Team 506: FPL Material Handling Robot

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Abstract

Automated warehouses are a growing industry popular for using advance technology, such as robots, in storage facilities. Robots help improve storing and fetching of packages while also lowering employee costs. These robots can change how a warehouse functions by replacing human workers and can work in dark spaces. A company can lower costs of utilities and employment by including robots in their warehouse. Pursuing this project will not only increase profits but will reduce safety hazards that can affect human workers still working in the warehouse.

This project develops an autonomous mobile robot that can work in dark warehouses. The robot is independent enough to track, receive, and store packages on its own. However, the robot will need human aid if something goes wrong in the warehouse. To track packages around the warehouse, packages will have a quick response (QR) code, which are like barcodes except they store more data. These codes are also helpful for creating a map of the warehouse for the robot. Black lines placed around the warehouse shape the robot's path and lead it to each package spot. The robot features a forklift device to lift and hold the packages. For testing, the robot will work in a scaled down warehouse including black lines, QR codes, and packages on small pallets.

This project allows us to practice joining a variety of subjects in a team setting to achieve a common goal. Each member can expand current knowledge they have of their own studies while gaining new skills. The mechanical engineers can improve their robotics skills while learning about online networks and path-planning. Computer and electrical engineers practiced creating databases and general programming skills, while also taking part in building a system.

Acknowledgement

We would like to thank the FAMU-FSU College of Engineering for sponsoring our team by providing us with the budget, materials, and tools necessary to design and building our project; the space for constructing and testing our design; and the faculty to advise us on design decisions to reach our goal.

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Additional thanks goes to Joshua Jones and Melanie Munroe for giving their time as teaching assistants for the class and for aiding our team in our project and answering related questions.

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Notation

ME	Mechanical Engineering
ECE	Electrical-Computer Engineering
EE	Electrical Engineering
AGV	Automated Guided Vehicle
AMV	Autonomous Mobile Vehicle
FAMU	Florida Agricultural and Mechanical University
FSU	Florida State University
AHP	Analytical Hierarchy Process

Chapter One: EML 4551C

1.1 Project Scope

Project Description: The objective of this project is to create an autonomous material handling robot that can work in a dark warehouse in conditions unfavorable to human workers. Achieving the objective will aid in the decrease in cost of operations by reducing the need for manpower or around the clock utility usage hence optimizing profits for the sponsor.

Key goals:

There are several key goals this team will be striving to meet. Regarding functions, the robot will move autonomously and will be capable of lifting a minimum load of 25 pounds. The robot will be able to detect obstacles and alert handling personnel when the robot needs assistance. Also, an interface will be included so handlers can track inventory as the robot navigates through the warehouse while providing real-time updates and error alerts for servicing. Additionally, the robot will be equipped with the tools necessary to reach spaces without damaging the product/item the robot will be handling. To ensure all goals are met, the team will design a model of the robot along with a model environment it is intended to work in to showcase the functionality as well as necessity of the system. By adding features of autonomy, user controls, and obstacle detection the robot should be able to maneuver itself in a dark warehouse environment allowing the customer to re-evaluate their need for manpower. The robot will also be able to be recharged.

Markets:

Primary markets would be warehouses that aim to reduce expenses from human workers and increase productivity (i.e. labor, A/C, heating, lighting of warehouses, and human injury costs). Secondary markets include a hardware store, such as distribution centers. Secondary markets can also include physical stores that can use robotics for inventory and stocking purposes. Another possible secondary market could include places like libraries, where the inventory is constantly being reshuffled, requiring constant organization.

Assumptions:

Several assumptions were made to better define and control the scope of the project. One of the assumptions includes that the robot will be operating in a relatively flat warehouse environment. The robot will be inside and will not have to be constantly traversing rugged terrain. To prevent logistical issues, only robots will be handling materials in the warehouse, human workers would only have to interfere if the robot needs assistance. The robot will be handling pallets specifically with materials or products packed on top of it. To provide an interface for inventory tracking, products that will be managed will have a machine-readable code that will allow the robot to collect and display data. The robot will have a wireless connection and Bluetooth module along with a series of sensors that will control the robot's movement and functions. Although the robot will send error alerts through an interface, , maintenance will be provided by a third party. . Finally, the robot will support a load and set it down without any liabilities. The assumptions above do not hinder the possibility of every key goal being met yet provides adequate boundaries that limit the scope of the project.

Stakeholders:

There are several stakeholders in this project, one of them being Dr. Hooker. He is the project sponsor and provides input on what direction the project will take, as well as answers questions the team has on the project. Dr. McConomy also holds stake in the project because he similarly answers questions on the project and aids the team. Dr. Ordonez, the ME team's faculty advisor, and Dr. Harvey, the ECE team's faculty advisor, both use their time to guide and advise the team on different possible methods and design choices for achieving the desired goal. The teaching assistants for the senior design class, Joshua Jones and Melanie Munroe, are stakeholders in the project since they use their time to help and answer questions concerning different aspects of the project. Another stakeholder is the FAMU-FSU College of Engineering. The College of Engineering is providing the resources for the team to complete the project, and the college gains a better reputation when students' complete projects that achieve the desired solution.

1.2 Customer Needs

In order to retrieve a list of customer needs, a series of questions was presented to the sponsor so the team can get a clearer idea of what specifications to make regarding the robot. Questions varied including topics of functionality, desired environments, purpose, and desired outcomes.

Table1: Customer Needs

What is the purpose of this robot?	The robot must be able to retrieve and deliver things in a warehouse setting. -Customer	Robot is autonomous in nature and capable of data-processing.

What are the surroundings and environment the robot will be operating in?	It will be used in a warehouse setting. The robot should be able to operate in conditions that are unfavorable to humans (i.e. hot temperatures that could make workers pass out or get heat strokes). -Customer/Dr. McConomy	The robot is able to navigate around a warehouse.
		The robot is able to sense and navigate around obstacles.
		The robot can perform tasks in the dark.
		Also, will perform in temperature conditions undesirable to humans.
What kind of items should the robot be able to handle? (Approximate weight)	Following OSHA regulations, a person should not be able to carry more than 50 lbs. If the robot were to malfunction a worker must aid it. Thus, the robot should carry a max load of 50 lbs. -OSHA	The robot can carry packages up to 50 lbs.
		The robot will follow OSHA regulations.
		When the robot malfunctions, it sends out an error alert for servicing.
What kind of retrieval methods should the robot achieve?	The robot should be able to pick things in a vertical and horizontal motion. Also, items shouldn't be damaged when being set down. -Customer	Robot will have multiple degrees of freedom for movement.
		Robot includes grasp force and manipulation control to prevent damaging items.
Would you want to have a handling input device?	"The robot can be operated under supervisory control. " -Customer	The user will operate and control the robot if desired.
What forms of power supply are accessible to	The robot has to have some way to recharge its battery fully so it can be active all hours of the working day.	Robot can operate over a 9-hour period before it has to recharge.

you? What kind of power source do you prefer?	-Customer	Robot navigates to an area where it can receive charging before the battery runs out.
Do you need the robot to track inventory as it delivers items?	Yes, it must be able to interface with our supply chain system	The robot will include modules to process machine readable codes and deliver information.

1.3 Functional Decomposition

To expand on the scope, the project is divided and broken down into subsections that best describe the basic functions and performance of the system. For analysis, a cross reference table and hierarchical functional decomposition breakdown chart is utilized to develop more insight of the system. The purpose of the product is to diminish cost while adding efficiency in supply chain management. By performing this decomposition, the team can cross reference tasks and actions while seeing which areas need to be prioritized as well as allowing room for simplifying the design. These primary general functions were determined based off the customer needs and how the system can fulfill them.

After acquiring our customer's needs and accumulating background research on the problem, the team was able to configure a list of key goals that encompass the desired performance of the system. With the reference of both the project's key goals and customer needs three major areas became the primary functions for the system: locomotion, manipulation, and navigation. Locomotion involves the physical movement of the robot since it is important that the robot can move around the warehouse. The function, manipulation, covers the package handling aspect of the robot. This is included since the robot will be moving and carrying the inventory to its desired location. Navigation is a key function that is included because the robot will be able to move partially autonomously. These main functions were defined to fulfill the customer needs of the project.

Although each function of the project is important for the project's success, it is useful to rank them to help with prioritizing them. The most important function to accomplish the project's objective is navigation. The objective of the project involves creating a robot with that is able to move with human guidance and with some level of autonomy. The more this system is improved, the more autonomous the robot would be, and making the robot more autonomous is the more difficult part of the project. Because of its vastness, the room for improvement in the field of autonomy with respect to this project is very large. Manipulation is the next most important function. This is chosen over locomotion because, while many robots can move, handling the inventory is something that is distinctive to this robot and is important in fulfilling the objective. Additionally, it is important that the inventory is not damaged by the robot, and manipulation has the greatest affect on this. Locomotion is still important, however, as the robot needs to move around the warehouse smoothly and effectively.

A useful tool the team used to better break down the robot and what it needs to do was a hierarchy chart. This chart starts with the overall project, breaks it down into functions, and continually breaks down the functions into sub-functions until the smallest possible function that defines the robot's performance is reached. It is important when constructing this chart to distinguish describing outcomes and physical actions from specifying solutions and equations. The purpose of the chart is to display what the robot does at the most basic level, but it does not describe how this will be done. Once all functions are stated, branches can be compared for any similarities to enhance streamlines or intersections between function.

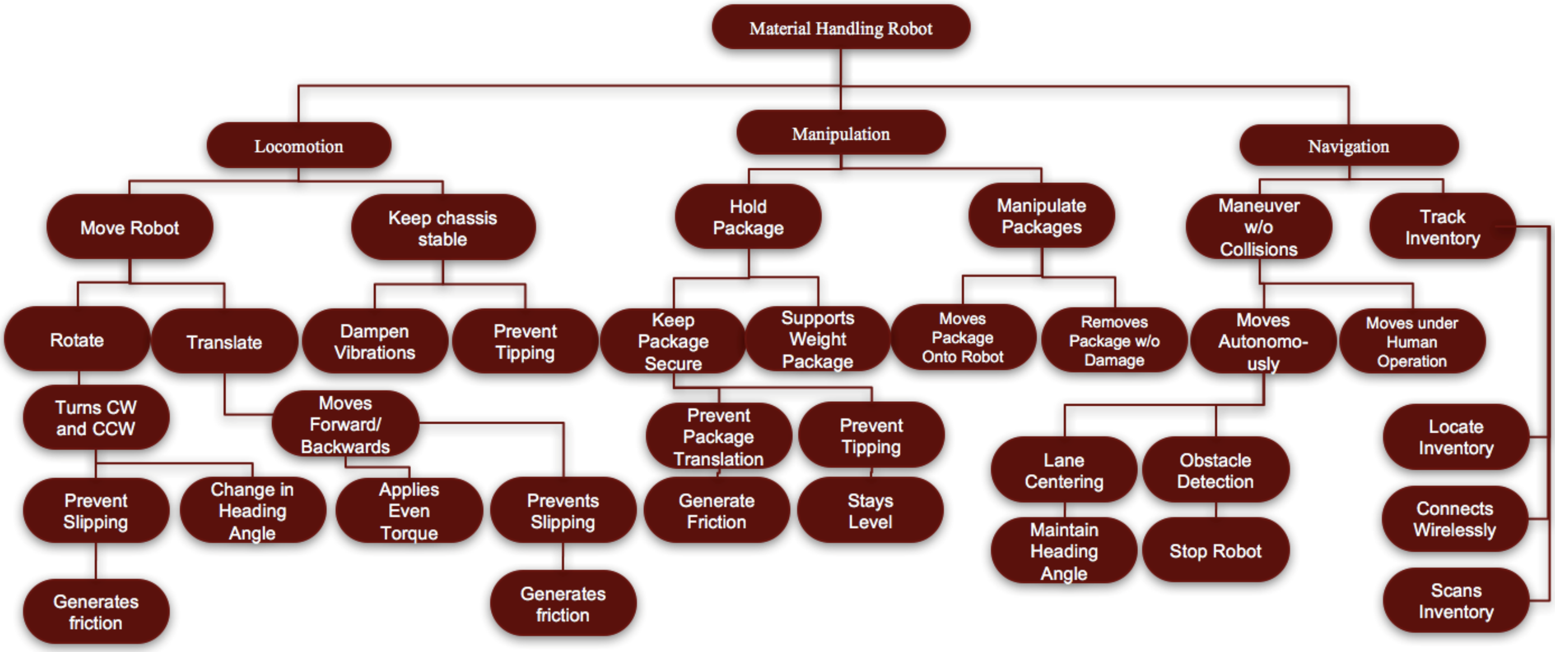


Figure 1: Functional Decomposition Hierarchy Chart

The first level of subsystems of the main functions were gathered from the customer needs of the robot and describes what the robot needs to do to perform successfully. These describe the robot's general actions it needs to perform. For locomotion, the general actions the robot needs to perform are to move and keep the chassis stable. The robot needs to be able to physically be able to move and stay stable so it can take and deliver inventory around the warehouse. Under manipulation, the robot will hold the package, or inventory, and manipulate the packages. Since the robot is delivering inventory around the warehouse, it needs to be able to manipulate, or move, it in some way, as well as hold it to transport it around the warehouse. The general functions under navigation are maneuver without collisions and track inventory. The process of collecting inventory data and tracking inventory falls under navigation because the robot is required to track the positions of the inventory it is handling during operation. The robot will not have collisions so it does not bump into shelves and objects, which could cause harm to the robot or inventory.

To further break down the functions, the team discussed how the robot would perform each function without specifying a solution. The functions needed to be broken down to a level that describes what is physically going on internal to the system. For example, for the robot to move successfully, it needs to translate and rotate. The purpose of this is for specifying what the robot needs to do at a fundamental level. Essentially, for a robot to move, a torque needs to be applied and friction generated, for example. Breaking the project down this far will make it easier to determine the targets and metrics the robot needs to be able to meet.

It is also important to note that there is overlap in the functional decomposition. The smallest functions the robot performs in one system can cross over and relate to another system, or function. This is useful to know because two functions can be integrated into one physical system on the robot. This was represented using a cross reference table, where the smallest function elements of one main system were compared to see if they could be applied to another main system. The cross-reference table is shown below in Table 1:

Table 2: Cross-Reference Table

Function	Systems		
	Locomotion	Navigation	Manipulation
Applies even torque	X	X	
Generate friction	X	X	
Change in robot heading angle	X	X	
Dampen vibrations	X		X
Prevent tipping	X		X
Moves package onto robot			X
Removes package without damage			X
Generate friction with package			X
Stays leveled			X
Supports package weight	X		X
Moves under human operation		X	
Maintain constant heading angle	X	X	
Stop robot	X	X	
Locate Inventory		X	
Connect wirelessly		X	
Scan Inventory		X	

The cross-reference table displayed the cross-over of several functions into another system. The functions torque, generate friction, and change robot heading angle are shown under the locomotion system, but can applied to the navigation system, as well. While they are vital to the locomotion, which allows the robot to physically move, these functions affect the robot being able to maintain following a certain path. Applying torque and changing the robot heading angle can be applied to help keep the robot straight and prevent it from veering off course, for example. Additionally, dampen vibrations and prevent tipping can be applied to both the locomotion and manipulation functions. These are under both these functions because locomotion and manipulation will work hand in hand since the package or inventory item will be on the robot as it is moving. Vibrations should be dampened and tipping prevented so the robot rides smoothly and is more stable, and this will keep the package from being damaged or from falling off. Supports package weight crosses into manipulation and locomotion systems because we need to ensure the robot can safely pick up the load and traverse around the warehouse while supporting it without failure. Maintaining a constant heading angle and stopping robot are functions that both are in the navigation and locomotion system because they are crucial for the robot's movement and path of direction.

The crossover between these high-resolution functions opens possibilities for improvement and smart integration in the system. Navigation and locomotion together provided the most opportunity for smart integration since their high-resolution functions cross over between each other the most. This is because they both work hand in hand for the robot to successfully traverse around the warehouse.

The outcome of the project will be a robot that is can be controlled by a human and that can also operate semi-autonomously in a dark warehouse. It will be able to track and move inventory to a desired location. Because of this, a company can save costs that would typically result from human employees, such as lighting and air conditioning. The robot will also eliminate errors that humans tend to make from tedious work. Additionally, inventory can be taken more often than once a month, which is typically done by humans. More work will also be done since a robot can work overnight and on holidays, which are times humans may prefer not to or are not physically capable of working.

1.4 Targets and Metrics

After the functions for the material handling robot are defined, a target and metric must be assigned to each function. A metric defines a parameter for how a function will be met or validated. The target that is assigned to the function defines a quantifiable goal, aligning with the metric, that the robot must achieve to properly perform a desired function. The full target catalog can be in the Appendix C in Table C1. From the Full Target Catalog, the critical targets and metrics are selected and further evaluated. These are the targets and metrics that need to be met so the project can be successful. Different processes have been explored to develop a method of validation for defined targets. Some of these validations can be very simple, while others might require more validation tools and measurements.

Mission Critical Targets/Metrics

The targets and metrics deemed as critical, meaning they are needed for the success of the project, are shown in Table 2 below:

Table 3: Critical Targets and Metrics

Attribute	Target	Unit of Measure	Metric	Description

Change Heading Angle	360°	Degrees	Angle	Robot turns in any direction.
Applies Even Torque	<1%	Percent	Error	Robot applies even torque on both sides of the wheels to move straight.
Moves Package onto Robot	224 N	Newton	Force	Robot can lift a package inventory.
Maintain Heading Angle (Relative to Path)	0°	Degrees	Direction	Robot accurately follows path.
Locate Inventory	1	N/A	Boolean	Robot knows where inventory belongs and takes/retrieves inventory to the correct location.
Connect Wirelessly	1	N/A	Boolean	Robot can successfully connect to inventory database and be controlled wirelessly.
Scans Inventory	1	N/A	Boolean	Robot can scan a label and identify inventory.

Adjusting the heading angle and even torque distributions are two critical targets included for the development of the robot's locomotion. The robot needs to be able to move and these targets and metrics mean the robot can move forward and backwards, as well as turn in any direction. "Moves package onto robot" indicates that the robot needs to be able to lift and lower the inventory as needed. One of the general purposes of this robot is to be able to handle and move inventory, so this was deemed a critical target and metric specifically for manipulation. Maintaining the heading angle is critical to the project for the sake of added accuracy; this metric is necessary in cases in which the robot must travel strictly in one direction. Locating and scanning inventory along with connecting wirelessly to an interface are critical metrics due to the needs of the customer. Our team will utilize a Boolean metric, or yes/no set up, so the robot is able to indicate when and whether it should perform the action.

Derivation of Targets/Metrics

Different methods were used to derive the targets and metrics for each function, since different physics or goals are involved. The target for "change in heading angle" is 360 degrees, with angle as metric, since this establishes that the robot can change its orientation to any direction it needs to. The robot will be capable of rotating 360 degrees in both clockwise and counterclockwise directions.

The function, "applies even torque," has to do with the robot's ability to move. A metric of "error" and a target of less than 1 percent were given to this function. This indicates that the motors on the robot allow the robot to move forward and specifies that the difference between the torques applied to the different robot wheels must be minimal so the robot can move straight and not lopsided.

"Moves package onto the robot" entails the robot physically lifting inventory, so a metric of force and target of 224 Newtons was applied to it. This target was found from OSHA regulations, which state that a worker in a warehouse must not be required to lift more than 50 pounds (224 Newtons). Although the robot may not necessarily be lifting all this weight, it must be capable of doing so.

The ability to "maintain heading angle relative to path" is crucial for the robot to effectively be able to navigate the warehouse without accidental collision. The function has a metric of degrees referenced to its path of direction, and an assigned metric of 0 degrees to ensure the robot will only travel on the desired path.

For the robot to understand what package it is manipulating and where it is going to be relocated, it must be able to scan and identify the inventory. Once the inventory is identified it must be able to locate the desired drop off location. A boolean metric was used for these two functions, a target of 1 to represent "yes" (whereas a 0 would represent "no"), was used to ensure while our robot is in use it can successfully scan, locate, and deliver packages within the warehouse.

Finally, the ability to connect wirelessly will allow the robot to traverse the warehouse and remain in connection with the user interface. This will ensure that the robot is constantly displaying the inventory it is manipulating and delivering throughout the warehouse. The target for this function is 1 representing yes, and the established metric is Boolean. The connection should be reliable throughout the entire warehouse to avoid losing connection while delivering or retrieving a package.

Some targets and metrics were determined using kinematics; establishing one target and metric would allow for calculating the next. A target and metric were created for controlling velocity of the robot. This was taken to be for the robot to be able to travel at a velocity of 2.25 meters per second. This was target was determined using benchmarking. An Amazon warehouse robot travels at a maximum velocity of 5 miles per hour, which converts to about 2.2

meters per second. Our robot will be able to travel at a faster speed than this. Additionally, a target and metric were created for accelerating the robot. The purpose of controlling the acceleration is so an inventory package will not fall off where it is held on the robot from the robot stopping or speeding up too quickly. The target for the robot to accelerate at a magnitude of about 1 meter per second squared was determined using kinematic equations. The known factors to do this were final velocity and initial velocity, which was just calculated (0 and 2.25 meters per second), as well as time to accelerate between the two, which was taken to be as 2.5 seconds. Using kinematics and the calculated acceleration and velocity, the target and metric for "senses obstacle" was found. The robot needs to be able to sense an obstacle at least a specified distance away, calculated to be 2.5 meters, so the robot slows down in time before colliding with the obstacle. Friction between the box and the robot/lifting mechanism was also calculated using the acceleration of the robot and mass of a 50-pound package, so enough friction would be generated so the package does not slide or fall off upon slowing down or speed up.

Method of Validation

There are multiple factors that must be considered to test the target and metric for moving the package. One important test that must be done is to test whether the lifting mechanism is able to produce enough force to lift a package. This can be tested using kinetic and kinematic analysis along with recording data during testing. Due to the nature of the packages that will be handled, the kinetic measures between the robot and loads are crucial for executing proper performance. To ensure the robot is capable of loco manipulation, the dynamics of the system will be modeled using MATLAB and Simulink. Simulations of the robot's dynamics will be developed along with testing the controls of the robot. The materials of the lifting mechanism must also not fail. To test these, a sample component of the lifting mechanism would need to be made used, whether that be through machining or being bought. This can be tested by securing the specified components of the mechanism and then applying the target force to them. For example, if a forklift mechanism were used, the forks would be secured, and the specified weight of 224 Newtons would be applied to the tongs to test whether the material yields or not. Weights would be needed for this test.

The function involving applying even torque can be measured by putting tape on the ground in a straight line and commanding the robot to move straight along the line of tape. If the robot moves off the straight line of tape, one can observe that even torque was not applied to the wheels. Once it is verified that the robot is physically able to move straight, testing can be done on whether the robot is able to accurately follow the specified path. This can be tested in a similar way. Tape can be placed on the ground mapping out a specified path to follow and test whether the robot is able to stick to the path. Additionally, barriers on the side of the path can be put up to mimic shelves to imitate a more real warehouse setting. Essentially a task-based performance testing method would be applied. The change in heading angle can simply be validated by commanding the robot to do a full 360-degree rotation and watching the angular displacement of the front of the robot.

Validating whether the robot scans inventory can be done by holding a scannable code in front of the scanner on the robot and checking if the robot received the data from the code. The scanner, which would be attached to the robot, is needed, as well as a sample code. Validating if the robot can locate inventory can be done by commanding the robot to go to a specified inventory object and seeing if the robot is able to find and stop at the location. To test this, a mock warehouse setting would need to be set up. This can be small scale, however, and would only require a section of the warehouse, such as a few shelves and some space to move around. Note that barriers with similar shapes as shelves can be used, such as tables or chairs, for example.

Target Summary

The targets and metrics focused on finer more specific functions within the overall functions of locomotion, manipulation, and navigation. Locomotion has to do with the overall physical movement of the robot. The locomotion targets and metrics had to do with the applying torque to the wheels, controlling robot kinematics, rotating, and friction between the wheels and the ground. These were represented by metrics of force, angle, velocity, acceleration, and error. The robot needs to move straight and turn, as well as maintain an appropriate speed. These locomotion targets and metrics involved more physics and dynamics calculations compared to determining the targets and metrics under the other main functions.

The manipulation function has to do with the robot handling the inventory. Several of the manipulation targets involved the package weight, including supporting its weight or generating enough friction so the box does not fall or slide off when the robot accelerates. These were consequently represented by metrics of force.

Navigation involves the robot's ability to locate and find inventory around a warehouse. Multiple targets and metrics for navigation are represented using Boolean metrics since several functions are tasks the robot can either do or not do. For example, when it comes to scanning inventory labels, the robot can either scan the inventory or it cannot. Another example is the robot sends an error message or not when an obstacle is present. Additionally, obstacle sensing was included, and the kinematics used under the locomotion targets were taken into consideration for this.

1.5 Concept Generation

Generation Tools

The team developed several concepts to begin creating plausible alternatives for the final design of the project. Different methods of concept generation were explored to develop enough suggestions that met the needs of the customer's as well as the targets. One tool used to generate a multitude of different ideas was the morphological chart. With over 50 suggestions produced from this chart, our team was able to envision all forms of design ideas to satisfy the needs of our sponsor. Not only was a morphological chart utilized but other methods of concept generation were employed to create more reasonable and detailed descriptions of design suggestions such as, but not limited to, biomimicry analysis, battle of perspectives, developing anti-problem situation, and generic brainstorming.

Though the morphological chart was our first approach several other tools were used to develop potential design ideas. Biomimicry was utilized to explore natural structures and behavior to inspire concepts for the robot. Animals/species that exhibited grasping qualities were explored such as octopus suction cups or sharp claw end effectors like an Eagles talon. Biomimicry allowed our team to seek solutions that already exist but may be invisible to the naked eye. Moreover, another analysis was also used called battle of perspectives. Situations were created with two different stand points and the team was split in half to generate ideas. Based off the side a team member was one, each member had to contribute a "perspective" that supported the side they were on. This technique was used to develop ideas for situations like a warehouse being ran by a senior, veteran manager versus a younger, new manager or another situation where one warehouse handles massive loads of packages whereas the other warehouse only handles small, varying packages. A third analytical technique that was used was developing anti-problem situations. The team thought of inconvenient circumstances that may occur with this kind of robot and a potential solution that can be applied; the solution is then considered a potential design concept since it would still hold qualities desired by the customer. Finally, to produce more creative, free-ranged concepts the team finalized the concept generation process with some brainstorming sessions. For brainstorming, our team met two different times to openly discuss concepts and feed off each other's suggestions. The culmination of all these techniques resulted in the creation of 100 different suggestions and the specification of medium and high-fidelity concepts. From these fidelity concepts, a final selection will be made after further comparative analysis.

Medium Fidelity Concepts

For the first medium fidelity design idea, a basic Ackermann design approach is considered with front wheel drive specifically. The drive system is meant to control the system from the front two wheels, assuming a four-wheel vehicle design is used. The system would be powered using a cord capable of plugging into a standard plug. Regarding manipulation, an end effector comprised of two clamps capable of grasping materials would be used to support the loads while being moved with. For navigation and path following, a GPS system will be utilized along with a Barcode scanner system. The barcode scanner system would be assisted by a Lidar obstacle detection system not only for detecting when something is in the robot's path but to identify where the barcodes are.

The second medium fidelity concept uses a similar design, but this concept utilizes an Ackermann design with rear-wheeled drive meaning the system's direction is defined by the rear wheels movement. This system would be battery powered and using black line paths would be strategically placed all along the warehouse floor, so the robot is able to navigate as well as include a GPS module for added efficiency when inventory tracking. Once the desired inventory is located, a barcode system would be used to identify specific products whilst using a push sensor bumper to prevent collision.

The third medium fidelity concept also incorporates a rear wheel drive Ackermann that is powered by alkaline batteries. Alkaline batteries are generally cost effective, less harmful to the environment when disposed correctly, and have fewer chances of exploding during handling. This system would be directed using induction wires in the floor and attached would be a push sensor bumper for collision prevention. To manipulate materials, the robot would have a mechanical hook capable of reaching for and pushing packages onto the robot so it could then be transported to desired location. Its navigation would be dictated by an induction wire that would be imbedded into the floor so when the robot roams the warehouse it is able to be controlled by the inductive electric fields. A GPS module would be used so the robot can identify exact positioning and April tags would be used for inventory tracking. Both the GPS module, and April tags are basic ways to perform functions for localizing and organizing without creating high financial burdens. Though effective in theory, it could present unwanted costs for our sponsor to utilize the path finding method in this concept.

The fourth medium fidelity concepts are driven using differential steering, meaning more torque is applied to one side of the vehicle than the other to cause the system to change direction. Unlike the other concepts, this concept utilizes lithium polymer batteries to power the system since they are compact in size and have high power density. Magnetic tape would be the primary way for the robot to localize itself within the warehouse. It would utilize a forklift-like configuration with two clamps used as end effectors for each leg. For navigation, this concept would utilize infrared sensors which are based off photo electric sensors rather than thermal. Accompanied with the IR technology would be RFID tags or radio frequency identification detectors; RFID tags emit electromagnetic fields as a mean to automatically identify themselves. Though magnetic tape is an efficient way of self-navigation and controlling the robots remotely, the tape itself can be costly.

The fifth medium fidelity concept uses differential steering with a nickel cadmium power supply. Nickel cadmium is known for having a great shelf life and highly established for industrial use. The end effector utilizes a single clamp/claw for manipulation and can grab/lift objects through this medium, especially singular materials/packages. Its navigation would be based on cost effective tools while still providing the basic functions necessary for localization. A combination of using pavement markers as well as a distance sensor would be how the robot navigates itself within the warehouse and is able to track inventory by scanning April tags specifying which package it is handling.

Though the concepts above show potential, the complexity and magnitude of the project did not seem to be met by some of the basic tools utilized in the medium fidelity concepts. Many of the concepts fulfill all the customer needs but do not hold the capacity to succeed within its desired environment because of the lack of capacity some of the tools hold or financial/technical obstacles that seems for costly in long term production than if more convoluted tools are used for concept selection. This is why some high-fidelity concepts were created since they hold more relevance and better chances of meeting usability needs of customer.

High Fidelity Concepts

Much like the medium fidelity concepts, details revolving main functions of the robots were specified to form a good as well as achievable design concept that will essentially be prototyped. The first high fidelity concept is like the second but with slight improvements. Rather than differential drive this concept utilizes omni-directional wheels for better mobility. Using the "universal" omni wheels, the robot would have four wheels positioned at a specific angle configuration while each wheel is connected a motor. Omni wheels have free rollers placed along the outer circumference of the wheel allowing the wheels to change direction more eloquently than your typical four-wheel, two-axled vehicle drivetrain configuration which supplies torque to all four wheels simultaneously. With omni wheels the user can control the robot with more precise movement, for example if the robot moves down a tight space and needs to return to a specific location, rather than the robot having to make a tight circle to make a 180 turn, the omni wheels allow the robot to instantly change directions solely from using the free rollers on the wheels. The power supply would still be lithium ion batteries since they are cost effective yet powerful enough to support the motors and sensors of the system. The navigation system will include three different factors: line path for self-navigation, ultrasonic obstacle detection for object detection, and infrared to determine how far or close the robot is to an object. To organize and track inventory, the robot will utilize QR codes for they are both standard forms of organization and inexpensive.

The second-high fidelity concept utilizes different drive for steering and is powered by lithium ion batteries. This approach is meant to maintain a high standard of functionality while using cost-effective resources to compose the robot. Localization will be executed using line path following along with infrared sensors. The line path is meant to help the robot self-navigate within the warehouse without human interference while the infrared sensors are meant to measure distance from the sensor to an object. For manipulation, fork-lift style design will be used to lift and transport materials. To regulate inventory, QR codes would be utilized for material identification.

The third, and final, high fidelity concept utilizes universal omni-directional wheels for steering; these are not to be confused with mecanum wheels, which are a different type of omni-directional wheels. For navigation, magnetic tape along with a lidar system would be used for localization and sensing where the scan code is. RFID tags would be used for inventory tracking and organization while a vacuum end effector would be used for material handling. Though vacuum end effectors can manipulate both large and small objects, they are highly expensive and outside of our budget.

1.6 Concept Selection

Once the ideation and concept generation are completed, there are a multitude of ideas to select an appropriate, or winning, concept. There are many different tools that have been created to go about this process, each relating to and contributing to another. For this concept selection, the tools are used in a specific order since they build upon one another. These selections tools are the binary pairwise comparison matrix, House of Quality, Pugh charts, and analytical hierarchy process (AHP).

Binary Pairwise Comparison

To determine the weighting of each customer requirement in the House of Quality, the binary pairwise comparison matrix is used. This involves comparing each customer requirement against the other. Each customer requirement is written on the side of the far left column, and they are written in the same order along the top row. Corresponding numbers are used on the top row for space and readability. The rows are compared to the columns. If the customer requirement in the row is deemed more important that the requirement in the column, it is given a 1, and it is given a 0 if it is not. If done correctly, the sum of each row is displayed on the right with the determined weight, or relative importance, of each customer requirement. The sum of the column of each customer requirement plus the sum of the row of the corresponding customer requirement should be equal to one less than the number of customer requirements. This is a method to check to make sure that two compared customer requirements, for example, were not both given a 1 or both a 0. The results of the binary pairwise comparison matrix is shown in Table 3 below in order of highest to lowest weight.

Table 4: Binary Pairwise Comparison Results

Binary Pairwise Comparison:		1	2	3	4	5	6	7	8	9	10	Total
Partial Autonomy	1	-	1	0	0	1	1	1	1	1	1	7
Obstacle Avoidance	2	0	-	0	0	0	1	0	0	1	1	3
Lift/Lower Object	3	1	1	-	1	1	1	1	1	1	1	9
Move	4	1	1	0	-	1	1	1	1	1	1	8
Scan Package	5	0	1	0	0	-	1	0	1	1	1	5
Manual Operation	6	0	0	0	0	0	-	0	0	1	0	1
Locate Package "Home"	7	0	1	0	0	1	1	-	1	1	1	6
"Dark" Navigation	8	0	1	0	0	0	1	0	-	1	1	4
Cost	9	0	0	0	0	0	0	0	0	-	1	1
Safety	10	0	0	0	0	0	1	0	0	0	-	1
	Total	2	6	0	1	4	8	3	5	8	8	90

From this, the top highest weighted customer requirements for the robot were lifting the package, being able to move, and partial autonomy. The highest weight of 9 was given to *Lift/Lower Object*. This is because without being able to lift the package, the robot is not a material handling robot. The robot will not have as much use in the warehouse if it cannot lift the packages. *Move* was given the next highest weight of 8, since it is important for the robot to change location. One purpose of the robot is to be able to deliver packages around the warehouse, and a stationary robot would be ineffective in transporting physical items around a large area. So, it is emphasized to be important that the robot can effectively traverse the warehouse. *Partial autonomy*, given a weight of 7 out of 9, can be described as the robot's ability to figure out and follow the best path to a given location. This was deemed as important since the purpose of this robot is to be able to replace humans for bringing packages to and from its desired location. Since the storage warehouse should only be used by the robot because human interaction could mess up the organization, the robot needs to be able to determine where things are and how to get there on its own, and this partial autonomy aspect of it is needed to do so.

The lowest ranking requirements were S*afety, Cost*, and M*anual Operation*. Although safety is important, the reason it has the lowest weight is because the robot is meant to work in a warehouse where there are no people. While the robot will be still be designed to be safe, its intended limited interaction with people makes this have less of a weight in terms of the design. Cost is also given a low weight when compared to the other customer requirements. The reason for this is the team will not be building a very large robot, since there is not enough time in a semester to do so. The robot will be scaled down for the purposes of this project, making cost have less of an effect on the project. Additionally, manual operation had a low weight. This is because the main goal of the project is a robot that can work on its own. While manual operation could potentially be a useful feature, the robot is still intended to work on its own.

The resulting weights of each customer requirement from the binary pairwise comparison matrix is used in the House of Quality in determining the most critical engineering characteristics.

House of Quality

The House of Quality is used to determine the ranking in importance of the engineering characteristics of the project in terms of best meeting the customer requirements. In this way, it infuses the voice of the customer into the design by allowing their needs and wants to help determine which engineering characteristics will help reach the desired end goal.

The relative weight of each customer requirement is taken from the results of the binary pairwise comparison matrix. The House of Quality uses a logarithmic scale to determine which engineering characteristics are critical for satisfying the customer requirements. This means the engineering characteristic's relation to meeting a customer requirement is scored as a 0, 1, 3, or 9. This allows each engineering characteristic to stand out more in its effect on meeting a customer requirement.This logarithmic score is multiplied by the weight of the customer requirement, and the sum of the column of scores multiplied by the corresponding weight (in the same row) is taken at the row that is third from the bottom. This shows the absolute importance. The sum of all the absolute importance values is taken as the raw score. The absolute importance of each engineering characteristic is divided by the raw score to find the relative importance. Based on what has the highest relative importance, the engineering characteristics are ranked. The results of the House of Quality are shown in Table 4 below in order of most highly ranked.

Table 5: House of Quality Results

House of Quality													
		Engineering Characteristics											
	Improvement Direction	↑	↓	↑	↑↓	↑	↑	↑	↑	↑	↑	↑	↑
Customer Requirements	Units	Nm	Degrees	m/s	kg	N	N	W	hours	1 or 0	m	m	m
	Importance Weight Factor	Wheel Torque	Heading Angle	Robot Velocity	Size	Generate Friction (Wheel)	Produce Lift Force	Rechargeable Power Supply	Time of Operation	Scanning	Path-Finding Sensor	Object Detection	Precision
Partial Autonomy	7	3	9	3	9	3	3	1	0	9	9	9	9
Obstacle Avoidance	3	1	3	1	0	1	0	0	3	3	9	9	3
Lift/Lower Object	9	1	0	3	3	3	9	0	3	3	1	1	3
Move	8	9	3	9	3	9	1	3	1	0	3	1	9
Scan Package	5	0	1	0	0	0	0	0	9	9	0	0	3
Manual Operation	1	1	3	3	0	3	0	0	3	9	1	1	0
Locate Package "Home"	6	3	9	3	3	1	9	0	3	9	3	3	3
Dark Navigation	4	3	3	3	0	3	3	9	3	9	9	9	3
Cost	1	1	3	3	1	1	0	0	9	3	3	3	1
Safety	1	3	3	3	1	3	3	3	1	3	9	9	0
Raw Score(1754)		140	176	162	134	148	179	70	132	249	190	174	217
Relative Weight %		8.0	10.0	9.2	7.6	8.4	10.2	4.0	7.5	14.2	10.8	9.9	12.4
Rank		9	5	7	10	8	4	12	11	1	3	6	2

The above table shows the ranking, in order, of the engineering characteristics in terms of satisfying the customer requirements. The top 4 most critical engineering characteristics are S*canning, Precision, Path-Finding Sensor*, and P*roduce Lift Force*, respectively. Scanning (rank 1) was determined to have the highest ranking. This is because it had a high relevance for several customer requirements with medium to high weights, including navigation around the warehouse, being able to scan a package, and knowing where a package is located. Precision (rank 2) had the next highest ranking. This has to do with accurately being able to “control” the robot. This does not mean to manually control but involves the robot’s ability to precisely line itself up with where it desires to be. This is important in being able to scan a package, accurately place a package in the correct spot (and not a few inches to one foot over to the right or left), and accurately follow the correct path, for example. The path-finding sensor (rank 3) characteristic is important because for the robot to complete tasks, such as navigate in the dark and choosing the correct path to transport a package, it must be able to accurately follow a path. This way it will have guidance and can be sure to reach the correct destination. Producing lift force (rank 4) was also deemed critical because the purpose of this project is for the robot to be able to transport the package to the desired location. If it cannot lift the package, however, it will not be able to effectively transport the package or place it onto a specified shelf. Rechargeable battery supply, time of operation, and size had the lowest ranks of engineering characteristics. While they are still important factors to consider, they are not as determinant of whether the customer requirements are fulfilled or not.

Because the engineering characteristics will be used in the Pugh Charts to compare different ideas, knowing the relative importance of each engineering characteristic to meet the customer's requirements is a valuable tool in determining an appropriate design from which concept works best.

Pugh Charts

Pugh charts are useful tools to compare concepts with one another. The engineering characteristics are used to compare each concept to a specified datum, which is what generally is used in industry. If a concept meets an engineering characteristic better than the datum, it receives a plus (+); if it performs that characteristic worse, it receives a minus (-); if it performs the same, it receives a satisfactory (S). The concepts with a lot of pluses are the better ideas, since they meet the engineering characteristics better than the current datum. Receiving too many minuses or satisfactory means the concepts are about the same or worse than what they are being compared to. These ideas are eliminated so the better ideas can be compared in following

Pugh chart iterations. For our Pugh charts, all engineering characteristics were used as criteria since this is a general comparison.

The first comparison Pugh chart is shown below in Table 5:

Table 6: Pugh Chart Iteration 1

Iteration 1		Concepts							
Selection Criteria	Human Operated Forklift (in the dark)	Med. Fid. 1	Med. Fid. 2	Med. Fid. 3	Med. Fid. 4	Med. Fid. 5	Hi Fi 1	Hi Fi 2	Hi Fi 3
Wheel Torque	Datum	S	S	S	+	+	+	+	+
Heading Angle		S	S	S	+	+	+	+	+
Velocity		S	S	S	S	S	+	+	+
Size		S	S	S	S	S	-	S	-
Wheel Friction		S	S	S	S	S	-	S	-
Produce Lift Force		-	-	-	S	-	S	S	S
Power Supply		S	+	S	S	S	+	S	-
Operation Time		S	+	S	S	-	+	+	-
Scanning		+	+	+	+	+	+	+	+
Path-Finding Sensor		+	+	+	+	+	+	+	+
Object Detection		+	-	-	+	+	+	+	+
Precision		+	+	+	+	+	+	+	+
	# Pluses (+)	4	5	3	6	6	9	8	7
	# Minuses (-)	1	2	2	0	2	2	0	4
	# Satisfactory (S)	7	5	7	6	4	1	4	1

To better reduce our top concepts to find our final solution, the medium-fidelity and high-fidelity concepts were compared in Pugh charts to better visualize what could be our top concept. A datum that these ideas were selected to was selected to be a human operated forklift in the dark. The bottom of the Pugh chart sums the total of each minus, plus, and satisfactory each fidelity had. The final count allows us to compare which characteristics outranked the others. The fidelities highlighted in green had the most pluses (+), fewest minuses (-), and/or showed to be highly satisfactory. For example, the first and second high fidelity ideas had the most pluses (9, and 8 pluses) and very little minuses; so, they were clear concepts to move on. The third high fidelity idea had the most minuses (4 minuses), but it also had the third most pluses (7 pluses), so it was decided to move onto the second iteration of the Pugh chart for further comparison. The medium fidelity 4 idea was also chosen to move on because it had no minuses and the same number of pluses and satisfactories. The first, second, third, and fifth medium fidelity concepts had the least number of pluses in addition to a few minuses and a high number of satisfactories. Because these ideas did not compare as highly to the other ideas, they were eliminated from further comparison.

The first high-fidelity concept was chosen to be the new datum since it has the greatest number of positives and thus more beneficial to compare to the other remaining concepts.

Table 7: Pugh Chart Iteration 2

Iteration 2		Concepts		
Selection Criteria	Hi Fi 1	Med Fed 4	Hi Fi 2	Hi Fi 3
Wheel Torque	Datum	-	S	-
Heading Angle		-	-	S
Velocity		S	S	S
Size		-	-	S
Wheel Friction		+	+	S
Produce Lift Force		-	S	-
Power Supply		S	S	-
Operation Time		S	S	+
Scanning		-	S	-
Path-Finding Sensor		+	S	+
Object Detection		S	S	+
Precision		-	-	S
	# Pluses (+)	2	1	3
	# Minuses (-)	6	3	4
	# Satisfactory (S)	4	8	5

In this last Pugh chart iteration, the same process is conducted and the summation of minuses, pluses, and satisfactories allow the team to eliminate or keep concepts for future consideration. The remaining medium fidelity concept has many drawbacks as compared to the first high fidelity concept, due to its low number of pluses and high number of minuses and satisfactories. It was thus removed. The result is two high fidelity concepts in reference to the datum concept. The second high fidelity concept is close in comparison to the first high fidelity idea, since it has a large amount of satisfactories. The third high-fidelity concept offers some drawbacks in comparison since it has a larger number of minuses. However, since it has the most pluses in this comparison it was chosen for further analysis. The datum (high fidelity 1) and the second and third high fidelity ideas were chosen to be compared for further analysis in the analytical hierarchy process (AHP).

Analytical Hierarchy Process (AHP)

The Analytical hierarchy process is a decision-making tool good for ranking priorities, and producing useful, comparative aspects that are both qualitative and quantitative. For the AHP, each characteristic is compared against other characteristics to start specifying which characteristics are more important than others. The first iteration seen below in Table 7, compares eight engineering characteristics with one another. The rankings used were odd numbers between 1 and 9, with 1 ranking the lowest and 9 ranking the highest in relative importance. The characteristics compared were chosen from the House of Quality chart and utilized the top scoring characteristics since they were deemed most important in the House of Quality chart. The engineering characteristics that were deemed most important to used for comparison in the AHP were *Wheel Torque, Heading Angle, Robot Velocity, Produce Lift Force, Scanning, Path-Finding Sensor, Object Detection,* and *Precision*.

Table 8: AHP Pairwise Matrix (Engineering Characteristics)

Pairwise Matrix									
	Wheel Torque	Heading angle	Robot Velocity	Produce lift force	Scanning	Path-Finding Sensor	Object Detection	Precision	Sum
Wheel Torque	1.00	0.20	0.33	0.20	0.11	0.14	0.33	0.20	2.52
Heading Angle	5.00	1.00	3.00	0.33	0.20	0.33	3.00	0.20	13.07
Robot Velocity	3.00	0.33	1.00	0.20	0.11	0.33	0.33	0.11	5.42
Produce Lift Force	5.00	3.00	5.00	1.00	0.33	0.33	5.00	0.20	19.87
Scanning	9.00	5.00	9.00	3.00	1.00	3.00	7.00	3.00	40.00
Path-Finding Sensor	7.00	3.00	3.00	3.00	0.33	1.00	5.00	0.33	22.67
Object Detection	3.00	0.33	3.00	0.20	0.14	0.20	1.00	0.14	8.02
Precision	5.00	5.00	9.00	5.00	0.33	3.00	7.00	1.00	35.33
Sum	38.00	17.87	33.33	12.93	2.57	8.34	28.67	5.19	

Table 7 shows the same engineering characteristics found in the House of Quality chart, however, this time rather than evaluating whether a characteristic meets a customer's requirements, the characteristics are compared with each other as a method of distinguishing which characteristics are very significant in the selection process versus having little relative significance. Each row is compared to the corresponding column; when a characteristic is deemed more significant, a value (either 1, 3, 5, 7, or 9) is given to demonstrate how significant the characteristic is, and the other characteristic is given the reciprocal to show it is less important. For example, when comparing *Lift Force* to *Wheel Torque*, our team decided that heading angle was more significant given the specific requirements involving accuracy and self-navigation for the project. Therefore, *Lift Force* is given a value of 5 for significant relevance and *Wheel Torque* is given the reciprocal, 0.20. It is also important to note that when a characteristic is compared against itself, it is given a value of 1. Once all values are determined and every characteristic was compared, the sum of each row and column is calculated for further analysis. The sum of each column will be used in a second chart which will result in new criteria weight assisting the team with establishing which characteristics are more crucial for success.

Below, Table 8 shows the second chart which displays a normalized version of Table 7.

Table 9: AHP Normalized Pairwise Matrix (Engineering Characteristics)

Normalized Pairwise Matrix									
	Wheel Torque	Heading angle	Robot Velocity	Produce lift force	Scanning	Path-Finding Sensor	Object Detection	Precision	Criteria Weight
Wheel Torque	0.03	0.01	0.01	0.02	0.04	0.02	0.01	0.04	0.02
Heading Angle	0.13	0.06	0.09	0.03	0.08	0.04	0.10	0.04	0.07
Robot Velocity	0.08	0.02	0.03	0.02	0.04	0.04	0.01	0.02	0.03
Produce Lift Force	0.13	0.17	0.15	0.08	0.13	0.04	0.17	0.04	0.11
Scanning	0.24	0.28	0.27	0.23	0.39	0.36	0.24	0.58	0.32
Path-Finding Sensor	0.18	0.17	0.09	0.23	0.13	0.12	0.17	0.06	0.15
Object Detection	0.08	0.02	0.09	0.02	0.06	0.02	0.03	0.03	0.04
Precision	0.13	0.28	0.27	0.39	0.13	0.36	0.24	0.19	0.25
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The values are calculated by dividing individual values of the table with the sum of the column that value is in. For example, when comparing *Robot Velocity (*row) and *Heading Angle* (column) the value is 0.02 in the normalized matrix, which is 0.33 divided by 17.87 (the value in the intersection divided by the column sum) from the original matrix. This calculation is made for each intersection, producing a new value. When all evaluations are done, the sum of each column should equal 1 and the sum of each row will then be considered the new criteria weight of the engineering characteristic of that row. Our pairwise matrix showcased that the three heaviest weighted characteristics were *Scanning*, *Path-Finding Sensor*, and *Precision*; the three lowest weighted characteristics were *Wheel Torque*, *Robot Velocity*, and *Object Detection*. It is important to understand that though certain characteristics weigh more than others, this does not mean they are not valuable. The rankings in this AHP give impartial suggestions using mathematical techniques geared towards distinguishing which characteristics will help achieve the primary goals of the project.

To check that the comparisons between different engineering characteristics were valid and consistent, a consistency table is formulated. This is shown in Table 9:

Table 10: Consistency Check (Engineering Characteristics)

	Weighted Sum Vector	Criteria Weights	Consistency Vector
Wheel Torque	0.19	0.02	8.77
Heading Angle	0.61	0.07	8.60
Robot Velocity	0.27	0.03	8.34
Produce Lift Force	1.02	0.11	8.95
Scanning	2.99	0.32	9.24
Path-Finding Sensor	1.35	0.15	9.32
Object Detection	0.36	0.04	8.41
Precision	2.42	0.25	9.69
		AVG Cons	8.91
RI Value	n	CR	
1.41	8.00		0.09

The weighted sum vector is calculated from matrix multiplication between the columns and rows of the first AHP pairwise matrix and the criteria weights. The consistency vector is the weighted sum vector in that row divided by the criteria weights in the same row. The n is the number of engineering characteristics being compared; the random consistency index (RI) is a value associated with the number of engineering characteristics. The consistency ratio (CR) is the difference between the average consistency vector value and the RI value, divided by the difference between the RI value and 1, divided by the number of elements being compared. If the consistency ratio is less than 0.1, then the comparisons between the engineering characteristics are correct and consistent.

The concepts are then compared using this same process against each other for which concept best meets that engineering characteristic. The tables for this are shown in Appendix E. For a reminder and summary of the concepts that will be compared, they are High Fidelity 1, High Fidelity 2, and High Fidelity 3. High Fidelity 1 has omni-directional wheel drive, lithium-ion battery for power, infrared sensors for line path following, forks for lifting a package, ultrasonic obstacle detection, and QR code sensing abilities. High Fidelity 2 has differential drive, lithium-ion battery power, infrared line path following, forks for lifting, ultrasonic obstacle detection, and QR code sensing. High Fidelity 3 has omni-directional wheels, lithium polymer battery power, magnetic tape line following capabilities, a vacuum end effector for lifting packages, RFID sensing, and Lidar obstacle detection.

For comparing the engineering characteristics, *Wheel Torque*, *Heading Angle,* and *Robot Velocity,* High Fidelity 1 satisfied the criteria the best because its omni-direction each have their own motor, resulting in more wheel torque overall and more control over each wheel, giving more control over the heading angle of the robot and more velocity capability. Additionally, High Fidelity 1 was better than High Fidelity 2 for *Heading Angle* because the forks are more even and level on the robot, whereas the vacuum end-defector would cause an imbalance, reducing control over the robot's orientation.

Comparing the concepts for *Producing Lift Force*, High Fidelity 1 and High Fidelity 2 were ranked as better than High Fidelity 3 because they have forks for lifting, which gives more strength than lifting with a vacuum end-defector. High Fidelity 1 was ranked as better than High Fidelity 2 for this criteria because its omni-directional wheels (as opposed to High Fidelity 2's differential drive) would allow it to line up more evenly along the package, distributing the weight evenly and making it more effective in lifting the package.

The *Scanning* criteria was met best by High Fidelity 1 and 2, which used QR codes. The RFID tags for High Fidelity 1 would make focusing in on a specific package more difficult, and an RFID sensor is much more expensive. High Fidelity 1 was determined to be more effective than High Fidelity 2 because its omni-directional wheels would allow it to line up with the QR code more easily than with differential drive.

High Fidelity 3 was better than 1 and 2 in terms of its *Path Finding* capabilities since magnetic tape would be easier to sense than a line with infrared. It is important to note that its downside would be its cost to fill an entire warehouse with since the materials for it are expensive.

High Fidelity 3 was also better than High Fidelity 1 and 2 for *Object Detection*. This is because lidar is more precise and accurate than ultrasonic sensing. One downside of Lidar that should be noted is the cost.

High Fidelity 1 fulfilled the *Precision* characteristic the best since its omni-directional wheels allow it to line up more precisely and accurately than differential drive. Additionally, its forks are even on the robot, allowing it to more evenly and accurately line up with the package.

A criteria weight for each concept when comparing for each engineering characteristic is determined. These can all be seen in Table 10.

Table 11: Criteria Weights for Concepts

Concepts	Wheel Torque	Heading Angle	Robot Velocity	Produce Lift-Force	Scanning	Path-Finding Sensor	Object Detection	Precision
Hi Fi 1	0.63335	0.63335	0.63335	0.64339	0.63335	0.2605	0.2605	0.63335
Hi Fi 2	0.10616	0.10616	0.10616	0.28284	0.2605	0.10616	0.10616	0.10616
Hi Fi 3	0.2605	0.2605	0.2605	0.07377	0.10616	0.63335	0.63335	0.2605

The overall composite weight for each alternative (each concept) is determined. For each concept, matrix multiplication is then performed between the criteria weights from comparing the engineering characteristics and the corresponding criteria weights for the concept for each engineering characteristic. For example, for the first high fidelity idea, the far right column of Table 8 is multiplied by the first row of Table 10. The overall composite weight of each concept is determined through this method. These weights of each concept can be seen in Table 11 below.

Table 12: Concepts' Overall Composite Weights

Concepts	Overal Composite Weight
Hi Fi 1	0.564
Hi Fi 2	0.176
Hi Fi 3	0.260

The concept with the highest overall composite weight is the concept that best satisfy the goal of the project. From the table above, the first high fidelity concept is the idea that will be used for the project since it has the highest overall composite weight.

Winning Concept

After analyzing and comparing each customer need and engineering characteristic a final concept is chosen by evaluating the overall composite weight in Table 11 along with the criteria weight for each characteristic in Table 10. Essentially, High Fidelity concept 1 was picked as the best design concept to achieve all the necessary aspects of the project so it could be successful. The concept selected incorporates omni-directional steering to drive the robot for an increase in mobility, more efficiency in operation, and better chances of applying accurate positioning to the robot. Each wheel would be attached to its own motor while being at a specific angular position to better facilitate changes in direction; by angling the wheels, you can have each wheel turning at different speeds, simultaneously, to manipulate position with more ease. The main form of material manipulation will come from using a fork-lift style design that lifts palettes of products versus manipulating the individual package itself. This approach was taken since the variety the robot would have to face when handling individual packages would be too great hence adding onto the complexity of the project.

The power supply would be lithium-ion batteries since they are both cost effective yet powerful enough to support the motors and sensors of the system. Multiple batteries will be utilized throughout the system of the robot. The navigation system will include three different factors: line path for self-navigation, ultrasonic obstacle detection, and infrared to detect he line path. The line paths would consist of lines being drawn on the ground with areas designated to stop-and-scan materials. This method of path tracking incorporates downloading an algorithm onto the robot so it can calculate accurate positions and sensors so the robot can detect the lines along with satisfying other functions.

The primary sensors that will be used are infrared scanners (with light) and ultrasonic sensors. The infrared scanner would be used for a rough localization estimate about the paths using an accessibility map while working with the robot's algorithm to perfect positioning as it moves along the paths. If the robot encounters an obstacle in the way, it will detect it with ultrasonic sensors and send out an error call through WiFi to the admins phone. The ultrasonic sensors will emit a high frequency and calculate the distance between the sensor and an object by waiting for the sound to bounce back. To organize and track inventory, the robot will utilize QR codes for scanning since they are standard forms of organization and inexpensive. QR codes will be placed on the ground of the warehouse so the robot just needs to hover over it and scan. Due to the wireless nature of this design concepts, it is important to recognize that the system will incorporate modems and wireless modules, so the robot is able to connect, be controlled, and operate wirelessly.

1.7 Spring Project Plan

In the figure below, the spring project planned timeline for the mechanical engineering team is presented.

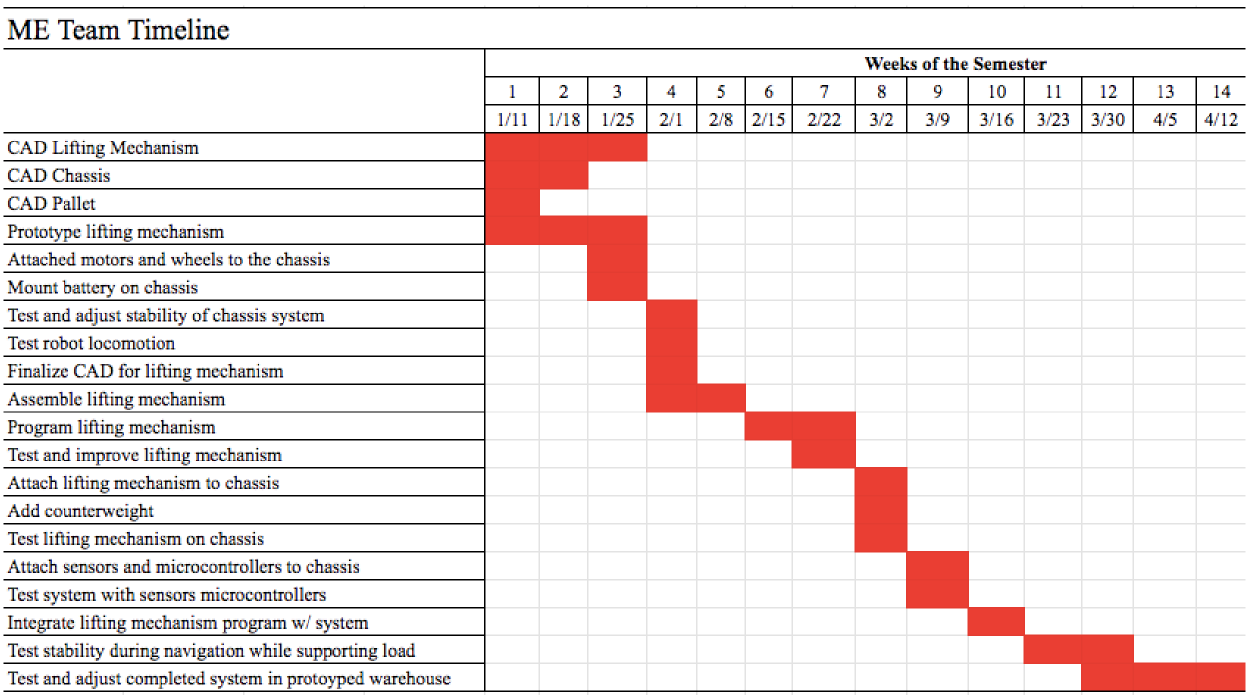


Figure 2: ME Spring Project Plan

It is also relevant to show the electrical-computer engineering team's spring project plan as well as their timeline and the work they get done affect the completion and overall success of the project. This is shown below:

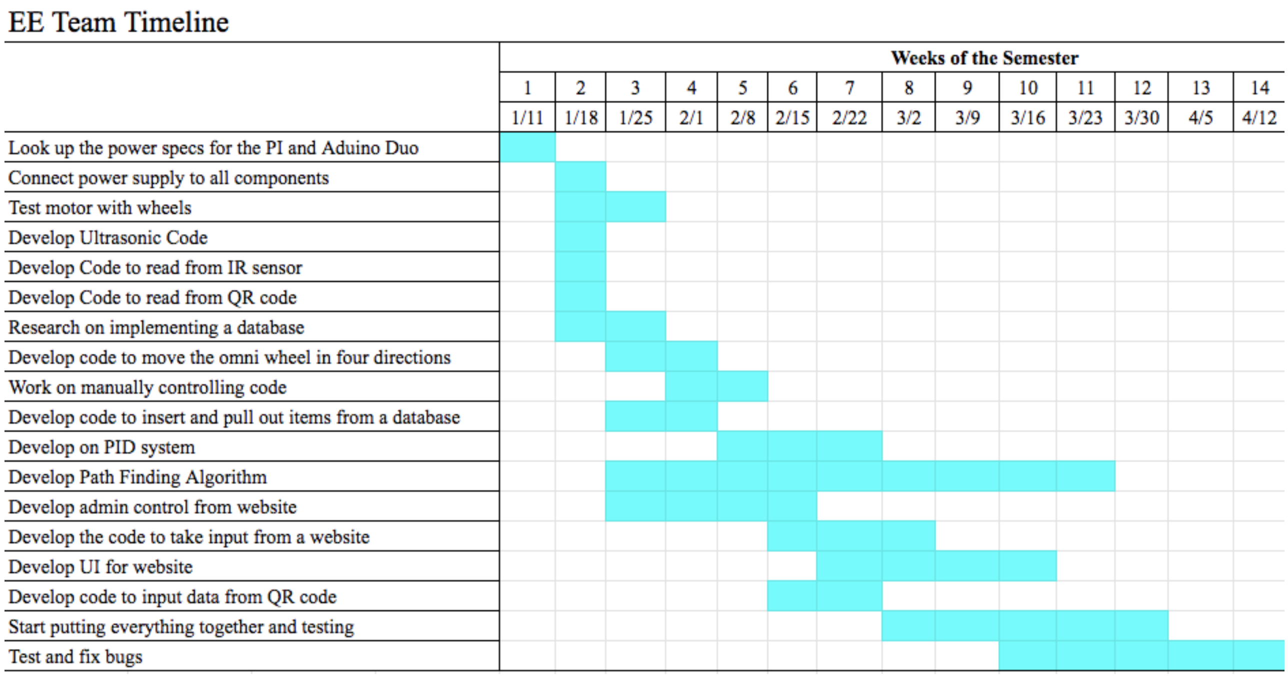


Figure 3: ECE Spring Project Plan

Chapter Two: EML 4551C

Results

At the final stage of validations, the robot passed several tests and achieved many of the goals set out for this project. For the drivetrain, the robot successfully moved in every linear, lateral, diagonal, and angular direction on command. The holonomic nature of the system occurred with less than 5% error by utilizing a PD controller for the motors that controlled the wheels along with the encoders to receive our variables for the controller. The line sensing of the system on the left, front, back, and right side of the robot's body functioned properly and capable of performing desired navigation. The robot was capable of sensing and following a line towards linear and lateral directions along with changing directions efficiently utilizing a PI controller. For the lifting mechanism, the Maxon motor used to lift the desired packages effectively lifted the goal load of 25 pounds by using a PD controller as well as carefully pick up and place packages at desired locations of the model warehouse. The integrity of the system from the base frame to the mast for the lifting mechanism maintained itself throughout all testing and demonstrations. Regarding the software aspect of the system, the network communication between user interface, Raspberry PI, and Arduino Due effectively executed commands from start to finish. The PI camera competently located and scanned QR codes for package identification and inventory tracking both in a well-lit environment and in the dark.

Discussion

After enduring the design process, the final concept underwent multiple tests for the sake of observation and validation. The team separated the system's testing into several stages with the drivetrain, sensor line testing, lifting mechanism, and full integration being tested at different times. The drivetrain and motor controls were the first set of testing that took place. The motor encoders were tested manually at first by spinning the motors once they were set up to the motor drivers and power supply. According to the motor encoders data sheet, one full rotation of the wheel on the shaft is 5736 pulses per revolution; we would add a marker onto the wheel and hand spin the wheel until one full rotation took place. The serial monitor on the Arduino IDE was utilized to print encoder values so we could ensure that the encoders were programmed and set up correctly onto the hardware by observing if the correct encoder value were printed for one revolution.

Once the encoders were accurate enough for testing, the drivetrain was tested by developing code for the wheel's motors to achieve the robot moving in different directions. Each direction was tested separately to ensure the wheels were able to achieve going forward, back, right, and left. Once the robot could move towards each direction, the timer for the system was checked by testing how long it would take the system to translate a certain distance; the timer was manipulated to ensure accuracy. When the robot showed accurate execution, integration between the Arduino and the Raspberry PI took place to start the development for the line sensing aspect of the system. Several tests took place to observe whether the line sensors were able to sense and accurately position the robot on command. With each attempt new problems and solutions were discovered. Some of the issues that arose were the placements of the sensors and them being too far from the ground to accurately read the black line. Customized sensor mounts were 3D printed along with soldering the sensors onto PCB boards to ensure the sensor was placed at most 10 millimeters from the ground. Also, the sensitivity of the sensors presented its own problems as anything that may have been slightly dark would make the sensor deliver a 1 or react as if it were on top of a black line. To account for the sensitivity, a filter was created to prevent the sensor from going off course when it senses a random "1" when on route to a package; the filter ensured if the sensor read a "1" in the center two as well as on the far right or far left, the sensor would ignore the "1" sensed at the far left/right and only recognize the center two nodes reading a "1". Once the logic underwent some adjustments, the team was able to execute accurate line sensing utilizing only the front sensor; after achieving good results with the one sensor, the left sensor, or positive lateral sensor, was integrated, and tested. A similar process was taken to test both the front and left sensor with repetitive testing and adjustments as slight issues or discrepancies presented themselves. However, multidirectional navigation was achieved and allowed us to integrate the last two back and right sensors; the same code applied to the front and left sensor were reciprocated to the back and right sensor.

When all four sensors are on the robot, and the system accurately performed commands from the PI executing specific functions for navigating and seeking packages took place. The first command tested was checking to see if the system could follow certain routes within the warehouse without getting off course, or overshooting. The robot followed both short and long-distance commands by defining which node, or intersection, the robot had to start and end in. For longer distances it the robot would begin crab walking or moving at a distorted angular position without minimizing its error. To fix this issue the heading angle of the robot was incorporated into the integral gain of the robot so the controller could also account for the angular position of the system; this solution minimized the crab walking entirely. After having enough test runs regarding the navigation and the robot demonstrating adequate results, picking up the package was the next set of tests ran on the robot.

Four separate tests were done to check pickup: level 1 pickup, level 2 pickup, picking up packages and delivering at a short distance, and picking up packages and delivering at long distances. Though the system was capable of performing all of the tasks, several issues presented themselves when defining the initial lift position of the forks. The motor used to lift the carriage and forks reset its position without any commands being sent into it; this caused error in the initial position of the forks since the reset would perform inconsistently. The team was not able to find an exact solution, however, several tests were done to find a semi-perfect height as well as incorporating a custom pallet that adds tolerance when lifting the package. The final round of testing was ensuring that the PI camera and training were working smoothly for inventory tracking and package identification. The functions were executed several times for the distance the camera needed to be set at to scan the QR codes on the packages needed to be set. All in all, testing happened repeatedly and many issues raised from loose wires not being plugged in properly or easy solutions regarding the hardware.

Conclusions

After several tests and observations, the robot was capable of consistently achieving some validations while inconsistently meeting others or not at all. For drivetrain, the robot succeeded in performing holonomic, or omnidirectional, steering as well as angular movements while remaining in the same lateral and linear position. For the line sensing, the sensors accurately detect and follow the black line, however, the sensors were tested on a white surface preset by the team. Tests on different surfaces with various finishes were not done or pursued. Regarding the lift mechanism, the system can carry and holding the maximum load of 25 pounds, however, the friction and moment created between the carriage holding the forks and the mast increases the instability of the lifting mechanism causing a potential for error when descending any load placed on the forks. The power supply showed to be capable of powering all the components of the system, however, a better configuration could have presented a more optimized power solution regarding energy cost. Though the system is functional, safety measures were barely taking into account and features such as a kill switch or kill code could have been implemented to avoid any hazards.

Future Work

Tasks that could be improved upon include but not limited to power supply, the lifting mechanism, some component designs and enhancing safety features. The power supply could use some improvements regarding how it is connected to all the components of the system. Since the system utilizes more motors, drivers, and contains several processing units it is imperative that the battery is capable of safely powering the system. Also, the lifting mechanism can use upgrading by utilizing a different design or a powered unit to lift loads rather than a simple pulley mechanism. Though the pulley mechanism can perform, the system can obtain greater potential with a hydraulic or linear actuator. Further testing and improvements can be done on the sensors to make the robot's motion smoother and more cohesive. Also, a change in material of the chassis frame, swapping aluminum with a more brittle material, may add strength to the structure as a whole. Overall, most of the work has been accomplished for the project but improvements can be made to enhance the system as a whole.

Appendices

Appendix A: Code of Conduct

Mission Statement

Team 506 is a group of committed individuals, striving to achieve the best solution within their means. Driven by excellence, integrity, and the pursuit of knowledge, Team 506 will produce well performing results that hold both value and positive impact. With a purpose in developing effective, economical resolutions, Team 506 will maintain a professional standard throughout any project's timeline.

Team Roles:

Each member is assigned a role that reflects the area of the project they are responsible for. Although each member is assigned a role, members of the project can contribute to different roles as needed. Ultimately the leader of the role is responsible for the work done in their area of the project. Miscellaneous tasks that arise will be assigned either by a team member volunteering to do it or will be given to the team member with the greatest skill set to perform said task. If no one volunteer shows experience with the topic of the task, the task will be assigned to the engineer that focuses on an area that is closest related to the topic of the task.

Mechanical Design Engineer: Taylor Harvey

Responsible for the mechanical design aspects of the system. Responsible for relaying design ideas to all group members and maintaining constant communication with the project manager.

Controls Engineer: Diandra Reyes

Accountable for the control of the mechatronic components of the system. Responsible for leading research into matters involving actuators and sensors. Responsible for updating the team on matters involving mechatronics.

Materials Engineer: Peter Watson

In charge of the material selection for different components of the robot. Responsible for ordering materials necessary to build the robot. Will keep track of and update the team on which materials are being ordered and their current status.

Systems Engineer: Alexander Wozny

Serves as the point of contact for the team. Leads communication with Dr. McConomy, the faculty advisor, sponsor, and electrical engineering (EE) team on behalf of the mechanical engineering team. In charge of organizing and planning meetings with the faculty advisor, sponsor, and EE team. Works with the EE team on dividing the different systems of the projects between the two groups, as well as makes sure each team is up to date on the other's design decisions. Also responsible for submitting assignments to Canvas.

Communication:

Team communication will be done primarily through text group chats and Basecamp, but email and zoom meetings will also be used. Scheduling will be done using Basecamp. Meetings with faculty and with sponsors will be done via email, and meeting within the group will be planned over text. An appropriate delay in response is 8 hours between group members and 24 hours for email messages with either a faculty advisor or sponsor. If anyone for any reason cannot attend an event, they should send an notify all parties 24 hours in advance.

Team Dynamics:

Ethics:

All team members are always required to perform at a high standard of respect; no form of discriminatory or bigoted language/actions/treatment will be tolerated. Continual disregard for the code of conduct will result in a reduction of points to that team member's peer evaluations.

Dress code:

Team meetings and meetings with the faculty advisor will be in casual attire. Presentations and meeting with the sponsor will be in professional attire. The dress code is subject to change depending on circumstance.

Attendance:

The primary method of attendance will be through zoom, unless otherwise specified. Attendance to the weekly meetings is mandatory.

Internal Business Weekly:

Team 506 will meet internally twice a week after Senior Design I is complete, to create new content or review past progress. Also, Team 506 will have internal meetings on Fridays at 10:30 A.M. weekly basis. The team will also have joint meetings with the Electrical-Computer team on Mondays at 3:30 P.M. to discuss project plans and progress, as well as meetings on Friday at 5:30 P.M. to work on the project in person together at the College of Engineering. In the case of a team member's absence, the absentee will need to reach out to one of the team members to catch up on what was missed before the next meeting. A team member's first absence results in a verbal warning from groups members. For a team member's second absence, they will receive a verbal warning and a written warning on Basecamp where Dr. McConomy will be able to see.

Continued absences after the second absence without a plausible cause will result in a reduction of points on that team member's peer evaluations. Excused absences are to be made known 8 hours in advance to team members and 24 hours in advance to project sponsor/faculty advisor. It is the absentee's responsibility to figure out what was missed and do any makeup work required. Excused absences include, but are not limited to, doctor appointments, family emergencies, religious holidays, etc.

Meetings with Sponsor:

Team will meet with the sponsor to communicate the progress that has been made, and address issues or concerns that have come up since the last meeting. Any unexcused absence will not be tolerated and will result in immediate reduction of points on that team member's peer evaluation.

Meeting with Assigned Faculty:

Team 506 will meet at least once a month with assigned faculty to present the progress of the project as well as ask about any potential issues presented during duration of tasks. Weekly joint meetings will occur with the Electrical-Computer team and their assigned faculty, Dr Harvey. Additional meetings will be scheduled on a needs based. Any unexcused absence will not be tolerated and will result in immediate reduction of points on that team member's peer evaluation.

Decision Making:

Decisions will be made with all group members present. If there is not a clear choice when deciding, a vote will be taken and the option with the most votes will be chosen. In the case of a close vote (2-2) to determine a high priority decision, the team member in charge of the decision's area of focus will have more say than other members.

Conflict Resolution:

The following method will be utilized when team members disagree on an aspect during the design process:

- Team Intervention: All parties shall present and convey their own view of said conflict to the team as well as the impact they have experienced. Team members that are not involved will then assist by offering objective perspective in the hopes of enlightening team members involved and create a compromise to resolve solution.
- Sponsor Intervention: If team intervention does not ease tension, potential intervention from Sponsor, Dr. McConomy, will be sought by the point of contact to offer both a professional and experienced voice in the matter.
- Counseling: If problem continues, seek professional assistance using counseling services presented by Florida Agricultural and Mechanical University and/or Florida State University.

Amending the Code of Conduct:

In the case that the Code of Conduct needs to be amended, all group members will meet and discuss the changes that need to be made. After an appropriate change has been agreed upon unanimously, the document will be edited to reflect that change.

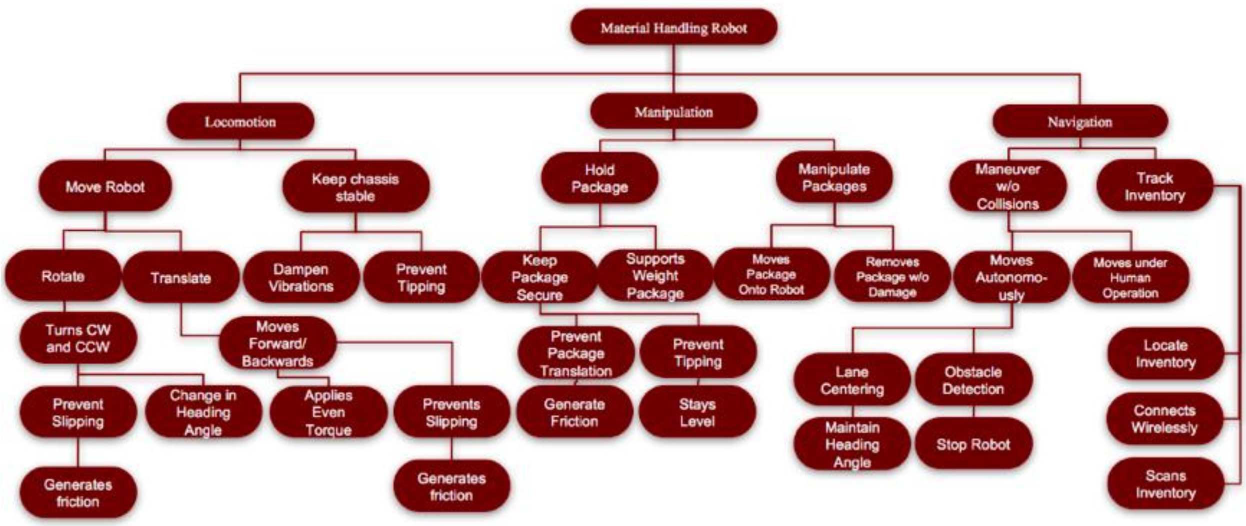
Statement of Understanding:

Signing below indicates an understanding and commitment to adhere to the rules outlined in the code of conduct.

Name	Signature	Date
Taylor Harvey	Taylor Harvey	1/11/2021
Diandra Reyes	DReyes	1/11/2021
Peter Watson	Peter Watson	1/11/2021
Alexander Wozny	Alexander Wozny	1/11/2021

Appendix B: Functional Decomposition

Figure B1: Hierarchy Chart



Appendix C: Target Catalog

Table C1: Full Target Catalog

Attribute	Target	Unit of Measure	Metric	Description
Generates Friction (wheels)	17.1 N	Newtons	Force	The wheels must have enough friction to prevent slip
Change in Heading Angle	360º	Degrees	Angle	Robot turns in a full circle.
Applies Even Torque	<1%	Percent	Error	Robot applies even torque on both sides of the wheels to move straight.
Control velocity	2.25 m/s	Meters per second	Velocity	Minimum traveling speed through the warehouse.
Generates friction (box)	≤ 22.68 N	Newtons	Force	The box must be prevented from sliding.
Generates friction (manipulator)	≤ 22.68 N	Newtons	Force	The manipulator must have enough friction

				to prevent box from slipping
Stays level	0º	Degrees	Angle	Robot maintains an even horizontal alignment.
Moves Package onto Robot	224 N	Newton	Force	Robot lifts package inventory.
Removes Package w/o Damage	0	Packages	Amount	Only a certain percent of packages show signs of damage.
Maintain Heading Angle (Relative to Path)	0º	Degrees	Direction	Robot accurately follows a path.
Stop Robot	0 m/s	Meters per second	Velocity	Robot stays in the stopping position.
Accelerate Robot	< 1 m/s^2	Meters per second squared	Acceleration	Robot must not accelerate (positively and negatively) so fast that the package falls off.
Moves Under Human Operation	1	N/A	Boolean	Robot responds to human input
Locate Inventory	1	N/A	Boolean	Robot knows where inventory belongs and takes/retrieves inventory to the correct location.
Connect Wirelessly	1	N/A	Boolean	Robot can successfully connect to inventory database and be controlled wirelessly.
Scans Inventory	1	N/A	Boolean	Robot is able to scan a label and

				identify inventory.
Senses Obstacles	2.5 m	Meters	Distance	Robot detects obstacle in its path.
Sends Error Message	1	N/A	Boolean	If the robot detects an obstacle it will send an error message to the appropriate personnel.

Table C2: Critical Targets and Metrics

Attribute	**Target**	**Unit of Measure**	**Metric**	**Description**
Change Heading Angle	360º	Degrees	Angle	Robot can turn in any direction.
Applies Even Torque	<1%	Percent	Error	Robot applies even torque on both sides of the wheels to move straight.
Moves Package onto Robot	224 N	Newton	Force	Robot can lift a package inventory.

Maintain Heading Angle (Relative to Path)	0º	Degrees	Direction	Robot accurately follows path.
Locate Inventory	Yes	N/A	Boolean	Robot knows where inventory belongs and takes/retrieves inventory to the correct location.
Connect Wirelessly	Yes	N/A	Boolean	Robot can successfully connect to inventory database and be controlled wirelessly.
Scans Inventory	Yes	N/A	Boolean	Robot can scan a label and identify inventory.

Appendix D: Concept Generation Ideas

Appendix D: Concept Generation

Table D1: 100 Concepts

Concept Idea	Concept Description
1.	Autonomous ground vehicle that will lift storage shelves/bins and transport them to desired locations within the warehouse

2.	Standard forklift design with wireless modules incorporated for autonomy and inventory tracking. Drive train comprised of rear wheel controlling direction.
3.	Standard forklift design with wireless modules incorporated for autonomy and inventory tracking. Drive train comprised of front wheel controlling direction.
4.	Organize incoming products/small material by entering them into a conveyor and the belt being sectioned to deliver packages in specific directions at specific times
5.	Establish a line of robotic arms with jaw-like end effector that has sensors incorporated to "see", scan, and strategically manipulate materials moving through the assembly line.
6.	Use drones with claw at the bottom of its base to grab and organize specific material according to a set scanning system.
7.	Robot with hand-like end effector picks up materials from general access pile and drops them into specified containers according to matching codes/user command. End effector would be placed on generic AGV
8.	Lift massive loads of products by manipulating pallets of product or the storage units used to organize using an automated ground vehicle-based design.

9.	Attach an industrial-sized, static vending machine-type mechanism to the shelves of the warehouse and organize inventory solely using this large organizer.
10.	Robot is tall (the body is high off the ground) and moves over the package. Then it has several arms that come down on the package like a “scooping cage” and moves around carrying the package underneath it.
11.	The robot body can lift itself to the height of package and has a mechanism that hugs the package into it to store inside of it while it moves.
12.	The robot is tall (shaped like a refrigerator), and it has a hugging mechanism that hugs the package into it.
13.	The robot can move along the rails of the shelves, lifting itself and moving horizontally along the shelves on some sort of track.
14.	The robot has a grappling hook that aims for and grapples the package.
15.	A network of tracks is on the ceiling of the warehouse. The robot hangs from a cable that has a piece attached to the track, allowing it to move along the track throughout the warehouse.
16.	The robot is a drone that can fly above and through aisles to grab a package.

17.	The packages are all on the ground. A claw is attached on the ceiling and moves around like a 3D printer nozzle. When it finds the right package, it goes down and grabs the package with its claw.
18.	The robot has arms like the monkey toy with symbols. It moves towards the package and holds the package in between its “symbol” hands. It raises its body up to the package.
19.	We hire people in India to control the robots from afar.
20.	The robot is powered by internal combustion engine, and can manipulate packages using a magnetic end effector.
21.	Robot is nuclear powered, and can locate packages using gps. It can manipulate packages using two end effector arms that have robotic fingers to grip the inventory
22.	Robot is solar powered, and locates packages using weight detection. The robot will pick up every package and weigh it until it finds the correct weighing package
23.	The robot powered by a combustion engine, moves along a track installed around the warehouse and uses a grappler it shoots at the inventory to obtain it.
24.	Robot can control a fleet of autonomous drones that can locate and retrieve packages by flying and using grapplers to get the inventory.

25.	Robot has vacuum arms to retrieve inventory and moves around the warehouse by a lithium rechargeable battery.
26.	The robot is just a series of conveyer belts that stores inventory in specific locations.
27.	The floor is a giant conveyer belt that takes workers to exactly where they need to be.
28.	We hire genetic dwarfs to be inside the robot and perform the needed tasks, just like Kenny Baker in R2-D2
29.	The robot is just a giant crane like the ones they use in shipyards to move cargo, we use mini shelves and it organizes the shelves.
30.	We make the robot look like Wall-E for comedic effect, also he is good at package protection and is very long lasting.
31.	We make the robot a quadcopter, so it is extremely mobile.
32.	We make the robot fueled on left over boxes, so its environment friendly.
33.	The robot is powered by the Wi-Fi, so it never has to recharge.
34.	The robot itself is a shelf and pulls and pushes boxes off it onto other shelves.
35.	The robot smells bad so human workers wont mess with it or anything it touches.

36.	The robot destroys all humans so there is not any need for a robot that handles materials in a dark warehouse.
37.	The robot is almost flat so it can go under shelves when it's not carrying a box.
38.	The robot can work in the trailer of a semi-truck so it can also unload.
39.	The robot just passes the package to another robot which creates a giant chain of robots passing boxes to other robots until it reaches it desired location.
40.	The boxes make noises at different pitches so that the robot can find them
41.	The robot has wheels that can lower/raise it in very precise increments so the box can be placed more accurately.
42.	We make a self-driving semi-truck that had robots inside that load the truck.
43.	Use bee-like nanobots to treat warehouse like a hive and handle all packages within "hive".
44.	The robot provides moral advice to convince businessmen to care about their workers salary and safety, thus eliminating the need.
45.	The robots are a bunch of tiny balls that roll under a package to deliver it.
46.	We buy a forklift and add sensors and motors to control it.

47.	Conveyor belt leads product into a main organizer shaped like an octopus and each arm simultaneously scans/picks/arranges different packages entering the organizer
48.	Nanorobots structured like ants' help carry and transport packages to desired location sent by user.
49.	Ceiling rails with hooks move packages along the warehouse by picking up and using the vertical space for transport. Rails are placed parallel to conveyor belts holding products for easier access.
50.	A robot with differential steering powered by lithium ion, that uses magnetic tape to follow paths. It also controls packages using forks, detects obstacles with a lidar system, locates inventory using a gps and scans the inventory using a QR Code.
51.	A robot with omni directional steering powered by lead acid, that uses line paths to follow paths. It also controls packages with a vacuum end effector, detects obstacles with thermal sensors, locates inventory using a gps and scans the inventory using a RFID tags.
52.	A robot designed like an Ackermann with rear wheel drive powered by lithium polymer batteries, that uses track rails to follow paths. It also controls packages using single clamps/claw, detects obstacles with visual inertial, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.

53.	A robot designed like an Ackermann with front wheel drive powered by alkaline batteries, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with infrared sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
54.	A robot steered on track rails powered by nickel cadmium batteries, that uses pavement markers to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
55.	A robot steered on track rails powered by alkaline batteries, that uses pavement markers to follow paths. It also controls packages using two clamps/claws, detects obstacles with distance sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
56.	A robot with omni-directional steering powered by lithium ion, that uses magnetic tape to follow paths. It also controls packages using forks, detects obstacles with a lidar system, locates inventory using a gps and scans the inventory using a QR Code.
57.	A robot with differential steering powered by lead acid, that uses line paths to follow paths. It also controls packages with a vacuum end effector, detects obstacles with thermal sensors, locates

	inventory using a inertial measurement unit and scans the inventory using a RFID tags.
58.	A robot designed like an Ackermann with rear wheel drive powered by lead acid batteries, that uses track line paths to follow paths. It also controls packages using single clamps/claw, detects obstacles with visual inertial, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
59.	A robot designed like an Ackermann with front wheel drive powered by lithium ion batteries, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with thermal sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
60.	A robot steered on track rails powered by lithium polymer batteries, that uses pavement markers to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using a color coded system.
61.	A robot with differential steering powered by lithium ion, that uses magnetic tape to follow paths. It also controls packages using magnetic end effector, detects obstacles with a lidar system, locates inventory using QR code location identifiers and scans the inventory using a QR Code.

62.	A robot with omni directional steering powered by nickel cadmium batteries, that uses line paths to follow paths. It also controls packages with a vacuum end effector, detects obstacles with ultrasonic sensors, locates inventory using a gps and scans the inventory using a RFID tags.
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64.	A robot designed like an Ackermann with front wheel drive powered by lead acid, that uses track rails to follow paths. It also controls packages with a magnetic end effector, detects obstacles with infrared sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
65.	A robot using differential steering powered by nickel cadmium batteries, that uses pavement markers to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.

66.	A robot with differential steering powered by lithium ion, that uses heated lines to follow paths. It also controls packages using forks, detects obstacles with a lidar system, locates inventory using a gps and scans the inventory using a QR Code.
67.	A robot with omni directional steering powered by lead acid, that uses line paths to follow paths. It also controls packages with a magnetic end effector, detects obstacles with thermal sensors, locates inventory using a gps and scans the inventory using a RFID tags.
68.	A robot designed like an Ackermann with rear wheel drive powered by lithium polymer batteries, that uses track rails to follow paths. It also controls packages using two clamps/claw, detects obstacles with a push sensor bumper, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
69.	A robot designed like an Ackermann with front wheel drive powered by lithium polymer batteries, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with a push sensor bumper, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
70.	A robot steered on a magnetic track powered by nickel cadmium batteries, that uses GPS to follow paths. It also controls packages using magnetic end effector, detects obstacles

	with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
71.	A robot steered on magnetic track powered by alkaline batteries, that uses magnetic tape to follow paths. It also controls packages using two clamps/claws, detects obstacles with distance sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
72.	A robot with omni-directional steering powered by nickel cadmium, that uses magnetic tape to follow paths. It also controls packages using a magnetic end effector, detects obstacles with a lidar system, locates inventory using a gps and scans the inventory using a QR Code.
73.	A robot with differential steering powered by alkaline batteries, that uses heated lines to follow paths. It also controls packages with a vacuum end effector, detects obstacles with thermal sensors, locates inventory using a inertial measurement unit and scans the inventory using a RFID tags.
74.	A robot designed like an Ackermann with front wheel drive powered by lead acid batteries, that uses track line paths to follow paths. It also controls packages using single clamps/claw, detects

	obstacles with visual inertial, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
75.	A robot designed like an Ackermann with rear wheel drive powered by lithium ion batteries, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with thermal sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
76.	A robot steered on track rails powered by lithium ion batteries, that uses pavement markers to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using GPS and scans the inventory using a QR code.
77.	A robot steered by magnetic tracks powered by lithium ion, that uses an induction wire to follow paths. It also controls packages using magnetic end effector, detects obstacles with a ultrasonic system, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
78.	A robot with omni directional steering powered by lithium ion batteries, that uses line paths to follow paths. It also controls packages with a vacuum end effector, detects obstacles with ultrasonic sensors, locates inventory using a gps and scans the inventory using a RFID tags.

79.	A robot designed like an Ackermann with rear wheel drive powered by lithium polymer batteries, that uses line paths to follow paths. It also controls packages using forks, detects obstacles with visual inertial, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
80.	A robot designed like an Ackermann with front wheel drive powered by lithium polymer batteries, that uses line paths to follow paths. It also controls packages with forks, detects obstacles with infrared sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
81.	A robot with differential steering powered by lithium polymer, that uses magnetic tape to follow paths. It also controls packages using a magnetic end effector, detects obstacles with a lidar system, locates inventory using a gps and scans the inventory using a QR Code.
82.	A robot with differential steering powered by lead acid, that uses line paths to follow paths. It also controls packages with two clamps/claws, detects obstacles with ultrasonic sensors, locates inventory using a code location identifier and scans the inventory using a RFID tags.
83.	A robot designed like an Ackermann with front wheel drive powered by lithium ion batteries, that uses track rails to follow paths.

	It also controls packages using single clamps/claw, detects obstacles with infrared sensors, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
84.	A robot designed like an Ackermann with rear wheel drive powered by lead acid, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with infrared sensors, locates inventory using GPS location identifiers and scans the inventory using April tags.
85.	A robot steered on magnetic track powered by lithium ion batteries, that uses GPS to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using RFID tags.
86.	A robot steered on track rails powered by nickel cadmium batteries, that uses induction wires to follow paths. It also controls packages using two clamps/claws, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
87.	A robot steered by magnetic tracks powered by lithium ion, that uses magnetic tape to follow paths. It also controls packages using forks, detects obstacles with a lidar system, locates

	inventory using QR code location identifiers and scans the inventory using a QR Code.
88.	A robot with omni-directional steering powered by lead acid, that uses line paths to follow paths. It also controls packages with a single clamp/claw, detects obstacles with thermal sensors, locates inventory using a inertial measurement unit and scans the inventory using a RFID tags.
89.	A robot designed like an Ackermann with front wheel drive powered by lead acid batteries, that uses track line paths to follow paths. It also controls packages using single clamps/claw, detects obstacles with a push sensor bumper, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
90.	A robot designed like an Ackermann with rear wheel drive powered by lithium ion batteries, that uses heated lines to follow paths. It also controls packages with a magnetic end effector, detects obstacles with infrared sensors, locates inventory using QR code location identifiers and scans the inventory using RFID tags.
91.	A robot steered on track rails powered by lithium polymer batteries, that uses track rails to follow paths. It also controls packages using a magnetic end effector, detects obstacles with ultrasonic sensors, locates inventory by identifying products

	using color coded intersections and scans the inventory using a color coded system.
92.	A robot with differential steering powered by alkaline batteries, that uses magnetic tape to follow paths. It also controls packages using magnetic end effector, detects obstacles with a lidar system, locates inventory using QR code location identifiers and scans the inventory using a QR Code.
93.	A robot with differential steering powered by nickel cadmium batteries, that uses line paths to follow paths. It also controls packages with a vacuum end effector, detects obstacles with ultrasonic sensors, locates inventory using a gps and scans the inventory using a RFID tags.
94.	A robot designed like an Ackermann with front wheel drive powered by lead acid, that uses heated lines to follow paths. It also controls packages using single clamps/claw, detects obstacles with push sensor bumper, locates inventory using inertial measurement unit and scans the inventory using a barcode scanner.
95.	A robot designed like an Ackermann with rear wheel drive powered by lead acid, that uses induction wires to follow paths. It also controls packages with a magnetic end effector, detects obstacles with ultrasonic sensors, locates inventory using QR code location identifiers and scans the inventory using a QR Code.

96.	A robot steered on track rails powered by lithium ion batteries, that uses pavement markers to follow paths. It also controls packages using a hook, detects obstacles with ultrasonic sensors, locates inventory by identifying products using color coded intersections and scans the inventory using an April Tag.
97.	A robot steered on magnetic tracks powered by nickel cadmium batteries, that uses induction wires to follow paths. It also controls packages using two clamps/claws, detects obstacles with a push sensor bumper, locates inventory by identifying products using color coded intersections and scans the inventory based off a color-coded system.
98.	A robot steered by differential drive powered by lead acid, that uses line paths to follow paths. It also controls packages using forks, detects obstacles with a lidar system, locates inventory using QR code location identifiers and scans the inventory using April tags.
99.	A robot with omni-directional steering powered by lead acid, that uses induction wires to follow paths. It also controls packages with two clamps/claws, detects obstacles with infrared sensors, locates inventory using a inertial measurement unit and scans the inventory using a color coded system.

100.	A robot designed like an Ackermann with rear wheel drive powered by lead acid batteries, that uses track line paths to follow paths. It also controls packages using single clamps/claw, detects obstacles with a push sensor bumper, locates inventory using inertial measurement unit and scans the inventory using a RFID tags.

Appendix E: Concept Selection Tables

Table E1: Wheel Torque Matrix:

(a) Pairwise Matrix

Pairwise Matrix: Wheel Torque				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	5	3	9
Hi Fi 2	0.2	1	0.33333	1.53333
Hi Fi 3	0.33333	3	1	4.33333
Sum	1.53333	9	4.33333	

(b) Normalized Pairwise Matrix

Normalized Matrix: Wheel Torque				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.65217	0.55556	0.69231	0.63334572
Hi Fi 2	0.13043	0.11111	0.07692	0.106156324
Hi Fi 3	0.21739	0.33333	0.23077	0.260497956
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	1.95	0.63	3.07
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	0.79	0.26	3.03
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E2: Heading Angle

(a) Pairwise Matrix

Pairwise Matrix: Heading Angle				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	5	3	9
Hi Fi 2	0.2	1	0.33333	1.53333
Hi Fi 3	0.33333	3	1	4.33333
Sum	1.53333	9	4.33333	

(b) Normalized Pairwise Matrix

Normalized Matrix: Heading Angle				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.65217	0.55556	0.69231	0.63334572
Hi Fi 2	0.13043	0.11111	0.07692	0.106156324
Hi Fi 3	0.21739	0.33333	0.23077	0.260497956
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	1.95	0.63	3.07
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	0.79	0.26	3.03
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E3: Robot Velocity

(a) Pairwise Matrix

Pairwise Matrix: Robot Velocity				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	5	3	9
Hi Fi 2	0.2	1	0.33333	1.53333
Hi Fi 3	0.33333	3	1	4.33333
Sum	1.53333	9	4.33333	

(b) Normalized Pairwise Matrix

Normalized Matrix: Robot Velocity				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.65217	0.55556	0.692307692	0.63334572
Hi Fi 2	0.13043	0.11111	0.076923077	0.106156324
Hi Fi 3	0.21739	0.33333	0.230769231	0.260497956
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	1.95	0.63	3.07
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	0.79	0.26	3.03
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E4: Lift Force

(a) Pairwise Matrix

Pairwise Matrix: Produce Lift Force				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	3	7	11
Hi Fi 2	0.33333	1	5	6.33333
Hi Fi 3	0.14286	0.2	1	1.34286
Sum	1.47619	4.2	13	

(b) Normalized Pairwise Matrix

Normalized Matrix: Produce Lift Force				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.67742	0.71429	0.538461538	0.643388869
Hi Fi 2	0.22581	0.2381	0.384615385	0.282839025
Hi Fi 3	0.09677	0.04762	0.076923077	0.073772106
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	2.01	0.64	3.12
Hi Fi 2	0.87	0.28	3.06
Hi Fi 3	0.22	0.07	3.01
		AVG Cons	3.07
RI Value	n	CR	
0.58	3.00		0.06

Table E5: Scanning

(a) Pairwise Matrix

Pairwise Matrix: Scanning				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	3	5	9
Hi Fi 2	0.33333	1	3	4.33333
Hi Fi 3	0.2	0.33333	1	1.53333
Sum	1.53333	4.33333	9	

(b) Normalized Pairwise Matrix

Normalized Matrix: Scanning				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.65217	0.69231	0.55556	0.63334572
Hi Fi 2	0.21739	0.23077	0.33333	0.260497956
Hi Fi 3	0.13043	0.07692	0.11111	0.106156324
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	1.95	0.63	3.07
Hi Fi 2	0.79	0.26	3.03
Hi Fi 3	0.32	0.11	3.01
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E6: Path Finding

(a) Pairwise Matrix

Pairwise Matrix: Path-Finding Sensor				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	3	0.33333	4.33333
Hi Fi 2	0.33333	1	0.2	1.53333
Hi Fi 3	3	5	1	9
Sum	4.33333	9	1.53333	

(b) Normalized Pairwise Matrix

Normalized Matrix: Path-Finding Sensor				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.23077	0.33333	0.21739	0.260497956
Hi Fi 2	0.07692	0.11111	0.13043	0.106156324
Hi Fi 3	0.69231	0.55556	0.65217	0.63334572
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	0.79	0.26	3.03
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	1.95	0.63	3.07
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E7: Object Detection

(a) Pairwise Matrix

Pairwise Matrix: Object Detection				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	3	0.33333	4.33333
Hi Fi 2	0.33333	1	0.2	1.53333
Hi Fi 3	3	5	1	9
Sum	4.33333	9	1.53333	

(b) Normalized Pairwise Matrix

Normalized Matrix: Object Detection				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.23077	0.33333	0.21739	0.260497956
Hi Fi 2	0.07692	0.11111	0.13043	0.106156324
Hi Fi 3	0.69231	0.55556	0.65217	0.63334572
Sum	1	1	1	1

(c) Consistency Check

	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	0.79	0.26	3.03
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	1.95	0.63	3.07
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Table E8: Precision

(a) Pairwise Matrix

Pairwise Matrix: Precision				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Sum
Hi Fi 1	1	5	3	9
Hi Fi 2	0.2	1	0.33333	1.53333
Hi Fi 3	0.33333	3	1	4.33333
Sum	1.53333	9	4.33333	

(b) Normalized Pairwise Matrix

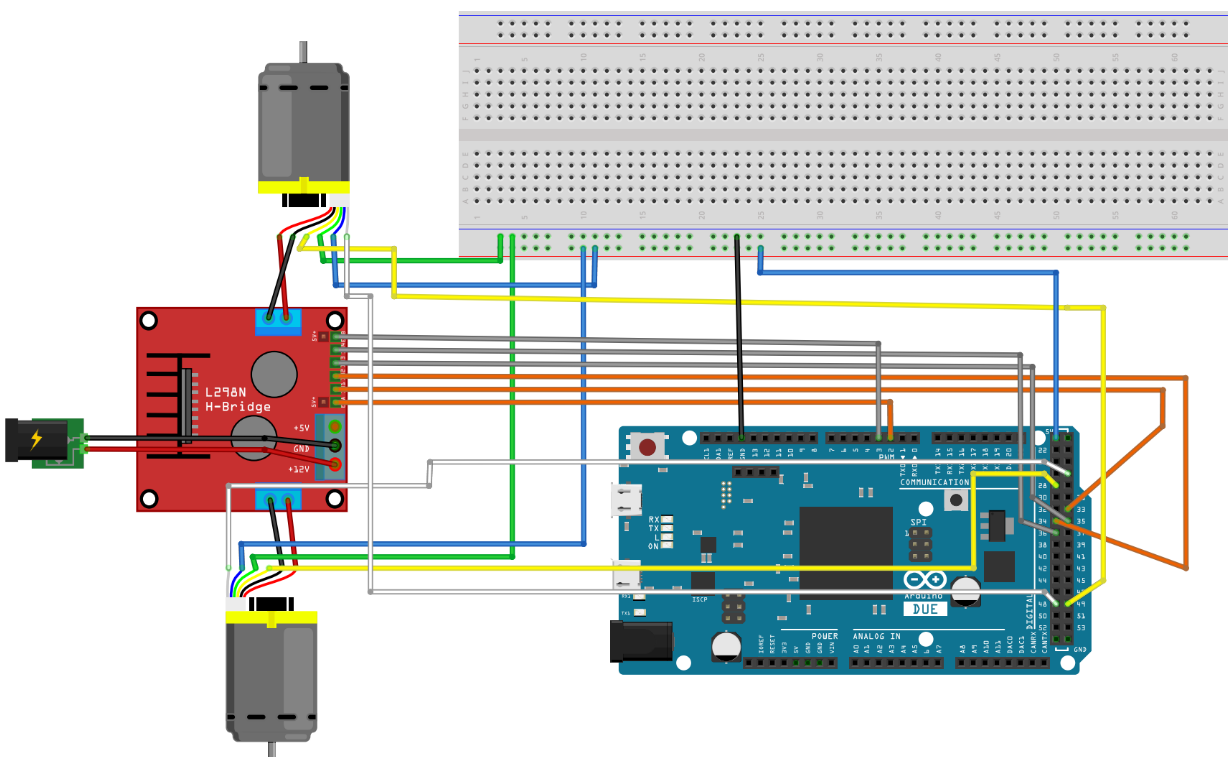
Normalized Matrix: Precision				
	Hi Fi 1	Hi Fi 2	Hi Fi 3	Criteria Weights
Hi Fi 1	0.65217	0.55556	0.69231	0.63334572
Hi Fi 2	0.13043	0.11111	0.07692	0.106156324
Hi Fi 3	0.21739	0.33333	0.23077	0.260497956
Sum	1	1	1	1

(c) Consistency Check

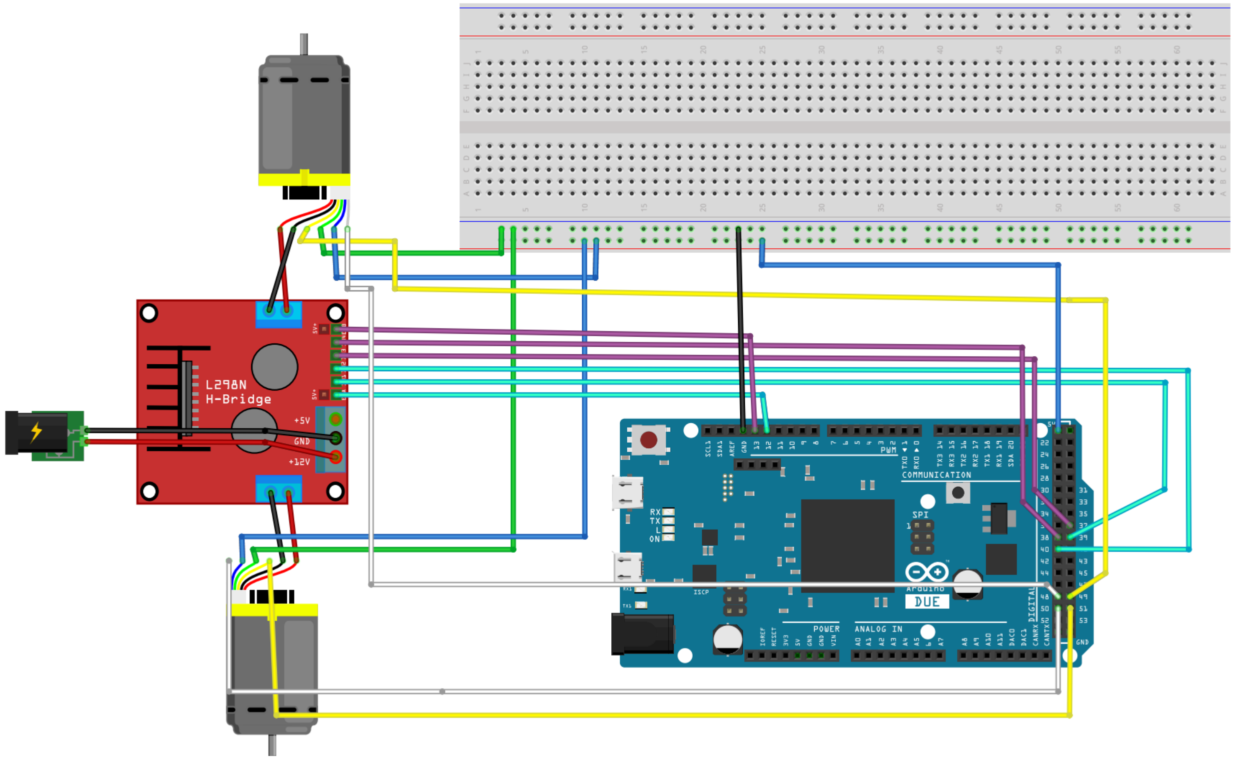
	Weighed Sum Vector	Criteria Weights	Consistency Vector
Hi Fi 1	1.95	0.63	3.07
Hi Fi 2	0.32	0.11	3.01
Hi Fi 3	0.79	0.26	3.03
		AVG Cons	3.04
RI Value	n	CR	
0.58	3.00		0.03

Appendix F: Circuit Diagrams

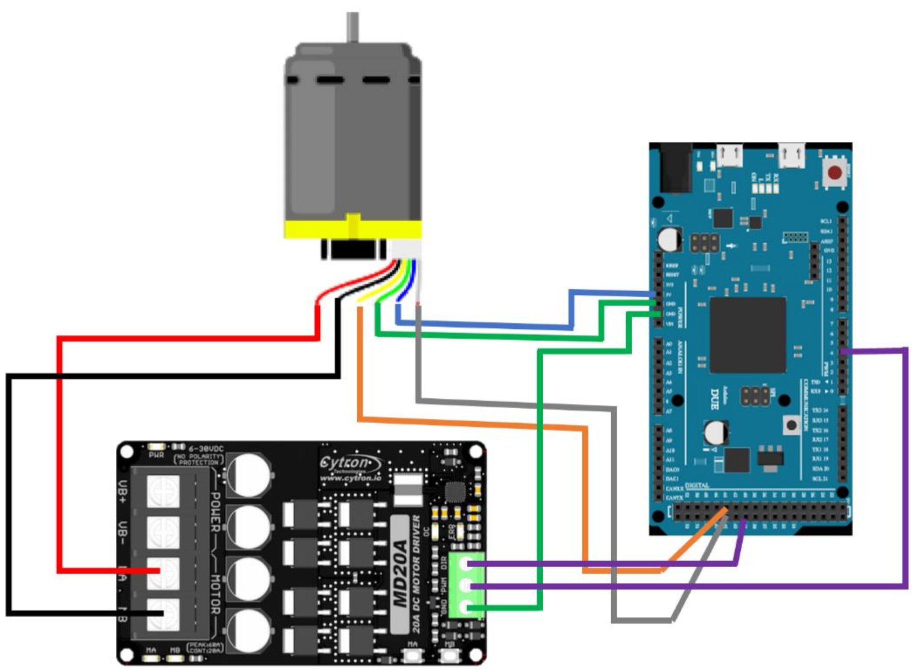
F.1: Circuit Diagram of motor driver 1 controlling motors 1 and 2



F.2: Circuit diagram of motor driver 2 controlling motors 3 and 4

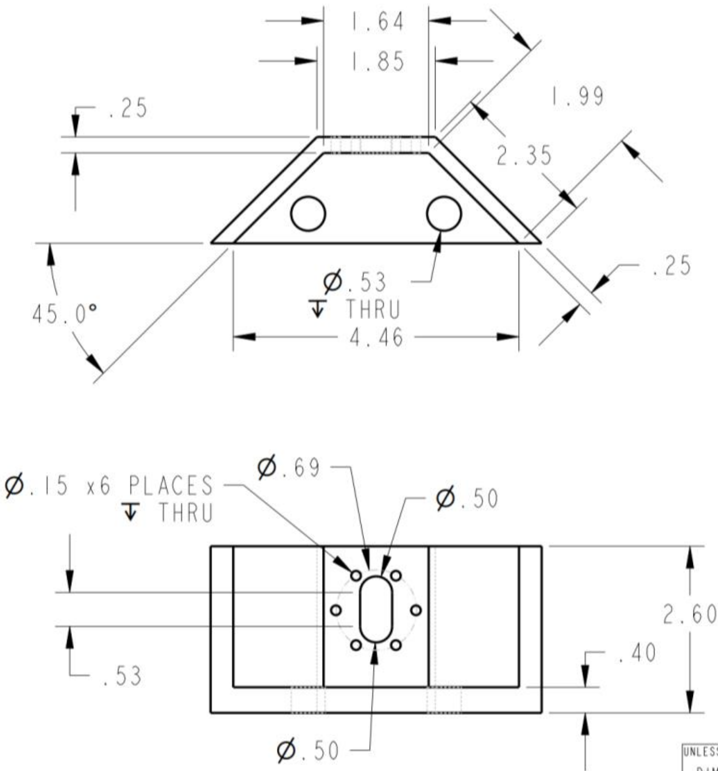


F.3: Circuit diagram of motor driver controlling the Maxon motor (lifting motor)



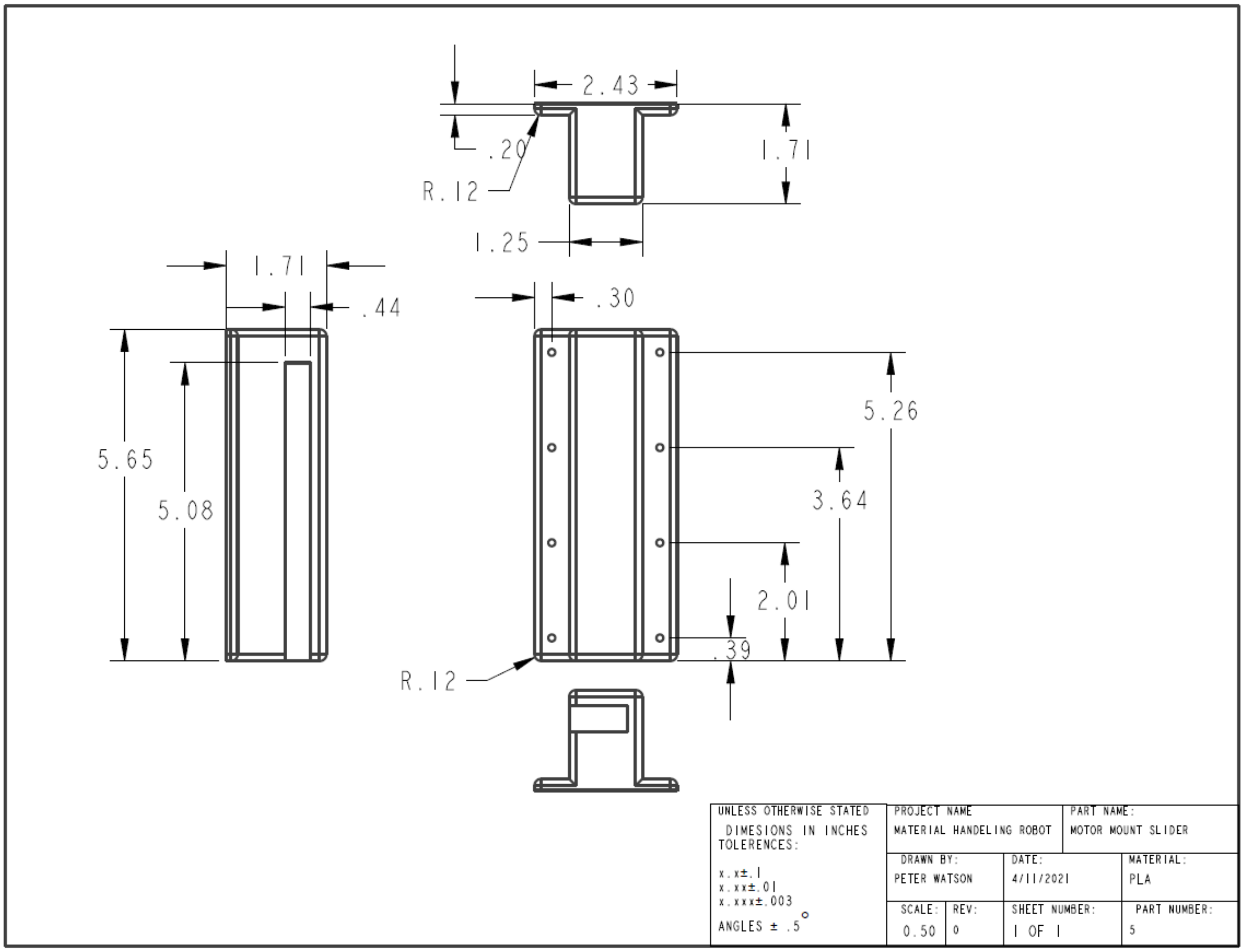
Appendix G: CAD drawings of custom parts

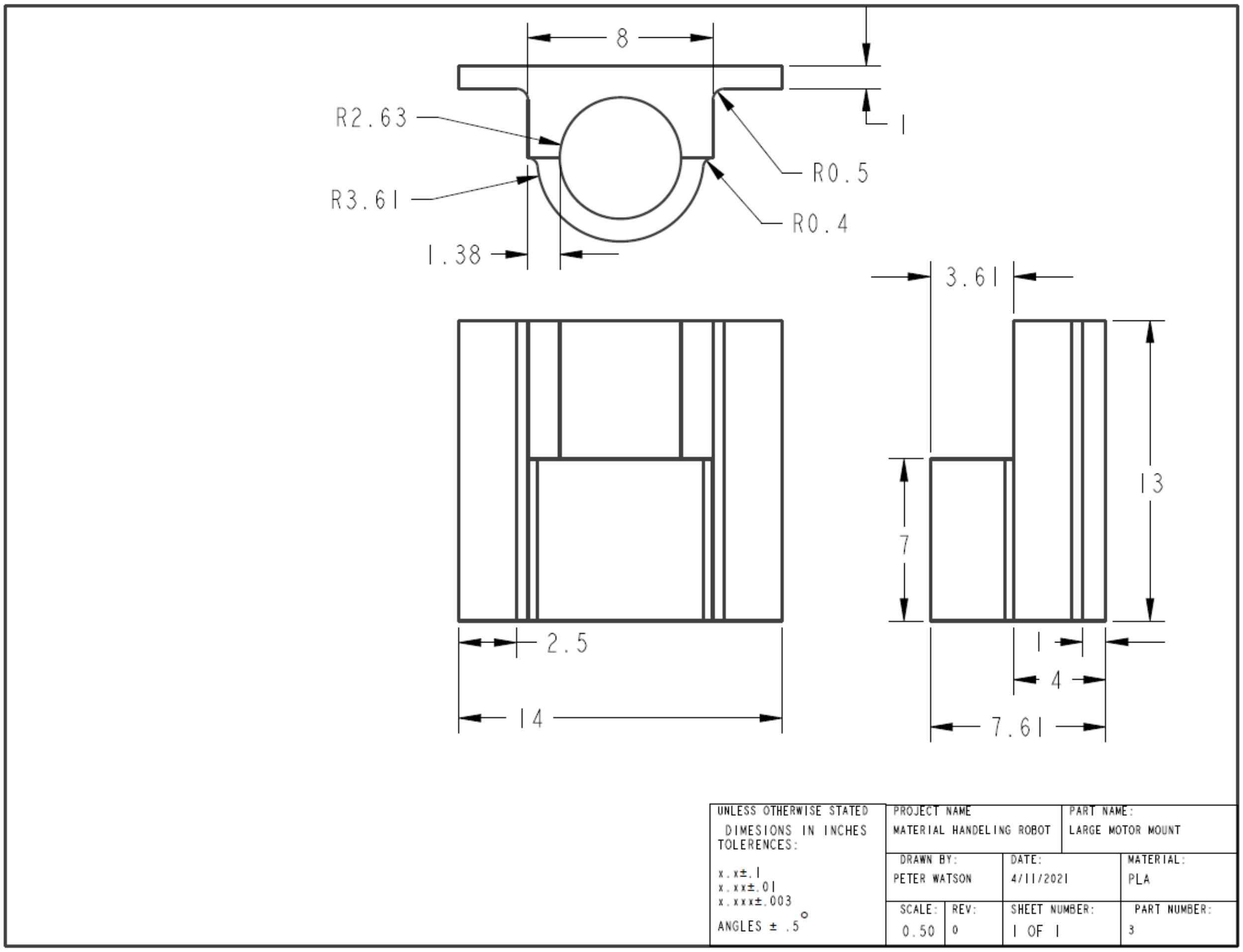
G.1: Motor mount for wheels

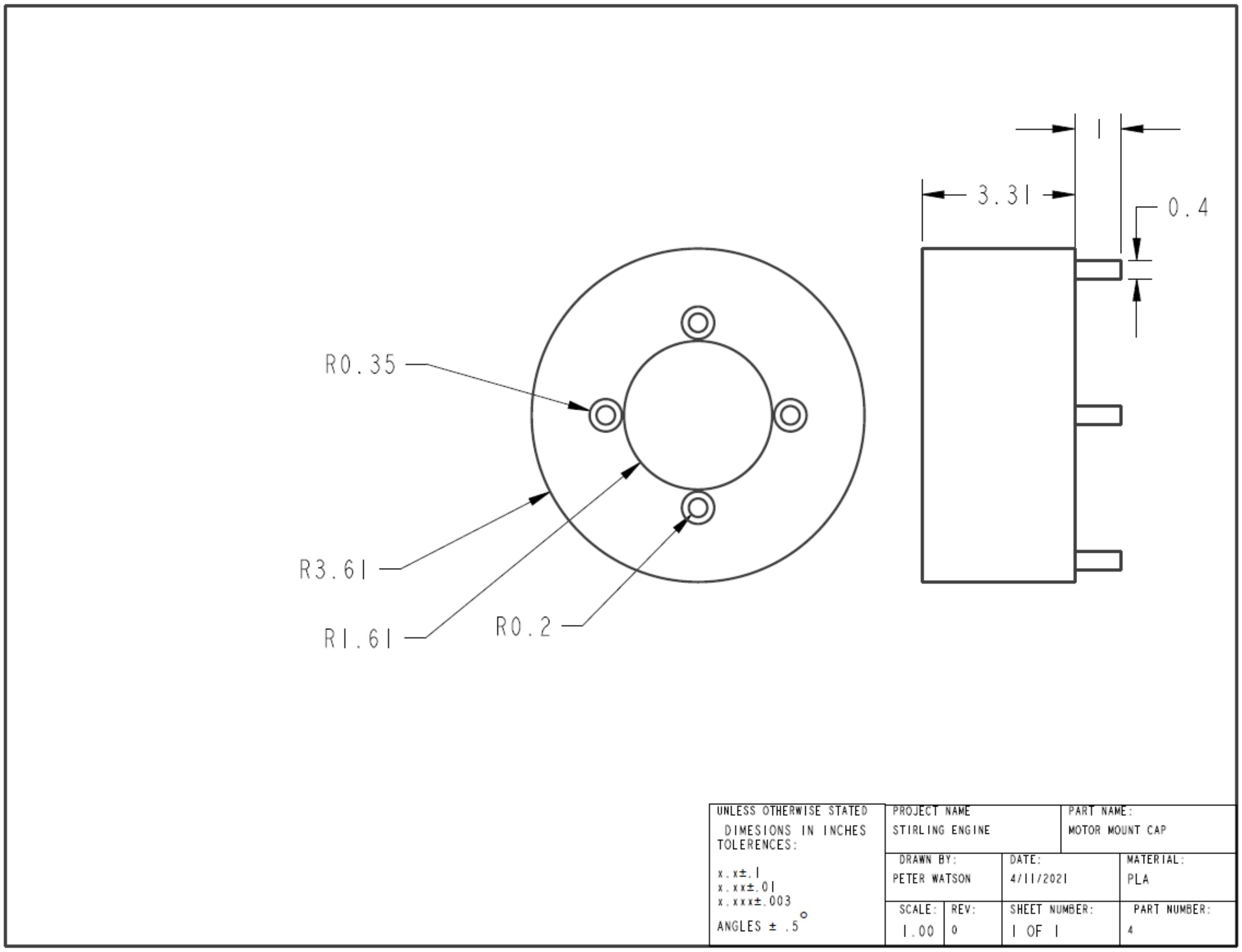


UNLESS OTHERWISE SPECIFIED	SIZE:	PART NAME:		PROJECT NAME:
DIMENSIONS IN INCHES	A	MOTOR MOUNT 45°		SENIOR DESIGN
TOLERANCES: X.X± .0.1 X.XX± .0.01 X.XXX± .0.003 ANGLES± 0.5°	DRAWN BY: ALEXANDER WOZNY		DATE: 3/19/2021	MATERIAL: PLA
	SCALE: 0.550	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP21-SD-P-003

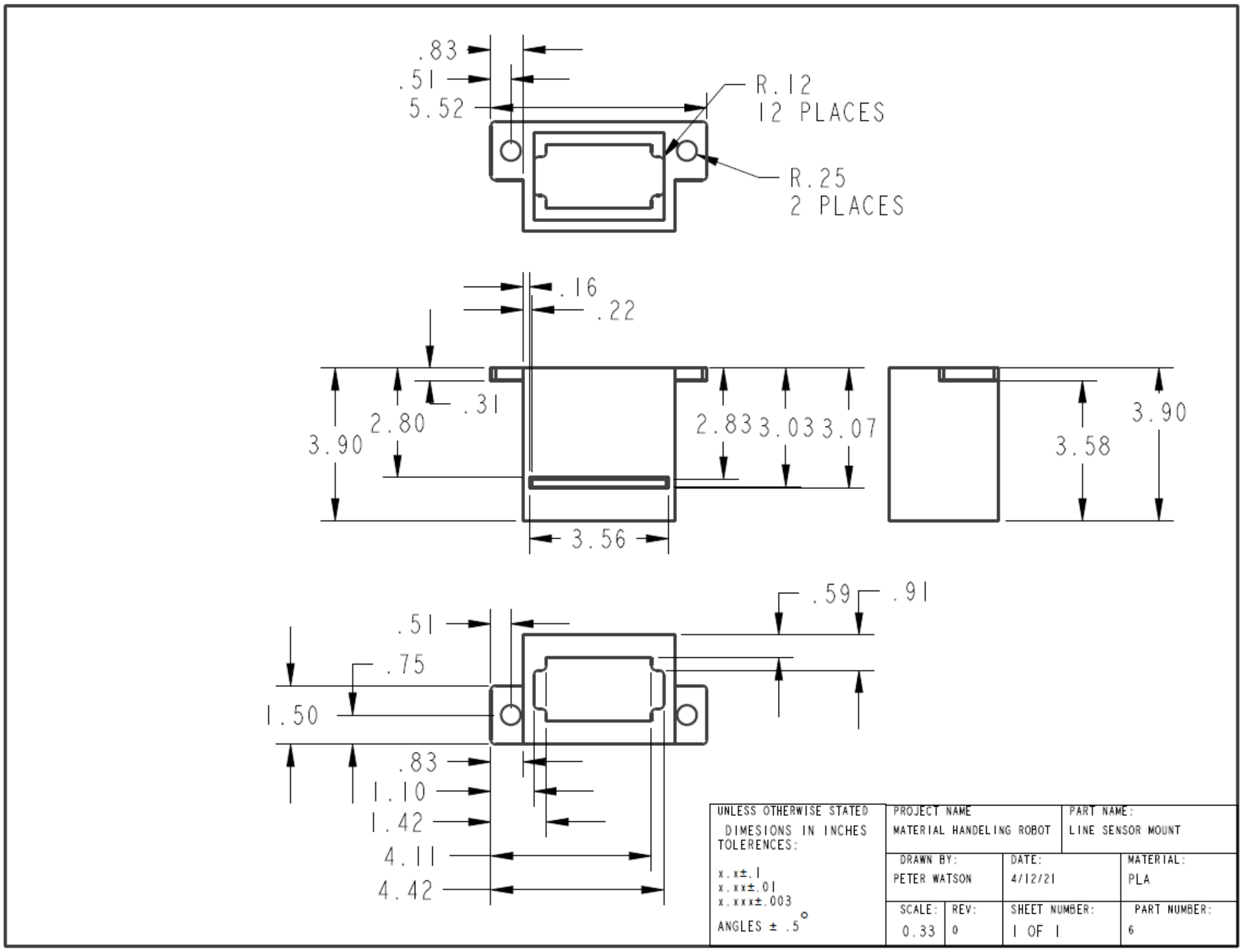
G.2: Motor mount for Maxon motor (lifting motor)



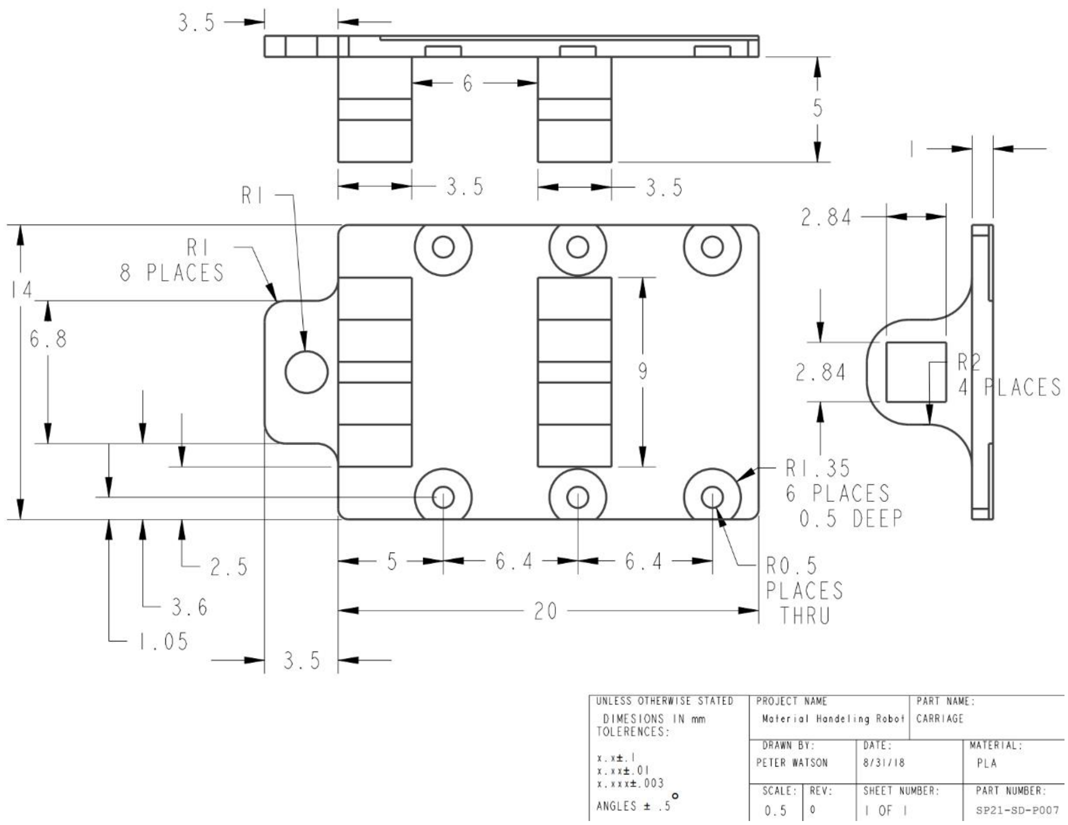

8
1
R2.63
R0.5
R3.61
R0.4
1.38
3.61
13
7
2.5
1
4
14
7.61
UNLESS OTHERWISE STATED
DIMESIONS IN INCHES
TOLERENCES:
x.x±.1
x.xx±.01
x.xxx±.003
ANGLES ± .5°
PROJECT NAME
MATERIAL HANDELING ROBOT
PART NAME:
LARGE MOTOR MOUNT
DRAWN BY:
PETER WATSON
DATE:
4/11/2021
MATERIAL:
PLA
SCALE:
0.50
REV:
0
SHEET NUMBER:
1 OF 1
PART NUMBER:
3



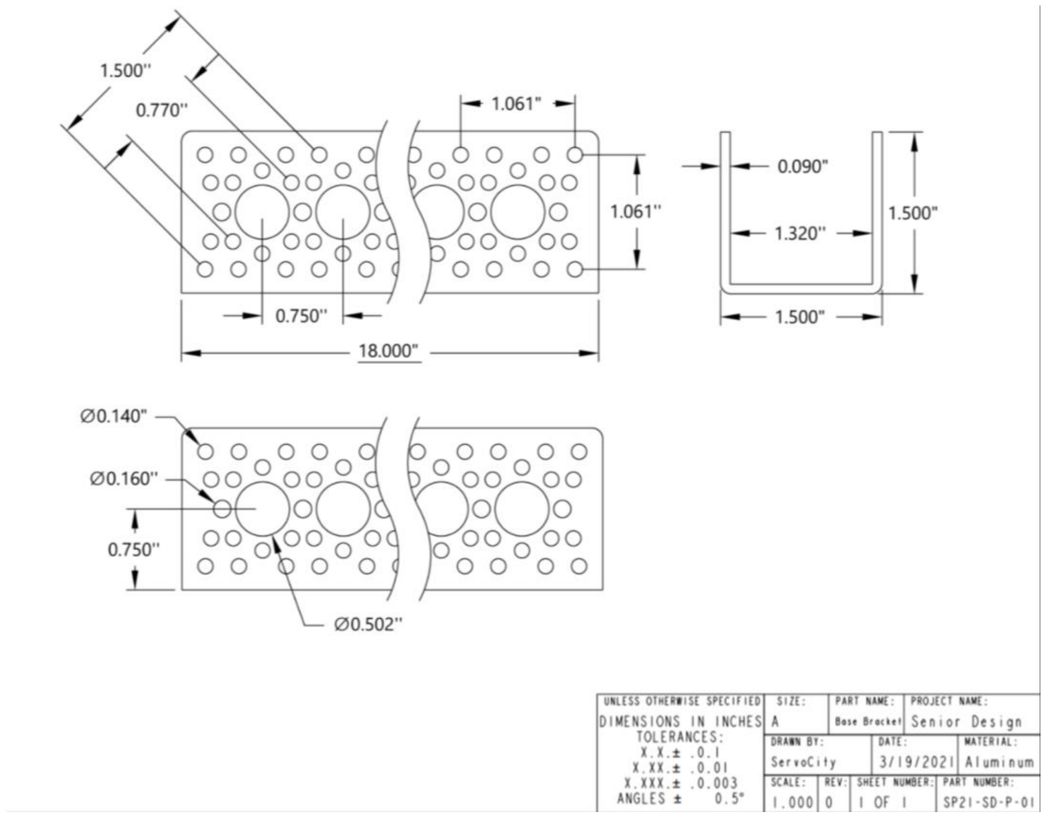
G.3: Sensor mount



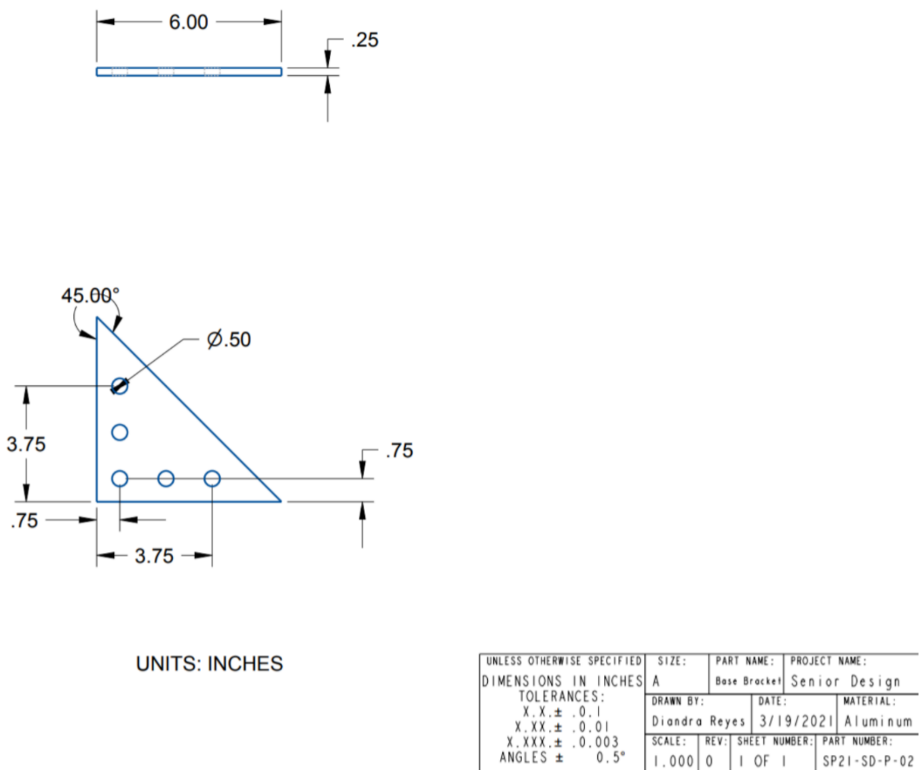
G.4: Carriage for lifting



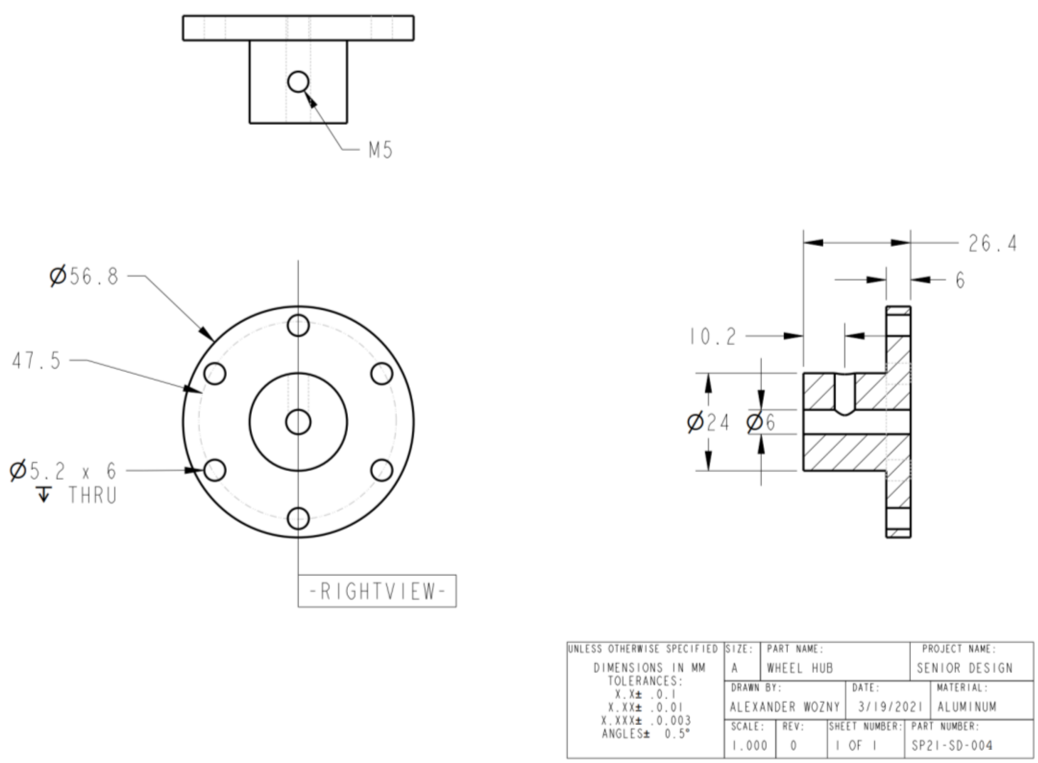
G.5: Aluminum brackets for base frame



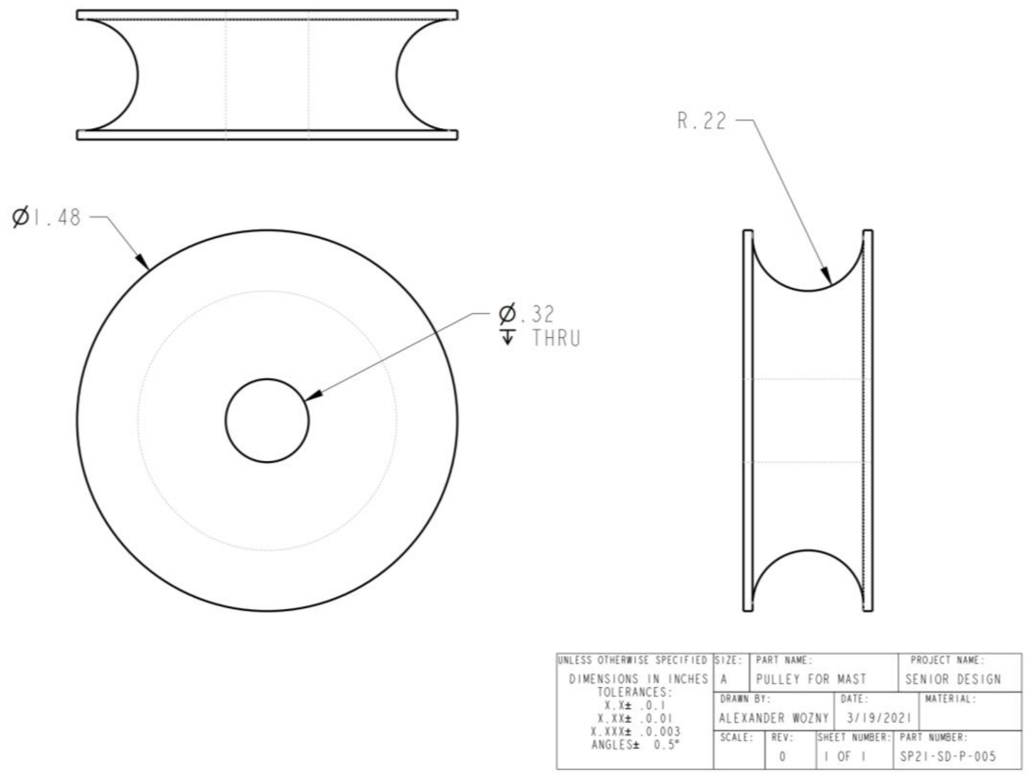
G.6: Custom Aluminum brackets for chassis



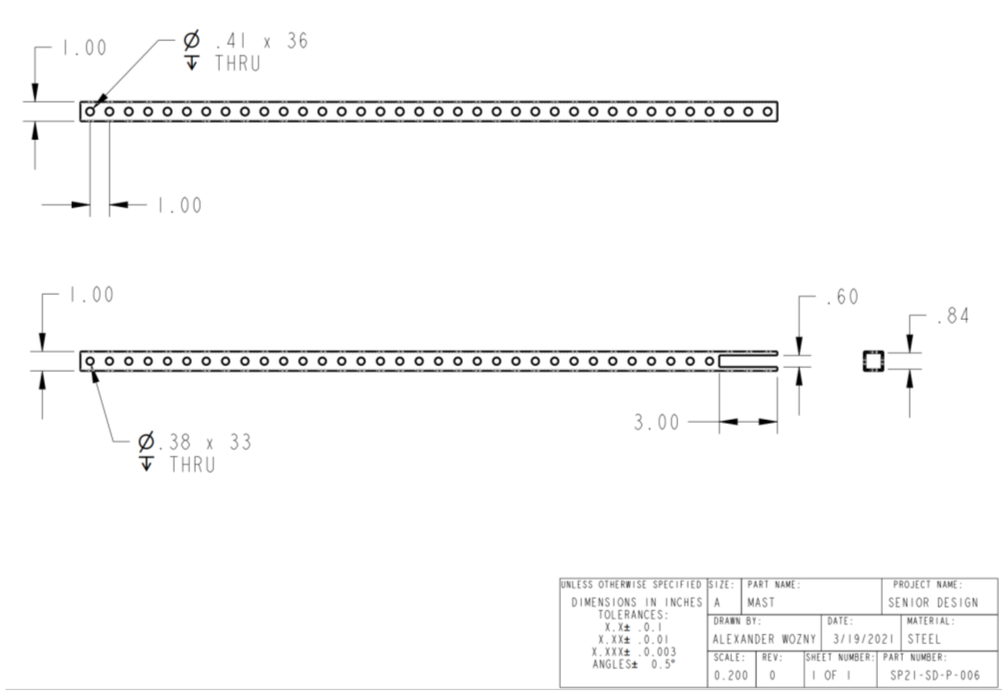
G.7: Wheel hubs



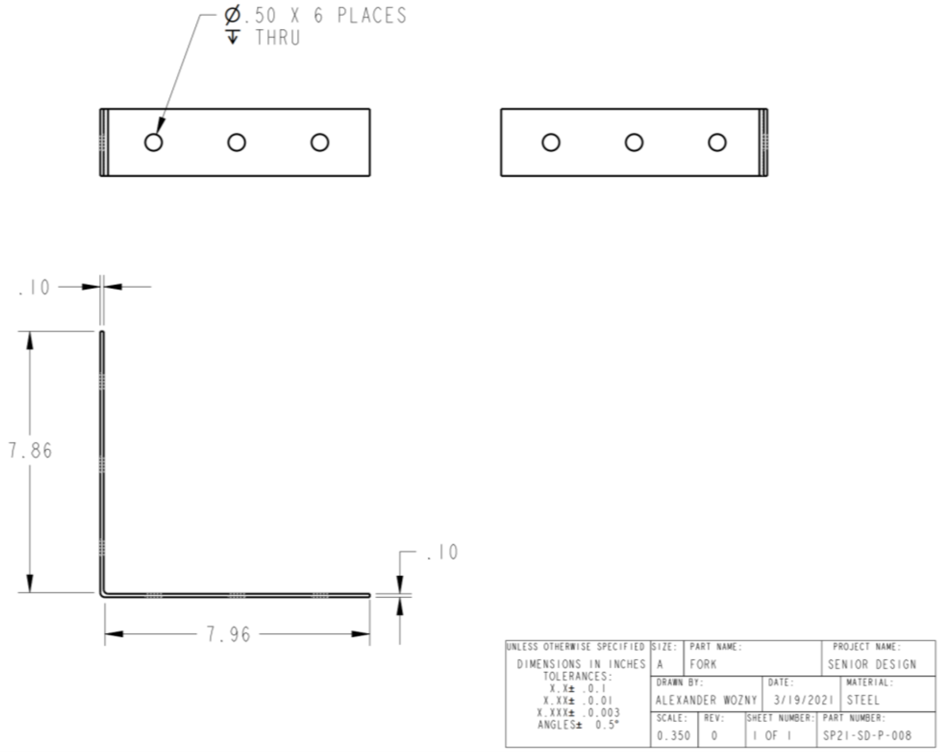
G.8: Pulley wheel for lifting mechanism



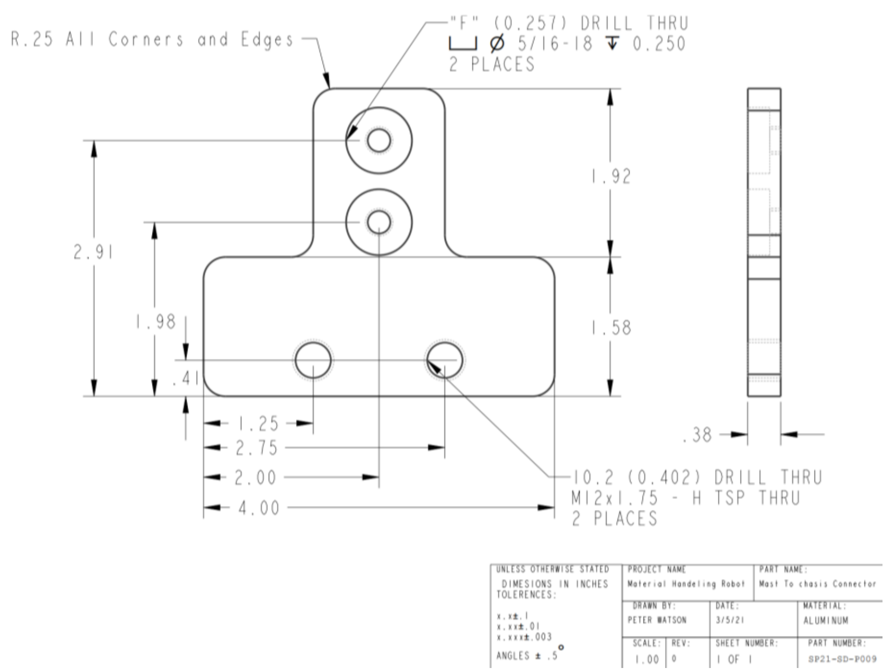
G.9: Mast



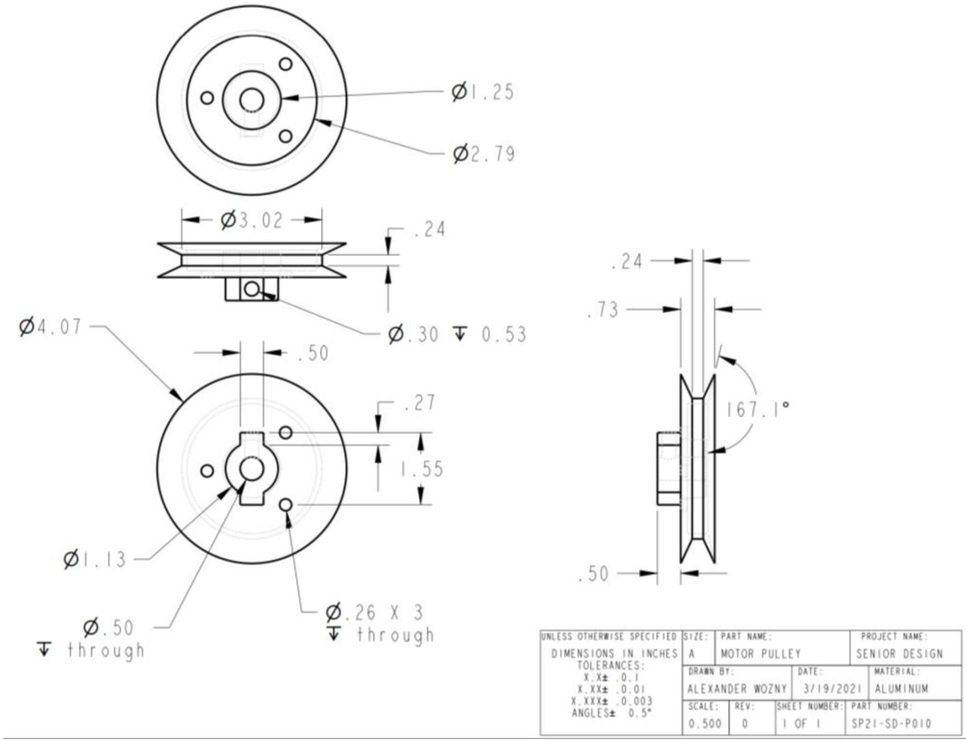
G.10: Forks



G.11: bracket to secure mast



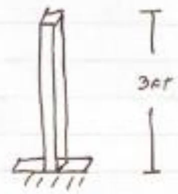
G.12: Wheel for lifting mechanism



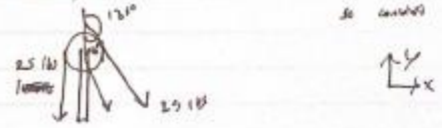
Appendix H: Calculations

H.1: Forces on Mast

Loadings on mast



"Rigging loading"



Force in x direction ~~sin (45)~~

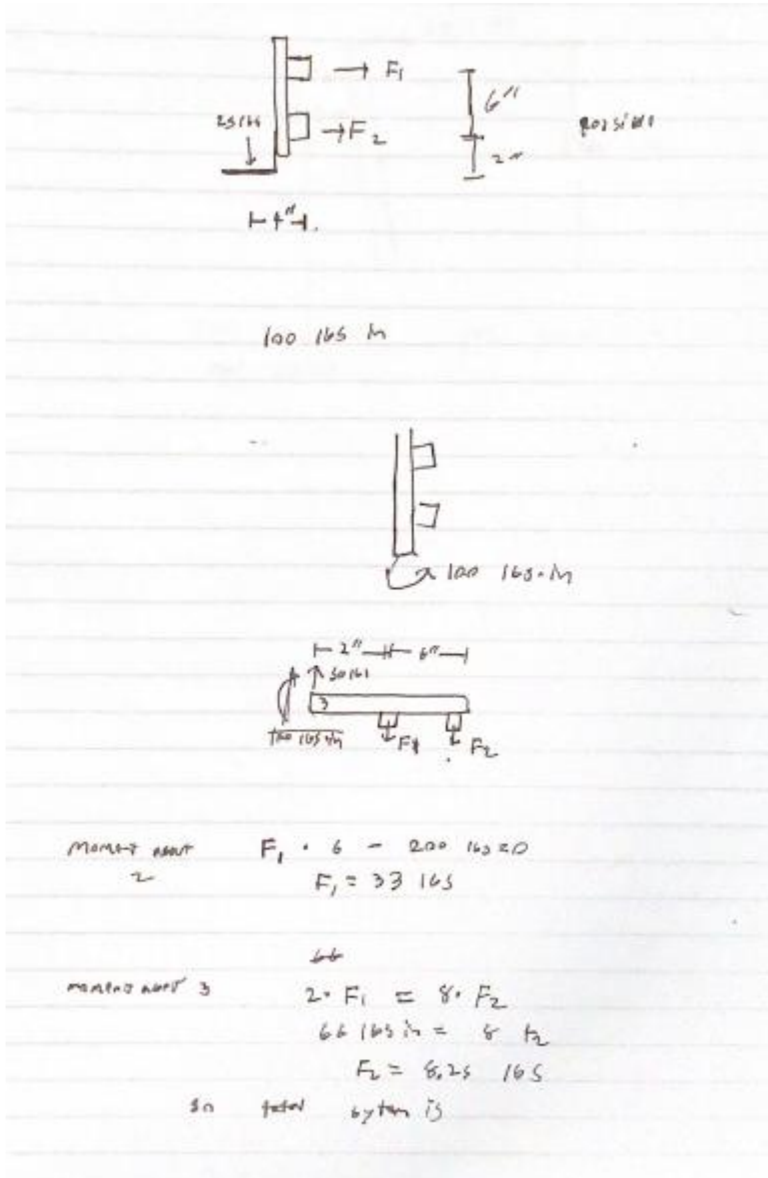
$F_x = 25 \sin(45°) + 25$

$= 17.7 + 25$

$F_x = 42.7$ lbs

we don't need to worry about y component for this case

You would think this would be the sum of all forces, however the system moves in a direction opposite of what's expected, when tested. It tilts away from the robot instead of towards. I belive this is caused by a moment from the carriage



H2: Fork Dimensions

Appendix I: Arduino Code

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