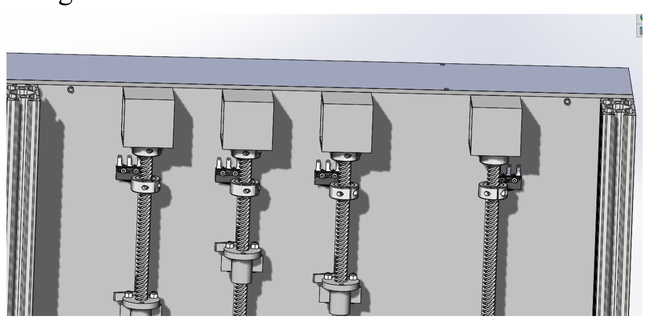
2. Attach two Brackets to corners of T-Slot Framing using twelve M6 12mm Socket Head Screws and T-Slot framing nuts



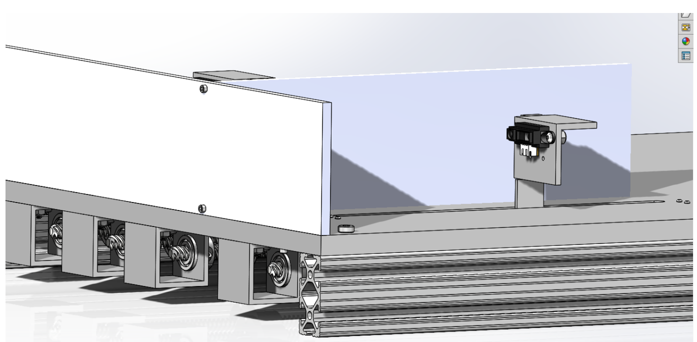
3. Attach Aluminum Framing to GameBoard using four 3-8 ⅝" screws.



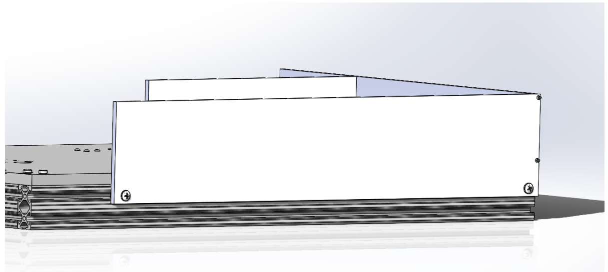
4. Fasten Back Wall using two 4-40 ½" screws



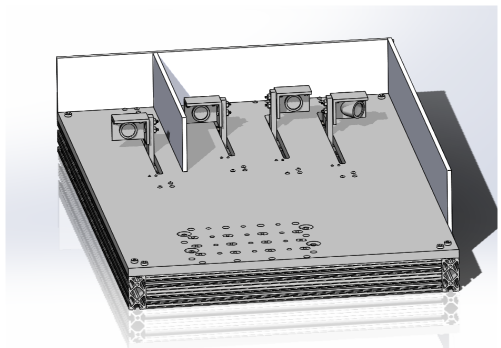
5. Fasten Obstacle Wall using two 4-40 ½" through the back wall and one screw through the game board base plate



6. Fasten Side Wall using two 1/4"-20 ½” and T-Slot framing nuts and two 4-40 ½” through the back wall



7. Fully Assembled Game Board



Appendix H - Arduino code

```
//Next Gen ME 350 Prototype Board

//-------------------------- Pin assignments ----------------------------//
const int startswitch = 7;              // Connected to limit switch (starts
each round when prompted)
const int toggleSwitch    = 9;          // Connected to toggle switch (turns
game board motion on and off)
const int PIN_NR_PWM_OUTPUT       = 11; // Connected to H Bridge (controls
motor speed)
const int PIN_NR_PWM_DIRECTION_1  = 12; // Connected to H Bridge (controls
motor direction)
const int PIN_NR_PWM_DIRECTION_2  = 13; // Connected to H Bridge (controls
motor direction)
const int backlimitswitch = 4;          // Connected to limit switch at back
of path
const int forwardlimitswitch = 5;       // Connected to limit switch at front
of path
const int photosensor = A0;             // Connected to photosensor to read
in flashlight values
// The encoder channels for the motor are digital pins 2 and 3 for the
interrupts


//------------------Variables for velocity computation-------------------//
const int MIN_VEL_COMP_COUNT = 2;       // Minimum encoder counts to
re-calculate velocity
const long MIN_VEL_COMP_TIME = 10000;   // Minimum time elapsed to
re-calculate velocity
volatile long motorPosition = 0;        // Motor position in encoder counts
(updates whenever the interrupt is called)
volatile int encoderStatus = 0;         // Encoder values, update in
interrupt function
float motorVelocity        = 0;         // [encoder counts/second] Motor
velocity
int previousMotorPosition  = 0;         // [encoder counts] Motor position
the last time a velocity was computed
unsigned long previousVelCompTime   = 0;// Saves timepoint of last
calculation
unsigned long executionDuration = 0;    // Saves how long each loop takes
unsigned long lastExecutionTime = 0;    // Used to calculate how long each
loop takes
```

```
//-------Variables for round timing/flashlight sensing and timing----------//
unsigned long roundStart = 0;           // Saves timepoint that the round
started at (then last 45 seconds after)
unsigned long flashlightTiming = 0;     // Saves timepoint that flashlight
was first identified (then waits 1 second)
int flashlight = 0;                     // Stores value from the photosensor
to determine if the flashlight is present or not

//----------------Variables for motion control/PI controller---------------//
const int CALIBRATION_VOLTAGE = -3;     // Motor voltage when calibrating
float desiredVelocity = 0.0;            // Desired velocity [encoder
counts/second]
float desiredVoltage = 0.0;             // Desired voltage from PI
controller/desired velocity
float endlessVelocity = 0;              // This variable is used to speed up
the target in endless round
const float FRICTION_COMP_VOLTAGE = 2.6;// [Volt] Voltage needed to overcome
friction
float velocityError = 0.0;              // Used to calculate proportional
gain in PI controller
float integralError = 0.0;              // Used to calculate integral gain in
PI controller
const float KP = 0.005;                 // Proportional gain
const float KI = 0.01;                  // Integral gain
const int SUPPLY_VOLTAGE = 12;          // Voltage supplied by power supply
int motorCommand = 0;                   // This variable stores the PWM sent
to the motor
const int MOTOR_VOLTAGE_CAP = 12;       // Cap for the voltage that the
H-bridge will attempt to send
const int LIGHT_LIMIT = 800;            // Light level at which photosensor
knows a flashlight is pointing at it

//----------------------------State Machine--------------------------------//

const int ROUND_ONE = 1;                // First (slower) 45 second round
const int ROUND_TWO = 2;                // Second (faster) 45 second round
const int ENDLESS_ROUND = 3;            // Last (endless) round
const int CALIBRATE = 4;                // Calibrates the targets to the back
limit switch before each round
const int CHANGE_ROUND = 5;             // Switches between rounds, waits for
GSI to prompt start
const int REPORT_RESULTS = 6;           // Ends trial and reports final
results
```

```
int nextRound = 1;                      // Determines which round is next
int state = CALIBRATE;                  // Start controller in calibrate mode

const int FORWARD = 1;                  // Controls which direction the motor
is moving during rounds
const int BACKWARD = 2;                 // Controls which direction the motor
is moving during rounds
int motionDirection = FORWARD;          // Controls which direction the motor
is moving during rounds

void setup() {
  // Setup the input/output pins
  pinMode(PIN_NR_PWM_OUTPUT,       OUTPUT);
  pinMode(PIN_NR_PWM_DIRECTION_1,  OUTPUT);
  pinMode(PIN_NR_PWM_DIRECTION_2,  OUTPUT);
  pinMode(toggleSwitch,    INPUT);
  pinMode(startswitch,    INPUT);
  pinMode(backlimitswitch,  INPUT);
  pinMode(forwardlimitswitch, INPUT);

  // Activate interrupt for encoder pins.
  // If either of the two pins changes, the function 'updateMotorPosition' is
called:
  attachInterrupt(0, updateMotorPosition, CHANGE);  // Interrupt 0 is always
attached to digital pin 2
  attachInterrupt(1, updateMotorPosition, CHANGE);  // Interrupt 1 is always
attached to digital pin 3

  //Start the serial monitor
  Serial.begin(9600);
}

void loop() {
  executionDuration = micros() - lastExecutionTime; // Tracks loop time for
debugging/integration purposes
  lastExecutionTime = micros();

  if ((abs(motorPosition - previousMotorPosition) > MIN_VEL_COMP_COUNT) ||
(micros() - previousVelCompTime) > MIN_VEL_COMP_TIME){
    // If at least a minimum time interval has elapsed or
    // the motor has travelled through at least a minimum angle ...
    // .. compute a new value for speed:
    // (speed = delta angle [encoder counts] divided by delta time [seconds])
```

```
    motorVelocity = (double)(motorPosition - previousMotorPosition) * 1000000
/
                            (micros() - previousVelCompTime);
    // Remember this encoder count and time for the next iteration:
    previousMotorPosition = motorPosition;
    previousVelCompTime   = micros();
  }

  flashlight = analogRead(photosensor);             // Read in photosensor
value to determine if flashlight is pointing at it

  switch (state) {
    case CALIBRATE:                                 // Starts in CALIBRATE
state, moves on to CHANGE_ROUND state when the target reaches the back limit
switch
      desiredVelocity = -500;
      Serial.println("Calibrating");
      if (digitalRead(backlimitswitch) == HIGH) {
        desiredVelocity = 0;
        Serial.println("Calibrated");
        roundStart = micros();
        state = CHANGE_ROUND;
      }
    break;

    case CHANGE_ROUND:                              // Waits for GSI to hit
limit switch to start each round
      if (digitalRead(startswitch)==HIGH) {
        state = nextRound;
        desiredVelocity = 0;
        Serial.print("Starting round ");
        Serial.println(nextRound);
        nextRound = nextRound + 1;
      }
      else {
        Serial.println("Waiting for start switch...");
      }
    break;

    case ROUND_ONE:                                 // First round, moves
slowest, lasts 45 seconds
      if (micros() - roundStart > 45000000) {       // Moves on to CALIBRATE
state when 45 seconds have passed
```

```
        Serial.println("End of round");
        state = CALIBRATE;
      }
      switch (motionDirection) {                    // Starts by moving
forward, turns around if hits front limit switch
        case FORWARD:
          if(flashlight < LIGHT_LIMIT) {
            flashlightTiming = micros();
            desiredVelocity = 500;
            if(digitalRead(forwardlimitswitch) == HIGH) {
              desiredVelocity = 0;
              motionDirection = BACKWARD;
              integralError = 0;
            }
          }
          else {                                    // Pauses target if
flashlight is sensed
            desiredVelocity = 0;
            //Serial.println("Flashlight detected");
            if(micros()-flashlightTiming > 1000000) {   // If flashlight
remains for 1 second, turn around
              Serial.println("Target stopped");
              motionDirection = BACKWARD;
              integralError = 0;
            }
          }
          break;
        case BACKWARD:                              // Move back to back
limit switch if flashlight stops target, or if target hits front limit switch
          desiredVelocity = -500;
          if(digitalRead(backlimitswitch) == HIGH) {
            desiredVelocity = 0;
            motionDirection = FORWARD;
            integralError = 0;
          }
        break;
      }
    break;

    case ROUND_TWO:                                 // Second round, moves
faster, lasts 45 seconds
      if (micros() - roundStart > 45000000) {      // Moves on to CALIBRATE
state when 45 seconds have passed
```

```
        Serial.println("End of round");
        state = CALIBRATE;
      }
      switch (motionDirection) {
        case FORWARD:                             // Starts by moving
forward, turns around if hits front limit switch
          if(flashlight < LIGHT_LIMIT) {
            flashlightTiming = micros();
            desiredVelocity = 1000;
            if(digitalRead(forwardlimitswitch) == HIGH) {
              desiredVelocity = 0;
              motionDirection = BACKWARD;
              integralError = 0;
            }
          }
          else {
            desiredVelocity = 0;
            Serial.println("Flashlight detected");    // Pauses target if
flashlight is sensed
            if(micros()-flashlightTiming > 1000000) {     // If flashlight
remains for 1 second, turn around
              Serial.println("Target stopped");
              motionDirection = BACKWARD;
              integralError = 0;
            }
          }
        break;
        case BACKWARD:                            // Move back to back limit
switch if flashlight stops target, or if target hits front limit switch
          desiredVelocity = -1000;
          if(digitalRead(backlimitswitch) == HIGH) {
            desiredVelocity = 0;
            motionDirection = FORWARD;
            integralError = 0;
          }
        break;
      }
    break;

    case ENDLESS_ROUND:                  // No time limit on this round, goes
until mechanism can't stop a target from hitting the front limit switch
      switch (motionDirection) {
          case FORWARD:
```

```
            if(flashlight < LIGHT_LIMIT) {
              flashlightTiming = micros();
              desiredVelocity = 1000 + endlessVelocity;
              if(digitalRead(forwardlimitswitch) == HIGH) {
                Serial.println("Test ended");
                state = REPORT_RESULTS;
              }
            }
            else {
              desiredVelocity = 0;
              Serial.println("Flashlight detected");
              if(micros()-flashlightTiming > 1000000) {
                Serial.println("Target stopped");
                motionDirection = BACKWARD;
                endlessVelocity = endlessVelocity + 200;    // Increases
motor velocity each time the target is successfully stopped
                integralError = 0;
              }
            }
            break;
          case BACKWARD:
            desiredVelocity = -1000;
            if(digitalRead(backlimitswitch) == HIGH) {
              desiredVelocity = 0;
              motionDirection = FORWARD;
              integralError = 0;
            }
            break;
        }
    break;

    case REPORT_RESULTS:
      analogWrite(PIN_NR_PWM_OUTPUT, 0);    // Turns off motor
      Serial.println("This is where the reporting goes");
      while(1);   // Infinite loop to halt program until new mechanism can be
placed and arduino can be reset to begin again
    break;

    default:
      Serial.println("Statemachine reached at state that it cannot handle.
ABORT!!!!");
      Serial.print("Found the following unknown state: ");
      Serial.println(state);
```

```
      while (1); // infinite loop to halt the program
    break;
  }

// Velocity Controller
  if (digitalRead(toggleSwitch)==HIGH) {
    // If the toggle switch is on, run the controller:

    //** PI control: **//
    // Compute the proportional/velocity error
    velocityError = desiredVelocity - motorVelocity;
    // Compute the integral of the velocity error  [encoder counts * seconds]
    integralError = integralError + velocityError *
(float)(executionDuration) / 1000000;
    // This is the actual controller function that uses the error in
    // velocity and the integrated error and computes a
    // desired voltage that should be sent to the motor:
    desiredVoltage = KP * velocityError +
                     KI * integralError;

    // Anti-Wind-Up
    if (abs(desiredVoltage)>SUPPLY_VOLTAGE) {
      // If we are already saturating our output voltage, it does not make
      // sense to keep integrating the error (and thus ask for even higher
      // and higher output voltages).  Instead, stop the integrator if the
      // output saturates. We do this by reversing the summation at the
      // beginning of this function block:
      integralError = integralError - velocityError *
(float)(executionDuration) / 1000000;
    }
    if (state == CALIBRATE) {
      desiredVoltage = CALIBRATION_VOLTAGE;
    }
    if (desiredVelocity == 0) {
      desiredVoltage = 0;
    }
  }

  else {
    // Otherwise, the toggle switch is off, so do not run the controller,
    // stop the motor...
    desiredVoltage = 0;
    // .. and reset the integrator of the error:
```

```
    integralError = 0;

    // Produce some debugging output:
    Serial.println("The toggle switch is off.  Motor Stopped.");
  }
  //** Send signal to motor **//
  // Convert from voltage to PWM cycle:
  motorCommand = int(abs(desiredVoltage * 255 / SUPPLY_VOLTAGE));
  // Clip values larger than motor voltage cap
  if (abs(desiredVoltage) > abs(MOTOR_VOLTAGE_CAP)) {
    motorCommand = 255*(MOTOR_VOLTAGE_CAP/SUPPLY_VOLTAGE);
  }
  // Send motor signals out
  analogWrite(PIN_NR_PWM_OUTPUT, motorCommand);
  // Determine rotation direction
  if (desiredVoltage >= 0) {
    // If voltage is positive ...
    // ... turn forward
    digitalWrite(PIN_NR_PWM_DIRECTION_2,LOW);  // rotate forward
    digitalWrite(PIN_NR_PWM_DIRECTION_1,HIGH); // rotate forward
  } else {
    // ... otherwise turn backward:
    digitalWrite(PIN_NR_PWM_DIRECTION_2,HIGH); // rotate backward
    digitalWrite(PIN_NR_PWM_DIRECTION_1,LOW);  // rotate backward
  }

  // Print motor states for debugging, can be commented out to speed up loop
  Serial.print(desiredVelocity);
  Serial.print("\t");
  Serial.print(motorVelocity);
  Serial.print("\t");
  Serial.print(desiredVoltage);
  Serial.print("\t");
  Serial.print(motorCommand);
  Serial.print("\t");
  Serial.println(velocityError);
}


// This interrupt function is called whenever the encoder values change
void updateMotorPosition() {
  // Bitwise shift left by one bit, to make room for a bit of new data:
  encoderStatus <<= 1;
```

```
  // Use a compound bitwise OR operator (|=) to read the A channel of the
encoder (pin 2)
  // and put that value into the rightmost bit of encoderStatus:
  encoderStatus |= digitalRead(2);
  // Bitwise shift left by one bit, to make room for a bit of new data:
  encoderStatus <<= 1;
  // Use a compound bitwise OR operator  (|=) to read the B channel of the
encoder (pin 3)
  // and put that value into the rightmost bit of encoderStatus:
  encoderStatus |= digitalRead(3);
  // encoderStatus is truncated to only contain the rightmost 4 bits by
using a
  // bitwise AND operator on mstatus and 15(=1111):
  encoderStatus &= 15;
  if (encoderStatus==2 || encoderStatus==4 || encoderStatus==11 ||
encoderStatus==13) {
    // the encoder status matches a bit pattern that requires counting up by
one
    motorPosition++;         // increase the encoder count by one
  }
  else if (encoderStatus == 1 || encoderStatus == 7 || encoderStatus == 8 ||
encoderStatus == 14) {
    // the encoder status does not match a bit pattern that requires counting
up by one.
    // Since this function is only called if something has changed, we have
to count downwards
    motorPosition--;         // decrease the encoder count by one
  }
}
```