Rocket MIP:
Mobile Inverted Pendulum

Instructor: Shorya Awtar
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Dylan Fisher, Michael Maynard, Mohammad Monem, Benjamin Wong

Table of Contents

ABSTRACT
Increasing interest and awareness of STEM through accessible and interactive projects could increase the number of students choosing a career in a STEM field. Our objective is to develop a low priced interactive educational kit in the form of a Mobile Inverted Pendulum (MIP), dubbed the RocketMIP, which can be manufactured, assembled, and operated by a student with access to a 3D printer and can be completed for a price of $100. This kit will motivate and educate high schoolers about the basics of 3D printing, mechanical and electrical assembly, and mechatronics, expanding their knowledge on topics not normally discussed until college.

1. BACKGROUND

Within the following section we detail major components affecting the needs within our project space; STEM education, additive manufacturing, proportional-derivative-integral control, interactive education.

1.1 STEM Education

The American College Testing Corporation (ACT) has determined that 45% of 2018 graduates were interested in STEM majors or occupations, but only 20% of graduates met the ACT STEM Readiness Benchmark. This metric is used by the ACT to benchmark whether the student is considered ready for first year college STEM courses such as physics or calculus [1]. Given this apparent gap in the readiness of students for STEM courses it is even more crucial to develop interest in STEM fields as employment in the area has grown 79% in the last three decades alone [2]. Furthermore, there is a disproportionately small number of women working in STEM fields as they only make up 27% of STEM careers while making up 48% of the general workforce [3]. It has been identified that throughout high school, 60% of women interested in furthering their STEM education lose interest before graduation [4].The lack of women interested in STEM is extremely concerning as it fosters a lack of diversity and inclusion within the workforce and ultimately limits the potential of the entire industry [5]. STEM as a career is booming and future innovations to technology are only going to continue its growth. Exposure to STEM as an interest as well as an occupation will help to enrich peoples lives if STEM education has inclusive and interesting projects to work on for people of all backgrounds.

1.2 Additive Manufacturing

As we have moved through the fourth industrial revolution (also referred to as industry 4.0) in the last decade, one of the most popular advancements has been the incorporation of additive manufacturing, specifically 3D printing [6]. According to Linkedin, as the demand for 3D printing increases so does the demand for professionals who want to pursue a career in additive manufacturing [7]. 3D printers are becoming more prevalent in our modern society. According to Open World Learning, “As of June 2019, there were an estimated 225,000 3D printers in the United States. This number is expected to grow to over 500,000 by 2022” [8]. As this technology continues to grow and advance 3D printers will only become more available and more popular in the industrial setting. From the increasing availability of 3D printers, individuals are able to gain exposure to manufacturing directly from their homes. This not only allows for original ideas to be imagined and built for a low cost and incredible convenience, but also offers a space for people to continuously try and fail without fear of critique from others. STEM as a field is not always straightforward and it is encouraged to continuously improve your work to advance your knowledge.

1.3 Proportional-Integral-Derivative (PID) Control

During 2022, more than 41,000 robotic arms were installed in the North American manufacturing sector, an increase of 12% from 2021 [9]. As the popularity of these robotic arms continues to grow so will the demand for controls programmers. The PID algorithm is the most commonly utilized in the manufacturing industry [10]. According to National Instruments, "The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner" [10]. The implementation of PID controllers continues to rise, with a predicted growth rate of 16.3% this year [11]. This intrinsic "simplicity" and ever growing demand is what makes PID control a good option for gaining a foothold within the controls space.

1.4 Interactive Education

Teaching advanced concepts at a high school level is often seen as difficult due to the overarching complexities within the topics. According to a study conducted by the Educational Testing Service, "Students whose teachers conduct hands-on learning activities outperform their peers by more than 70% of a grade level in math and 40% of a grade level in science." [12]. The Thinking Kid further explains, "Hands-on learning better engages both the left and right sides of the brain…By using multiple styles of learning, the brain creates better connections and can store more relevant information…Through hands-on learning, students have the opportunity to interact with what they are learning" [13]. Hands-on learning is even more beneficial when it comes to learning content that applies to the workplace as it lessens the imbalance between academic content and employment by familiarizing the student with the environment they will be confronted with in the field [14]. For these reasons hands-on education is often the first choice for teachers when it comes to teaching complex subjects like STEM.

2. MOTIVATION

Increasing interest and awareness of STEM through accessible and interactive projects could increase the number of students choosing a career in a STEM field. Many of the kits that are currently commercially available are "buy and assemble" kits (meaning you are provided with all of the components and you simply assemble them together), often having little to no embedded educational modules, and can have a high price point. We determined that a kit with direct educational ties and a price under $100 would both improve accessibility to STEM education and peak interest in high school students to further pursue STEM opportunities, like high school robotics, in the future.

3. PROBLEM OBJECTIVE

RocketMIP will deliver a complete purchasable kit of electronics, downloadable STL's of all the 3D printed parts, and an instruction manual with integrated learning modules that will teach the students about 3D printing, mechanical and electrical assembly, and mechatronic controls for under a price of $100. Each module will step the student through a portion of the kit, and will result in a fully assembled MIP after every module has been completed. In order for this kit to be successful we must be able to create an interactive and educational table top inverted mobile pendulum that can be assembled from a kit with 3D printed components that will improve a student's knowledge on what 3D printing is, important 3D printing settings, PID control theory, and PID tuning, while increasing their overall interest in future STEM education.

4. DESIGN CONTEXT

The decisions that the team makes will have a trickle down effect which will be informed by many factors outside of the immediate objective identified. Stakeholders will play a role in the formation of ideas where some will benefit positively from the project whereas others will not. Ethical decisions will ensure that the project aims to be inclusive and considers the impacts the project can have such as environmental factors, which will inform our manufacturing and design decisions to create a more sustainable project.

4.1 Stakeholders

In order to understand the many contextual factors that are involved in our project, a stakeholder analysis was initially conducted in order to understand the diverse parties involved. The main stakeholders of the project were split into three categories: primary, secondary, and tertiary. Where primary stakeholders are individuals directly impacted by the creation of the RocketMIP, secondary stakeholders are individuals who apart of the problem but may not be impacted directly by the problem or solution themselves, and tertiary stakeholders are individuals who do not play a direct role in the development of the RocketMIP but can influence its success or failure of it [15]. Furthermore, the stakeholders can be broken down by the specific role they serve in the overall problem context and it is possible for a stakeholder to possess more than one role and reside on more than one different level. The categorized list of stakeholders is shown in Figure 1.

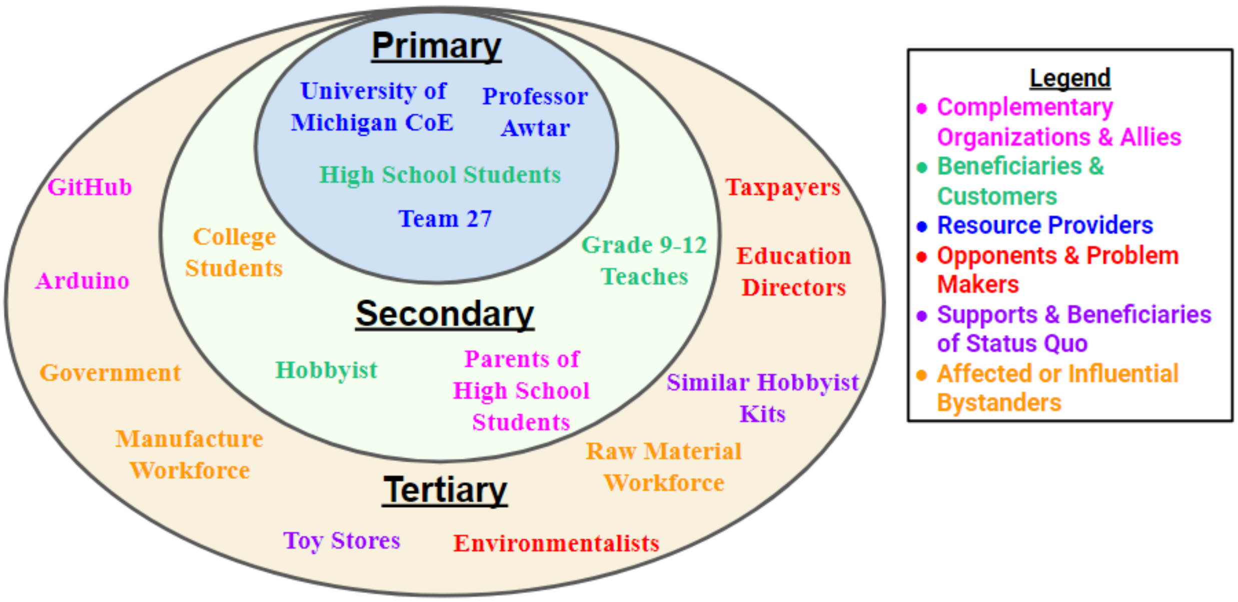


Figure 1: Categorized map of important stakeholders

Professor Awtar, Project Team 27, and University of Michigan were determined to be primary stakeholders as well as resource providers because of the knowledge and funding aspect they provide to the team and project. Furthermore, Professor Awtar is an essential primary stakeholder given his previous knowledge with inverted pendulum projects and his many years of experience. The University of Michigan completely funds the project and provides the facilitators and facility for the team to design and prototype. Team 27 is the driving force behind the project and combines the knowledge of four senior engineering students with a variety of experiences. Also, since the education of high school students is a main priority of the project, they are primary stakeholders and beneficiaries.

Hobbyists and Grade 9-12 Teachers were also determined to be customers and beneficiaries of the RocketMIP since they might buy the kit to educate themselves or class. However, since the kit is not targeting hobbyists specifically and teachers with a college degree would have already learned about the concepts, both groups might not be directly affected by the problem or solution which would make them secondary stakeholders. Parents of high school students and college students were determined to be allies and affected bystanders, respectively, mainly due to the encouragement parents can have on students' learning and how college students could utilize the kit to facilitate learning even though they are not the intended audience. Both stakeholders would be considered secondary since they are a part of the problem context, but are not directly affected by the problem or solution.

While tertiary stakeholders are not a part of the immediate problem, they can still influence the success of the project. An assortment of relevant tertiary stakeholders are presented in Figure 1. Some of the main tertiary stakeholders include taxpayers, who may be an opponent of the project as they may be the ones who might have to burden the cost for schools, and the manufacturing workforce that will assemble the subcomponents, whose livelihood could be affected by the increased, or decreased, demand for the RocketMIP.

4.2 Ethical & Inclusivity Considerations

Ethical dilemmas arise mainly from the sourcing of components that will comprise the kit. A 2020 study conducted by the US Department of Labor found that forced and child labor was used in the production of electronics on every continent of the globe, except for Antarctica [**16**]. Navigating recommended suppliers and constructing kits that do not profit from unethical labor is vital as we design and select components.

Inclusivity concerns arise from the overall price of the kit and the accessibility of 3D printers. Even with a target price of $100, with 60% of Americans living paycheck to paycheck, there is a legitimate concern if the groups our kit would help support would even be able to afford it [**17**]. Also, if the student does not possess a 3D printer at home, there are concerns of how they would gain access. An alternative place for students to access a 3D printer would be from their school district. The state of Michigan provides grants of up to $200,000 through its MiSTEM initiative in order to fund STEM programs [**18]**. There are many similar programs across the country, but many schools have not invested in such. In Michigan, for example, when examining the expenditures of 100 schools with the lowest spending per student, the average spending is just $4,842 per student which is $11,238 below the national average [**19**][**20**]. Operating with knowledge, the team has been working to find solutions to mitigate this problem.

4.3 Environmental Factors

As of 2019, the world was producing 50 million tonnes of electronic waste per year according to the United Nations [**21**]. The creation of RocketMIPs will create more electronics in circulation, however, the impact of its creation can be offset by partnering and integrating components from companies with a global environmental initiative. Companies like Texas Instruments, an electronics manufacturer, started its carbon neutrality initiative in 2015 with a goal of reducing its emissions by 25% by 2025 [**22**]. Some other environmental concerns our project may face would be the home manufacturing, the use of 3D printing, and disposal of batteries. The majority of complex components would have to be packaged and then shipped to the student before learning can begin. Depending on the origin of the product, the journey it takes through land, air, or sea could contribute greatly to carbon emissions. Also, in its current state, conventional 3D printing requires a relatively high amount of electricity to operate. Considering a standard 10g 3D print that takes an hour to print, the approximate electricity consumption from a 3D printer would be about 70Wh whereas the injection molded part would only consume about 34.9Wh [**23**][**24**]. With only about 20% of the energy in the United States coming from renewable sources, the long term effects of consuming approximately double the energy compared to injection molding is an aspect the team is considering throughout our iteration process [**25**]. A benefit of 3D printing over injection molding to offset energy consumption differences would be the ease of modularity of the RocketMIP. By producing a platform which is fully accessible and can be altered to the consumers content, there would be reduced need for purchasing additional kits to obtain altered functionality. Additionally, the ability and right to repair the RocketMIP allows consumers to continue using the majority of their initially purchased kit, thus reducing material waste. Lastly, in order to power the RocketMIP, the use of a battery is required. There are several different options for portable batteries available on the market, but most readily available ones all pose some environmental concern. For example lithium-ion batteries, which are commonly used rechargeable batteries, have a low recovery rate of recyclable materials and carry inherent risk due to the potential of the acids they contain leaking which can pollute freshwater systems if not properly treated [**26**]. According to the Department of Environment, Great Lakes, and Energy, “the best way to dispose of lithium-ion batteries is to treat them as hazardous waste, and utilize the household hazardous waste and electronic waste collection programs available” [**27**]

5. PROBLEM DEFINITION

We have broken down this section into user requirements and engineering requirements and specifications. The user requirements cover the needs of the stakeholders and what requirements the final product should meet to be considered successful. The engineering requirements/specifications are then determined based on the user requirements of the project, and present quantifiable targets and values that the solution needs to achieve.

5.1 User requirements

The user requirements are the result of internal team discussion about the goals we have for the project, as well as making assumptions of requirements that the stakeholders would want/need based on the research into the problem. In order to set realistic requirements and ensure the completion of a solution that meets the vision of the project within our given timeline, the user requirements are broken down into those that are within and out the scope of our project. This ensures that the final deliverable at the end of the term will be feasible given the length of the course and the resources available. Tables 1 and 2 present the scope components in descending order of importance; we ordered the elements by interpreting their relative importance to our mission to provide an affordable kit with an educational aspect that will increase interest in STEM related fields.

Table 1: In-Scope user requirements

User requirement	Justification
Provide a kit which contains the following: a. Electronic components b. STL's and sample code c. Instruction booklet	Creating an electronics kit reduces the risk and the overall price for the consumer. As the kit manufacturer we can buy in bulk to reduce the price and guarantee that all the components will be there (reducing sourcing frustrations). As the kit supplier we also would be able to better navigate market fluctuations such as price hikes, supply issues, and product discontinuations.
Open-Sourced a. Github with all code b. Google drive with all CAD and instructions c. Bill of materials d. Accessible to anyone with internet	In order to make the rocketMIP as accessible as possible, the CAD files for all components used, as well as all of the code and instructions will be posted online for anyone to access for free. A bill of materials will also be available for all components that need to be purchased.
Teach FDM 3D printing fundamentals a. Background info b. Slicer settings c. Best practices	Most kits on the market are assembled injection molded parts, whereas ours would be manufacturable at home (or a public space with 3D printer). 3D printing is a growing area that has become crucial in High school robotics over the last few years as a method for rapid prototyping and reducing weight.
Teach Controls/Feedback fundamentals a. PID Theory b. PID Tuning	Controls/feedback is not part of the normal high school curriculum, unless in robotics etc, and is a widely utilized control scheme. An intro to PID controls would allow students to explore another topic in a fun and interactive manner. PID loops are also crucial to high school robotics when it comes to properly and safely controlling automated components (such as automated arm positioning).

Produce an instructional booklet utilizing embedded teaching modules	The instructional booklet shall include explicit instructions on how to assemble the components (body, attach motors, attach controller, etc), connect the wires, and install the program to balance the MIP. Integrated teaching modules within the instruction manual will provide justified background to the key features of the MIP (explaining our choices for 3D printing [temperatures, layer heights, print speed, etc.], introducing them to what PID control is, and how the PID values should be tuned for this robot kit)
Produce sample code that will be complete in every aspect except for the PID values	A large component about PID control is tuning the controller, so by providing code that allows for the user to tune the PID controls (with some embedded safeties to ensure they don't input too large of values) they will get a first hand experience with how to tune a PID controller.
Target age 10th-12th graders	High school students are more likely than (elementary or middle school) to find additional opportunities like the First Robotics Competition (FRC) to further their knowledge. They will also be more likely to understand the concepts and successfully apply them in the near future. Supporting Fact: FRC comprises 3,225 teams, including more than 80,000 students and 25,000 mentors from 26 countries [28]
Ethical Component Sourcing	Ethical component sourcing is important here because of the use of electronic components. Many of these components are created using forced and child labor [16], and that is something that we aim to avoid utilizing.
User Safety	In order to market these kits to an audience with limited electrical knowledge and safety training, the electronics must be RoHS compliant to protect the user from hazardous chemicals and possible shock hazards. In

	addition, all printed components should have no sharp edges.

Table 2: Out-Of-Scope user requirements

User requirement	Justification
Teach about CAD modeling	Focusing our teachings on PID and 3D printing would allow the guides to go more in-depth in a few subjects rather than more broad in many. A second iteration of the kit can be made later that has an emphasis on the fundamentals of CAD in collaboration with a major software.
User Control Interface	Development of an app would take too much time to complete within the project window. The app development aspect can be completed in a future 450 project or continued outside this course.
Teach about and utilize soldering	While soldering is a useful process, it can be extremely dangerous without a proper setup to extract fumes and isolate the hot tip of the iron. Requiring soldering also adds an extra cost barrier to the kit as most people don't have access to a soldering iron.
At-home component sourcing	Placing the burden of having the user source the parts themselves as opposed to being supplied the parts in the kit adds unnecessary complications which depend on factors outside of our control such as price fluctuations, supply issues, product discontinuation.
Teach about Pulse Width Modulation (PWM)	There exist kits on the market that already accomplish this task successfully. With the wide availability of these kits we determined that there wasn't an educational need for a product that teaches about PWM. This allows us to focus on just PID.

Packaging	The organization of parts and choice of container for the kit are factors to consider near the end of project development and are not critical to meeting our planned educational goals.
Profit Optimization	Focusing on the bottom line of our profit margins for this kit would take away from us sourcing the most ideal components for the functionality of the kit as a whole.
Additional Maneuverability	The MIP will focus on auto-balancing based upon the coded PID values. The current version of the MIP will not be able to be driven by the user.

It is important to note here that many of the components which we considered to be out of scope are still reasonable targets which would contribute to a better end product, but are not feasible due to the inherent time constraints and resource constraints presented by the current setting of the project. A major example of this is the user interface. Originally we wanted to create a mobile application that would allow the user to get the readout from multiple sensors and actively tune the PID values directly from their phone. Ultimately, we realized that this feature, while very valuable to the user experience, would require a significant amount of time in order for us to learn about and code this mobile application within our timeframe. Thus it ended up being a component that was placed out of our current project scope. In the future if the kit is successful another iteration could better focus on accomplishing some of these out of scope goals and future aspirations, but within the current timeline and outlook for the project we have decided to prioritize the core functionality and the educational components at this time.

5.2 Engineering Requirements and Specifications

Engineering requirements and specifications of the project are determined based on the in-scope user requirements. This ensures that the engineering requirements and specifications are reasonable within the duration of the course and the resources available. Table 3 outlines our requirements and specifications in order of decreasing importance based on the needs of the stakeholders.

Table 3: Engineering Requirements and Specifications

Requirements	Specifications	Justification
Low Price	Overall price for the kit ≤$100	Minimize the overall price of components to make the product more accessible
Teach Educational Goals	Users will have gone through X modules and successfully completed each application check. Completion of all application tests will result in a fully assembled and coded MIP	In order to quantify that users successfully learn the content, each module will end with applying what they learned towards an aspect of the MIP.
Home Manufacturability	100% of body parts can be printed using PLA on an FDM printer.	Reduces kit cost by manufacturing components at home and provides avenue to teach 3D printing
User Friendly	High School focus groups will be able to assemble and have a fully functioning MIP in <60 minutes when provided the software, 3D printed parts, and electronic components.	To maximize the amount of learning that is taking place in the imbedded learning modules, the assembly of the kit between the 3D print and coding stages should be kept to a minimum
Dynamic Stability Control #1	The system will be able to fully recover balance when the angle body angle is changed by ≤15°	The balancing code needs to be robust enough to take user perturbations and recover balance
Dynamic Stability Control #2	The system will be able to fully recover balance if a force of X is applied	The balancing code needs to be robust enough to take user perturbations and recover balance
Safe Electronics	100% of electronics will be RoHS compliant	Consumer protection from hazardous substances per RoHS compliance [29]
Electrical Connectors	All electrical connections are done via JST or other molded connectors	Using electrical connectors will improve ease of assembly/disassembly.

Easy Component Sourcing	All components non fabricated parts will have short-lead times, large stock, and come from reliable vendors	In order to make sure the kit can be produced within the project timeline and allow for repurchasing in the event of broken components, the aforementioned requirements should be met
Robust Fabricated Parts	0.2mm ±0.005mm layer height, ≥4 perimeters, specified print orientation	Increase kit lifespan and overall ability to take misuse. ASME standard Y14.46-2022
Smooth Edges	All non mating edges should be rounded to ≥.125”	Consumer protection from sharp/brittle edges per ASTM F963
Break Even	Cost ≤ Price	Ensure that all material costs are covered under the kit price
Compact Size	Robot will fit within a volume of 6”x6”x6”	Reduce amount of material required and keep compact desktop sizing
Lightweight	Total Weight ≤ 1lb	Reduce the amount of filament utilized for construction and make it easier to pick up.

Note: Some of the specifications provided have unspecified numbers due to the need for further research in order to set reasonable and realistic targets.

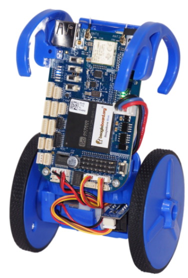
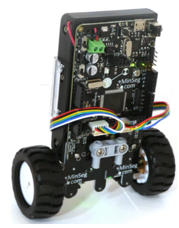
5.3 Standards

To ensure our 3D printed components are durable and that our product is safe, we will need to follow some design standards. To ensure that we are using optimal settings to produce durable 3D printed parts we should follow ASME standard Y14.46-2022 “Product Definition For Additive Manufacturing” [30]. To ensure that this kit remains safe we need to follow ASTM standard F963 “Standard Consumer Safety Specification for Toy Safety” [31]. To ensure that our electronics don’t contain hazardous materials, we will source RoHS compliant components [29]. Using these standards together will ensure that our kit ends up delivering a durable MIP that will be safe for the users to use and experiment with.

6. BENCHMARKING

Using our engineering requirements and specifications as a guideline, existing solutions were explored that closely matched what an ideal solution would want to achieve. Due to the market being overcrowded with a variety of solutions, several of the best options to benchmark were selected and presented in Table 4 which covers the majority of the market. These solutions are benchmarked against each other based on our user requirements and relevant engineering specifications. We have also included our initial solution to highlight how it differs in some aspects compared to the solutions that exist in the market.

Table 4: Benchmark Comparison of Available MIPs

					
	eduMIP [32]	**MiniSeg V4 [33]**	**WowWee MIP*[34]**	**ELEGOO Tumbller V1.1 [35]**	**RocketMIP**
Controller Board:	BeagleBoard Blue	Arduino MEGA 2560 R3	Proprietary	Nano V3.0	TBD
Transmission:	Wow-Wee Brushed Micro Motors	Dual Micro Gear Motors	Wow-Wee Brushed Micro Motors	GA37-520 DC geared motor	TBD
Chassis Material:	Injection Molded Plastic	Injection Molded Plastic	Injection Mold Plastic	Aluminum	3D Printed
User Age:	College Students	N/A	8yrs-15yrs	13yrs+	14yrs-18yrs
Assembly Type:	Screw and Component	Screw and Component	Pre-assembled	Screw and Component	TBD
Educational Aspects:	N/A	N/A	Block Coding	PID,PWM, coding	3D Printing, PID
Price:	$128	$205	$99.99	$84.99	$100
Best Attributes:	Controller board with fully integrated sensors	Small motors and transmission (Proprietary	Smartphone wireless connectivity and app	Guided instructions for assembly	3D printing, PID Tuning, Embedded learning

	N20 style)	integration	and code	modules

* Denotes Discontinued Product

From our benchmarking of the existing products on the market, we distilled the best attributes of each product and listed them at the bottom of the table. This includes the best attribute and biggest differentiator of the rocketMIP which is the self manufacturing aspect by way of the 3D printed body. By identifying these attributes, we will be able to incorporate them into our concept generation of the rocketMIP to make sure that our solution will be unique and stand out from the competition. Due to the timeline constraints of the project, we will not include wireless connectivity as part of the attributes we leverage in our design of the rocketMIP, but is still noted here as a valuable attribute which would result in a better solution.

7. DESIGN CHALLENGES

Throughout the development of this project there will inevitably be some problems that we will have to deal with to make the project a success. In the current state of this project we have identified two key problem areas from our requirements and specifications that we foresee encountering.

One of the biggest challenges we foresee is designing parts and designating print settings that will provide usable parts from most at home 3D printers. We see this as being our main challenge because of the diversity of 3D printers, and thus it is very difficult to quantify the quality and capabilities of the "average" at home FDM printer. To overcome this difficulty, our training material will be based around a universal slicer (like Cura), researching and averaging the capabilities of the most commonly bought consumer printers, and by printing prototype components on a variety of consumer grade 3D printers.

The second major challenge that we are likely to encounter is quantifying the success of our educational aspect requirement. Due to the condensed time period that completing this project during the semester will demand, it will be very difficult to acquire a control group to test the prototypes of the project and provide us feedback on how much they learned from assembling the Rocket MIP. To combat this problem we are going to utilize the resources that a team member has through their high school robotics team to set up a small focus group that will complete the project and answer a few questions from which we will extrapolate trends that can be used to predict future outcomes and success.

8. DESIGN PROCESS

In order to guide the team through future challenges, anticipated or not, we will be following a model that will guide the design process in a series of organized steps. The process will be dedicated to helping the team fulfill our requirements and specifications as closely as possible with regard to our final product while also allowing us the opportunity to challenge our understanding of preliminary information. Figure 2 below outlines the design process we will be using for this project, adapted from the 'third-generation process' model by Wynn and Clarkson in "Models of Designing" [35].

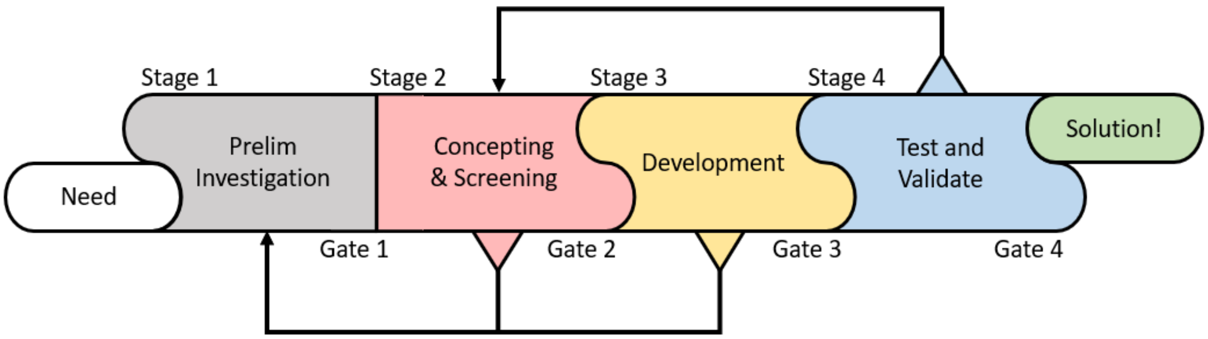


Figure 2: Project design process adapted by the team for guiding decisions for our design challenges

Our model utilizes the fluid nature of the stages presented by Wynn and Clarkson, but allows a greater sense of feedback from later stages back to earlier stages if needed. Another distinction is the lack of fluidity from stage 2 back to stage 1. This was done to help our team create clear requirements and specifications prior to starting work and preventing the temptation to modify them to the benefit of our project. If we feel we need to change a requirement and specification, we must go back to preliminary investigation and thoroughly make sure our previous work is still validated up to the stage we came from. This process will be most useful to our group since the final product is relatively well defined as a MIP. The targeting of a specific type of device narrows our background and reduces the chances that new information will come into consideration. To better understand the stages presented by our model, Table 5 specifies each stage and its relevant subject matter.

Table 5: Design Stage Breakdown

Stage 1 - Preliminary Investigation	Stage 2 - Concepting & Screening
● Define the problem ● Background research ● Stakeholder needs ● Requirements & specifications	● Decomposition of the problem ● Ideation sessions ● Filtering/grouping ideas for screening ● Justify best concepts
Stage 3 - Development	Stage 4 - Test & Validation
● Design solutions for requirements & specifications ● CAD, BOM, drawings, etc.	● Testing ● Quantified justification of solution fulfillment

- Engineering analysis of subsystems
- Stakeholder feedback/verification

9. CONCEPT GENERATION

In order to structure our concept generation, our team implemented a morphological chart to organize our divergent thinking. According to the industrial design wiki, “The morphological chart is a method to generate ideas in an analytical and systematic manner. Usually, functions of the product are taken as a starting point. The various functions and sub-functions of a product can be established (or "decomposed") through a function analysis”[37]. These functions were then refined using pugh charts until the top four ideas per function were identified. From those results compounded designs were created.

9.1 Morphological Chart

Through analyzing our engineering requirements, as are shown in Table 3, it was determined that our critical requirements fall under three categories, user accessibility, learning and teaching aspect, and ease of manufacturing and assembly. From these three critical requirement categories it was determined that the critical functions of the Rocket MIP could be broken down into three categories: drive type, pendulum type, and drive type. To encourage individuality and reduce group setting pressure, the individual members of the design team were tasked with filling out these function categories as many ideas as they could possibly come up with. The results of these individual sessions were compiled, and duplicates removed, and are shown in Figure 3:

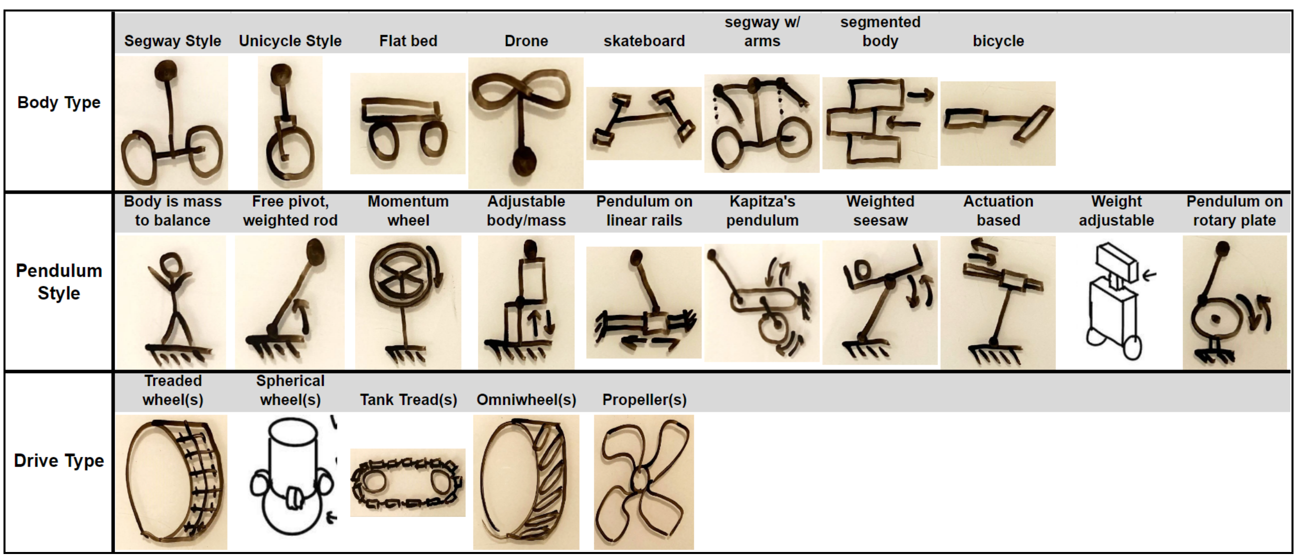


Figure 3: Completed morphological chart from divergent concept generation.

From Figure 3, we can see that there was a healthy amount of ideas created. However, not all of these ideas are viable options and thus will require further refinement before the designs can become complete. For this refinement we decided to utilize pugh charts for each function, in order to select the top four ideas for each function. Pugh charts were selected for this task as we recognize that they provide systematic convergence along with individualistic thinking and requirement alignment.

9.2 Pugh Refinement: Body Type

We selected the ranking categories as; 3D printability, complexity of design, uniqueness, display of educational aspect (balance). These categories were sourced directly from our engineering and in scope user requirements, as are shown in Table 3 and Table 1 respectively. Our 3D printability and complexity categories are based upon the ideas that 3D printing is one of our educational areas and that the components must be able to be printed on a consumer grade printer. Our uniqueness aspect comes in regards to interesting students in the project. The way we see it is that students will not be drawn to this project unless they see it as something that is new and unique. We also ranked the display of educational aspect, because we realized that it will be more user friendly if the students can recognize the balancing of the robot while tuning the PID values. These categories were then weighted, on a scale of one to five, based on their importance to the success of the project, with a five being the heaviest (most important) weight. Here we weighted the display of educational aspect as the heaviest because we want to focus on the functionality and learning components of the kit. With this said we also weighted the uniqueness as the lowest here due to wanting to further the functionality. We recognize that the uniqueness is important to draw the users in, but it does not further the experience once they have the kit. From Table 4 we determined that the ELEGOO Tumbller V1.1 was the most comparable product on the market to what we want to accomplish. So, we decided to compare the rest of our ideas against it. In this case that means that our control element is segway style. After the chart was constructed the members of the design team filled out their individual rankings to ensure there were no outside influences. The complete body type pugh chart is presented below in Table 6.

Table 6: Body Type Selection

Body Type	Team member	3D printablility	complexity of design	uniqueness	Display of Educational aspect (balance)	Total	Score
Weight	N/A	4	3	2	5	N/A	N/A
Segway style	Ben	0	0	0	0	0	0
	Michael	0	0	0	0	0	
	Mohammad	0	0	0	0	0	
	Dylan	0	0	0	0	0	
Unicycle style	Ben	-1	-1	1	1	0	8
	Michael	-1	-1	1	1	0	
	Mohammad	0	-1	1	1	4	
	Dylan	0	-1	1	1	4	
Flat bed	Ben	1	1	-1	0	5	10
	Michael	1	1	-1	-1	0	
	Mohammad	1	1	-1	0	5	
	Dylan	1	1	-1	-1	0	
Drone	Ben	-1	-1	1	1	0	-5
	Michael	-1	-1	1	0	-5	
	Mohammad	-1	-1	1	1	0	
	Dylan	-1	-1	1	1	0	
actuated segmented body	Ben	-1	-1	1	0	-5	-15
	Michael	-1	-1	1	0	-5	
	Mohammad	-1	-1	1	0	-5	
	Dylan	-1	-1	1	1	0	
bicycle	Ben	-1	-1	1	1	0	6
	Michael	0	0	0	-1	-5	
	Mohammad	0	-1	1	1	4	
	Dylan	0	0	1	1	7	
skateboard	Ben	0	1	1	-1	0	-10
	Michael	0	-1	0	-1	-8	
	Mohammad	0	1	0	-1	-2	
	Dylan	-1	-1	1	1	0	

From Table 6, we see that our top four body types are; segway style, unicycle style, flatbed style, and bicycle style.

9.3 Pugh Refinement: Pendulum Type

We ranked the pendulum type on the same categories as the body type, with the addition of the kitability/assembly aspect. This aspect rises out of our requirement to ensure that this kit is easy to put together to ensure that most of the time is spent in the 3D printing and the PID tuning stages. Here we weighted the display of educational aspect as the heaviest because we wanted to focus on the functionality and learning components of the kit. We also weighed the “kitability” as the lowest here due to wanting to further the functionality. We recognize that the time spent between the educational areas should be minimized, but we prefer to focus on the user experience within the learning modules to ensure that the users gain the most knowledge from the kit. As mentioned above, we are utilizing the ELEGOO Tumbller V1.1 as our benchmark and thus the body mass being balanced is our control for the pendulum type chart. The complete pendulum type pugh chart is displayed below in Table 7 .

Table 7: Pendulum Selection

Pendulum Type	Team member	3D printablility	complexity of design	uniqueness	Display of Educational aspect (balance)	kitability / # of parts / assembly	Total	Score
Weight	N/A	4	3	2	5	1	N/A	N/A
Body is mass to balance	Ben	0	0	0	0	0	0	0
	Michael	0	0	0	0	0	0	
	Mohammad	0	0	0	0	0	0	
	Dylan	0	0	0	0	0	0	
Free pivot, weighted rod	Ben	0	0	-1	0	0	-2	4
	Michael	0	0	-1	1	0	3	
	Mohammad	-1	0	0	1	0	1	
	Dylan	0	1	-1	0	1	2	
Reaction wheel	Ben	-1	-1	1	0	-1	-6	4
	Michael	0	-1	1	-1	-1	-7	
	Mohammad	0	-1	1	1	-1	3	
	Dylan	1	1	1	1	0	14	
Adjustable body/mass	Ben	-1	0	1	1	0	3	7
	Michael	-1	-1	0	1	0	-2	
	Mohammad	-1	-1	1	1	0	0	
	Dylan	0	0	1	1	-1	6	
Pendulum on linear rails	Ben	0	1	-1	1	0	6	2
	Michael	-1	-1	0	1	0	-2	
	Mohammad	-1	0	0	1	0	1	
	Dylan	-1	-1	0	1	-1	-3	
Kapitza's pendulum	Ben	-1	-1	1	1	0	0	-3
	Michael	-1	-1	1	1	-1	-1	
	Mohammad	-1	-1	1	1	-1	-1	
	Dylan	-1	-1	1	1	-1	-1	
Weighted seesaw	Ben	-1	-1	1	1	-1	-1	-4
	Michael	-1	-1	1	1	-1	-1	
	Mohammad	-1	-1	1	1	-1	-1	
	Dylan	-1	-1	1	1	-1	-1	
Actuation based	Ben	-1	-1	0	0	0	-7	-26
	Michael	-1	-1	0	0	0	-7	
	Mohammad	-1	0	0	0	0	-4	
	Dylan	-1	-1	0	0	-1	-8	
Pendulum on rotary plate	Ben	-1	1	-1	1	0	2	0
	Michael	0	0	0	-1	-1	-6	
	Mohammad	0	0	0	1	0	5	
	Dylan	-1	-1	1	1	-1	-1	

From Table 7, we see that our top four pendulum types are; body is balanced mass, pivoting mass on rod, reaction wheel, and adjustable mass/length rod. It is important to see here that between the group members there was some strong divergence in the way that we assessed particular pendulum types. Specifically we see this with the reaction wheel, in which Dylan rated it a 14 and Michael rated it a -7. This diversity of opinion is extremely important in selecting the true top components by relying on team members' different experiences and backgrounds. This concept is also why we utilized pugh charts to refine our results, as it provides a systematic way to combine and analyze these differing opinions.

9.4 Pugh Refinement: Drive Type

The last function we explored was drive type. Here the drive type as we are defining it, mainly envelopes the retention of the motor to the body, the retention of the motor to the wheel(s) and the wheel(s) themselves. We ranked the drive typed based on; 3D printability, complexity of design, uniqueness, torque transfer, and transmission volume.Our 3D printability and complexity categories are based upon the ideas that 3D printing is one of our educational areas and that the components must be able to be printed on a consumer grade printer. Our uniqueness aspect comes in regards to interesting students in the project. The way we see it is that students will not be drawn to this project unless they see it as something that is new and unique. Our torque transfer and transmission volume categories come from the compact and user friendly requirements as it will be easier to balance if the torque transfer rate is higher for the main drive. Here we weighted the torque transfer aspect as the heaviest because ultimately we believe that transferring more of the torque from the drivetrain to the surface will make it easier for the first time PID tuners to develop good PID values without needing to account for possible slipping conditions. We also weighted the uniqueness as the lowest here due to wanting to further the functionality and practicality of the drive system. We recognize that the uniqueness is important to draw the users in, but it will likely make the drive train less effective at transferring the torque from the motor. We are utilizing the ELEGOO Tumbller V1.1 as our benchmark and thus, the threaded wheel is our control for the drive type chart. The complete drive type pugh chart is displayed below in Table 8

Table 8: Drive Type Selection

Drive Type	Team member	3D printablility	complexity of design	uniqueness	Torque Transfer	Transmission Volume	Total	Score
Weight	N/A	4	3	2	5	3	N/A	N/A
treaded wheel	Ben	0	0	0	0	0	0	0
	Michael	0	0	0	0	0	0	
	Mohammad	0	0	0	0	0	0	
	Dylan	0	0	0	0	0	0	
Sherical Wheel	Ben	-1	-1	1	0	0	-5	-38
	Michael	-1	-1	1	-1	0	-10	
	Mohammad	-1	-1	1	-1	-1	-13	
	Dylan	-1	-1	1	-1	0	-10	
Tank Treads	Ben	-1	-1	1	1	-1	-3	-13
	Michael	-1	0	-1	1	-1	-4	
	Mohammad	-1	-1	1	1	-1	-3	
	Dylan	-1	-1	1	1	-1	-3	
Omniwheels	Ben	-1	0	1	-1	0	-7	-28
	Michael	-1	0	1	-1	0	-7	
	Mohammad	-1	0	1	-1	0	-7	
	Dylan	-1	0	1	-1	0	-7	
Propellers	Ben	-1	-1	1	-1	-1	-13	-41
	Michael	-1	-1	1	-1	-1	-13	
	Mohammad	-1	0	1	0	0	-2	
	Dylan	-1	-1	1	-1	-1	-13	

From Table 8, we see that our top three drive types are: Treaded wheel(s), tank track(s), and omni-wheel(s). It is important to note here that we decided to take our top three options here due to the highly negative outcome of the pugh chart we decided to forgo the fourth option as it took a drop off in score from -28 to -38, which means that it is much worse than our control and ultimately not useful to move forward with.

9.5 Top Ranking Functions

Combining the top results from Tables 6, 7, and 8, we get the top ranking functions, in the order they were scored, as presented in Table 9

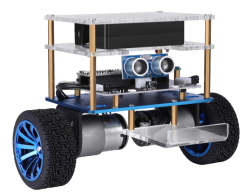
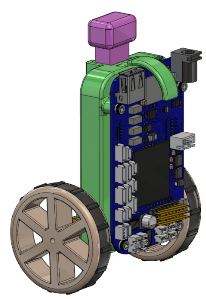
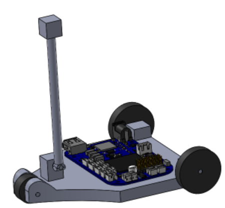
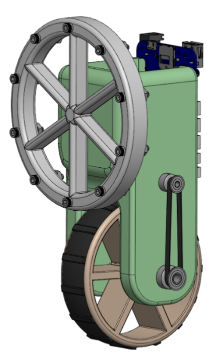
Table 9: Top Ranking Function Styles

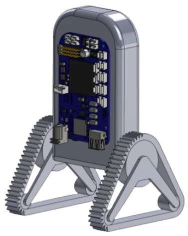
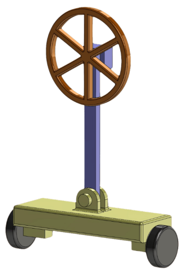
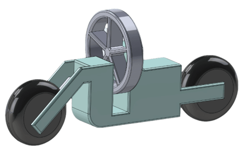
Ranking	Body Type	Pendulum Type	Drive Type
1st	Segway Style	The body is the mass being balanced	Treaded Wheel(s)
2nd	Unicycle Style	Pivoting mass on end of rod	Tank Track(s)
3rd	Flatbed	Reaction wheel	Omni-Wheel(S)
4th	Bicycle Style	Mass on rod with adjustable length/mass	N/A

9.6 Compounded Designs

From the top ranking function styles, as are presented in Table 9, each member was tasked with coming up with one to two compounded designs. Each of these compounded designs were to be the creators top two combinations that they considered complementary and that they felt best would fulfill the engineering requirements, in Table 3, and user requirements in Table 1. These compounded designs are presented in Table 10:

Table 10: Combined Concept Designs

Function	Concept Drawing	Body	Pendulum	Drive
ELEGOO Tumbller (Baseline)	 [35]	Segway Style	Body is mass	Dual Treaded Wheels
A		Segway Style	Body is the mass being balanced with adjustable mass on top	Dual Treaded Wheels
B		Flatbed	Freely pivoting mass on end of rod (single plane pivot)	Dual Treaded Wheels
C		Unicycle	Reaction Wheel/body mass	Treaded Wheel

D		Segway Style	Body is the mass being balanced	Tank Treads
E		Segway Style	Pivot rod and reaction wheel	Dual Treaded Wheels
F		Bike	Body is mass w/ reaction wheel	Dual Treaded Wheels

10. CONCEPT SELECTION: ALPHA DESIGN

In order to systematically converge our thinking from the six concepts presented in Table 10, a pugh chart was constructed. In this pugh chart our requirements were again considered in order to construct the categories for which the compound designs were ranked. For the compounded designs we ranked on: Use of 3D printed parts, complexity of design, uniqueness, display of educational aspect (balance), ease of printing, and number of ordered parts. The use of 3D printed parts, Complexity, and number of ordered parts categories were derived from. the ideas that 3D printing is one of our educational areas and that the components must be able to be printed on a consumer grade printer. Our uniqueness category comes in regards to interesting students in the project. The way we see it is that students will not be drawn to this project unless they see it as something that is new and unique. Our ease of printing category is derived from our user friendliness requirement as this is designed to be an entry level kit when it comes to 3D printing and thus must be simple enough to minimize frustration from complex printing techniques. We also ranked the display of educational aspect, because we realized that it will be more user friendly if the students can easily see the balancing of the robot while tuning the PID values. Here we weighted the display of educational aspect as the heaviest because we want to focus on the functionality and learning components of the kit. With this said we also weighted the uniqueness as the lowest due to this desire to further the functionality. We recognize that the uniqueness is important to draw the users in, but it does not further the user experience once they have the kit. From Table 4 we determined that the ELEGOO Tumbller V1.1 was the most comparable product on the market to what we want to accomplish. So, we decided to compare the rest of our ideas against it as the baseline. After the chart was constructed the members of the design team filled out their individual rankings to ensure there were no outside influences. The complete body type pugh chart is presented below in Table 11

Table 11: Compound Design Selection

Design	Team member	Use of 3D Printed Parts	Complexity of design	Uniqueness	Display of Educational aspect (balance)	Ease of Printing	# of ordered parts	Total	Score
Weight	N/A	3	4	2	5	4	3	N/A	N/A
ELEGOO Tumbller (Baseline)	Ben	0	0	0	0	0	0	0	0
	Michael	0	0	0	0	0	0	0	
	Mohammad	0	0	0	0	0	0	0	
	Dylan	0	0	0	0	0	0	0	
A	Ben	0	0	1	0	0	0	2	20
	Michael	1	0	0	0	0	0	3	
	Mohammad	1	0	1	1	0	0	10	
	Dylan	0	0	0	1	0	0	5	
B	Ben	1	0	-1	1	0	0	6	18
	Michael	1	0	0	1	-1	0	4	
	Mohammad	0	0	0	1	0	0	5	
	Dylan	0	0	-1	1	0	0	3	
C	Ben	1	0	1	1	0	-1	7	13
	Michael	1	-1	1	1	0	-1	3	
	Mohammad	1	-1	1	1	0	-1	3	
	Dylan	0	-1	1	1	0	-1	0	
D	Ben	1	-1	1	1	-1	-1	-1	-16
	Michael	1	-1	1	0	-1	-1	-6	
	Mohammad	1	0	1	0	-1	-1	-2	
	Dylan	-1	-1	1	1	-1	-1	-7	
E	Ben	0	-1	1	1	-1	0	-1	7
	Michael	0	-1	1	1	-1	0	-1	
	Mohammad	1	-1	1	1	0	0	6	
	Dylan	1	-1	1	1	0	-1	3	
F	Ben	1	-1	1	1	-1	0	2	3
	Michael	1	-1	1	0	-1	-1	-6	
	Mohammad	1	-1	1	0	0	0	1	
	Dylan	1	0	1	1	-1	0	6	

From Table 11, we see that the top ranked compound designs were design A and design B. From here with the top two designs we talked it out as a team and determined that our top ranked option A was the most viable option that will meet our requirements and specifications within our given timeline. A major factor that played into this selection was the resources available for segway style MIPS with the body as the balanced mass. Compared to flatbed style MIPS the segway style is much more popular and thus provides us with many benchmarks, as are seen in Table 4 (p. 15), and more resources to utilize in making the rocket MIP meet our requirements.With everything considered at this point we have systematically converged upon design A, a segway body with an adjustable mass and dual treaded tires, as our alpha design to further develop at this time.

10.1 Alpha Design

Through a culmination of concepting the team settled on our current Alpha design shown in Figure 4:

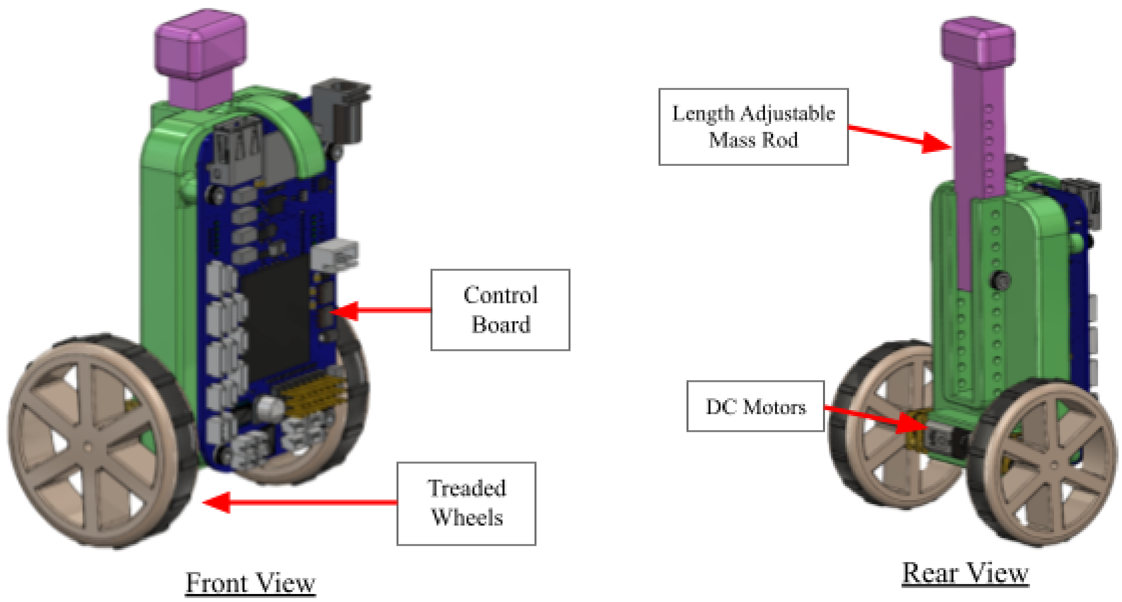


Figure 4: Front and rear views of the MIP Alpha design

The current design utilizes a pendulum style body attached to two bottom wheels for mobility and stability. As of now, our design will utilize two DC motors to operate the two bottom wheels in order to maintain the MIP in an upright position. All components will be controlled by a back-mounted control board.

With respect to our top user requirements, our current Alpha design would be able to teach about controls and feedback through the tuning of the pendulum body and engage and immerse students in 3D printing through several simple prints.

11. BUILD DESIGNS

Following Design Review 2, the team met with the course instructor in order to evaluate the proposed Alpha Design. Receiving positive feedback with the general Alpha Design of the MIP, the team proceeded to create a Build Design of the MIP.

11.1 Build Design V1

The initial Build Design of the MIP is show in Figure 5:

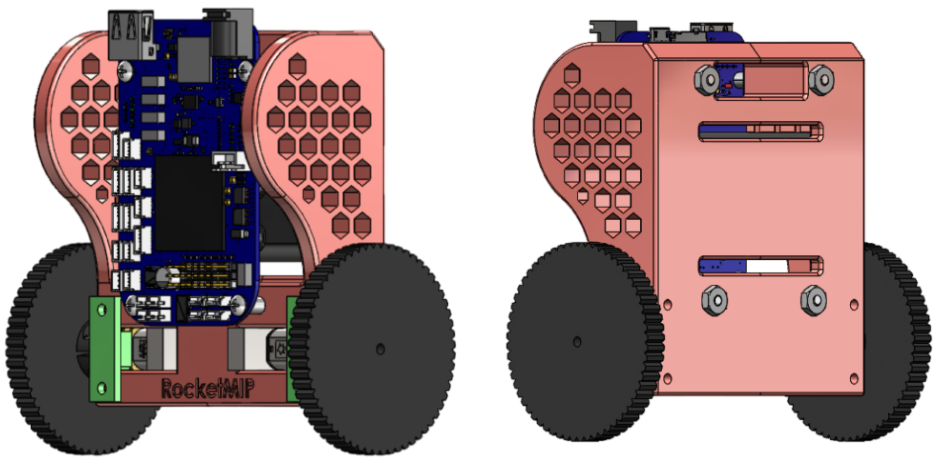


Figure 5: Build Design V1

Build Design V1 serves to be a more advanced and thought through version of the Alpha Design, but by no means the final design. Within this design we have seen a major change in the shape of the body. Between the alpha design and the completion of build design V1 we added two side rolls, which are designed to protect the protruding components of the control board in the event that the MIP falls over. Another change is the adjustable mass and its removal. The decision was made to remove this feature in this version because of the complicated geometry that was involved with the holes in the adjustable track. It was determined that these features would increase the length of the print and would involve a lot of support material. At this stage in the design the adjustable mass was removed to allow for a more effective system to be implemented later down the line. Another change is the location of the motors. Originally they were located on the back, moving to the front allowed us to optimize the print settings and remove a large amount of support material that was previously required.

The control board was selected through a rigorous benchmarking process. First we took a look at other kits that existed on the market and discovered that BeagleBoard, Arduino, and Raspberry PI were the most common commercially available controllers that were utilized in these kits. From that we took a look at the sensors and components that we required to make the MIP function. We require an IMU to get angular data about the body, a H-bridge to control the DC motors, and encoder ports to receive angular information from the wheels. While looking for all of these requirements we realized that by minimizing the amount of electronics will minimize assembly time and minimize the amount of electrical connections that could be assembled wrong. We also want to minimize the cost of the overall electrical assembly as low cost is one of our engineering requirements. The boards we investigated are listed below in Figure 6.

Name	Cost	Point of Sale	Size	Code Language	Missing Components
Arduino UNO r3	$27.60	Arduino	2.7"x2.1"	Arduino IDE (C+ interface)	IMU, H-bridge
beaglebone blue	$47.99	Amazon	3.5" x 2.15"	Built on Linux can code outputs with any language	N/A all necessary components are present
Raspberry Pi 3 Model A+	$25.00	Adafruit	2.6"x2.2"	C+ or python	IMU, H-bridge
beaglebone black	$51.45	Digikey	3.54" x 5.12"	Built on Linux can code outputs with any language	IMU, H-bridge
Arduion MKR zero	$30.30	Arduino	3.15 x 2.28	Arduino IDE (C+ interface)	IMU, H-bridge
raspberry pi zero WH	$16.00	Adafruit	2.6"x1.2"	C+ or python	IMU, H-bridge
Raspberry Pi Pico H - Pico with Headers Soldered	$5.00	Adafruit	.83"x2"	C+ or python	IMU, H-bridge
Arduino Nano 33 IoT	$25.50	Arduino	1.8" x.7"	Arduino IDE (C+ interface)	H-bridge

Figure 6: Benchmarking of control boards (Full benchmark in Appendix C)

From Figure 6 we see that the BeagleBoard blue has all of the necessary components embedded within the board and the The motors used in Build Design V1 were generic N20 motors with a gearbox which were tentatively chosen due to their current use in competitor designs, compact size, and large variety of gearbox ratios and torque output options. A general battery was also in a similar way, by averaging average battery sizes from various manufacturers.

11.2 Build Design V2

Through a in-depth CAD review with our course instructor, several design considerations from Build Design V1 were identified as shown in Figure 7:

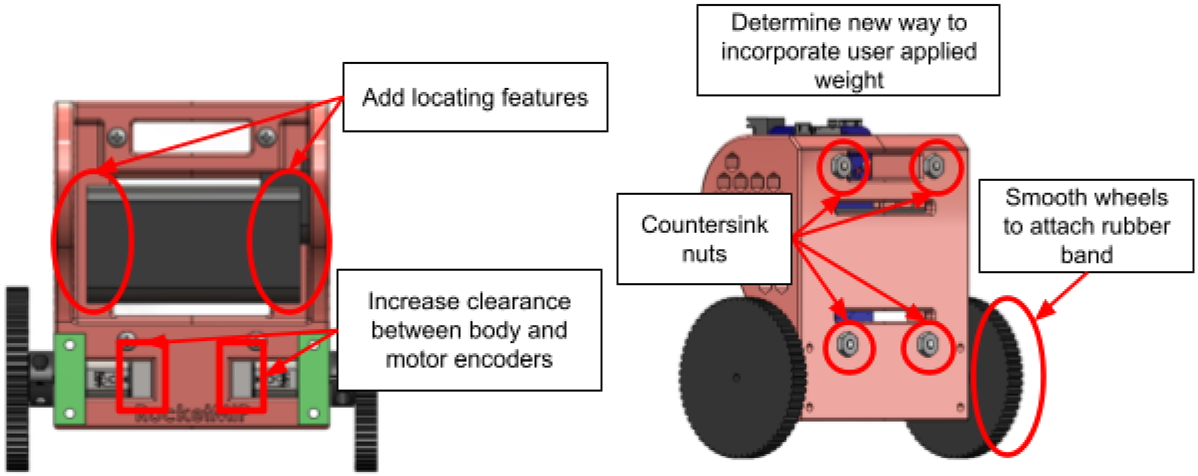


Figure 7: Build Design V1 considerations from instructor CAD review

From these suggestions, the team iterated on Build Design V1 to incorporate the feedback from the instructor. We added location features to ensure that the battery was snuggly attached. An increased clearance was added to the body to ensure that the motor encoders would always clear even with different manufacturers and tolerances. The wheels were also smoothed out to incorporate a rubber band, which will be used to increase the coefficient of friction between the MIP and the surface. The nuts were also countersunk to make assembly easier and to provide more opportunity to teach 3D printing techniques. Build Design V2 utilizes all of the feedback from the instructor and now includes a plate on the top of the MIP for users to apply a mass as shown in Figure 8:

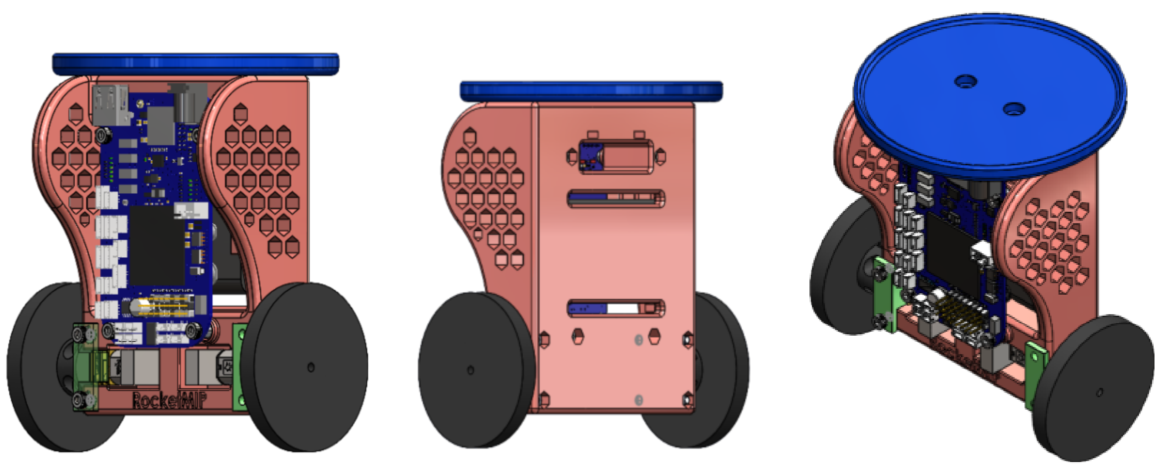


Figure 8: Front, back, and top view of Build Design 2

This plate was the evolution of the original adjustable mass, as it was introduced in section 10.1. This plate is a separate piece that is easier to print and still accomplishes our goal of changing the center of mass for the system to provide more opportunities to retune the PID controller. Build

Design V2 utilizes two 75:1 DC N20 motors, a BeagleBone Blue control board, and a 2000 mAh dual cell li-po battery (Full bill of materials can be found in Appendix D). An exploded view of the MIP is shown in Figure 9 with important components labeled:

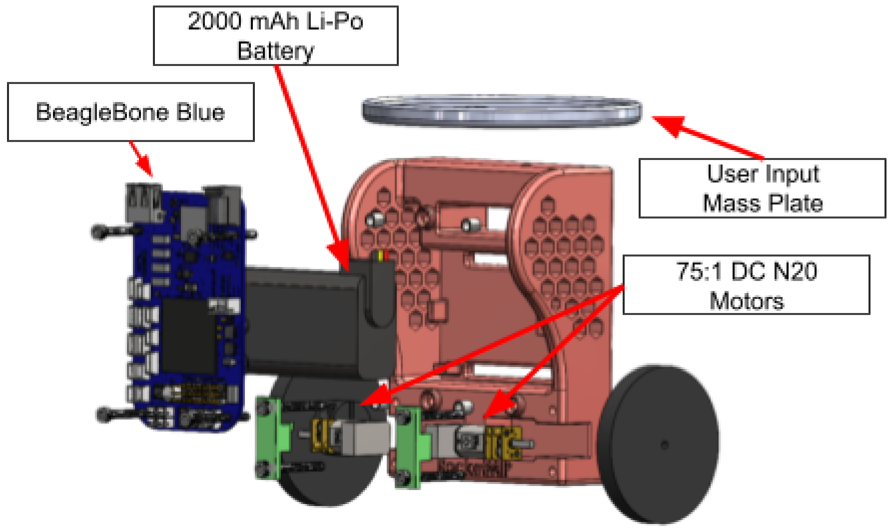


Figure 9: Exploded view of Build Design V2 with critical components labeled

The DC N20 motors were selected utilizing a mix of benchmarking against competitors and rudimentary calculations. When looking at the existing products on the market, as are shown in Table 4, it was quite evident that most of these designs utilized micro DC motors. By choosing to go with the N20 configuration we get integrated gearboxes which keeps the transmission compact and reduces the amount of design work, because we don't need to create a custom gearbox. See section 12.1(p. 36) for detailed justification for our motor selection.

With our motors and controller board selected we can choose a battery. The BeagleBoard has integrated circuitry to charge and receive power from a two cell lithium ion battery. With the type set the main thing we had to set was the capacity. Unfortunately there is little to no documentation about just how much energy the BeagleBoard Blue consumes. However there is a product on the market (the EDU MIP) which uses a BeagleBoard Blue and DC micro motors. From research this kit utilizes a 1400 mAh battery [32]. We decided it would be best to use a similar sized battery as the EduMIP. The team's selected battery is a 2000mAh battery with 14.8 Wh. Given the max power draw at stall of the motor is 4.02 W, we determined that the RocketMIP should be good for at least 3.7 hours of continuous operation.

12. ENGINEERING ANALYSIS

In order to make informed decisions about component sizing and controller values, various engineering models were required to model the expected states that our system could encounter throughout its operation.

12.1 Initial Motor Sourcing

In order to have time to iterate on the first build design, the team decided to source motors utilizing a simplified analysis of the RocketMIP system using static analysis based on our specifications. The justification for this approach comes from the availability of papers detailing motor specifications which worked for their inverted pendulum projects in a similar package as the one we are shooting for. To start, we have Figure 10, a simple model of our system represented by a hinged inverted pendulum.

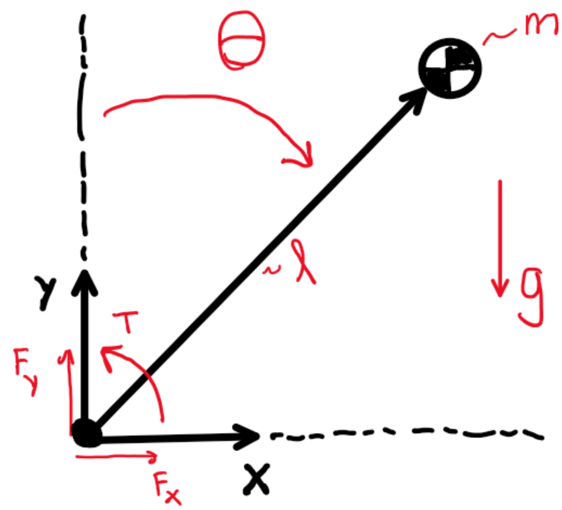


Figure 10: Simplified static model of the Rocket MIP system

In order to make our model simple enough for basic calculations a few assumptions were made. The main assumptions are that the angular velocities and accelerations of the wheel and body are zero and there are no frictional effects. This system was represented at a static state to represent the RocketMIP being suspended at a specific body angle offset and let go. This represents a movement that we anticipate seeing regularly This simplified model is designed to provide the minimum torque required to balance the center of mass a specific length away from the drive shaft. Using the laws of dynamics we can find the required torque to maintain a static position using equation 12.1

$$T = lmgsin(\theta) \tag{12.1}$$

Using equation 12.1 with a value of 15 degrees for theta and a max weight of 1 pound, as defined in our engineering specifications, we find our minimum required torque is 1.14 oz-in. In a perfect system a value any higher than this torque would result in rotation of the pendulum body towards vertical. Given the high uncertainty of this torque value a safety factor of 3 was applied resulting in a torque of 3.42 oz-in being required. Additionally, we do not want to operate our motor near stall torque, so we will define our max operating torque to be 85% of stall torque to reduce wear and tear on the motor. So our motor stall torque requirement is 4.0 oz-in.

The static model was able to give us a relative torque value to aim for when sourcing a motor but provides limited details on the angular velocity needed for control. To aid our process we resorted to benchmarking against other MIPs motors. We made sure to reference similarly sized and weighted products based on our engineering specifications such as the EduMIP, Miniseg, and Elegoo Tumbller previously discussed in Section 6. Overall, the range of these products' motors were in the 200 to 300 rpm range. We acknowledge this was likely not the best approach to take but the desire to have time to iterate on the initial build design combined with the low cost and ease of replacement heavily influenced our decision.

In the end, we ended up with low power N20 motors with a 75:1 gear ratio, stall torque of 4 oz-in and a max speed of 265 RPM.

12.2 Lagrange Analysis

In order to produce a product that is controllable from an initial unstable state, can respond well to external force inputs, and has the ability to track and regulate its position, direction, and eventually controllability by an end user, a comprehensive dynamic model for creating a robust controller is required. A detailed model can also help us verify our motor selection more thoroughly.

To create a model of the RocketMIP system, it was deemed best to start with an analysis utilizing the Lagrangian. In Lagrangian mechanics, the equations of motion are found by using the energies present in the system, namely the potential energy (PE) and Kinetic energy (KE) [37]. In contrast to Newton-Euler formulation, we have a simpler analysis by not needing to solve for time-varying constraint forces between bodies and having less geometric components to track. The Lagrangian of a system is defined as follows

$$\mathcal{L}(\boldsymbol{\theta},\ \boldsymbol{\theta}') = \sum_{j=1}^{n} KE(\boldsymbol{\theta},\ \boldsymbol{\theta}') - \sum_{j=1}^{n} PE(\boldsymbol{\theta}) \tag{12.2}$$

From the Lagrangian we can take derivatives to create a generalized forces term, $\boldsymbol{\tau}$. The generalized forces term is a conjugate to the chosen generalized coordinates for a system. The generalized forces term is defined below.

$$\frac{d}{dt}\left[\frac{\partial \mathcal{L}}{\partial \boldsymbol{\theta}'}\right] - \left[\frac{\partial \mathcal{L}}{\partial \boldsymbol{\theta}}\right] = \boldsymbol{\tau} \tag{12.3}$$

Through inverse kinematics and the use of sensors such as gyroscopes and accelerometers, we can use θ, θ', and θ'' terms to find $\boldsymbol{\tau}$ for controlling our motor torques at each wheel. With $\boldsymbol{\tau}$, we will also have a virtual representation of the RocketMIP to simulate designing of a controller to keep the system stable in an upright position [38]. To start our analysis, we begin with a simple model of our expected system, as shown in Figure 11 below, and use relevant reference material to help guide our analysis [37,38,39].

12.3 Model

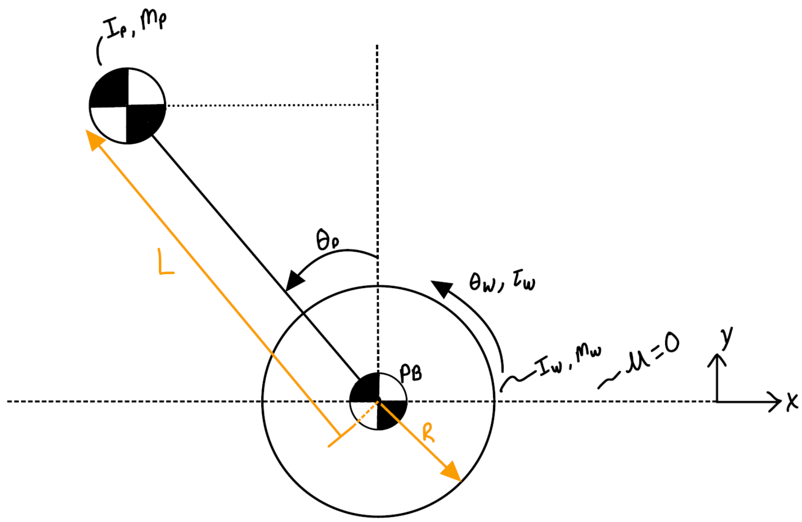


Figure 11: 2 dimensional planar representation of RocketMip with relevant variables defined in Table 12 below

The definitions for the representative variables are given in table 12 below. It should also be noted the z-axis runs into and out of the page.

Table 12: Definitions for 2 dimensional planar variables used in the following Lagrange analysis

φ	= Wheel angle	N_w	= Number of wheels
$\boldsymbol{\Theta}$	= Pendulum angle from yz-plane	PB	= Pendulum base/pivot point
θ'	= Angular velocity	L	= Length from PB to pendulum COM
θ''	= Angular acceleration	I_w	= Rotational inertia of wheels about PB
m_w	= Mass of a wheel	I_P	= Rotational inertia of pendulum about PB
m_P	= Mass of rigid pendulum body	x_w	= Horizontal displacement of wheels
R	= Radius of wheel	y_w	= Vertical displacement of wheels
$\mathbf{B_m}$	= Viscous damping constant joint φ	x_P	= Horizontal displacement of pendulum body
$\boldsymbol{\tau}_m$	= Motor torque joint φ	y_P	= Vertical displacement of pendulum body
$\boldsymbol{\tau}_f$	= Coulomb friction constant joint φ	g	= Acceleration due to gravity

12.4 Assumptions

1. Wheel contact is never slipping and always contacting the ground

2. Individual bodies are completely rigid
3. Wheels act as a singular body, transmitting consistent angular rates and torques
    a. Implies there are n = 2 bodies in the system
4. System is considered planar (no movement in z-axis)
5. No mechanical or electrical losses in the system
6. No mechanical or electrical delays in the system

12.5 Euler Lagrange - Equations of Motion (EOM)

To determine the minimum number of generalized coordinates needed, we first calculate the number of degrees of freedom (DOF). The number of DOF is given by equation (12.4) below

$$DOF = 3n - k \tag{12.4}$$

Where *n* is the number of bodies in the system (n = 2, given our assumption) and *k* is the amount of holonomic constraints. Holonomic constraints are those which are integrable and constrain the configuration of a system [40]. The holonomic constraints are as follows

1. $x_w = -R\varphi$
2. $y_w = 0$
3. $x_p = -R\varphi - Lsin(\theta)$
4. $y_p = y_w + y_L = Lcos(\theta)$

Resulting in k = 4 holonomic constraints, resulting in 2 DOF. We define these generalized coordinates as φ and θ. This combination is not unique and other coordinates can be chosen to represent the system.

Having defined our generalized coordinates, we can find the kinetic and potential energies of each body to be used in the Lagrange equation (12.2). Starting with the wheels, the KE is as follows with N_w = 2 wheels.

$$KE_w = \frac{1}{2}N_w m_w (R\varphi)^2 + \frac{1}{2}N_w I_w \varphi'^2 \tag{12.5}$$

The potential energy of the wheels are

$$PE_w = 0 \tag{12.6}$$

given that the starting baseline for PE was defined at the wheel axle. This was the most convenient spot to place our PE baseline as the geometry becomes very easy to calculate. Continuing to our second body, the pendulum, the KE is below.

$$KE_P = \frac{1}{2}m_p\left[(-R\varphi' - Lcos(\theta)\theta')^2 + (-Lsin(\theta)\theta')^2\right] + \frac{1}{2}I_P\theta'^2 \tag{12.7}$$

The potential energy of the pendulum is

$$PE_P = m_p gLcos(\theta) \quad (12.8)$$

Knowing the energies of all bodies in the system, we now have an expression for the Lagrange of our simplified model of the RocketMIP. Plugging equations (12.5), (12.6), (12.7), and (12.8) into (12.2) we can formulate the Lagrange.

$$\mathcal{L} = \varphi'^2 M + \theta'^2 I + \varphi'\theta' cos(\theta) m_p RL - m_p gLcos(\theta) \quad (12.9)$$

M and I are defined as follows,

$$M = m_w R^2 + I_w + \frac{1}{2} m_p R^2 \quad (12.10)$$

$$I = \frac{1}{2} m_p L^2 + \frac{1}{2} I_p \quad (12.11)$$

From here we proceed with taking derivatives of the Langrange to obtain the generalized forces for each conjugate generalized coordinate. We start with the generalized coordinate θ_w below.

$$\frac{\partial \mathcal{L}}{\partial \varphi'} = \left[2\varphi' M + \theta' cos(\theta) m_p RL\right] \quad (12.12)$$

$$\frac{d}{dt}\left[\frac{\partial \mathcal{L}}{\partial \varphi'}\right] = \left[2\varphi'' M + \theta'' cos(\theta) m_p RL - \theta'^2 sin(\theta) m_p RL\right] \quad (12.13)$$

$$\frac{\partial \mathcal{L}}{\partial \varphi} = [0] \quad (12.14)$$

Following, we continue to take the derivatives with respect to the generalized coordinate θ_P

$$\frac{\partial \mathcal{L}}{\partial \theta'} = \left[2\theta' I + \varphi' cos(\theta) m_p RL\right] \quad (12.15)$$

$$\frac{d}{dt}\left[\frac{\partial \mathcal{L}}{\partial \theta'}\right] = \left[2\theta'' I + \varphi'' cos(\theta) m_p RL - \varphi'\theta' sin(\theta) m_p RL\right] \quad (12.16)$$

$$\frac{\partial \mathcal{L}}{\partial \theta} = [-\varphi'\theta'] \quad (12.17)$$

Finally, we take equations (12.12), (12.13), and (12.14) to find τ_w in equation (12.18) and we use (12.15), (12.16), and (12.17) to find τ_P in equation (12.19).

$$\boldsymbol{\tau}_w = 2\varphi'' M + \theta'' cos(\theta) m_p RL - \theta'^2 sin(\theta) m_p RL \quad (12.18)$$

$$\boldsymbol{\tau}_p = 2\theta'' I + \varphi'' cos(\theta) m_p RL - m_p gLsin(\theta) \quad (12.19)$$

Having found the equations for the equivalent forces, we can add onto the tau terms to include motor torque at the joints from the motor, damping forces from the motor, and dry friction from the motor.

$$\tau_w = \tau_m - 2sgn(\varphi')\tau_f - 2\theta' B_m \quad (12.20)$$

$$\tau_p = 0 \quad (12.21)$$

Where τ_m is the overall torque input, τ_f is the dry friction of a motor, and B_m is the viscous damping coefficient of a motor. For simplicity, these equations assumed both motors had the same amount of dry friction and damping. To continue, we will be dropping the frictional and damping values as well as continuing to assume both motors will output equivalent torque which can be summed into one term. We started with this set of equations and assumptions to allow us to quickly understand how to correctly model our system without making it too complicated to start, as well, to gain a basic understanding of the torque response that can be expected so that we can build a more thorough model later with a new motor sourced for the RocketMIP which we will have the dry friction and damping coefficient values for.

Recollecting our terms and implementing our assumptions, the EOM can be expressed as follows,

$$\phi'' + \theta'' cos(\theta)C2 - \theta'^2 sin(\theta)C1 = \frac{\tau_{total}}{2M} \quad (12.22)$$

$$\theta'' + \phi'' cos(\theta)C4 - sin(\theta)C3 = 0 \quad (12.23)$$

$$C1 = C2 = \frac{m_p RL}{2M} \quad (12.24)$$

$$C3 = \frac{m_p gL}{2I} \quad (12.25)$$

$$C4 = \frac{m_p RL}{2I} \quad (12.26)$$

Note from equations (12.22) and (12.23) our EOM are highly nonlinear from the presence of sin() and cos() terms as well as state variables which have powers associated with them.

12.6 Model Verification

To begin using our simplified model of the RocketMIP, we first needed to define the variables unique to our build design. Obtaining the weight of each component is relatively simple but due to the complex geometry of some parts the moments of inertia and center of mass are not so simple to find. To aid in our calculations we made use of the SolidWorks mass properties toolbox to find these values.

To obtain the correct moments of inertia, we first define our rotational axis equivalent to the one in our model. Specifically, this reference coordinate system is located along the axis of the drive shaft of our motors which will be our Z axis. Our X axis is then defined as being parallel to the ground plane, and our Y axis is defined as being perpendicular to ground. An example of this can be shown below in Figure 12 where we calculate the moments of inertia for the body of the RocketMIP about the reference coordinate system.

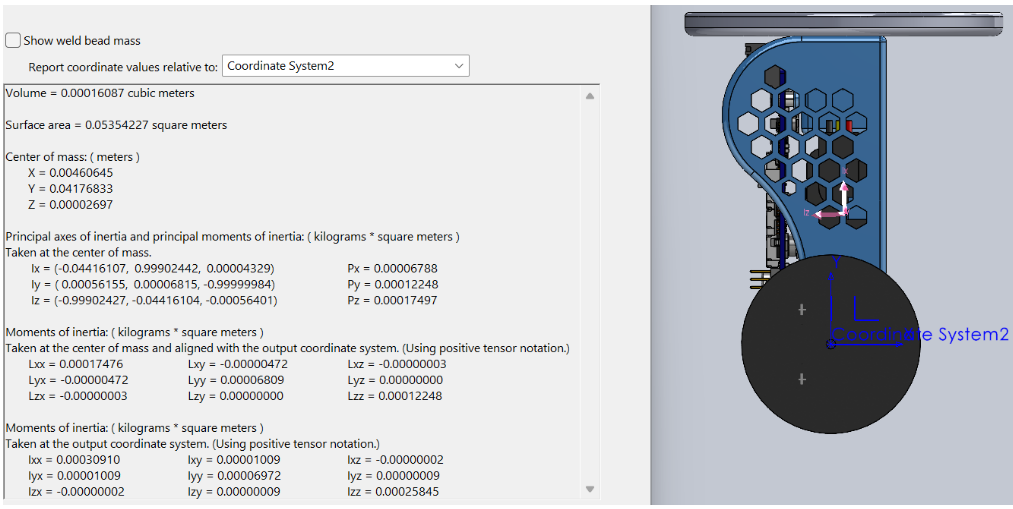


Figure 12: Solidworks mass properties tool used for finding the center of gravity of the RocketMIP as well as the moments of inertia of the pendulum body and wheels about the reference coordinates (shown in blue as "Coordinate System2").

From our use of the mass properties toolbox in SolidWorks we obtained the following values for our variables defining the RocketMIP system.

Table 13: Euler-Lagrange model variables

L =	0.043	[m]	Iw =	5.43e-06	[kg*m^2]
R =	0.029	[m]	Ip =	7.62e-04	[kg*m^2]
g =	9.81	[m/s^2]	M =	1.21e-04	[kg*m^2]
mp =	0.26	[kg]	C1 = C2 =	1.30	[-]
mw =	0.014	[kg]	C3 =	87.24	[1/s^2]
I =	6.18e-04	[kg*m^2]	C4 =	0.25	[-]

Having found the values we need to solve our EOM, we turned towards creating a Simulink model of our equations to verify the model. This allows us a visual representation of our equations which can be easily modified and referenced from a Matlab script. The model for our system is given below in Figure 13.

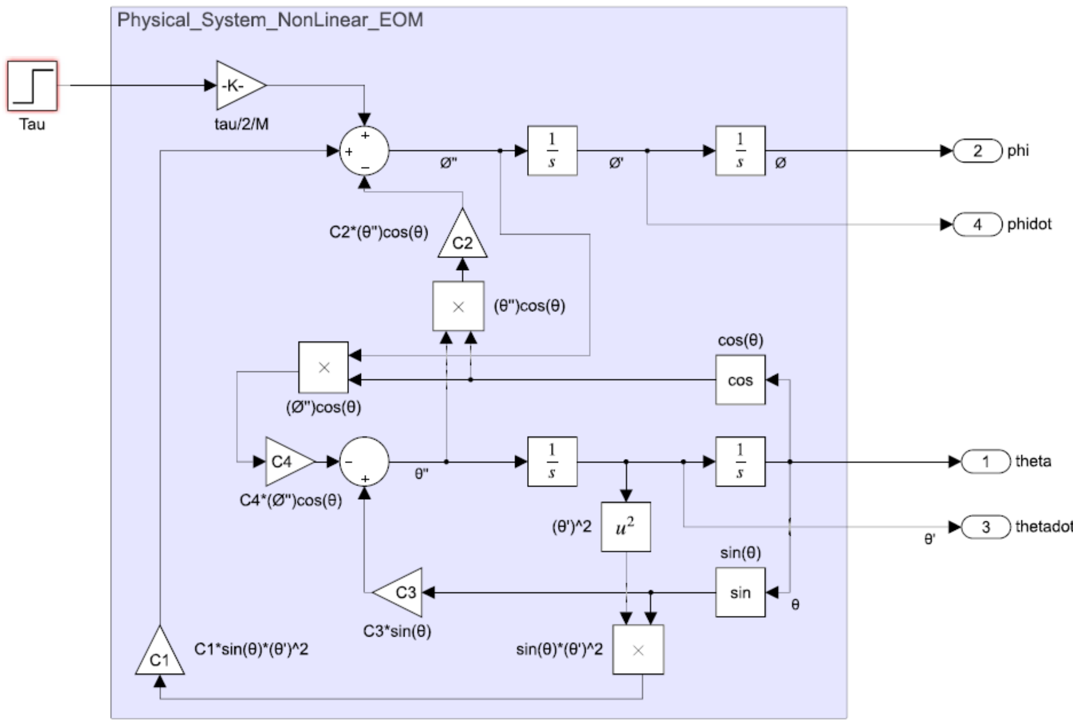


Figure 13: Simulink model of the nonlinear RocketMIP system with one input, Tau, and four outputs; θ, θ’, ϕ, ϕ’

With the model of our system in Simulink, we are now able to simulate the RocketMIP. It is important to note that for our modeling we used a constant time step of 0.01 seconds and implemented an AlgebraicLoopSolver command as there are loops in the model depending on values of θ’’ which is undefined at the start of the simulation. To help verify our model, we also included the results from solving our EOM with ode45 to see if the results would match. The initial conditions used where [θ θ’ ϕ ϕ’] = [5 0 0 0] in degrees. From the simulation we receive the results shown in Figures 14 and 15 below.

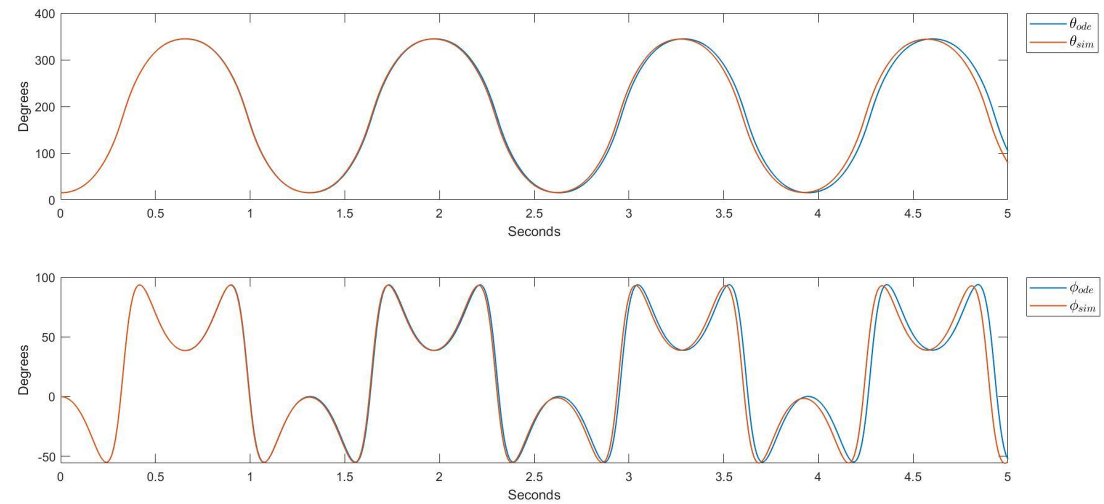


Figure 14: Solved θ (top) and ϕ (bottom) from the EOM of the RocketMIP. Shown in blue is the result of ode45, and shown in orange is the result from Simulink. Note the models match until 3 seconds at which round off error from the models starts to drift the results.

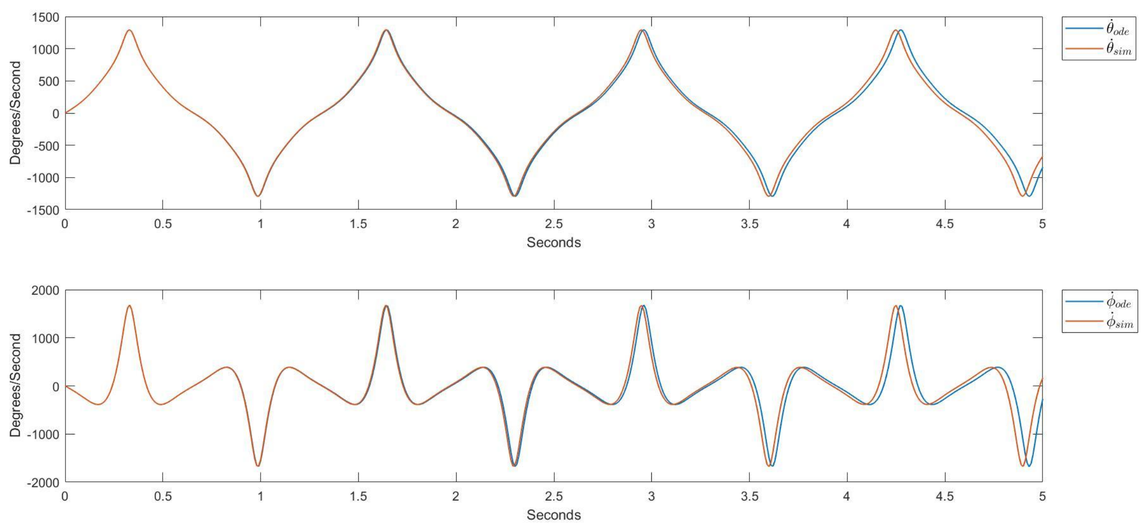


Figure 15: Solved θ' (top) and ϕ' (bottom) from the EOM of the RocketMIP. Shown in blue is the result of ode45, and shown in orange is the result from Simulink. Again we start to see round off errors drift the models from each other around 3 seconds.

From the simulation we expect to see no losses in energy due to the absence of a damping term in our EOM, which would be present with the viscous damping constant of the motors. Otherwise, the model depicts a reasonable result of the model which has a period of oscillation of ~1.3 seconds to get from 5 degrees to -5 degrees in a counterclockwise direction, back to 5 degrees. The team also visually animated these results and showed the motion is again as would be expected of our system. While we could not take data of the actual RocketMIP system in oscillation, the model is still helpful to us for verifying a simple model which can be used as a tool to help us learn to control our system. At which point we can go back to adjust our model as needed based on real data when we are ready.

12.7 Linearization

Given our model is nonlinear, many control tools are unavailable to us which can only be applied to linear systems. Since we have a small operating range defined as -15 to 15 degrees from vertical for the angle offset of the pendulum body, it would make sense to linearize our system about 0 degrees for theta. By linearizing our EOM, we simplify the nonlinear model to only work within a small region of theta values, the range of which we can find by comparing to our nonlinear model response. The trade off is rigorous control tools at our disposal which have been developed for years.

To start the process of linearization, the nonlinear terms in the EOM are first identified. Referencing equation (12.22), we find there are two nonlinear terms as highlighted in yellow below,

$$\phi'' + \boxed{\theta'' cos(\theta) C2 - \theta'^2 sin(\theta) C1} = \frac{\tau_{total}}{2M}$$

From equation (12.23) we can also identify the two nonlinear terms, again highlighted below,

$$\theta'' + \boxed{\phi'' cos(\theta) C4 - sin(\theta) C3} = 0$$

To linearize these terms we can find the first order taylor expansion around our specified operating point $\theta_* = \theta_*' = 0$. Seeing that our nonlinear terms only include θ, we have to specify the parameter shifts by the value of the operating point resulting in $\bar{\theta}$ and $\bar{\theta}$' as defined below.

$$\bar{\theta} = \theta - \theta_* = \theta \qquad (12.27)$$

$$\overline{\theta'} = \theta' - \theta_*' = \theta' \qquad (12.28)$$

To be brief, the simple first order taylor series expansions of cos(θ) and sin(θ) can be shown below.

$$sin(\theta) \approx \theta \qquad (12.29)$$

$$cos(\theta) \approx 1 \qquad (12.30)$$

Our final first order taylor series expansion can be expressed below,

$$\theta'^2 sin(\theta) \approx \theta'^2_* sin(\theta_*) + \frac{\partial}{\partial\theta}\theta'^2 sin(\theta)|_{\theta_*,\theta'_*}\bar{\theta} + \frac{\partial}{\partial\theta'}\theta'^2 sin(\theta)|_{\theta_*,\theta'_*}\bar{\theta} \qquad (12.31)$$

which can be reduced as follows.

$$\theta'^2 sin(\theta) \approx \theta'^2\theta \approx 0 \quad (12.32)$$

Replacing the nonlinear terms in equations (12.22) and (12.23) with the associated linearized terms found in equations (12.29), (12.30), and (12.32) we result in our linearized EOM presented below.

$$\phi'' = \frac{\tau_{total}}{2M} - \theta''C2 \quad (12.33)$$

$$\theta'' = \theta C3 - \phi''C4 \quad (12.34)$$

Acquiring our linearized EOM we can again create a representation of these equations with a Simulink model. To reiterate, the linearized model can only represent a small region around the operating point which we show in Figures 17 and 18 below on page 44. This model is provided below in Figure 16.

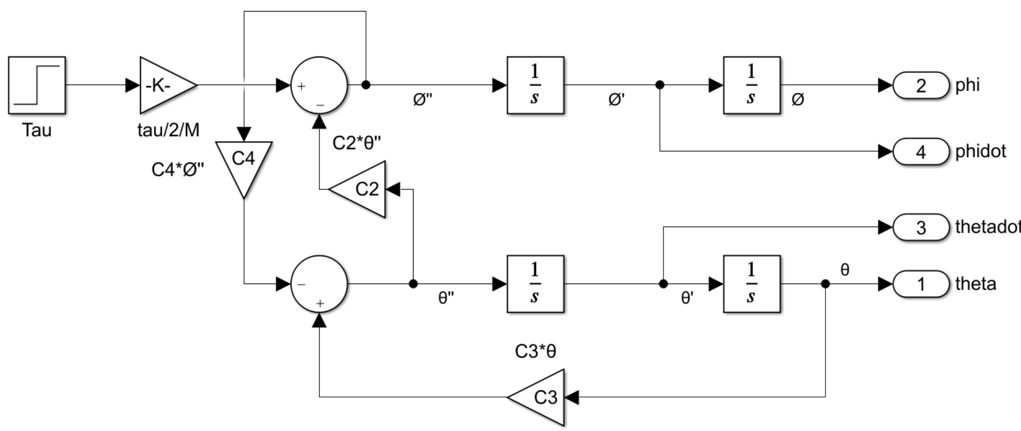


Figure 16: Linearized representation of the RocketMIP physical system given the assumptions provided from our nonlinear EOM in equations (12.22) and (12.23) on page 36.

Running the simulation of the linearized model vs the nonlinear model we can now determine the range of theta. The linearization is useful for controlling the RocketMIP. To do this we simply run the two models with the same settings as previously mentioned for the nonlinear simulation with new initial conditions as follows, [θ θ' ϕ ϕ'] = [1 0 0 0] in degrees. The result of the overlaid models is given in the Figures 17 and 18 below where the nonlinear model is denoted by the subscript NL and the linear by L.

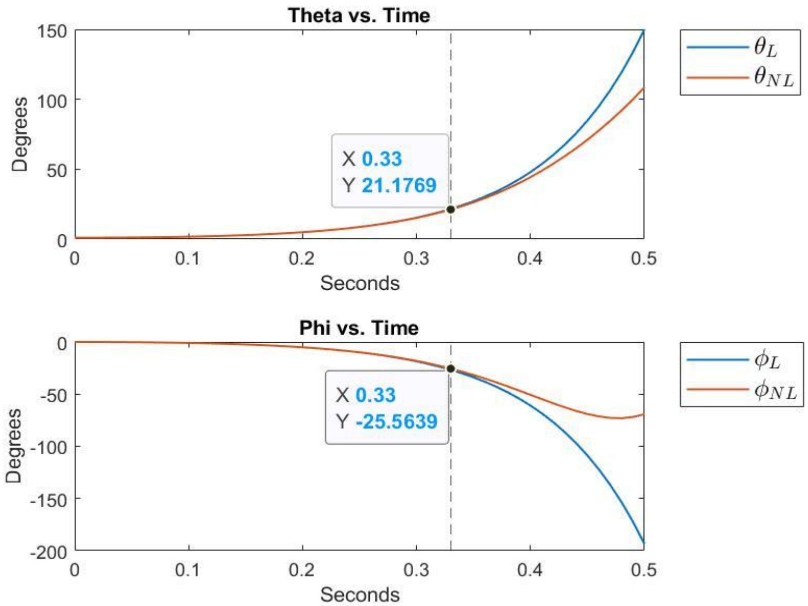


Figure 17: Overlay of the linear (blue) and nonlinear (orange) models for θ and ϕ. It can be seen the models start to diverge from each other at $\theta \approx 21$ degrees. Matching the time stamp of 0.33 seconds, the same behavior can be seen for ϕ.

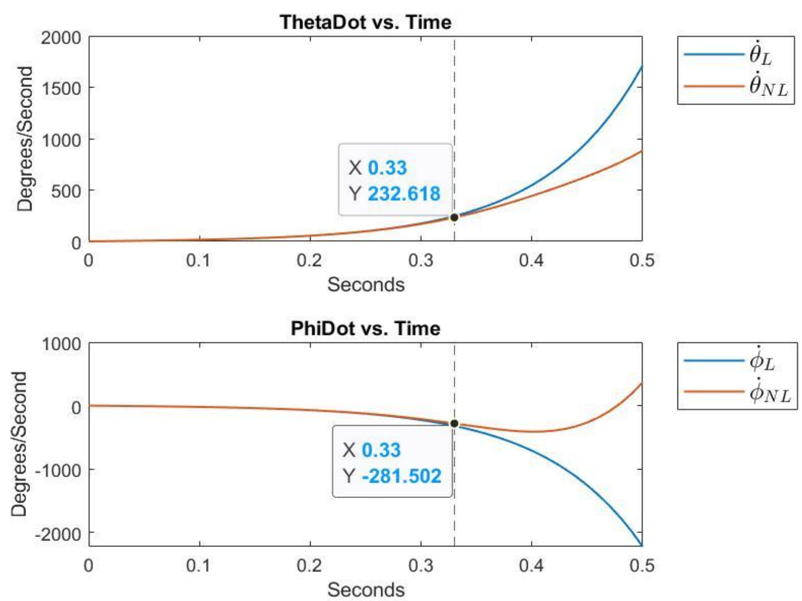


Figure 18: Overlay of the linear (blue) and nonlinear (orange) models for θ' and ϕ'. Referencing the same time of 0.33 seconds from the figure showing θ and ϕ, the same diverging behavior is seen in the graphs for θ' and ϕ'.

From Figures 17 and 18 above, it can be inferred a safe working range of our linearized model is $\theta = [-\ 20\ 20]$ degrees. This range includes our requirement of being able to recover from an offset of 15 degrees, so it is likely this linearization will be satisfactory for balancing the RocketMIP given there are no extraneous effects of our system which can influence the size of this range drastically. This may include the addition of motor damping or dry friction in the model and any delays in response which are currently not modeled, such as those from the electrical and mechanical motor delays or estimation delays of our angular velocities.

12.8 State Space Representation

Having linearized our model, we now have access to the robust linear control methods which were unavailable to us with the nonlinear model. The first important step to developing our controller is to represent our linearized model in state space format which improves the efficiency of analysis for multiple input multiple output (MIMO) systems.

To start we first need to isolate the highest order derivatives. Starting with ϕ we take equation (12.34) which already has θ'' isolated and plugged it into equation (12.33) to achieve the following term.

$$\phi'' = -\frac{C2C3}{(1-C2C4)}\theta + \frac{\tau_{total}}{2M(1-C2C4)} \tag{12.35}$$

To solve for θ'' we now do the reverse plugging equation (12.33) into (12.34) to obtain the expression for θ''.

$$\theta'' = \frac{C3}{(1-C2C4)}\theta - \frac{\tau_{total}C4}{2M(1-C2C4)} \tag{12.36}$$

Expressions (12.35) and (12.36) can now be expressed in the standard state space format given below.

$$x' = Ax + Bu \tag{12.37}$$

$$y = Cx + Du \tag{12.38}$$

We define our matrices for this form as follows,

$$x = \begin{bmatrix} \theta & \theta' & \phi & \phi' \end{bmatrix}^T$$

$$x' = \begin{bmatrix} \theta' & \theta'' & \phi' & \phi'' \end{bmatrix}^T$$

$$y = \begin{bmatrix} \theta & \theta' & \phi & \phi' \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{C3}{(1-C2C4)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{C2C3}{(1-C2C4)} & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ -\frac{C4}{2M(1-C2C4} \\ 0 \\ \frac{1}{2M(1-C2C4)} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix}^T$$

Using the matrices we can calculate the controllability of our system by taking the calculation given below,

$$\text{rank}([B\ AB\ A^2B\ \dots\ A^{n-1}B]) \qquad (12.39)$$

If the result of the rank function is equal to the order n of a system, also equivalent to the row or column count of matrix A, then the system can start from any initial state condition and achieve a final value through the use of an input in a finite time. For our system the rank is 4, which matches the dimensions of our A matrix serving as an initial check for developing our controller.

12.9 Full State Feedback

Representing our system in state space and knowing it is controllable, we can now move forward with implementing a linear quadratic regulator (LQR) full state feedback controller to our system. This method involves negative feedback of our states of the system multiplied by the vector K, which is then subtracted from our reference signal to produce an error vector of values. Our current reference signal is 0 for all values, so the error is simply the feedback states multiplied by K. These values are then summed as an input which commands what the motor torque for our system needs to be at a given moment for balancing of the system.

To help us obtain optimal values we use the LQR command in matlab which reduces the "cost", or error of our values, and allows us to choose the relative magnitude of our controlled input to reduce this cost. To use LQR we must first define the matrices Q and R. Q is a square matrix with sides equivalent to the number of feedback values and defines a "proportional importance" method of optimizing a system. In our case, we are feeding back θ, θ', ϕ, and ϕ', so Q is a 4x4 matrix. Q is given as follows,

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.2 \end{bmatrix}$$

Where the value 1 is tied to θ, 0.1 to θ' and ϕ, and 0.2 to ϕ'. So our controlled will be optimized to reduce the error of θ as an utmost priority and the other variables will be treated with their proportional values as compare to θ.

We also need to define R for LQR, which is tied to the relative magnitude response of our input. For smaller values of R, the input can be characterized as having more jerk and is abruptly applied as compared to a larger R value. The tradeoff of a larger R value can be slower rise times and sluggish responses among other considerations. For our system we define R as 10,000. Using the LQR function in matlab with our Q and R values we obtain the K vector below.

$$K = \begin{bmatrix} -0.51 & -0.052 & -0.0032 & -0.0053 \end{bmatrix}^T$$

The implementation of full state feedback in our Simulink model is given in Figure 19.

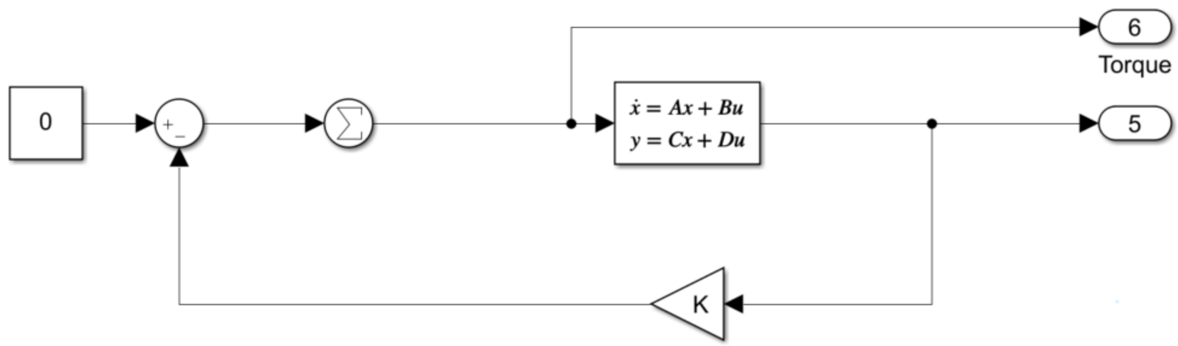


Figure 19: Full state feedback applied to the linearized model with K values as found from the use of LQR based on values assigned to Q and R.

Simulating the response of this controlled system we obtain the following results in figures 19 and 20 given the initial conditions as follows, [θ θ' ϕ ϕ'] = [-15 0 0 0] in degrees.

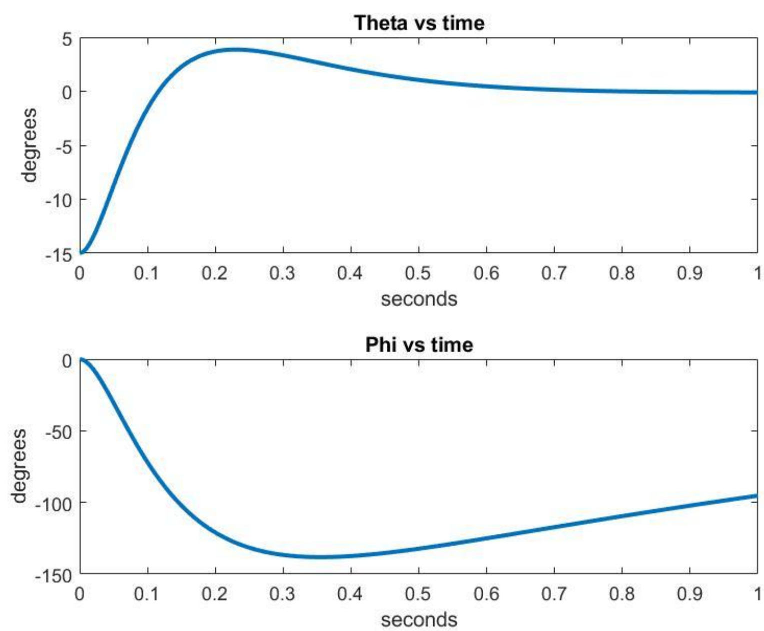


Figure 20: Recovery response from an initial unstable position of the pendulum body -15 degrees from vertical. It can be seen the response of theta is quick as to be expected from our weight prioritization in Q as compared to phi which takes more time to return to 0 degrees.

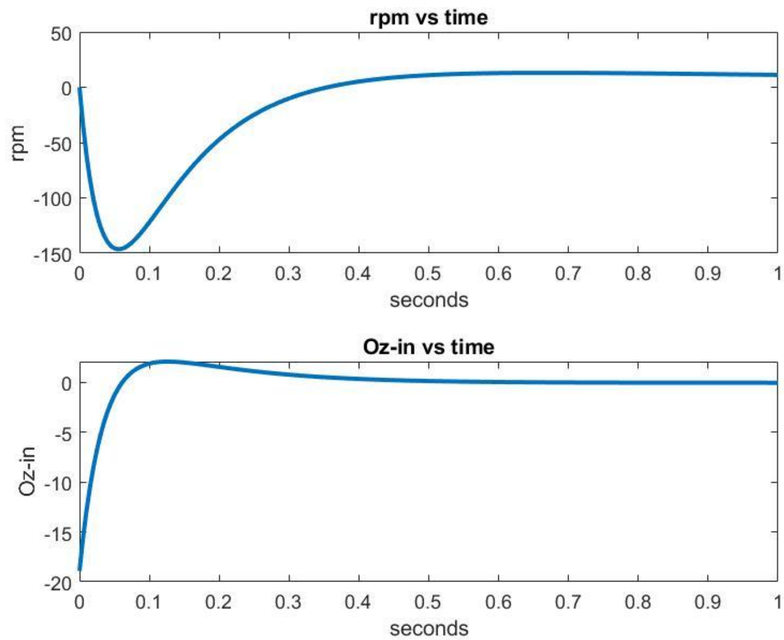


Figure 21: Motor response to the unstable initial conditions. From simulated responses such as this we can learn how our motor will respond to a given set of conditions before physically running any tests.

Now that we have developed a method for modeling our system and achieving controllability, we can adjust the control variables to better suit the capabilities of our motor. Seeing that the commanded torque is much too high for the two N20 motors we currently have, we can increase the value of R to reduce the abrupt command for torque. We set our new value to 100000. From this new setting the values of K come out to be as follows.

$$K = \begin{bmatrix} -0.1575 & -0.0152 & -0.0010 & -0.0022 \end{bmatrix}^T$$

Additionally, we have added in the effects of dimensional changes to the length from the driveshaft to the center of mass of the body and changes to the radius size of the wheel, maintaining everything else equal. These results are given below.

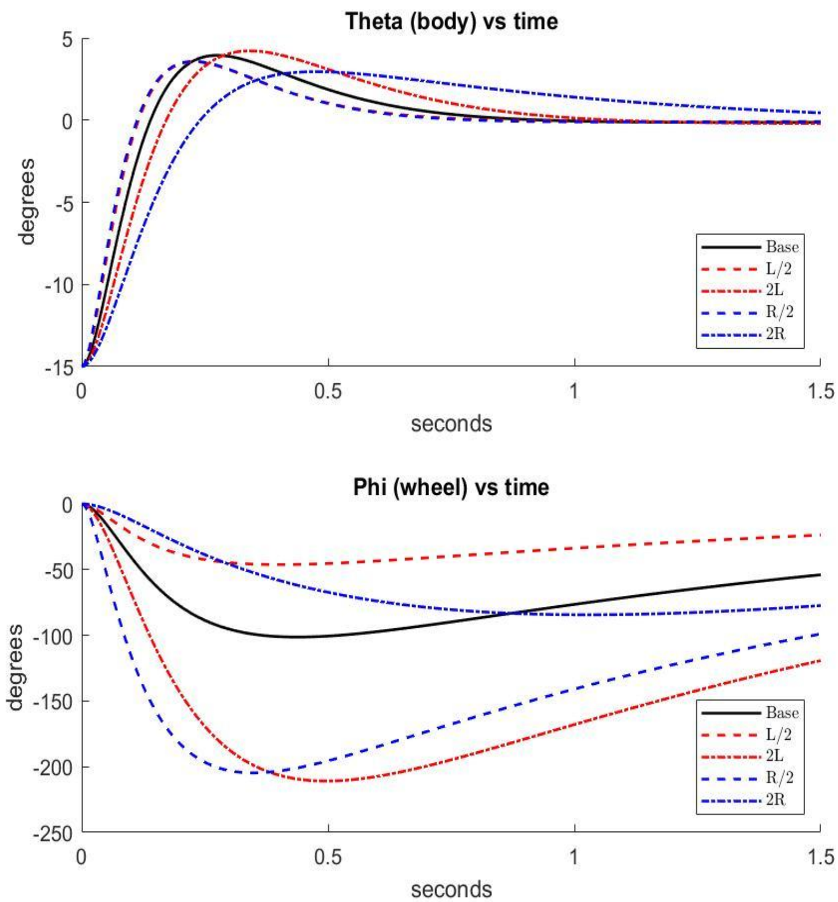


Figure 22: Controlled response of theta and phi over time from the updated feedback gains from an initial theta of 15 degrees

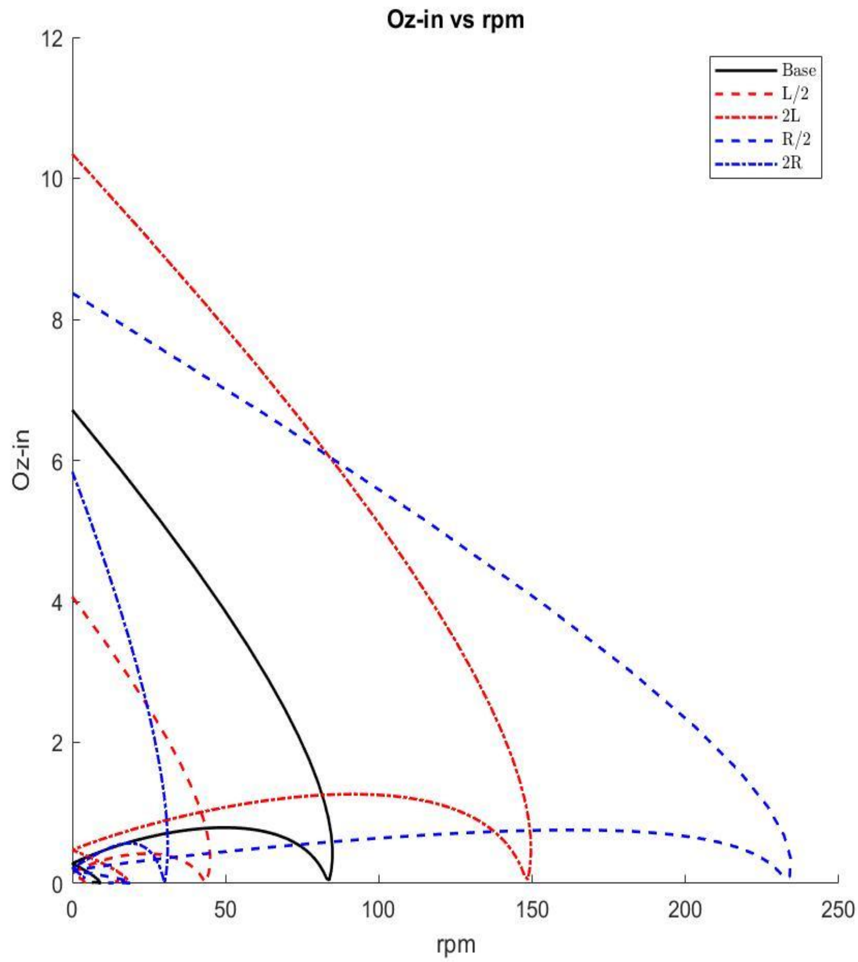


Figure 23: Controlled response showing commanded torque vs commanded rpm from the updated feedback gains with an initial theta of 15 degrees

From Figure 23 we can see the baseline response, our current build, responds with a maximum total commanded torque of 6.75 oz-in and a maximum commanded rpm of 75. As of now we have not been able to analyze this model any further with regard to application.

While we have created an adequate model with positive control, it has still yet to be integrated into the RocketMIP due to time constraints of the course. If the team had more time, the model could help further assist with part selection as it can demonstrate how changes affect the system which could guide further part selection and refinement. Also, given more time, the team could add more requirements and specifications based on the model such as rise time and/or overshoot targets.

13. DESIGN VERIFICATION & VALIDATION

In order to ensure that MIP performs as we designed it to, the team has embarked on various verification tests in order to ensure its usability. In general all of the specifications can be broken down into four categories of verification: compliance, inspection, and testing.

13.1 Compliance Verification

To ensure that all specifications relating to a set standard and/or general range were met, simple verifications of said information were conducted as shown in Table 14:

Table 14: Compliance Verification of Engineer Specifications

Specification	Verification/Plan
Overall price for the kit ≤$100 Cost≤Price	Build Design V2 currently costs the team $95.65 which is less than $100
100% of electronics will be RoHS compliant	All components sourced are branded and/or certified by the manufacturer to be RoHS compliant
All electrical connections are done via JST or other molded connectors	Motor, encoder, and battery connections all utilize JST connections
All components non fabricated parts will have short-lead times, large stock, and come from reliable vendors	All components have been sourced from Amazon from sellers with >4.5/5 star feedback and can received as soon as next day
Users will have gone through X modules and successfully completed each application check. Completion of all application tests will result in a fully assembled and coded MIP	The team is currently focused on completing the MIP and have diverted resources to finishing that first. Verification of this specification will be if the modules can completely assemble a MIP

13.2 Inspection Verification

To ensure that the MIP fulfills its physical and build specifications, an inspection of the MIP was conducted in order to verify and the results are shown in Table 15:

Table 15: Inspection Verification of Engineer Specifications

Specification	Verification/Plan
0.2mm ±0.005mm layer height, ≥4 perimeters, specified print orientation	A layer height of 0.2mm and at least 4 perimeters were used in all 3D printed parts
All non-mating edges should be rounded to ≥ 0.125”	Filets of 0.2” were used on all sharp corners
Robot will fit within a volume of 6” x 6” x 6”	Fully assembled dimensions of Build Design V2 are 5.25” x 4.87” x 4”
Total Weight ≤ 1lb	Fully assembled weight of Build Design V2 is 0.617lbs

13.3 Testing Verification

Some specifications require testing in order to ensure that they perform as we designed/specified it to. Testing methods can be as simple as using focus groups or actual physical tests of the MIP as shown in Table 16:

Table 16: Inspection Verification of Engineer Specifications

Specification	Verification/Plan
100% of body parts can be printed using PLA on an FDM printer.	All components for Build Design V2 that are 3D printable have been produced using the personal FDM 3D printers owned by team members (Prusa Mk3+, Ender 3 Pro, Voxelab Aries)
High School focus groups will be able to assemble and have a fully functioning MIP in	Once the MIP is fully completed, user testing will be completed with various local high

<60 minutes when provided the software, 3D printed parts, and electronic components.	school focus groups in order to ensure that the kit can meet the specification
The system will be able to fully recover balance when the angle body angle is changed by ≤15°	Once the MIP is fully operational, the team plans on conducting physical testing in order to ensure the MIP can upright itself if perturbed by an angle no greater than 15° from the center. The general testing setup will consist of the MIP in a stationary position and in several trails it will be perturbed 10°, 15°, and 20° (Schematic of the test is in Appendix E)
The system will be able to fully recover balance if a force of 50N is applied	Once the MIP is fully operational, the team plans on conducting physical testing in order to ensure the MIP can maintain its balance even if a force of 50N is applied to it. 50N was chosen based on a study conducted by Virginia Tech on the average "poke" force of a person [41]. The general testing setup will utilize a pendulum with a mass at the end to strike the MIP in order to see if it can maintain stability (Schematic of the test and calculations are in Appendix F)

13.4 Validation Plans

Our validation plan will involve comprehensive focus group testing of the PocketMIP with our target audience of High School students. This testing will consist of multiple steps, with survey data being collected via questions on interactive Google Forms, and include:

- Pre-Assessment: We will assess students' prior knowledge on 3D printing and PID tuning and theory via structured questions, which allows us to establish their baseline level of understanding.

- Project Completion: The students will then complete the PocketMIP project, using the standard kit and instructions.
- Post-Assessment: After completion of the project, a second set of structured questions will be given to students to assess their current knowledge and confidence level. Comparing the results with those of the Pre-Assessment will let us understand the impact of the project and how much information students retained.
- Feedback Collection: A set of open-ended questions will be used to capture student feedback on improvements that can be made.

14. DISCUSSION

14.1 Problem Definition

Given more time and resources, the team would have investigated a mobile application that could house the assembly instructions, education modules, and code tuning. Ultimately this would have improved the user experience and made it more visually appealing. Allowing for the PID values to be tuned in the app could help with the interfacing problems with the BeagleBoard and ultimately any confusion that could develop from having the end user modify and upload their own raw code. Incorporating the learning modules within an interactive app would make them easier to follow and could break up the large walls of text that are present in the printed version. Ultimately, there was not enough time or resources to allow us to explore this idea within the semester.

14.2 Design Critique

The team recognizes that there are many strengths and weaknesses present in the final build design.

14.2.1 Design Strengths

RocketMIP's strengths in its design are evident across various categories:

The body prioritizes functionality ensuring durability against moderate abuse while securely housing 3D printed parts and hardware during operation. Its simplicity also fosters a mostly straightforward top-down assembly method, facilitating ease of replication with the implementation of guided instructions.

The integration of the BeagleBone Blue board stands out for its comprehensive instrumentation, empowering aspiring engineers with ready-to-use tools for control and interfacing. Offering versatile connectivity options through Bluetooth, Wi-Fi, and multiple motor interfaces, this board caters to diverse engineering needs and provides advanced tinkerers with room for developing the RocketMIP in their own image or repurposing the board for other projects.

The design adeptly leverages 3D printing methods, incorporating features like sunk holes for nuts, weight reduction via cutouts, and precise locating features for fasteners, optimizing functionality and simplifying assembly. Crucially, all parts, excluding hardware and fasteners, are 3D printed, highlighting confidence in this technology's capabilities and emphasizing potential cost-efficiency and rapid prototyping benefits to the end user if they wish to modify the design. Furthermore, the design's compatibility with commercially available 3D printers ensures accessibility and cost-effectiveness in production, contributing to its wider adoption potential within engineering spheres.

14.2.2 Design Weaknesses

RocketMIP encounters notable engineering challenges due to specific weaknesses:

The BeagleBone Blue's small connectors make crimping without dedicated tools exceptionally challenging, complicating assembly. Moreover, the necessity to download and flash an image onto the board, exclusive interfacing via the Linux command line, and limited documentation present significant hurdles to accessibility. Our team was not experienced in Linux so setting up the board and interfacing with it became a significant time crunch. The board also seems to be getting phased out limiting its support and adds uncertainty and potential compatibility issues for future iterations. Another issue that could be seen is the extensive amount of hardware present on the board. It more than accomplishes its goal in the RocketMIP, leaving many unused components on the board such as two spare DC motor drivers, eight servo motor drivers, and multiple I/O pins. Whether or not end users would make use of these additional components is unclear and may be unnecessary given the targeted users are those developing an interest in STEM.

Issues persist with the current motors, ranging from difficulties in proper connector crimping for compatibility to inconsistent motor conditions upon delivery. Furthermore, the motor encoder's instability on the extended shaft impacts reliability as an encoder has fallen off before due to interference with poor soldering, while insufficient documentation and our current simplistic calculations hinder comprehensive understanding and optimal utilization of the motors.

RocketMIP faces a possible pricing issue in the future. The cost of components is currently $95.65 which could easily break over our $100 target with some price fluctuation. The BeagleBone Blue board contributed a significant portion of the overall cost. The pricing proximity demands a critical review of cost-cutting strategies, especially in exploring alternatives or negotiating pricing to align with budget constraints without compromising the project's functionality. The fact that the board is ~45% of the total price seems problematic especially in the case that a board might need to be replaced. That is a high cost to pay proportional to what end users would spend on the product.

14.3 Design Process Challenges

Improving the design process for RocketMIP necessitates a thorough review. Foremost, dedicating more time to thoroughly comprehend the necessary hardware for the solution is imperative. Delving deeper into hardware research, focusing on compatibility and addressing issues related to interfacing and unfamiliarity will mitigate hurdles encountered with motors and the BeagleBoard. By investing in a more profound understanding of these components, the design process can be streamlined, curbing issues rooted in compatibility and expertise gaps.

Incorporating end-users' perspectives at the project's inception holds significant merit. Early involvement in the conceptual phase enables a better grasp of high schoolers' opinions regarding the novelty of mini-segways. Given technological advancements and market availability, understanding their perceptions will shape a more relevant and appealing product. As of now our team has little information to go off of regarding the opinions of high schoolers and their thoughts of a controllable segway. This insight will guide the design towards meeting user expectations and enhancing the product's attractiveness in a competitive market landscape.

Moreover, allocating additional time during the project's initial stages employing simplistic computational/hand written calculations to justify design choices will fortify the process. This analytical approach supplements intuitive design with empirical evidence, fostering a more robust foundation for decision-making. Some areas of application include body force analysis at the motor as we didn’t put very much time into failure analysis and if the 3D printed body could sustain the motor torque load, as of now we don’t have enough evidence to prove it wouldn’t fail soon. Another example involves the wheel constraint to the motor shaft. This is another area where analysis wasn’t thoroughly done and that part is at risk of spontaneous failure as well. Utilizing data-driven reasoning will enhance product functionality and performance, reducing reliance solely on intuition.

By assimilating these improvements into the design process, RocketMIP can address critical hardware intricacies, incorporate end-user preferences effectively, and bolster design rationale. This approach holds the potential to refine the RocketMIP’s trajectory and yield a more purposeful and user-centric solution.

14.4 Risk assessment

Throughout the course of the RocketMIP project, various challenges arose, demanding strategic approaches to maintain progress and effectiveness. The assessment of risks played a pivotal role in understanding and addressing these challenges. By evaluating factors like design concept filtering, alignment with project timelines, management of external dependencies, and balancing project goals, the team navigated these hurdles.

Achieving unanimous agreement among team members on design concepts was a critical step. To accomplish this, the team utilized multiple filtering methods, including individual concept exploration, Pugh charts, morphological charts, and open debates. These diverse approaches effectively mitigated personal biases, fostering a consensus-driven selection process that led to solutions aligning with the project's goals and objectives.

Adhering to the course timeline while filtering design concepts was imperative. Recognizing the constraints posed by time, the team strategically narrowed down concepts that were feasible within the given timeframe. This pragmatic approach ensured that the chosen designs were not only innovative but also realistically implementable within the project's scope, optimizing resources and efforts.

Breaking ties with the project's sponsor marked a pivotal shift. Due to the sponsor's unavailability within the project timeline, the team chose to become self-reliant. This decision allowed for faster, more autonomous decision-making processes, ensuring that the project remained on track without delays caused by waiting for external guidance or approvals.

Balancing project goals and workload became a significant focus area. Initially aiming to tackle multiple aspects—designing a physical product, delving into control theory, and developing instructional modules—the team encountered challenges in managing the workload efficiently. To streamline progress, the decision was made to prioritize the creation of a functional product before delving into instructional module development. This strategic adjustment optimized efforts, offering the team deeper insights into instructional content while accelerating progress toward achieving a tangible solution.

In order to mitigate the risk for the end user of the Rocket MIP the team followed multiple design standards and safety regulations. Our main safety requirements included rounding corners, ensuring components were resistant to fracture and ensuring that our electronics were RoHS compliant.

15. TEAM REFLECTION

With the conclusion of the semester and the project, it is important to reflect on the choices the team made since starting researching the topic four months ago.

15.1 Design Context - Revisited

The goal of the RocketMIP was to create a mobile inverted pendulum kit in order to educate high school students in the realm of 3D print, mechanical/electrical assembly, and PID control. With the conclusion of the project, the team has created a working prototype that would accomplish more than half of what the team set out to do. Once completed the RocketMIP has the potential to give rise to a whole new generation of STEM students.

In terms of the RocketMIP itself, the team fulfilled its goal of exclusively using Rohs compliant parts for electrical safety and future disposal, optimized 3D prints to print in the least amount of time possible to conserve electricity, and attempted to source parts from highly reputable sellers on Amazon.

When examining who the RocketMIP will impact, the team continually reviewed the stakeholder map created at the beginning of semester, Figure 1 (p. 7). Even though the project is targeted at high school students, it has the potential to reach college students, other professionals wanting to learn, factories in the United States and abroad, as well as workers who source the raw materials.

15.2 Team Dynamics

The organization of Team 27 was at random and constructed by the professors based on the students' similar interests. Each team member *hails* from a different area in Michigan, but geological differences did not hamper the team. From the beginning of the project, there was an established professionalism amongst team members. The comradery of the team and ambition to produce the best project was strengthened further due to administrative complications mid-semester. Within the team, there were never arguments and any questions about how to proceed or with what approach to go with was handled by all members with the opportunity for everyone to give their input.

Since the project did not have a formal industry sponsor, decisions were made by all team members and discussed with the course mentor, Professor Shorya Awtar. With minimal real industry experience, the team often looked to Professor Awtar for guidance given his professional and research background. At times there were disagreements between the team and professor about what the best approach was, however, through discussions a clear consensus was always agreed upon.

16. RECOMMENDATIONS

In order to turn the RocketMIP into a viable product, there are several key areas that need to be addressed as mentioned in the discussion section. The following recommendations will serve to help future 450 teams if they choose to continue the development of the RocketMIP.

16.1 User friendliness

The BeagleBone Blue control board, while seemingly appealing with its extensive hardware, sensor integration, and built-in Wifi and Bluetooth communication functionality, is ultimately not a good fit for this product going forward. This is due to the large learning curve required to interface with the BeagleBone, as a moderate degree of knowledge in both Command Line Interfaces (CLIs) and the Linux operating systems is required. We also often found that the documentation of the BeagleBone board and its corresponding software was confusing, fragmented, or outdated. In addition, the overwhelming functionality of the board may end up preventing users from easily tinkering with the device. In order to improve on user friendliness, it is recommended that an Arduino control board be used in the future instead, with the required sensors and hardware, such as the IMU and motor drivers, being attached to the board. Since Arduino boards are already targeted towards younger users, and there are plenty of accessible tutorials and resources online on how to use them, they would be a better option. In addition, Arduino boards can interface easily with most computers and can be easily replaced.

16.2 Learning modules

While part of the scope of this project, the learning modules have yet to be completed and will need to be implemented as part of future work. These modules should be constructed in a way that embed the learning within the manufacturing and assembly process of the MIP in order to keep the attention of the end user. It is also recommended that the modules be built into the eventual app which allows for additional interactivity such as a 3D model viewer.

16.3 Cost reduction

Although we reached our goal of a total cost under $100 dollars, the price could always be reduced further in order to improve the accessibility of the product to all prospective users. The main challenge here will be to reduce the price while also replacing the BeagleBone Blue, which originally presented us with a cost-effective all-in-one solution for the robot's electronics, with an Arduino board and accompanying hardware in order to improve user friendliness.

16.4 Improved Functionality

The scope of the RocketMIP's functionality was limited to self-balancing, however adding additional functionality to include more complex behavior such as controllable movement, steering and having the ability to tune the RocketMIP via the app without having users edit the code, will aid with their learning as they will be able to see how their values affect the MIP in real time.

17. CONCLUSION

In order to increase interest in STEM related fields, this project will deliver a low priced, hands on kit that teaches students about the concepts behind additive manufacturing in the form of 3D printing, the basics of PID control, and how to effectively tune a PID controller.

Considering the other products currently present on this market, we have determined that we should model ours closest to is the ELEGOO Tumbller V1.1. This product hits a lot of our important specifications, like target age range, providing education modules, and keeping the price under $100. However, this product does not embed the educational modules within the assembly instruction (to make it a cohesive learning and building experience) and does not touch on 3D printing. These aspects are where our kit will aim to be unique and stand out from the competitors.

Throughout the concept generation process, the team conducted hours of free discussion and utilized many pugh charts in order to converge and rank designs. One of the main takeaways the team had from this process was how to utilize the feedback from the pugh charts. In several instances, categories with high end scores were not used. Even though, on paper, some subsections scored higher, after group discussion the team determined several ideas seemed to stray too far from the intended goal of the project and/or were too complicated given the intended audience and stakeholder requirements.

When selecting an alpha design the team initially used an unweighted pugh chart to rank (Appx A). After deliberation and using the feedback from the unweighted pugh chart, the team decided on Design C and an initial Alpha Design CAD model was created shown in Figure 24 (Auxiliary views in Appx B):

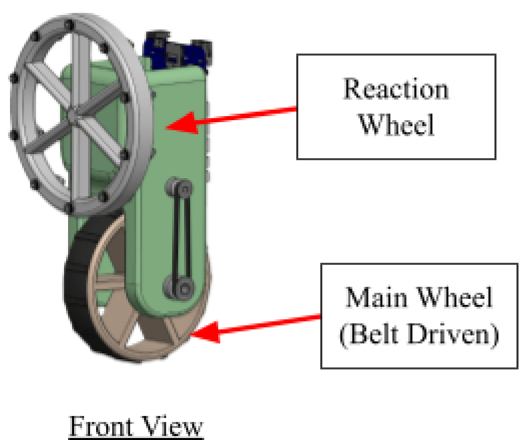


Figure 24: Front view of initial Alpha Design C

Design C implemented a pendulum style body attached to a bottom wheel for mobility and stability. Also, attached to the front is a reaction wheel with adjustable screw weights that can impart an opposing momentum if a force is applied to the MIP. Through discussion with our mentor as well as assessing the feasibility of the project the team decided it was best to revisit the pugh charts and determine a category weighting system that better reflected the abilities of the team members and aligned with top user requirements. With the new weighting system, the team found it easier to understand how design choices and stakeholder requirements affected our design which led us to choose a modified version of Design A as our current Alpha Design. Design A is a segway style MIP with an adjustable body mass that utilizes two treaded wheels. The initial concept for design A is shown in Figure 25.

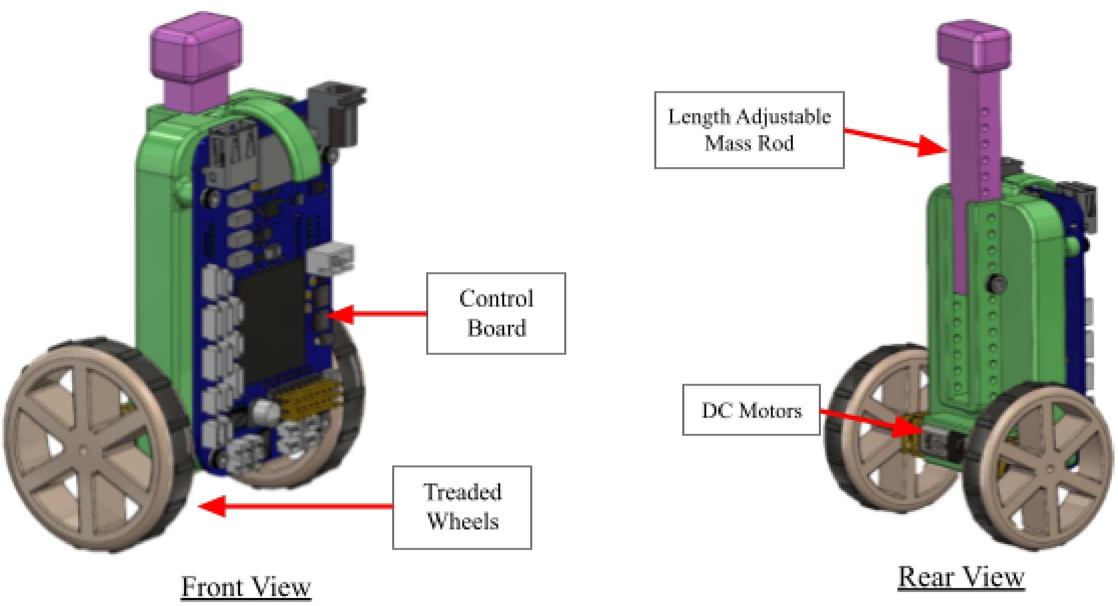


Figure 25: Front and rear views of the alpha design A

After further refinement and selecting the BeagleBoard Blue as our controller we came up with our Build design V1. This design features many upgrades over the alpha design. Within this design we have seen a major change in the shape of the body. Between the alpha design and the completion of build design V1 we added two side rolls, which are designed to protect the protruding components of the control board in the event that the MIP falls over. Another change is the adjustable mass and its removal. The decision was made to remove this feature in this version because of the complicated geometry that was involved with the holes in the adjustable track. It was determined that these features would increase the length of the print and would involve a lot of support material. At this stage in the design the adjustable mass was removed to allow for a more effective system to be implemented later down the line. Another change is the location of the motors. Originally they were located on the back, moving to the front allowed us to optimize the print settings and remove a large amount of support material that was previously required. Build design V1 is shown in Figure 26.

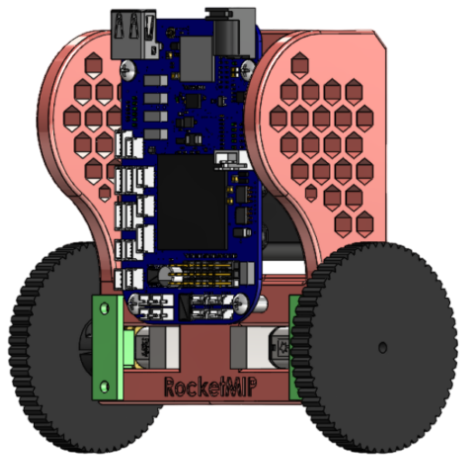


Figure 26: Front view of build design V1

From our build design V1 we learned a lot about the system through experimentation and meetings with our advisor. From this knowledge we created our build design V2, our working prototype as is shown in Figure 27.

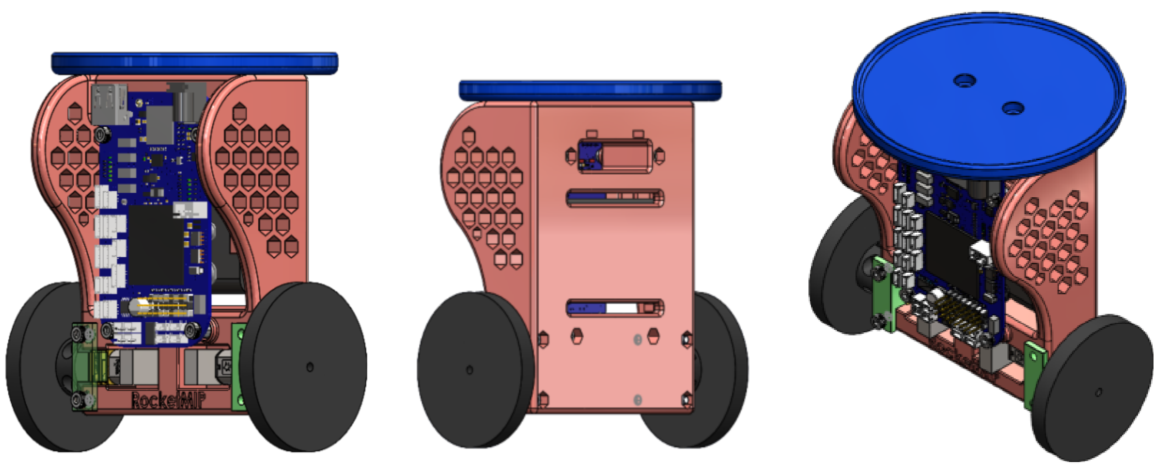


Figure 27: Front, back, and top view of Build Design 2

From build design V1, we added location features to ensure that the battery was snuggly attached. An increased clearance was added to the body to ensure that the motor encoders would always clear even with different manufacturers and tolerances. The wheels were also smoothed out to incorporate a rubber band, which will be used to increase the coefficient of friction between the MIP and the surface. The nuts were also countersunk to make assembly easier and to provide more opportunity to teach 3D printing techniques. This design also sees the return of the adjustable mass in the form of the top plate. This plate is a separate component that is easier to print and still accomplishes our goal of changing the center of mass for the system to provide more opportunities to retune the PID controller. Design V2 utilizes two 75:1 DC N20 motors, a BeagleBone Blue control board, and a 2000 mAh dual cell li-po battery (Full bill of materials can be found in Appendix D).

Within this final design we recognize that there are some distinct strengths and weaknesses with the design and the process. The main strengths of the physical design are: our 3D printability, ease of assembly, part strength, controller board compactness, use of 3D printing techniques, and board modularity. Our main weaknesses are: small JST connectors, board interfacing, poorly constructed motors, motor documentation, motor size, and cost.

In order to mitigate risk associated with the project we took several steps throughout the semester. To ensure that the project was as complete as possible by the end of the semester we: removed our sponsor, utilized a comprehensive design selection/generation process, and created a comprehensive model of the system. To mitigate risk toward the end user we: utilized lead free and RoHS compliant electronics, designed covers for gears, and ensured that all corners are rounded.

Throughout the design process we recognize that our backgrounds and ethical stances influenced our design processes and decisions. However we implemented an intensive and vigorous design process in order to minimize the effect of these biases on our final design.

18. ACKNOWLEDGEMENTS

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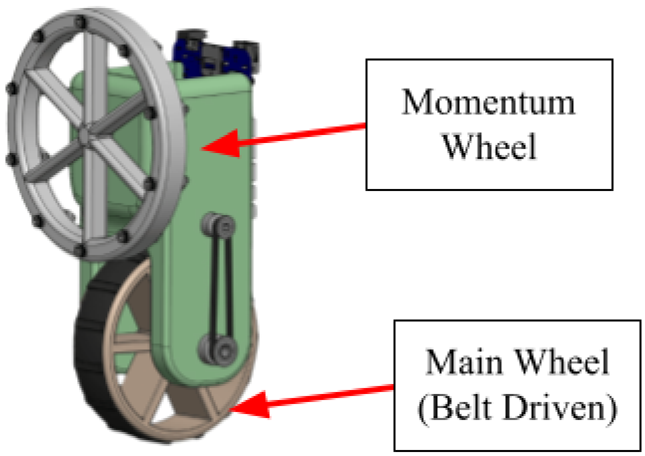
APPENDIX A: UNWEIGHTED PUGH CHART OF COMPOUNDED DESIGNS

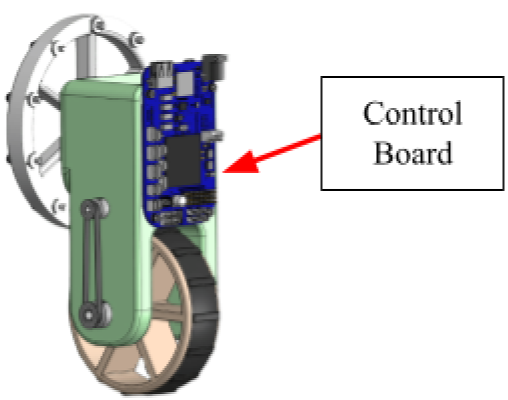
Design	Team member	Use of 3D Printed Parts	Complexity of design	Uniqueness	Display of Educational aspect (balance)	Ease of Printing	# of ordered parts	Total	Score
ELEGOO Tumbller (Baseline)	Ben	0	0	0	0	0	0	0	0
	Michael	0	0	0	0	0	0	0	
	Mohammad	0	0	0	0	0	0	0	
	Dylan	0	0	0	0	0	0	0	
A	Ben	0	0	1	0	0	0	1	5
	Michael	1	0	-1	0	0	0	0	
	Mohammad	1	0	1	1	0	0	3	
	Dylan	0	0	0	1	0	0	1	
B	Ben	1	0	-1	1	0	0	1	3
	Michael	1	0	0	1	-1	0	1	
	Mohammad	0	0	0	1	0	0	1	
	Dylan	0	0	-1	1	0	0	0	
C	Ben	1	0	1	1	0	-1	2	4
	Michael	1	-1	1	1	0	-1	1	
	Mohammad	1	-1	1	1	0	-1	1	
	Dylan	0	-1	1	1	0	-1	0	
D	Ben	1	-1	1	1	-1	-1	0	-3
	Michael	1	-1	1	0	-1	-1	-1	
	Mohammad	1	0	1	0	-1	-1	0	
	Dylan	-1	-1	1	1	-1	-1	-2	
E	Ben	0	-1	1	1	-1	0	0	3
	Michael	0	-1	1	1	-1	0	0	
	Mohammad	1	-1	1	1	0	0	2	
	Dylan	1	-1	1	1	0	-1	1	
F	Ben	1	-1	1	1	-1	0	1	3
	Michael	1	-1	1	0	-1	-1	-1	
	Mohammad	1	-1	1	0	0	0	1	
	Dylan	1	0	1	1	-1	0	2	

APPENDIX B: DESIGN C INITIAL ALPHA DESIGN

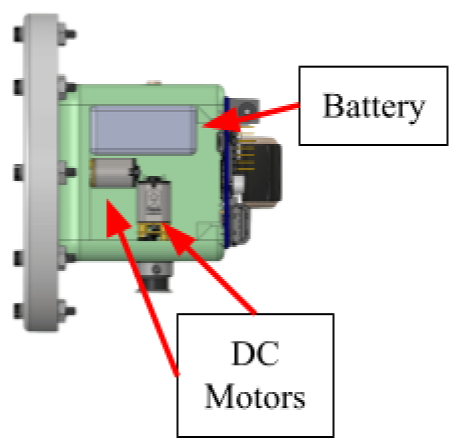


Front View

Top View



Rear View

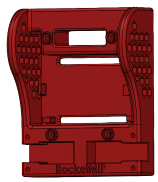
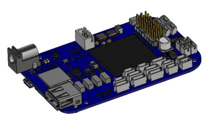
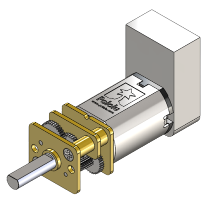
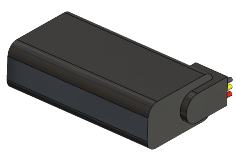
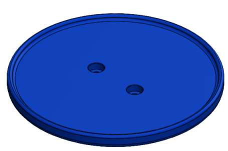


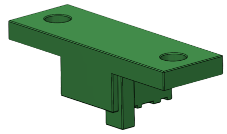
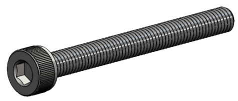
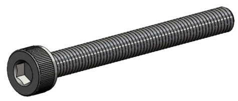
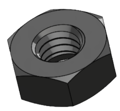
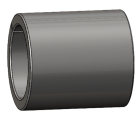
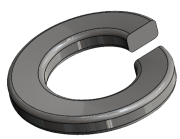
APPENDIX C: CONTROL BOARD BENCHMARKING

Name	Cost	Point of Sale	Size	Code Language	Missing Components
Arduino UNO r3	$27.60	Arduino	2.7"x2.1"	Arduino IDE (C+ interface)	IMU, H-bridge
beaglebone blue	$47.99	Amazon	3.5" x 2.15"	Built on Linux can code outputs with any language	N/A all necessary components are present
Raspberry Pi 3 Model A+	$25.00	Adafruit	2.6"x2.2"	C+ or python	IMU, H-bridge
beaglebone black	$51.45	Digikey	3.54" x 5.12"	Built on Linux can code outputs with any language	IMU, H-bridge
Arduion MKR zero	$30.30	Arduino	3.15 x 2.28	Arduino IDE (C+ interface)	IMU, H-bridge
raspberry pi zero WH	$16.00	Adafruit	2.6"x1.2"	C+ or python	IMU, H-bridge
Raspberry Pi Pico H - Pico with Headers Soldered	$5.00	Adafruit	.83"x2"	C+ or python	IMU, H-bridge
Arduino Nano 33 IoT	$25.50	Arduino	1.8" x.7"	Arduino IDE (C+ interface)	H-bridge

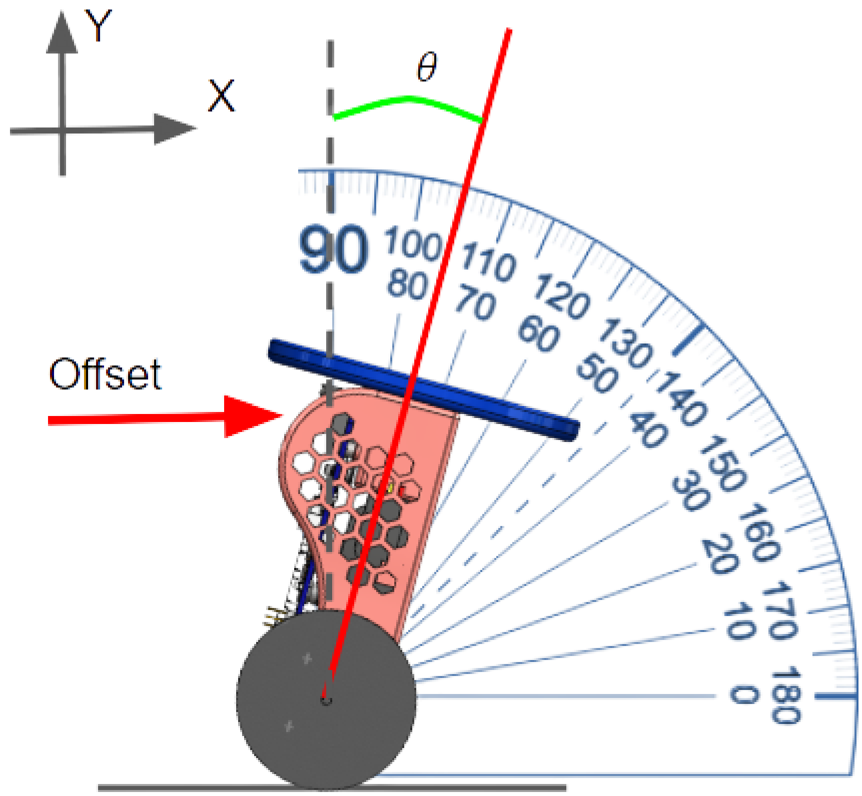
Off Shelf Add-on that Addresses Missing Components	Cost of Missing Component Solution	Point of sale	Running total	Complete	Notes
Arduino motor shield v3	$27.60	Arduino	$55.20	NO	still missing IMU
N/A	N/A	N/A	$47.99	YES	Seems to be most complete solution
N/A will need to source third party or custom components	unknown	N/A	$25.00	NO	
beagle board robotics cape	$45.00	renaissance robotics	$96.45	YES	
MKR IMU shield	$29.30	Arduino	$59.60	No	still requires H-bridge
N/A will need to source third party or custom components	unknown	N/A	$16.00	NO	
N/A will need to source third party or custom components	unknown	N/A	$5.00	NO	
Arduino Nano Motor Carrier	$77.80	Arduino	$103.30	YES	Board itself has an IMU, could work if we go servo route without additional controller

APPENDIX D: BUILD DESIGN V2 BILL OF MATERIALS

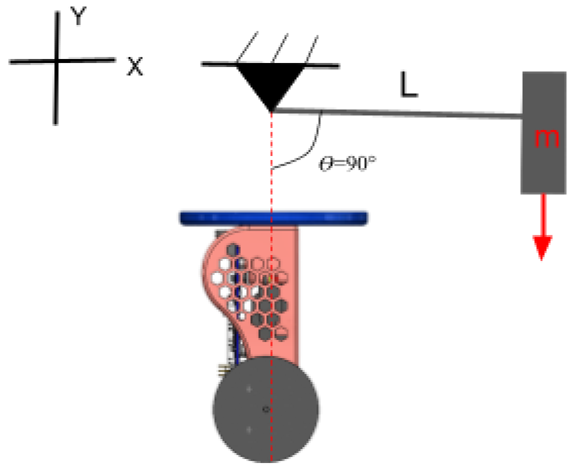
Build Design V2 BOM						
Part No.	**Part Title**	**Part Image**	**Quantity**	**Material**	**Cost/Unit**	**Supplier**
1	Main Body		1	PLA	N/a	Self-printed
2	BeagleBone Blue		1	PCB	$47.99	Amazon
3	75:1 N20 Motor		2	Metal Motor	$13.99	Amazon
4	2000 mAh Battery		1	Lithium-Ion	$10.52	Amazon
5	Top Plate		1	PLA	N/a	Self-Printed
6	Wheel		2	PLA	N/a	Self-Printed
7	Wheel Coupler		2	PLA	N/a	Self-Printed

8	Motor Bracket		2	PLA	N/a	Self-Printed
9	M3 Fastener 20mm length		8	18-8 stainless steel	$0.09	mcmaster
9	M3 Fastener 12mm length		6	18-8 stainless steel	$0.06	Mcmaster
10	M3 Nut		14	Steel	$0.03	Mcmaster
11	Spacer		4	Low carbon steel	$0.07	Mcmaster
12	Lock Washer		4	Stainless steel	$0.02	Mcmaster
13	JST-SH connector		2	Plastic housing with metal crimps	$0.24	Amazon
14	JST- ZH connector		2	Plastic housing with metal crimps	$0.11	Amazon
				Total cost:	**$95.65**	

APPENDIX E: ANGLE DYNAMIC STABILITY VERIFICATION



APPENDIX F: APPLIED FORCE DYNAMIC STABILITY VERIFICATION



Applied Force Calculation:

- $m \cdot g \cdot h = \frac{1}{2} m \cdot V^2$
- $V = \sqrt{2 \cdot g \cdot h}$ where h=L
- $F = m \cdot a = m \cdot \frac{V}{\Delta t}$
  - $\Delta t = V/a$
    - $a = V^2/L$
  - Hence $\Delta t = L/V$

Where:

- **m** is the mass of the weight at the end of the pendulum
- **g** is the gravity constant
- **L** is the length of the pendulum string/arm
- **Δt** is the time it takes the mass to strike the MIP
- **a** is the acceleration of the mass

APPENDIX G: MOTOR BENCHMARKING

Motor	Encoder?	Price	Seller	Max torque	Top speed	Shaft Type	Length	Diameter	Drive voltage	Brushed?	Wheel?	Notes
Hobby Motor	No	$2.10	Sparkfun	N/A	6600±10%rpm	10 tooth gear	N/A	1"	1-12V	Yes	No	
Hobby Motor Encoder KIt	Yes	$21.50	Sparkfun	N/A	135RPM	machined shaft	N/A	N/A	3-6V	yes	yes	includes two right angle motors, two wheels, two encoders
Mini pancake	No	$8.99	Amazon	N/A	1730RPM	machined shaft	.98"	.98"	1.5-9V	Yes	No	6 pack
DC Gear Motor	Yes	$16.09	Amazon	N/A	1200 RPM	machined shaft	52mm?	25 mm	12 (assuming can go lower)	Yes	No	Other lower speeds available
Right angle gear motor	Yes	$16.78	Amazon	N/A	100 RPM	machined shaft	76.8 mm	24.4mm	12 (assuming can go lower)	Yes	No	Other lower speeds available
Mini N20	Yes	$13.99	Amazon	N/A	265 RPM	3mm machined shaft	34mm	12mm	6V	Yes	No	
DC Gear Motor	Yes	$18.63	Amazon	N/A	100RPM	machined shaft for wheel	N/A	N/A	6v	Yes	Yes	kit is wheel , motor+servo, and mount
DC Gear Motor	Yes	$11.90	dfrobot	.2kgcm	530 rpm	machined shaft for wheel	40.5 mm	10mm	6v	Yes	No	Other ratios are available, good documentation

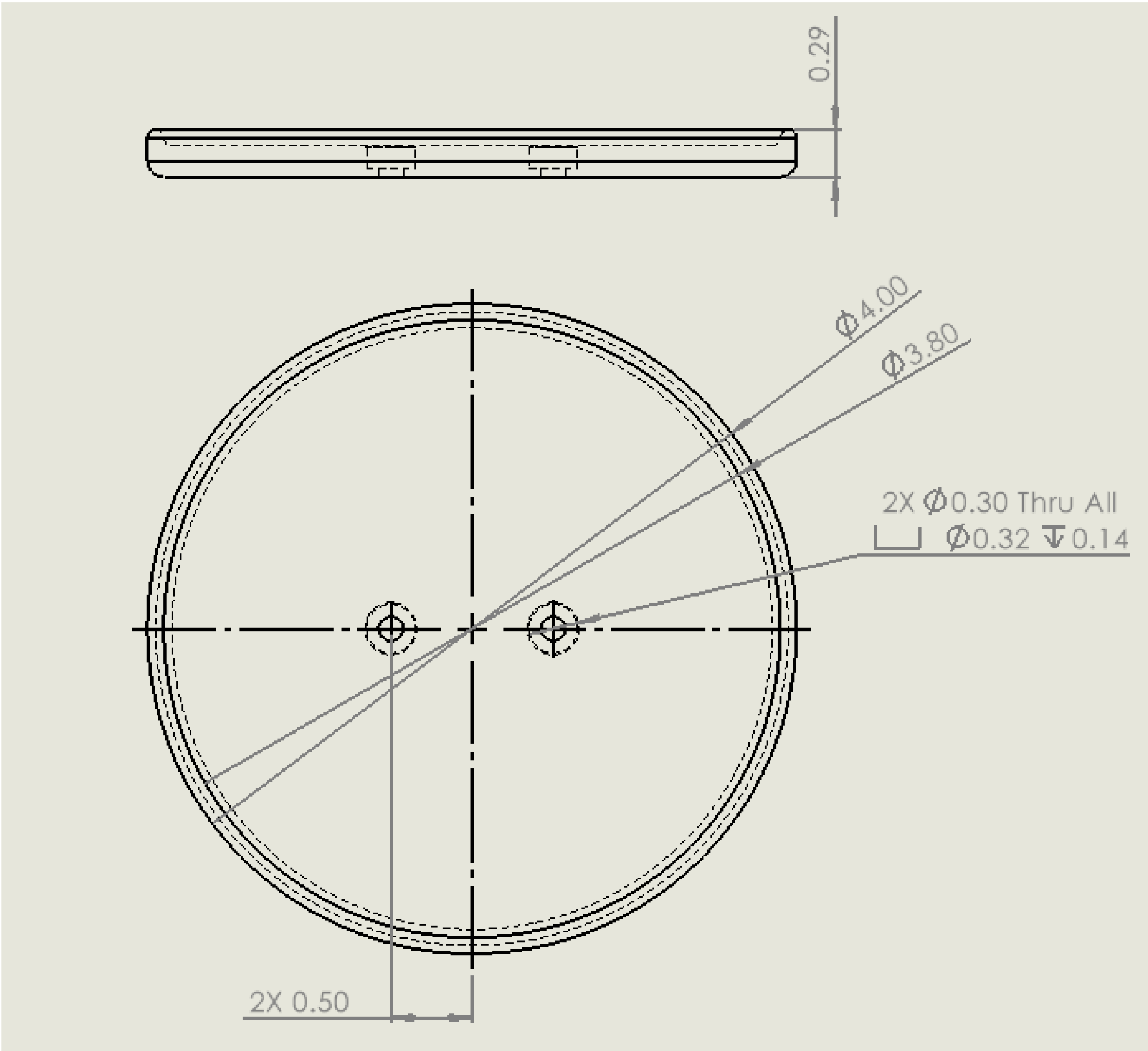
Benchmarking sheet also available here:
https://docs.google.com/spreadsheets/d/1Y0TPYSNpn3pBtjp48F3Iozze65qLkiXP0BwnX9lVFe
k/edit?usp=sharing

APPENDIX H: BATTERY BENCHMARKING

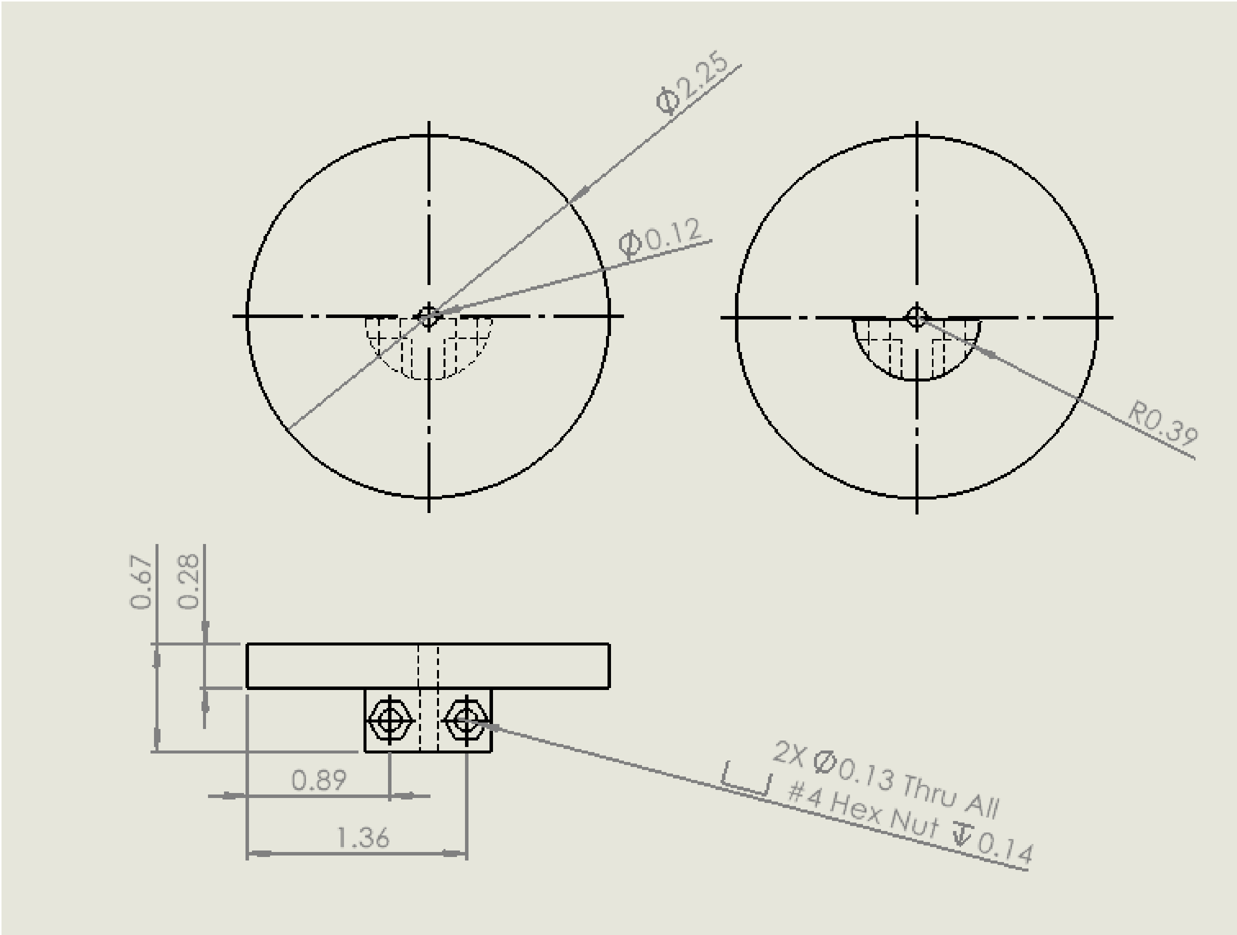
Name	Price	Supplier	Capcity	Size	ROHS Compliant	JST-Xh-3p connector	charger included	notes
Zeee 2S	$25.99	Amazon	2000mAh	67mm x 37mm x 19.5 mm	Yes	yes	yes	two batteries and charger
Turnigy 1000	$3.48	Hobby King	1000mAh	72mm x 34mm x 14mm	No	Yes	No	
Turnigy 1600	$6.26	Hobby King	1600mAh	69mm x 43mm x 16mm	No	Yes	No	
URGENEX 7.4	$24.99	Amazon	900mAh	53mm x 23mm x 16mm	No	Yes	yes	two batteries and charger
RadioMaster 5000	$15.99	Heli direct	5000mah	72mm x 42mm x 22mm	Yes	yes	No	

Benchmarking sheet also available here:
https://docs.google.com/spreadsheets/d/1df7yT1Na79WKPJPKBxknfHAWZF7hELqMBhPyUd4m-pQ/edit?usp=sharing

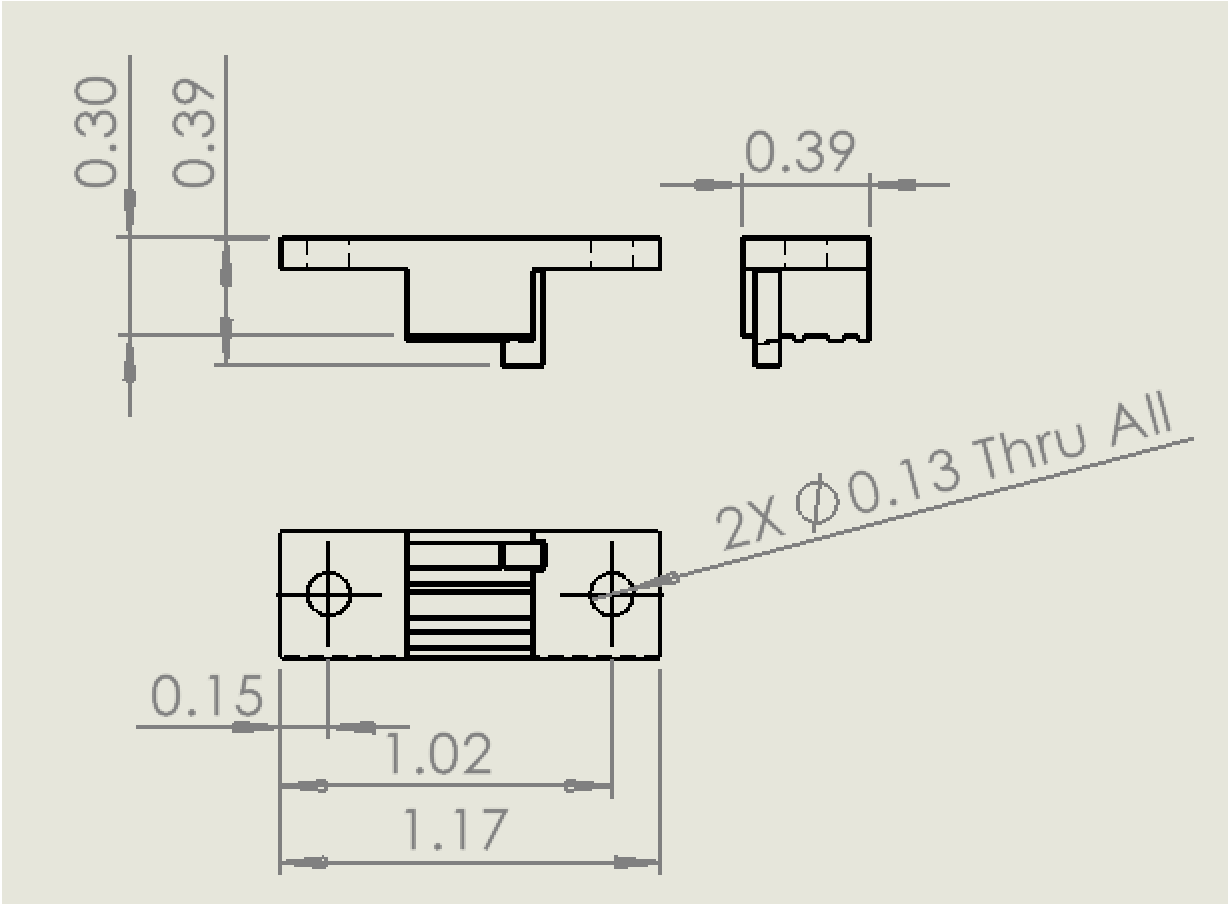
APPENDIX I: PART DRAWINGS



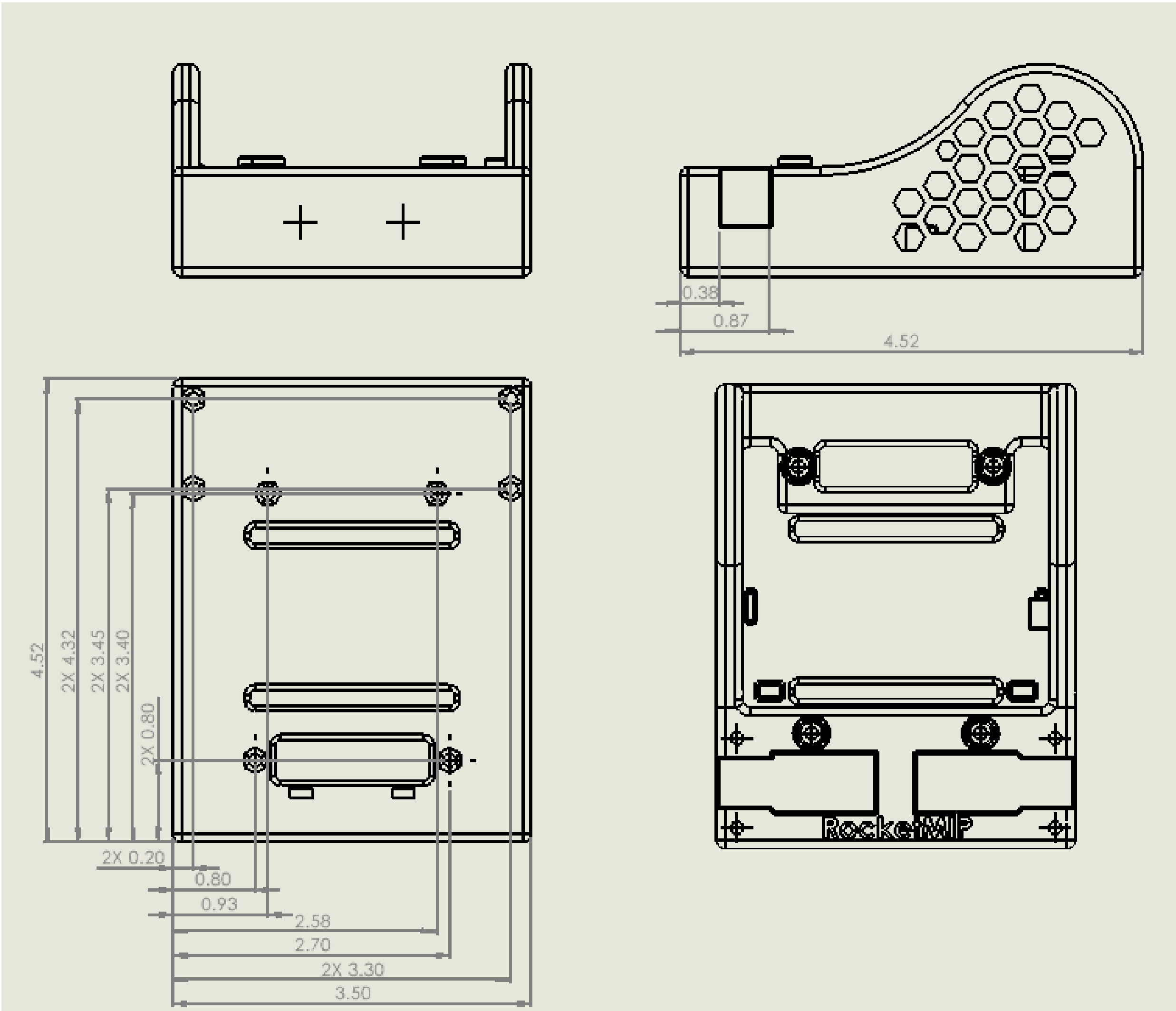
Top Plate



Wheel



Motor Bracket



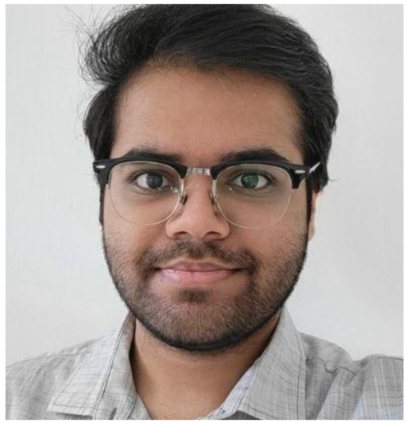
MIP Main Body

BIOS

My name is Michael Maynard, I am a senior majoring in Mechanical Engineering and minoring in Electrical Engineering. I am from the small town of Leslie MI, where I currently reside and coach robotics. I became interested in mechanical engineering at a very young age. As a child I was always taking things apart and trying to figure out how they worked (even though after I got a hold of things they often ended up with missing components). My electrical background and interest comes from the christmas light show that I have worked on since I was 10. Every year over the thanksgiving break I work outside to put up thousands of lights and computer controllers. Our display has grown over the years to span our entire yard and house, with the addition of computer controllers and "smart" lights we now synchronize most of the props to music. The light show never would have existed without the influence of my great grandmother who decorated her entire farm back in the 70's and 80's. A lot of the show elements that I now utilize were her original wireframe yard ornaments that I have stripped down, restored, and installed LED lights on to. Another thing that is really important to me and my draw to this specific project is my association with the Leslie robotics program. Originally my senior year, my AP Calculus teacher and I founded the team in her classroom. I was brought in as the Technical coach two years ago. Just over the last two years that I have been back involved with the team we have seen great advancements from the team and have even expanded the program to now include a high school team, two middle school teams, and five elementary teams. The program is definitely a large time commitment but giving them the opportunity to increase their technical knowledge and get hands on with manufacturing has been invaluable to furthering my knowledge and our community. In terms of future plans, I have been working with Dart Container over the past two summers in both the plastics operations and machine design sectors and have accepted a position in the plastics department after I graduate.

Hello, my name is Benjamin Wong and I am from Brownstown, Michigan. I am currently a senior studying mechanical engineering with a concentration in manufacturing at the University of Michigan. I chose to major in mechanical engineering mainly due to my interest in mechanical components. Legos were one of my favorite toys growing up so mechanical engineering seemed like a natural path to continue my curiosity of how things work and how everything fits together. Also, my father just retired from working over 34 years at Ford Motor Company. Something I always looked forward to every year was Take Your Kids to Work Day. I really enjoyed going and seeing what my father did every day and jumping in the newest cars that Ford had to offer. During the summer after my sophomore year, I was able to follow in my father's footsteps by working as a Product Development Intern at Ford on the Computer Aided Engineering Vehicle Component Validation Team. This past summer I decided to change companies and work at Caterpillar as a Product Development Intern in the Medium Tractor Products on the Electrical Installation Team. After college I will be joining the workforce at Caterpillar where I work in product development within the Medium Tractor Products arm of the company. Outside of school and work I enjoy rock climbing, hanging out with friends, and trying out new places to eat. I am really excited to see my project develop this semester and hopefully have it production and release ready by the end of the semester. Go Blue!

My name is Dylan Fisher. I was born and raised in the small village of Shepherd, Michigan. I come from a community and family (both sides) of farmers which had a substantial impact on my interest growing up. I always helped my father work with and fix equipment and I also spent some time working with my older brother in his metal fabrication shop. We were always a family that enjoyed hobbies such as boating, side-by-siding, and biking. My experiences with these different mechanisms of travel always fascinated me and increased my interest in the study of how things moved and the ways in which we could control methods of movement! As of now, my educational interests most align within mechatronics. I am currently working part-time in test and development with the company Pratt Miller through the school year. They are involved in a variety of motorsport, defense, and mobility projects and are most well-known publicly for leading the competition and development of the corvette racing program in partnership with GM. I also finished an internship with them this past summer as a Production Engineer. My future plans are to take time off from school to thoroughly develop my career interest and get back to spending more time on my personal hobbies! You'll find me every summer in northern Michigan on Burt lake kayaking, swimming, wakeboarding, and jet skiing. I also enjoy longboarding, cooking, road trips, hiking, and video games!



My name is Mohammad Monem. Although I was born in the city of Lahore, Pakistan, I moved to the state of Michigan when I was just a few months old, coming with my father, a researcher who now studies Immunology at the University of Michigan. I grew up in Ann Arbor, just minutes away from the campus, and during my childhood I developed a strong interest towards building physical things like LEGO sets and models. As I progressed in my studies, I became interested in mechanical engineering because the idea of creating new, complex, and physical inventions appealed to me. A fun fact is that whenever I tell anyone about my major, they always assume that I chose it because I was interested in making cars. Now, while I like cars, my real passion has been in applying my technical skills to help make a positive interest in the world. One of my main areas of interest throughout my studies has been improving the state of STEM education in the US, such as by helping grade-school students learn how to 3D print. Along with additive manufacturing, I also am interested in the field of mechatronics and am considering studying this field as part of a graduate degree. My future plans are to continue to remain in Michigan and work on research that aligns with my aspiration of making a positive impact in the world through technology. I am also interested in going back to further my education after gaining more experience.