Introduction to Engineering Design with Professional Development 1

Final Report for
Project Legion

Team: ATLIS Innovation
Section 01
Instructors: Amy Corron and Hisham Mohamed

Version 1.0
August 20, 2020

Prepared by
Jenna Ackerson (2023 / Mechanical Engineering)
Frantz Doerrer (2022 / Computer Systems Engineering)
Kessler Dupont-Teevin (2023 / Electrical & Computer Systems Engineering)
Christian Johnson (2023 / Mechanical Engineering)
Kristopher Riordan (2023 / Aerospace and Mechanical Engineering)
Catherine Worthington (2023 / Civil Engineering)

Rensselaer Polytechnic Institute

Executive Summary

This report details the Atlis Legion autonomous warehouse robot which is capable of self-navigating a warehouse environment to handle and move packages of up to 200lbs. It will reduce the operational cost and environmental impact of any compatible warehouse while increasing efficiency and automation, and the market for this kind of solution is ripe.

Table of Contents

1 Introduction

The ATLIS team set out to tackle the problem of transporting large, heavy, cargo in a dynamic warehouse efficiently and at a reasonable cost. Current solutions, such as forklifts and other manned vehicles, discussed in section 3, require additional costs for extended hours, during nights, or over holidays while an automated fleet maintains the same operation cost. These existing solutions or research projects are either outdated, underdeveloped, or not available to every company. With this in mind, the ATLIS team proposes an automated, full-stack solution that addresses the many challenges of transporting different sized packages from warehouse shelves to outbound delivery vehicles: the ATLIS Legion.

2 Project Objectives & Scope

Mission Statement

To use a network of autonomous robots to transport a variety of warehouse cargo from storage racks to shipping containers and vice versa.

Customer Requirements

As the ATLIS Legion's primary function is to transport cargo more efficiently than currently possible, the top customer requirements address the variety of potential packages to be moved, specifically acknowledging the weight and size of these packages, as well as the types of containers they're likely to be in. Additionally, the ATLIS robot's arm is designed to be able to move items from their storing shelves, onto its storage bay, and back. Therefore, it is critical that the arm is able to move with precision and be able to reach the majority of shelves being used, as well as hold the packages while loading and unloading them. Another key aspect of the device's functionality is the ability to sense its current position and navigation to its destination in a safe, yet efficient manner. Table 2.2-1 below shows the specifications and values assigned to each of these functions that this device strives to meet.

As shown in table 11.1 of Appendix B, an extended list of metrics was compiled that more completely fulfills the needs of modern warehouses and associated companies. However, many of these were considered to be of secondary importance when preparing for a demonstration of the device and were therefore left out of scope of the project for the time being. Some of the requirements, such as the overall dimensions of the system, were simply reduced to show proof of concept while others of lesser importance, such as user comfort considerations and functionality in a variety of extreme temperature ranges remained outside of the scope of focus through design planning thus far and would likely be addressed at a later point, before full-scale production would begin.

Table 2.2-1 - Customer Requirements

Customer Need	Requirements (aka Technical Specifications)	Target Value / Range of Values
Can lift all types of warehouse cargo	*Lift Capacity*	*100-200 lbs*
	Can Lift & Handle Cardboard Boxes	*Yes*
	Be able to hold the weight of itself and the cargo	*0 structural failures*
	Cargo dimensions	*< 4' x 4' x 4'*
Can grab boxes off of a shelf	*Degrees of Freedom*	*≥ 3*
	Fully Extended Span	*4' - 8'*
	Position Accuracy	*< 0.6 degrees of variation*
Be able to transport a package successfully	*Packages do not fall off the robot*	*< 0 dropped packages during transportation*
Can support warehouse cargo at full extension	*Holding Torque*	*> 4000 lb-ft*
Size – can move things throughout a warehouse	*Width x Depth x Height (pertains to the robot frame perimeter)*	*< 6'x8'x10'*
Sensors are quick enough to navigate while moving	*Speed of sensor readings*	*< 1 ms*

Technical Specifications

As shown in both Table 2.2-1 above and Table 11.1 in Appendix B, several of the customer needs identified correspond to multiple technical specifications. For instance, a top priority amongst customers is that the device must be capable of interacting with a wide variety of cargo. Therefore, this requirement was broken down into four subcategories to address the weight, size, and shape and material of the packages in question. Similarly, a key aspect of the design is that the arm is able to interact with boxes currently stored on a shelf. To address this, separate metrics were put in place to ensure the arm would be long enough to reach packages that are higher up, with enough degrees of freedom to maneuver as needed, and a high enough accuracy to be able to actually grab the desired object. In contrast, many of the needs identified were more specific, such as the size of the device itself being relatively minimized so as to avoid crowding the warehouse floor. These requirements lead to individualized metrics, specifically addressing that particular concern as fully as possible.

3 Assessment of Relevant Existing Technologies

ATLIS investigated multiple versions of existing warehouse product movers to provide a better understanding of their advantages and disadvantages. Researching existing products yields inspiration for elements not thought of initially by the team. ATLIS looked into Boston Dynamics' Handle Robot, Amazon’s Kiva Robot, and forklifts.

3.1 Boston Dynamics’ Handle Robot

Figure 11.1 in Appendix B, displays Boston Dynamics’ warehouse robot, the “handle”. This design features a fully autonomous system. The robot is able to freely maneuver around the warehouse. It uses an arm system with a suction interface to pick up and put down boxes in any desired location. This robot allows for man to be completely eliminated from the product moving process. This robot is 6.5 feet tall and can move at a speed of 13.2 feet per second. This robot is difficult to mass produce because Boston Dynamics focuses on research, not selling their products. This opens up a market and allows ATLIS to distribute its product to warehouse operators looking for a similar product.

Table 3.1: Boston Dynamics’ Handle Robot Specifications.

Advantages	Disadvantages
• Can lift and transport weight • Fully autonomous robot • Able to pick up and put down products • Drives 13.2 ft/s	• Takes up space • Difficult to mass produce • Expensive

The handle robot is relevant to ATLIS’s legion because they both use an arm system to pick up packages and are fully autonomous.

3.2 Amazon's Kiva Robot

Figure 11.2 in Appendix B, displays the product mover used in Amazon's warehouses, the "Kiva Robot". The robot is used to deliver a shelf stocked with products to employees to grab from the shelf and pack. By moving the items autonomously, it allows for the warehouse packing process to move at an accelerated pace. The robot is approximately 2 feet wide by 2.5 feet long by 18 inches high, and lifts up to 1000 pounds. Amazon's Kiva robot is only available to Amazon and is not sold to consumers. This opens up a market and allows for ATLIS to distribute its product to warehouse operators looking for a similar product

Table 3.2: Amazon's Kiva Robot Specifications.

Advantages	Disadvantages
• Can transport multiple products at once • Fully automated driving system • Does not take up space	• Products must be handled by a human worker • Not sold to consumers • Cannot lift heavy packages

The Kiva Robot is relevant to ATLIS's legion because they both feature fully automated driving systems.

3.3 Forklifts

Figure 11.3 in Appendix B, displays a standard product mover on the market, the "Runtx's FD40T Forklift" (2021). This design was explored because of its popularity in the industry. Forklifts are popular in the field because they are easy to use and can lift anywhere from 5000 kg to 7000 kg. The forklift is operated similarly to a car. It is driven to a desired location and then raises or lowers its arms to pick up the product.

Table 3.3: Runtx's Forklift Specifications.

Advantages	Disadvantages
• Lift and transport 5000 kg to 7000 kg • Easy to use • Can pick up products on the ground	• Takes up a lot of space in the warehouse • Manned operation

and up to 10 ft in the air ● Strong & durable 4' arms	● Expensive ($6000 - $18600)

Forklifts are relevant to ATLIS's legion because they are both used in a warehouse setting to pick up and carry heavy objects.

4 Professional and Societal Considerations

The engineering design process was used to produce a solution that meets the specified needs with consideration for the topics found in Table 4.1 - Engineering Solutions Impact.

Table 4.1 - Engineering Solutions Impact

Area of Impact	Impact	Description of Impact
Public Health and Safety	Y	Reduce heavy machinery accidents and musculoskeletal disorders (OSHA, 2004)
Global	Y	Improve efficiency of international exporting and importing (Research and Markets, 2021)
Cultural	Y	Backlash in western world; expanded market in nations like Japan (Ito, 2018)
Societal	Y	Increase demand for high-skilled workers; create low training jobs to operate/maintain the robots (Koppelman, 2020)
Environmental	Y	Reduced emissions by utilizing fewer heavy machines reliant on fossil fuels (Rimmer & Yarnell, 2009)

Economic	Y	Productivity growth; high efficiency movement of goods (Anthony, 2021)

5 System Concept Development and Selection

With customer needs prioritized and analyzed two major system level designs were considered. Seen in Figure 5.1 are sketches depicting the overall design with the primary features being considered are the ability to grab and move boxes onto the robot, the chassis structure, and the drivetrain. The first of the two concepts involves a chassis shaped as a rectangular prism with a robotic arm placed at the rear to leave room for boxes to be stacked in the front of the bot. Additionally four wheels were located at each of the four corners of the chassis. The second of the two systems had a similar drivetrain and chassis, except that the front of the chassis tapers to the ground to form an incline surface between the warehouse floor and the upper surface of the chassis. This system utilizes wheels and a conveyor belt to draw the boxes sitting in front of the robot up onto the top surface of the chassis.

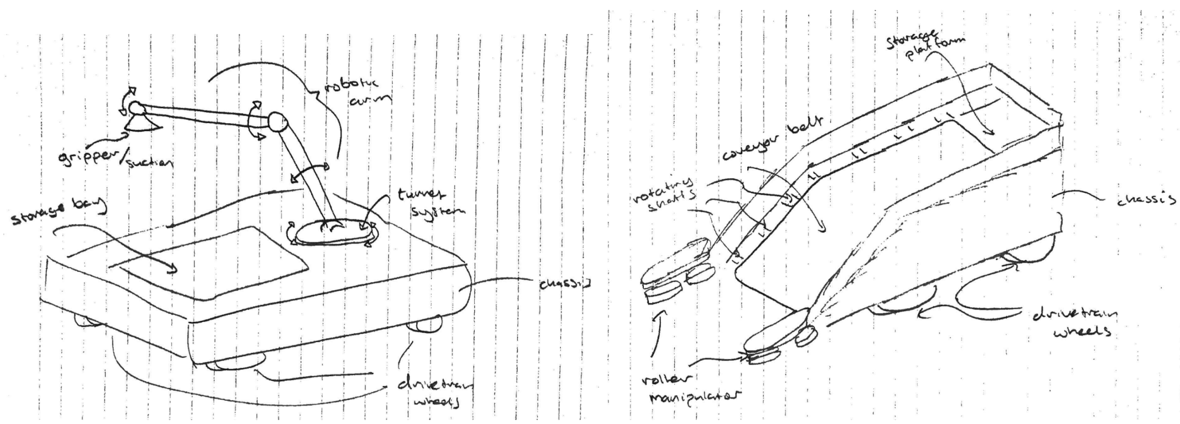


Figure 5.1: System Level Concept Generation

Another use of these systems is to simplify them and use them in conjunction with other simpler robots in a “buddy” system. That is, a simpler smaller robot with an arm would place boxes onto moving robots that merely act as land barges in a warehouse. Another concept that was considered is to have a passive incline bot that acts that stays stationary as another robot pushes boxes up onto the top of the chassis to be transported throughout the warehouse. Overall this constitutes four general system level designs to be used to satisfy the customers. A screening matrix, seen in Table 5-1, outlines the criteria used to select between which system to use for the final design. The original two concepts shown in Figure 5.1 both presented themselves as viable system level solutions, so a vote was used to make the decision to move forward with the “Arm” based concept that drove around the warehouse using its arm to lift and stack packages onto and off of itself.

Table 5-1: System Level Design Screening Matrix

	Concepts			
Selection Criteria	**Conveyor Belt**	**Arm**	**Buddy System Conveyor**	**Buddy System Arm**
Cost	0	0	-1	-1
Difficulty of Implementation	1	0	0	-1
Creativity	0	0	1	1
Efficiency	1	1	-1	-1
System Weight	1	-1	1	0
Size	1	0	1	0
Practical	-1	1	0	1
Safety	1	0	0	-1
Mobility Precision	0	1	0	0
Durability with Average Usage	1	1	0	0
Versatility	-1	1	0	1
Potential Speed	1	1	0	-1
Sum of +1's	7	6	3	3
Sum of 0's	0	0	0	0
Sum of -1's	-2	-1	-2	-5

Net Score	5	5	1	-2
Rank	1	1	3	4
Continue?	**Y**	**Y**	**N**	**N**

Over the course of the subsystem design the system design itself evolved. A final CAD model for the full system can be seen in Figure 5.2. The top right displays a chassis and drivetrain assembly with a mockup of the arm. The detailed CAD model of the arm is seen on the left figure. The bottom right of the figure shows an internal view of the chassis showing how each subsystem will be integrated into the final design. Further description of these subsystems and their functions will be discussed in Section 6.

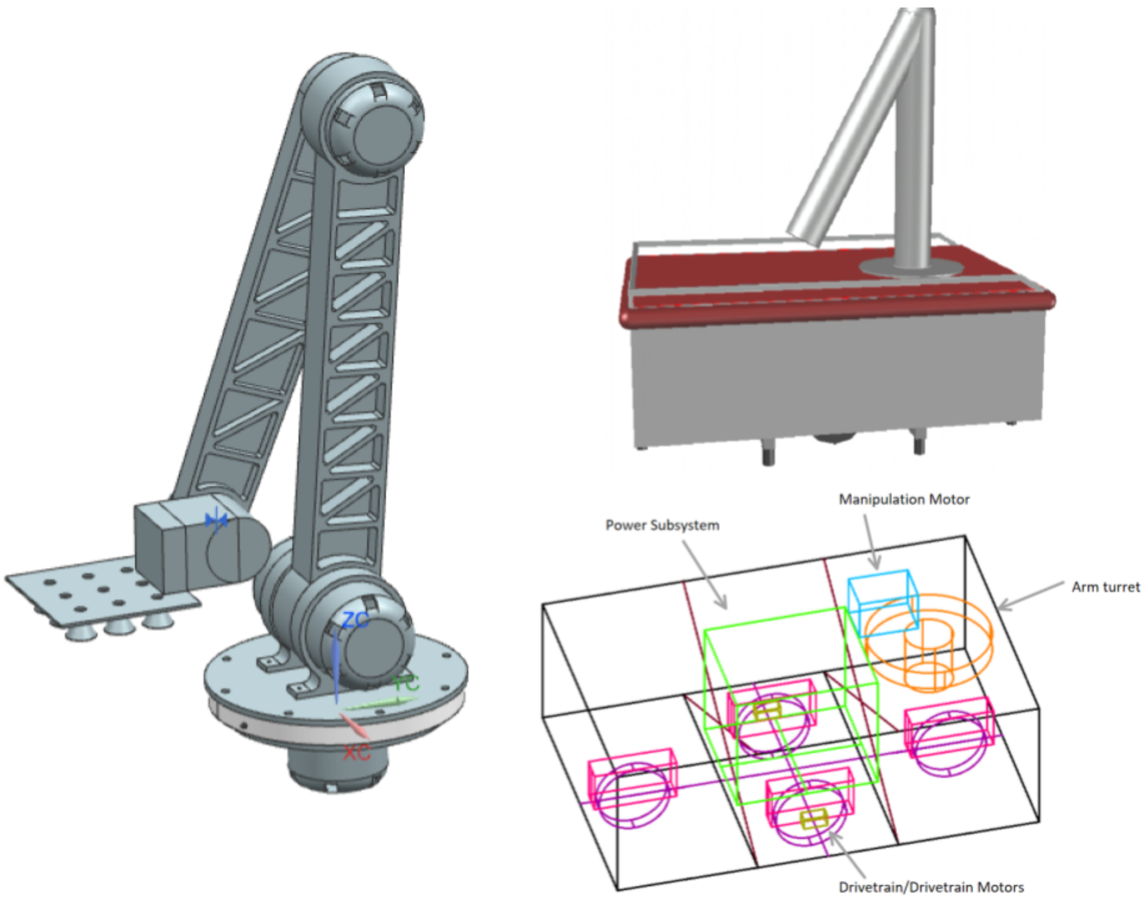


Figure 5.2: Final System CAD Model

6 Subsystem Analysis and Design

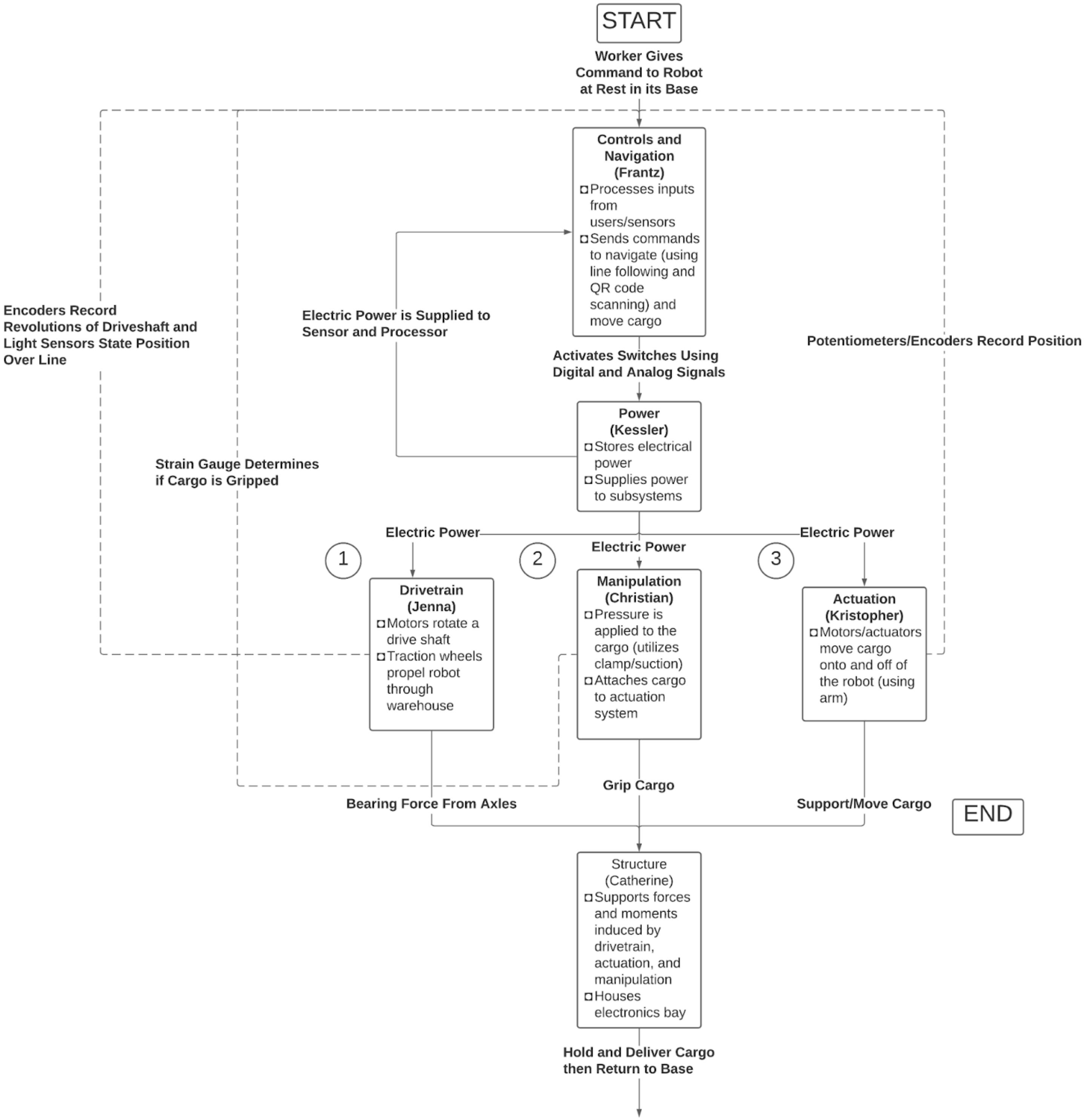


Figure 6.1 System Inputs/Outputs Flow Diagram

The proposed solution is an autonomous robot that is capable of precisely and accurately navigating throughout a dynamic warehouse setting to deliver packages from the desired storage or shipping locations. To do so, the robot will be able to lift and place boxes of cargo onto and off of itself. As seen in Figure 6.1, the Controls and Navigation subsystem converts user inputs and sensor readings into commands that will correspond to the activation of switches in the Power subsystem. The stored energy in the Power system stores the energy required to power all electronic components on the robot. By activating switches, electric power will be applied across the components within each of the three following subsystems: Drivetrain, Actuation, and Manipulation.

The Drivetrain will primarily receive power from the motor controllers. This will then allow the motors in the drivetrain to have the proper amount of current passing through them to spin at the desired speed with the desired torque. This will allow the drivetrain to accelerate the chassis of the robot, and therefore everything on it, giving it the ability to move from point A to point B in the warehouse. The user operating the robot will need a specific order filled, and the tasks of the robot will be determined by the user through a basic user interface system that will be described in Section 6.1. Encoders in the Drivetrain will record the angular motion of the drive axles and feed the values to the Controls and Navigation system. This will allow the robot to have a greater awareness of its state in order to make proper decisions. Additionally, the drivetrain will have an array of color sensors integrated into it so that the robot can follow a line. Along these lines will be QR codes which will be scanned from underneath the robot telling the robot at which aisle it is currently located. This will be the primary mode of navigation throughout the warehouse.

The Actuation subsystem will be driven by stepper motors whose speeds and torques will also be regulated by motor controllers. Again, encoders will be used to monitor the state of the drive axles. Accelerometers and strain gauges will also be implemented to monitor the forces and motion of actuation components.

The Manipulation system will be controlled via the Power system applying current to a compressor such that suction is used to grip the cargo and support its weight. Here strain gauges and accelerometers may be used as well to determine if the cargo has been fully gripped by the manipulator mechanism.

All of the sensor values for these three subsystems will be sent as inputs into the Controls and Navigation system as stated before to provide the microprocessor with more information about the state of the machine in order to make proper decisions based on feedback loops. These feedback loops will compare the present state of the system with the desired state of the system set by the warehouse workers' inputs, and will send commands to adjust the present state accordingly to meet the desired state.

The outputs of these three subsystems will involve sustaining a force. These forces that are applied both internally and externally must be supported by the Structure subsystem, which will involve the chassis and the remainder of the structural components in the body (e.g. a robotic arm frame). The output of the Structure subsystem will be the support and movement of large masses of cargo throughout the warehouse in a stable manner until the robot returns to its base.

The primary system level concept consists of the robotic arm actuation system coupled with the pneumatic suction manipulator. While the concept screening matrix showed that the conveyor and arm concepts were equally viable, the high level of versatility in the arm addressed the needs of the consumers far better than the conveyor belt system design. The drivetrain will consist of two driven traction wheels with two undriven omni wheels mounted near the rear and front of the chassis for stability reasons. The drivetrain motors and gearbox will be selected once more details are known about the design of the other subsystems. A Raspberry Pi is the primary candidate for the microprocessor that will drive the operations of the Controls and Navigation system.

(Note: All Section 19 table and figures are found in Appendix J)

Controls and Navigation

6.1.1 Final Subsystem Design

Sensors

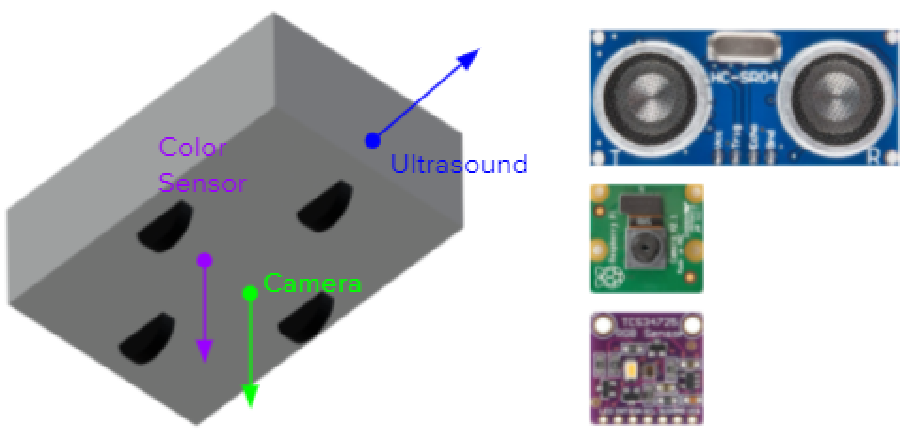


Figure 19.1.1: Placement and appearance of the sensors. The colors of the arrow has the color of the sensor's board

The final subsystem would consist of two sensors pointing down, one for color and one for QR, to detect the floor markings of the warehouse as it navigates floor markings like the one pictured below. The floor markings must have the constraints of restricting QR codes to corners where turning is necessary, and the dash marks between them would be separated by a fixed distance so that the distance travelled can be measured by the software. An additional forward-facing ultrasound sensor will be placed in front of the robot so the software can detect obstacles and engage breaking when it does.

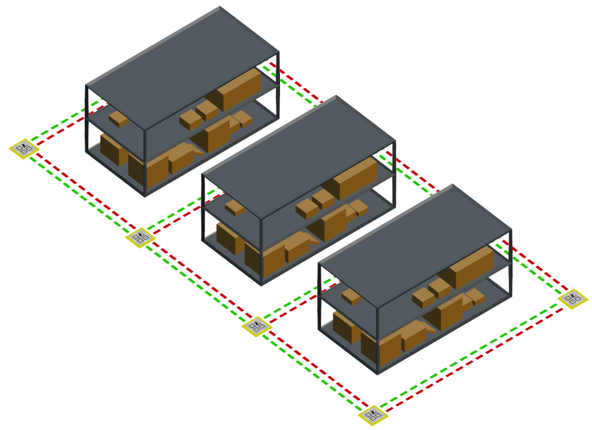


Figure 19.1.2: Mock-up warehouse floor markings. Yellow: QR codes, Red and green: lines for line following

Motors

The motors of the drivetrain (wheels) are DC and can thus be powered by enabling and disabling a voltage source to turn on and off, and flipping the charge of the voltage between positive and negative to alternate between forward and reverse. Two digital pins connected to the Raspberry Pi will interfere in a circuit to alternate between the on, off, forward, and reverse states for the motor.

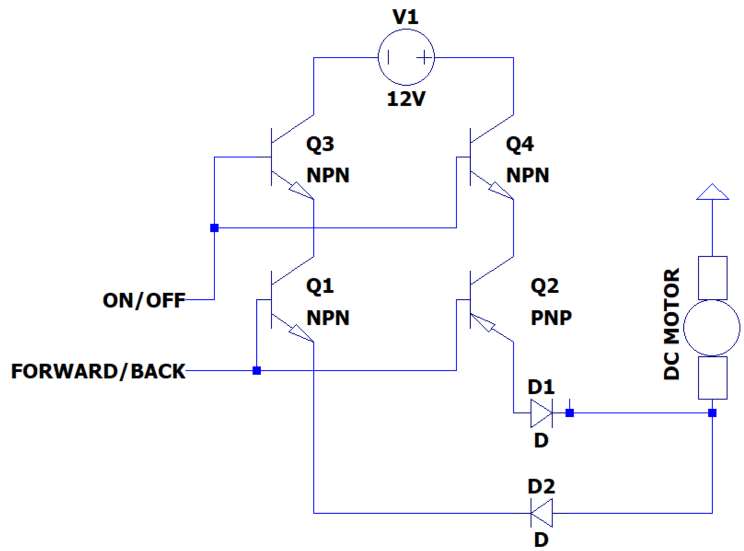


Figure 19.1.3: Circuit design for the interface between the microcontroller and motor

For the motors of the arm, a more complex embedded circuit is necessary for them to be interacted with by the computer software, i.e. the servo motor hat for the raspberry pi, which would convert an external DC voltage source into a pulse based on digital inputs.

Software

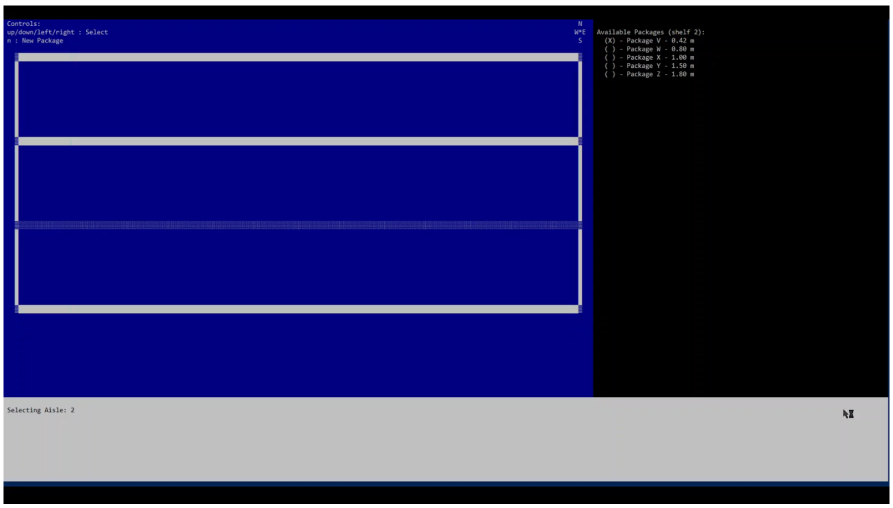


Figure 19.1.4: Dummy terminal user interface

The software gives the ability for the user to direct the robot through a computer terminal GUI by navigating a gui with keyboard keys over a computer network.

6.1.2 Specification and Objectives

The goal of the control system is to gather data from sensors and inputs to direct the steering of the arm and wheels of the ATLIS robot. The only metric that constrains it is that it should be able to control the ATLIS robot with the inputs of only one person at a time, which the GUI is capable of accommodating

6.1.3 Benchmarking

To benchmark for this subsystem, different devices for the navigation needed to be considered. The most important features to take into account were the cost and ease of implementation, as this needs to be easily deployable in warehouses in order to upgrade economies of scale without too much overhead in the infrastructure. Based on the devices used by the amazon kiva robots, it seemed

6.1.4 Concept Selection

The devices considered for navigation need to be cost-effective while still allowing the robot to navigate effectively throughout the warehouse. Different sensors were considered such as…

- reading the distance of infrared beacons laid about the warehouse to triangulate position.
- reading QR codes on the floor as the Amazon kiva robots do to indicate the position.
- reading road markings to measure the distance travelled and get the direction.
- using an accelerometer gyroscope to measure the distance travelled and direction.

6.1.5 Modeling and Prototyping

The prototype constructed for the demonstration was a simple computer terminal user interface that could potentially be used to control and navigate the warehouse. All that needed to be demonstrated is that the robot could be commanded with the inputs of one worker. The details of this demo are explained in Appendix I.

Power Delivery Subsystem

6.1.1 Final Subsystem Design

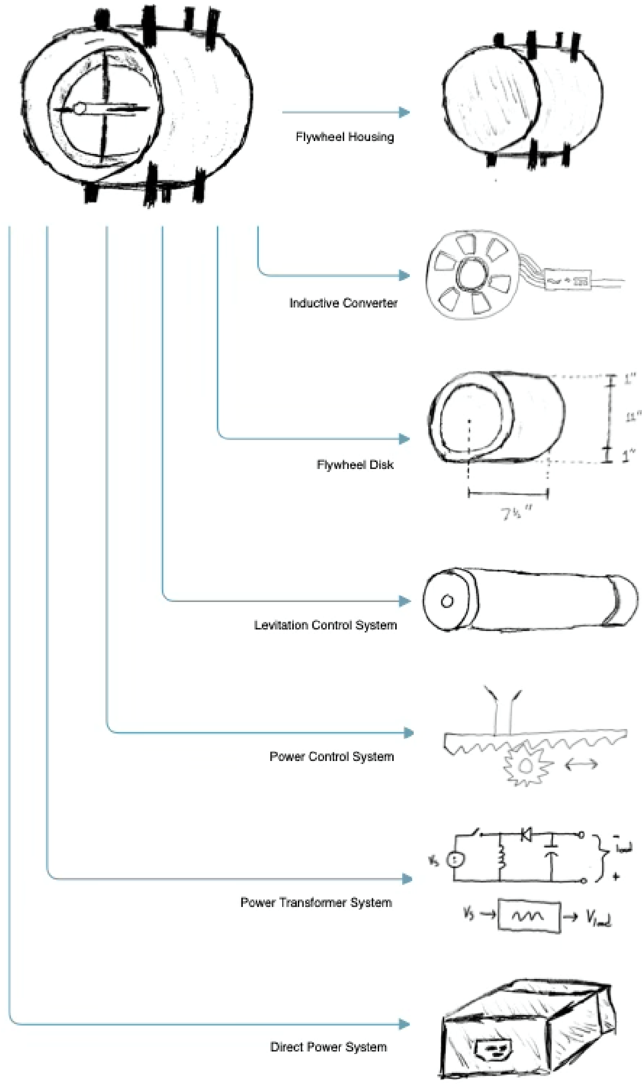


Figure 19.2.1: The design components of the power delivery subsystem

The power delivery subsystem uses a variety of control elements to deliver adequate power to every other subsystem. It does so by storing electrical energy in the form of rotational energy in a disk-shaped device known as a flywheel. This energy is transferred to the various subsystems via electrical wiring.

6.1.1.1 The Disk

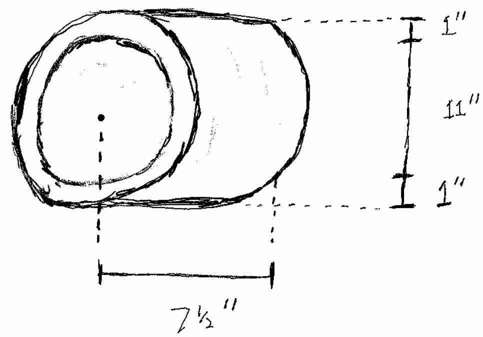


Figure 19.2.2: Dimensions of the disk

The disk is the part that of the power delivery subsystem stores rotational energy. It is an 8.1 kilogram disk with an inner radius of 11 inches and an outer radius of 13 inches that is 7.7 inches long. This disk is made of carbon fiber because it needs to withstand high rotational acceleration during operation.

6.1.1.2 The Levitation Control System

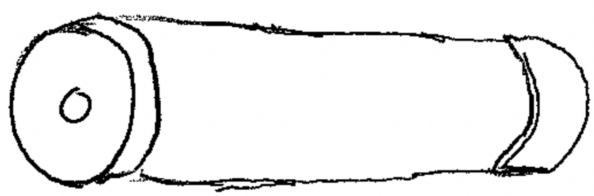


Figure 19.2.3: Illustration of part of the levitation control system

The levitation control system ensures that the spinning disk is safely isolated from the external environment. It does this via an array of different magnet types. Permanent magnets are designed to hold most of the weight while electromagnets prevent catastrophic misalignment of the disk.

6.1.1.3 FES Housing

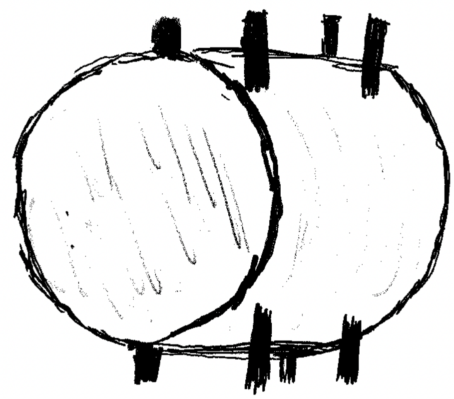


Figure 6.2.4: The housing design

The FES housing is a carbon fiber enclosure that is designed to isolate the FES disk in a near-vacuum space to increase efficiency. It is also designed to prevent serious danger in the event of catastrophic misalignment.

6.1.1.4 Inductive Converter

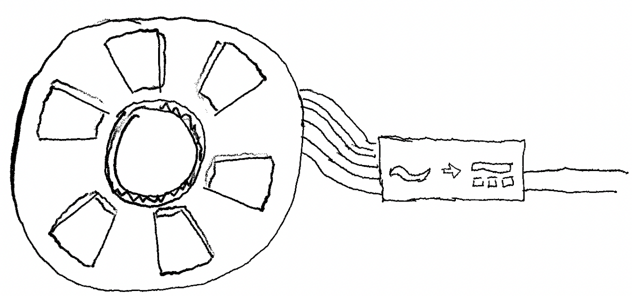


Figure 6.2.5: The inductive converter is an array of coils and wire.

The inductive converter converts rotational energy to electrical energy by inducing a magnetomotive force in a coil of wire. This electrical energy is routed through a regulator circuit to transform electrical power into the specified power needed by each subsystem.

6.1.1.5 Power Control

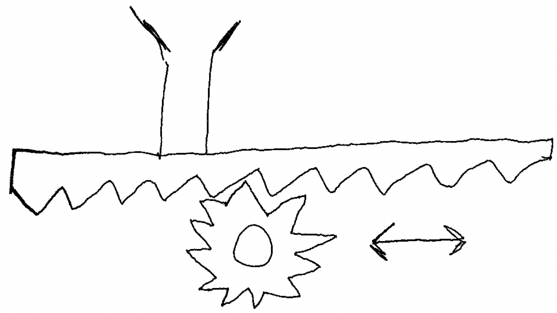


Figure 6.2.6: The power control rail guidance mechanism controls power draw

The power control mechanism controls how much power is drawn at the present moment. This piece is essential to the efficiency of the Legion: without it, the robot would have to draw peak power output continuously instead of drawing more power only when needed. In many industries, machines having the ability to enter a standby mode meet regulation when they otherwise would not have.

6.1.1.6 The Direct Power Feature

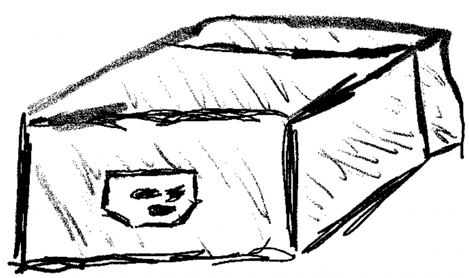


Figure 6.2.7: The direct power system

A robot that is required to work for long time periods at full power would be impractical if it only has on-board power. The direct power link solves this problem by allowing the Legion to bypass the FES and perform tasks using energy from the grid or other generators, such as solar and wind arrays.

6.1.2 Power Specifications & Objectives

6.1.2.1 Powering the Legion

Energy Index	
System	**Watts**
Drivetrain	34
Arm	25
Controls	3
Pneumatics	3
Total	65

Figure 6.2.8: Total power usage in one run by subsystem.

In one run, the Legion can use up to 65 Watts of power. The amount of power used will depend on the distance traveled and the weight of the package being moved. The following sections will outline the process that led to this design being selected, and will justify design choices.

6.1.3 Benchmarking

Benchmarking for this subsystem explored the broad spectrum of energy generation with a focus on being environmentally friendly. This is how systems such as the flywheel and thermal storage were found, which will be discussed in the next section. Benchmarking also included looking at forklifts and powerful construction equipment such as machines from companies like Bobcat and John Deere to gain a better understanding of the power capacity these machines typically require.

6.1.4 Concept Generation

6.1.4.1 Early Concepts

Storage System Selection												
Type	Sa	Si	P	E	D	Rc	Rl	C	Rp	Cn	Ei	Score
Weight	3	1	3	3	3	2	3	2	1	2	3	
Li-Ion	0	1	0	0	1	0	0	1	0	1	-1	5
SSB	1	1	0	0	1	0	0	0	0	1	-1	6
Reactor	-1	1	0	1	1	0	-1	-1	-1	0	-1	-5
Thermal	0	0	0	0	0	-1	0	0	0	0	1	1
FES	0	-1	1	1	0	1	1	0	0	1	1	15
Petroleum	0	1	1	-1	1	1	0	0	0	1	-1	5

Figure 6.2.9: Weighted decision matrix used to find the optimal design for powering the Legion

Selection of the FES system involved the creation of a weighted selection matrix to analyze various energy storage mechanisms based on the following 11 criteria:

1. Safety
2. Size
3. Peak Power
4. Efficiency
5. Density
6. Rechargeability
7. Reliability
8. Cost
9. Repairability
10. Control
11. Environmental Impact

6.1.5 Competitive Benchmarking of FES Systems

6.1.5.1 Overview of Benchmarking

Benchmarking was needed to determine the Legion's power usage during lifting and driving activities. Since batteries and combustion engines are the typical answers to this type of problem, benchmarking was critical to verifying the capabilities of a less common design choice.

6.1.5.2 Gyrobus

Figure 6.2.10: The Gyrobus G3, built in 1995

Compared to the Legion, the Gyrobus G3 featured a large flywheel that spun at a low frequency. Another important consequence of the large flywheel was its effect on the turning of the bus. However, it was capable of storing kilowatts of energy, which made the promise of an FES system appear more realistic.

6.1.5.3 Modern Construction Equipment

Figure 6.2.11: The Aichi Vertical Mast Lift WM1230J

The WM1230J can hold 500 lbs by using four 6 volt, 225AH deep cycle batteries to power a 24 volt AC drive system. This system was analyzed to understand the power requirements of lifting a load on an arm-like system.

6.1.5.4 Modern FES Systems

The observed modern FES systems did not have much relation to long-term storage because they were designed as intermediate power sources. These included various FES systems found in cars for regenerative braking and larger FES systems used to provide impulses on the order of megawatts to engage fusion reactors.

6.1.6 Modeling & Prototyping

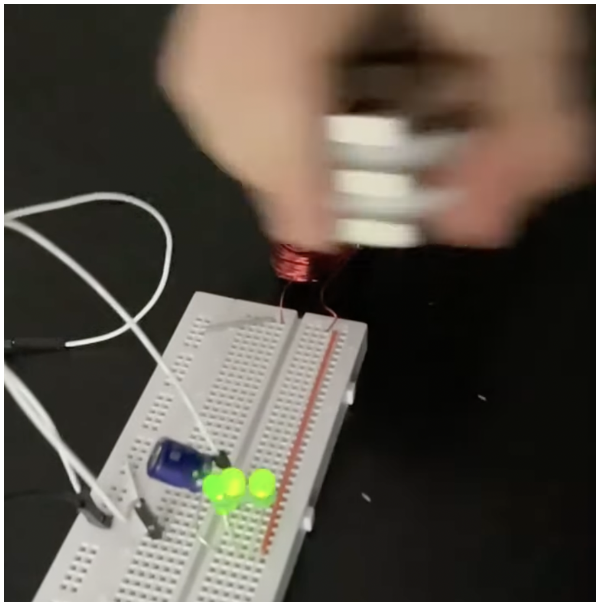


Figure 6.2.12: Moving magnet inducing a voltage in a coil, powering an array of green LED diodes

Through experimentation with induction charging, it was determined that a dynamic control system would need to be implemented to control the power draw from the FES. This is due to the changing velocity of the magnetic induction system relative to the FES disk. While using a coil with 100 turns might generate a reasonable voltage and current when the FES is spinning at a low frequency, the coil would draw dangerous levels at higher frequencies. This was empirically demonstrated by moving the magnet at different speeds across the path of the coil to simulate the different operating frequencies experienced in different phases of the discharge cycle.

6.1.13: A demonstration of magnetic force being used to levitate a 5lb weight.

A model of the levitation control system was created to test the claim that passive magnetic levitation could hold the bulk of the FES disk's weight in the final design. Through experimentation with strong N42 neodymium ($Nd_2Fe_{14}B$) magnets aligned axially to produce magnetic repulsion, it was determined that the system would be more stable if it was supported by a system that employed curved bar magnets. Nonetheless, it was empirically shown that an array of magnets could hold the weight of the flywheel.

Drivetrain

6.1.7 Drivetrain Specifications and Objectives

As shown in Appendix J in Table 19-3.1, the specifications for the system from Table 2.1 that the drivetrain was responsible for incorporating were the ability to maintain a safe yet efficient traveling speed, predetermined to be between 3 and 5 mph, as well as the ability to support the desired weight of the load (100-200 lbs), in addition to the weight of the system itself.

6.1.8 Benchmarking

The benchmarking done for this subsystem faced the added difficulty of not having a similar product currently on the market. Other devices, such as Amazon's Kiva Robot and the Boston Dynamics Handle Robot operated in a very different manner and, as such, required drastically different drivetrain components. Instead, benchmarking was done primarily on the components themselves, as discussed further in the next section.

6.1.9 Concept Generation

A key aspect of the drivetrain is determining the ideal wheel type for the specific needs of the device. In this case, caster, omni, and mecanum wheels were all considered due to their versatility. It was decided early in the planning process that these wheels would be placed with one at the front and one in the back of the device and would primarily be used to facilitate more precise steering and turning. They would then be accompanied by two additional wheels evenly distanced in the center to provide traction and support the bulk of the weight. Additionally, the selection of a motor and gearbox system was required to power the system at the desired speed. There was minimal concept generation done for this aspect as explained in the following section.

6.1.10 Concept Selection

To determine which of the three proposed wheels would be the most beneficial moving forward, the concept selection matrix shown in Appendix J, table 19.3-2 was created. This table weighs the merit of each wheel against one another on a number of relevant criteria, the two heaviest-weighing metrics were the load capacity of each wheel and the precision with which each is able to maneuver. Using this matrix, it becomes clear that omni wheels were ultimately the best choice for the ATLIS Legion. When deciding on a motor to run the drivetrain, it quickly became apparent that a DC motor would be needed due to their high torque and their enhanced ability to control speed, both of which were top concerns in this case. From there, deciding on a specific motor and gearbox system was done purely to fulfill the speed specification as accurately as possible and required no comparison of separate concepts.

6.3.5 Modeling and Prototyping the Drivetrain System

In testing the drivetrain's functions, the most important metrics to check for are that it allows the device to hold the predetermined weight and is capable of driving within the speed range. To demonstrate the strength, a series of loads are placed on the assembled chassis before attempting to power the drivetrain. In order to test the speed of the wheels, one can either measure the distance traveled over a period of time once the device is assembled, or monitor the rpm's achieved by the motors. As shown in Figure 19.3-1, the correlation between rpms and distance covered is a simple calculation. Given the size of the wheels selected, it can be concluded that the motors need to run between 168 and 280 rpm to meet this specification, which can easily be measured to confirm. This was done with the prototype to prove the concept and supported the notion that the full-scale model would function as planned.

Manipulation

6.4.1 Final Subsystem design

The final design of the Manipulation subsystem includes a rectangular array of rubber suction cups of variable quantity to allow for variability on a case by case basis with the smallest option being a two by two rectangular array. Shown in figure 6.4.1 is a 3D model of a 3x3 rectangular array.

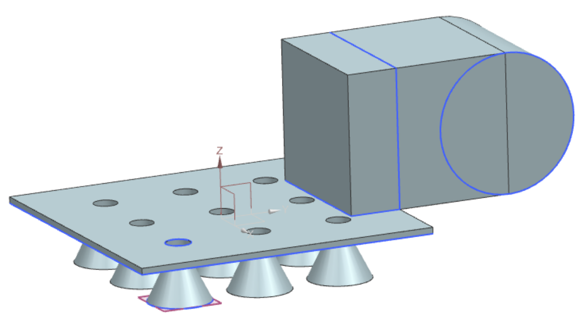


Figure 6.4.1: Full Subsystem CAD Assembly

This model illustrates the structure of the system where the suction cups are mounted onto a metal plate with holes going through the plate and the suction cup to allow for a vacuum pump to apply pressure. The vacuum pump will be connected to this model by a series of hoses that will end up in each of the holes shown above. A vacuum pump, mounted inside the Legion's structure, will apply a force between -0.04 MPa and -0.06MPa divided between each of the suction cups. The vacuum pump is designed to shut off at any values outside of this range so as not to provide any damage to the packages. Again, this component is variable and can be found off the shelf so that it can provide exactly what our customer may need. The following sections will outline how I came to this design choice.

6.4.2 Specifications and Objectives

The specifications from Table 2.1 for which the Manipulation System is specifically responsible for are shown in Appendix J in Table 19.4.1. The needs are to handle the standard weight and size of warehouse cargo without failing. The standards for warehouse cargo were found in our benchmarking outlined in the next section.

6.4.3 Benchmarking

The benchmarking done for this subsystem included looking at current arm models and the methods utilized to pick up various objects. It was discovered that factories who utilize an arm, can handle packages of up to 200 pounds in weight and around 4 feet in all dimensions. It was also found that there were two methods of handling packages that were considered for the final design. These two methods will be further discussed in the next section.

6.4.4 Concept Generation

In industry, there are two methods of arm manipulation systems, a gripper hand as seen in Figure 19.4.1 in Appendix J and a suction hand as seen in Figure 19.4.2 in Appendix J. The gripper system utilizes a motor to drive gears to open and close two levers. The levers are designed to open and close around a box to grab it firmly and transport it. The suction system utilizes a vacuum pump to grab onto a box from any side and transport it.

Detailed in Table 19.4.2 in Appendix J are the criteria used to decide between these two systems. It was decided that the suction system would work best, as it allowed for the most versatility which is important in a warehouse setting.

6.4.5 Proof of concept

To demonstrate the use of the suction system, 9 suction cups were attached to a wooden plate with pre-drilled holes as shown in Figure 19.4.3 in Appendix J. A user could then apply pressure by pressing on the plate to attach it to a surface. To fulfill the criteria labeled for the manipulation system, the prototype plate was attached to 3 textbooks to fulfill the weight requirement, a poptart box to fulfill the ability to lift a box, and a pringles can to fulfill the ability to lift odd-shaped objects present in a warehouse. A vacuum pump was not used in the prototype due to the price of the vacuum pump needed for the scale of the prototype. Without a vacuum pump, the model was able to fulfill the requirements set out by the customer.

Actuation

6.1.11 Final Subsystem Design

The final design for the actuation system consists of a three-jointed robotic arm mounted on a turntable with the capability to rotate 360 degrees. A 3D model of this design can be seen in Figure 6.5.1.

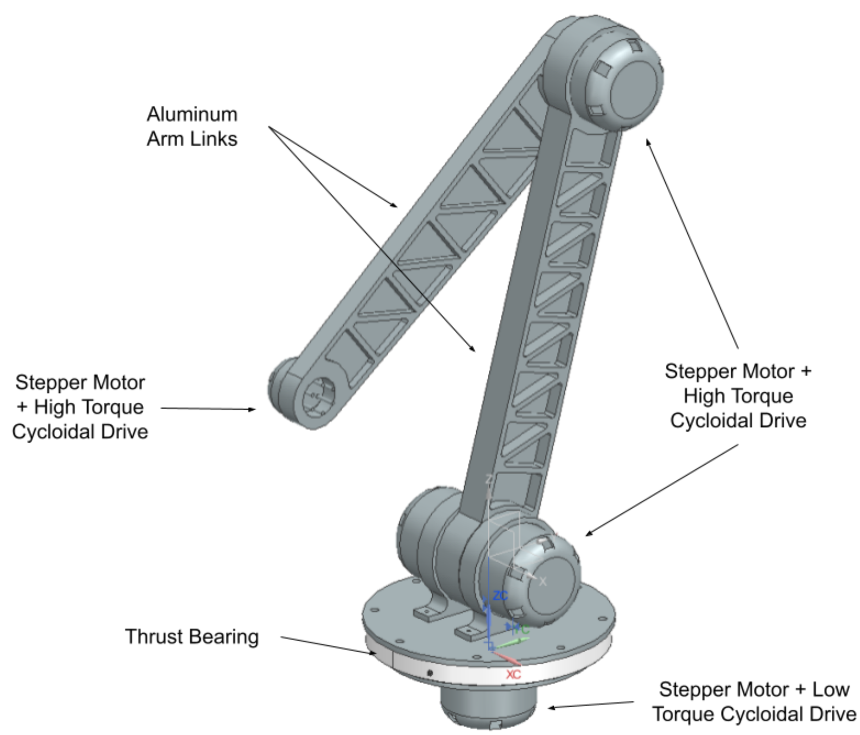


Figure 6.5.1: Full Subsystem CAD Assembly

The figure illustrates how each joint will be driven using DC stepper motors which will drive high reduction cycloidal gearboxes mounted at each joint. This same system will be used to drive the 360 degree turret mechanism. The following sections will outline the process that led to this design being selected, and will justify all design choices.

6.1.12 Actuation Specifications and Objectives

The specifications from Table 2.1 for which the Actuation System is specifically responsible for are shown in Appendix J in Table 19.5-1. In summary these needs include: the ability to grab cargo off of shelves, the ability to lift and move cargo, and the ability to be compact when not in use. In order to meet metrics corresponding to these needs, a greater understanding of common robotic arm designs was gained through benchmarking which is covered in the next section.

6.1.13 Competitive and Patent Benchmarking for Robotic Arm Systems

In addition to the benchmarking done pertaining to existing warehouse machinery, competitive and patent benchmarking was done to ascertain the current standards of design for robotic arm actuation systems. Primary considerations were analyzing joint design to allow for necessary degrees of freedom while also analyzing motor selection and implementation to allow for precise motion with high torque. A table describing the detailed findings of this benchmarking can be seen in Table 19.5-4 and Table 19.5-5.

6.1.14 Concept Generation

6.1.14.1 Early Concepts

Following the selection system level design, many sketches involving manipulation systems actuated using robotic arms were produced. Early concepts included less detail and were also addressing a broader set of specs before refinement to the final specs. The first design was an arm with lower than 4 degrees of freedom only capable of sliding boxes up onto itself using an incline built into the chassis. The second design more closely resembles the final design in that it can rotate about its base and has three joints that can reach vertically, giving it 4 degrees of freedom. These designs can be seen visually in Figure 19.5.1 and Figure 19.5.2.

Developing on the second of the prior designs, more detail was considered for how the arm would be assembled and how it would be given the vertical rotation capabilities that would allow it to manipulate cargo in any direction about the robot. Early concepts for this incorporated a plate sprocket or plate gear as the base for the arm to be mounted, utilizing a plate sprocket/gear would act as the mounting plate for the arm. This sprocket or gear would be supported by thrust bearings to take axial loads, and their large size would allow for high torque while reducing part count. Depictions of this concept can be seen in Figure 19.5.3 and Figure 19.5.4.

6.1.14.2 Refining Functional Specifications

At this phase, combinations of the previously generated concepts led to the generation of the final concepts that can be seen in the decision matrix in Table 19.5-2. The first fully developed concept for the turret mechanism utilizes an electric motor driving a gearbox to increase the torque output. This gearbox then drives a machinable plate sprocket, but rather than acting as the plate for the arm, this sprocket is bolted to another plate that would rotate with the sprocket. This plate is what would support the arm, and would be supported axially by thrust bearings. This design is further detailed in Figure 19.5.5. Another concept utilizing a pinion and internal ring gear in place of the smaller and larger sprocket was also sketched and can be seen in Figure 19.5.6.

The final turret mechanism design, seen in Figure 19.5.7, removes the indirectly driven sprocket/gear and directly drives the turntable plate with the motor output shaft. While slightly increasing manufacturing complexity due to machining an additional custom part, this decreases points of failure to merely the motor, the gearbox, the motor shaft, and the connection to the turntable. The purpose of this is to make maintenance easier, minimizing technical training for the robot operators.

The next component is the arm mechanism, the first fully developed concept of which can be seen in Figure 19.5.8. This design consists of motors mounted to the base of the arm that each drive a gearbox. These gearbox outputs are then driving sprockets that have chains routed to each joint that needs to rotate, engaging with fixed plate sprockets that create the pivoting motion about each joint. Similar issues arise in this mechanism as they did with the turret pertaining to maintenance. Belts and sprockets add points of failure, and the upkeep of the chain or belt adds more training for the workers who will sustain the system's operations. Taking the same approach as was seen with the turret mechanism, a design was generated that consisted of motors and gearboxes directly driving each joint. A detailed sketch of this can be seen in Figure 19.5.9. Some drawbacks of this design are that it adds the additional concern of higher rotational inertia and higher torque applied by the weight of the motors and heavier gearboxes mounted far from the base joint. The benefits of this concept are again a lower training required to maintain, as well as fewer parts to include in manufacture.

6.1.15 Concept Selection

Separating the entire system into these two mechanisms seen in the concept generation, the arm and the turret mechanisms, and breaking them down into basic components led to the creation of the weighted score matrices seen in Appendix J under Tables 19.5-2 through 19.5-4. These matrices outline the analysis that was used to select the final concepts. For the arm it was decided to use the *Direct Drive with Gearbox* concept, and for the turret *Direct Drive with Gearbox* was selected. An additional matrix was used to analyze the proper motor used to drive these mechanisms, and for both mechanisms a stepper motor will be used to aid with high torque at low RPM as well as high precision rotation control.

6.1.16 Modeling and Prototyping the Actuation System

6.1.16.1 Mathematical Model

Before considering the full scale design, to prove that this could be accomplished on a small scale, a mathematical model of the prototype design was created. A depiction of the prototype can be seen in FIgure 6.5.2. Because actual testing was to take place using real motors, power supplies, and structural components, it is important that this model be accurate for the tests to be successful. The results of these will be discussed in Section 7.

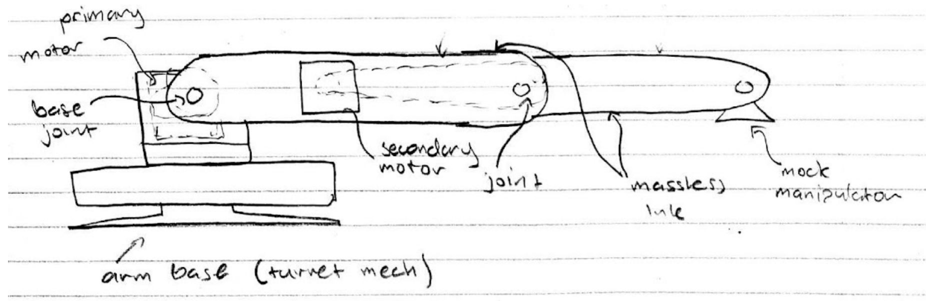


Figure 6.5.2: Prototype Model Visualization

The mathematical model presented in Appendix J in Figure 19.5.10 makes assumptions that greatly simplify the system. The mass of the wooden links, aluminum pulleys, belts, and bolts were neglected. Additionally, frictional forces were assumed to be negligible. The holding torque provided by the NEMA 17 stepper motors is 28 oz-in. The pulleys provide a reduction of 3:1, increasing the torque by a factor of 3. This gives the value of torque seen in the figure as 84 oz-in. The torque applied by the gravitational force on the secondary motor at its maximum perpendicular distance from the shaft is shown in the figure to be 19.3 oz-in. This is well below the holding torque provided (84 oz-in), and will thus be held in equilibrium (Adafruit n.d.). It is then also assumed that the second motor is capable of driving the “massless” secondary arm link. Note that the prototype did not use direct drive for each arm, as using a belt system is much easier on a small scale, and the concept of motor precision was still able to be tested in this configuration. A more detailed CAD model of this design can be seen in Figure 19.5.11.

Figure 19.5.12 exhibits the calculations done to model the full scale, showing the forces and moments that would be applied to the arm, again with simple assumptions being made to facilitate meaningful calculations, these being: massless arm links, secondary motor/gearbox weighs approximately 10lbs, manipulator mechanism weighs 5lbs. Again setting the conditions to create the maximum loads, the arm is fully extended to generate the maximum torque that must be overcome by the motors and supported by the structure of the system. The calculations were done to meet a combination of specification extremes. The results shown in Table 19.5-6 would aid in making design decisions such as: motor selection, gearbox selection, material selection.

Structure

6.6.1 Structure Specifications and Objectives

The specifications from table 2.1 that the structure is responsible for helping deliver are shown in Appendix J in table 19.6-1. The subsystem design concentrates on the base of the robot, specifically, how the base supports the weight of itself and the cargo and where the components of the overall system are stored internally.

6.6.2 Final Subsystem Design

The following final subsystem design in Figure 6.6.1 was thoughtfully created in order to deliver the subsystem's core functions and meet the metrics set in table 19.6-1.

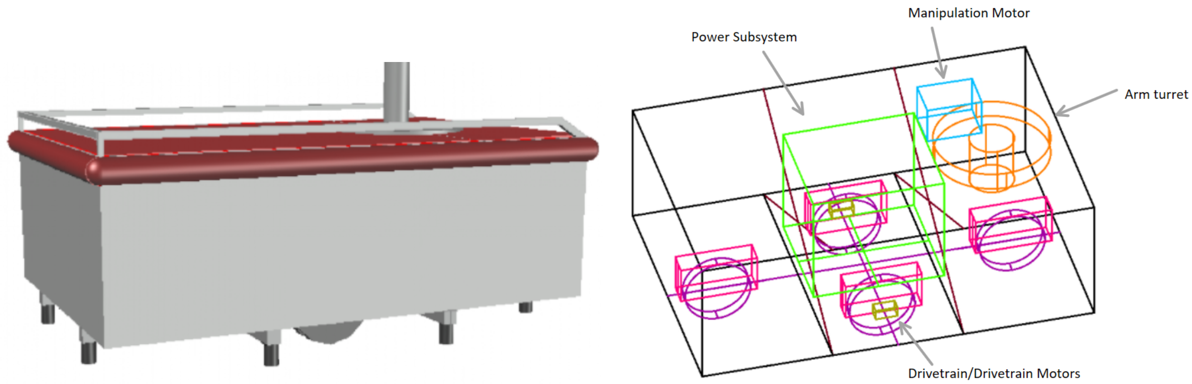


Figure 6.6.1: Final Subsystem CAD Design

The exterior final design features a main body that is 4 feet wide, 6 feet long, and 2 feet tall that is supported by internal X-bracing. The body is made of ¼ inch steel plates. Around the exterior of the body is a high density foam bumper to protect the robot in case of crashes, and elevated rails are placed on top of the base to help prevent cargo from falling off the storage bay. Finally, rubber stabilizers are placed on the bottom 1 inch above the resting ground plane to help protect the robot from tipping over. The internal final design features the components of the other subsystems housed inside the chassis. The parts housed were thoughtfully placed based on size and function, and can be seen labeled in figure 6.6.1.

6.6.3 Concept Generation

6.6.3.1 Early Exterior Concepts

The early concepts created focused on exterior functionality. The first generated concept can be seen in figure 19.6.1 in Appendix J. The design is basic, it does not account for the stability of the structure. The design conveyed the first draft of the chassis shape and an area to store the package.

The second draft in figure 19.6.2 in Appendix J considers some exterior stability elements. The concept introduces the idea of elevated edges to help keep the cargo secure in the storage bay, stabilizers under the chassis to help ensure the robot does not tip over, and a bumper wrapping around the exterior to minimize damage in the case of a crash.

The shape of the chassis was also considered. The first shape considered was a rectangular prism, seen in figures 19.6.1 and 19.6.2 in Appendix J, which features more of a balanced setup, with the arm on one side of the rectangular base and the storage bay on the other side. The other shape considered was a triangular prism, seen in figure 19.6.3. This concept has the arm positioned at one of the points on the triangular base.

6.6.3.2 Interior Framing Concepts

To account for the strength of the structure and its ability to withstand force, concepts for interior framing were generated. Structural framing is a durable and reliable way to help support the structure from failing when force is applied. The interior framing concepts can all be seen in figure 19.6.4 in Appendix J. The first frame concept includes horizontal and vertical framing in a criss-cross pattern. The second concept features diagonal bracing, and the third concept includes X-bracing.

6.6.3.3 Internal Placement of System Components

To account for the internal placement of parts inside the chassis, concepts for the internal placement were generated. Side and top views of the concepts can be seen in figures 19.6.7, 19.6.8, 19.6.9, and 19.6.10 in Appendix J. Each concept attempts to maximize space based on the size of each component, while still providing an efficient structure. The first concept places the power subsystem on the edge of the body, and the second concept places it in the center. The placement of the power system was significantly considered because it must have access to the other components and is a heavy system.

6.6.4 Concept Selection

Separating the subsystem into the sections seen in the concept generation allowed for weighted score matrices to be used to choose the best concepts. The matrices can be seen in table 19.6-2, 19.6-3, and 19.6-4 in Appendix J. For the shape of the chassis, it was decided that the rectangular prism is the best option. The rectangle is a better option because it has a more even center of mass and is easier to integrate with the other subsystems. For the framing type, it was decided that the X-bracing with fixed joints was the best option. X-bracing is the best option because it has the best overall strength. A final CAD drawing of the internal framing can be seen in figure 19.6.5 in Appendix J. For the internal placement, it was decided that the power in the center of the body is the best option because it has a better weight distribution and ease of integration.

6.6.5 Modeling and Prototyping the Structure

6.6.5.1 Internal Model

One of the main functions of the structure subsystem is to house all the necessary parts inside the chassis. To model and test this, CAD was utilized. This function focuses on the size and shape of the parts, so each part was modeled to scale and moved around the chassis to determine where they would be best placed. When placing parts, the system's center of mass, accessibility, and functionality were considered. After using trial and error and weighted decision matrices, it was concluded that having the power subsystem in the center on the chassis was the best option. Having the power in the center allowed for the most efficient use of space, the best weight distribution, and the most ease for power supply to reach each component inside the chassis.

6.6.5.2 Structure Stability Model

To model the stability of the structure, the software SAP2000 was used. The software models the shape and material of the system. The frame of the structure was modeled with steel applied. A total load of 1000 pounds was applied to the top of the system to overestimate the total weight of the cargo and the weight of the system on the structure. In figure 19.6.6 in Appendix J, it can be seen that the structure has no deformation when 1000 pounds are applied. Also, a physical prototype was created using wood to help demonstrate the structure's strength. The prototype was made of wood and did not feature the proper framing system, yet was still able to meet the minimum target value of 150 pounds. This helps to prove that the structure meets the requirement: be able to hold the weight of itself and the cargo.

7 Results and Discussion

Results

The testing performed by Atlis Innovation was based on a smaller scale. For the Controls and Navigation, a user interface was created and the feasibility of a user being able to properly input data was tested. Additionally, the controls and navigation subsystem was used to demonstrate the range of motion of the actuation arm. This subsystem's test worked successfully and properly showed the use of the controls and navigation subsystem.

The Power Delivery Subsystem was tested by waving a magnet over a coil to produce voltage through an LED. Additionally this subsystem was tested by hovering a bar over magnets and testing the weight that could be applied to the bar before failure. The subsystem worked as expected and provided an efficient energy system although it was not implemented into the other subsystems.

The Drivetrain subsystem was tested on speed where a wheel was attached to a motor and the rotations per minute were counted via a stopwatch on a slow motion camera. From there, calculations were made to convert the rotations per minute to miles per hour to compare with the customer requirements. The testing performed met the criteria listed in Table 11.1 in Appendix B.

The Manipulator subsystem was tested by building a small plate with suction cups attached to it. This plate was then utilized by lifting up three objects, 3 textbooks to simulate weight, a poptart box to simulate the ability to lift a box, and a pringles can to simulate odd-shaped objects. The test performed without failure and when simulated at a larger scale, the final design would meet the required specifications.

The Actuation subsystem was tested by marking the arm at 90 degrees and testing the degrees that the arm was off the mark. There was an expected 3 degrees of tolerance but the testing proved that the arm worked within 0 degrees of tolerance. This was an unexpected but welcome result as it showed that the actuation system worked better than expected. Additionally, a single suction cup was mounted to the arm and a test was performed to see if it could pick up an empty poptart box. This test succeeded and showed a working implementation of the arm and manipulator subsystems.

The Structure was tested using a software called SAP 2000. The software modeled the shape and material of the system and applied a 1000 pound load to the top of the system to simulate the weight of the device as well as any cargo. This is an overestimation of the daily load expected on the device and no visible deformation was shown. Additionally, a physical prototype was built out of wood and the bracing decided in the concept generation was not implemented but the prototype still held the minimum 150 pounds.

For the future of Project Legion, we would scale up the physical prototypes. Only pieces of subsystems were implemented together, so a full prototype would showcase the arm properly bolted to the structure as well as placing the power system into the structure. Additionally, with an increased budget, the proper materials and scale can be prototyped and implemented together.

Significant Technical Accomplishments

Although the prototypes all worked as expected or better, there were a few tools and processes we had to learn how to use. Not every member of ATLIS Innovation knew how to use modeling softwares or needed a refresher course. Additionally, a few members had not modeled anything on this scale before. This provided some challenging aspects when team members would ask each other for completed 3D models. The team also had to make budget decisions when modeling the prototype because the final design was too expensive for the team to cover. This led to a very detailed discussion on who could afford to buy which parts and who should cover the majority of the cost. It was ultimately decided that each subsystem designer would cover the cost of their own subsystem.

8 Conclusions

Project Legion began with the pursuit of creating an autonomous cargo transportation system to be implemented in warehouses around the world. The design that was generated is based on extensive market research and analysis of customer needs to meet all necessary standards. Considering a wide scope of possible system level and subsystem level concepts, the design was chosen meticulously through numerous screening processes. Moving forward with the design, a team would need to test full scale integration of the system, as integration was never done fully with demo prototyping, and most calculations need to be refined.

9 References

1. Anthony, C. (2021, May 19). 3 Ways Robots Affect the Economy. Investopedia. Retrieved 18 August 2021, from https://www.investopedia.com/articles/markets-economy/091316/3-ways-robots-affect-economy.asp.
2. Autodesk AutoCAD 2019 [Computer Software] Retrieved August 18, 2021
3. *Boston Dynamics' Handle robot brings mobile manipulation to logistics*. (2019, March 28). The Robot Report. Retrieved August 18, 2021, from https://www.therobotreport.com/boston-dynamics-handle-robot-pallets/
4. *5 Ton Lpg&gasoline Forklift With Double Air Filter - Buy Forklift 5 Ton Lpg,5 Ton Lpg Forklift,Lpg Forklift Truck Product on Alibaba.com*. (n.d.). Www.alibaba.com. Retrieved August 18, 2021, from https://www.alibaba.com/product-detail/5-ton-LPG-Gasoline-Forklift-With_62004350617.html
5. How warehouse robots will impact industry employment. 6 River Systems. (2020, August 28). Retrieved 18 August 2021, from https://6river.com/how-warehouse-robots-will-impact-i
6. Ito, J. (2018, July 30). Why Westerners Fear Robots and the Japanese Do Not. Wired. Retrieved 18 August 2021
7. Koppelman, L. (2020, August 28). How warehouse robots will impact industry employment. Retrieved August 20, 2021, from https://6river.com/how-warehouse-robots-will-impact-industry-employment/
8. MROSupply.com. (n.d.). FAG 54211 Double Direction Thrust BALL BEARIN. MROsupply.com - Since 1898 - MROSupply.com. Retrieved 19 August 2021, from https://www.mrosupply.com/bearings/thrust-bearings/2171660_54211_fag-bearing/?utm_source=google&utm_medium=cpc&utm_campaign=PLA&gclid=CjwKCAjwgviIBhBkEiwA10D2jyxJY2Ims3CladPH2s3Z2_PR9XzshyzUV54sEhaTlW7xzgdHRdXSIBoCtCoQAvD_BwE.
9. OSHA. (2004). Occupational Safety and Health Administration. . Retrieved 18 August 2021, from https://www.osha.gov/sites/default/files/publications/3220_Warehouse.pdf
10. Pincherx 100 robot arm. Trossen Robotics. (n.d.). Retrieved 19 August 2021, from https://www.trossenrobotics.com/pincherx-100-robot-arm.aspx.
11. *Quand Amazon rachetait une technologie robotique pour la retirer du marché et se la garder*. (n.d.). Reinformation.tv. Retrieved August 18, 2021, from https://reinformation.tv/robots-kiva-amazon-hommes-jallais-89365-2/
12. Research and Markets. (2021, June 22). Global warehouse AUTOMATION robots, technologies, and Solutions market REPORT 2021: Market is forecast to Reach $37.6 billion by 2030 - future investments FOR brownfield and greenfield projects. Retrieved August 20, 2021, from https://www.prnewswire.com/news-releases/global-warehouse-automation-robots-technologies-and-solutions-market-report-2021-market-is-forecast-to-reach--37-6-billion-by-2030---future-investments-for-brownfield-and-greenfield-projects-301317422.html
13. Rimmer, T. W., & Yarnell, S. H. (n.d.). Controlling forklifts' exhaust emissions. Retrieved August 20, 2021, from https://ohsonline.com/Articles/2009/01/01/Controlling-Forklift-Exhaust-Emissions.aspx
14. Ruifeng, L. (2015, July 22). Six-degree-of-freedom humanoid robot arm. Retrieved August 20, 2021
15. SAP2000 21 [Computer Software] Retrieved August 18, 2021
16. Stair Parts: Handrails, Stair Railing, Balusters, Treads, & Newels. (n.d.). StairSuppliesTM. Retrieved August 20, 2021, from https://www.stairsupplies.com
17. Stepper motor - nema-17 size - 200 steps/rev, 12V 350MA. (n.d.). Retrieved August 20, 2021, from https://www.adafruit.com/product/324
18. STP-DRVAC-24025. AutomationDirect. (n.d.). Retrieved 19 August 2021, from https://www.automationdirect.com/adc/shopping/catalog/motion_control/stepper_systems/stepper_drives/stp-drvac-24025.
19. STP-MTRA-ENC12. AutomationDirect. (n.d.). Retrieved 19 August 2021, from https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/rotary_encoders/surestep_m

odular_kit_encoders_for_stepper_motors/stp-mtra-enc12.
20. Stp-mtrac-34156d. AutomationDirect. (n.d.). Retrieved 19 August 2021, from https://www.automationdirect.com/adc/shopping/catalog/motion_control/stepper_systems/dual_shaft_and_encoder_stepper_motors/stp-mtrac-34156d?gclid=CjwKCAjwgviIBhBkEiwA10D2j8A34z8qhcSLL2SC7W9ILi0pAKZgxGr0OASN1CWCBEXrgC8Xw55evhoCBSYQAvD_BwE.
21. 1/4" Steel Plate Hot Rolled | Online Prices. (n.d.). Www.metals4uonline.com. Retrieved August 20, 2021, from https://www.metals4uonline.com/steel-plate-hot-rolled-1_4th
22. YouTube. (2019). Handle Robot Reimagined for Logistics. YouTube. Retrieved 19 August 2021, from https://www.youtube.com/watch?v=5iV_hB08Uns.

10 Appendix A: Selection of Team Project

After team formulation, each member was tasked with generating at least three potential problem areas to be addressed with an engineered solution. Using Webex Teams, each member posted a list of their proposed problem areas, being as general as possible. These were then compiled into a table such that one column listed all unique problem areas. The group sat around a table together and one person read aloud each problem area, and each member raised their hand to indicate an interest in the project. The results of this can be seen in Figure 10.1.

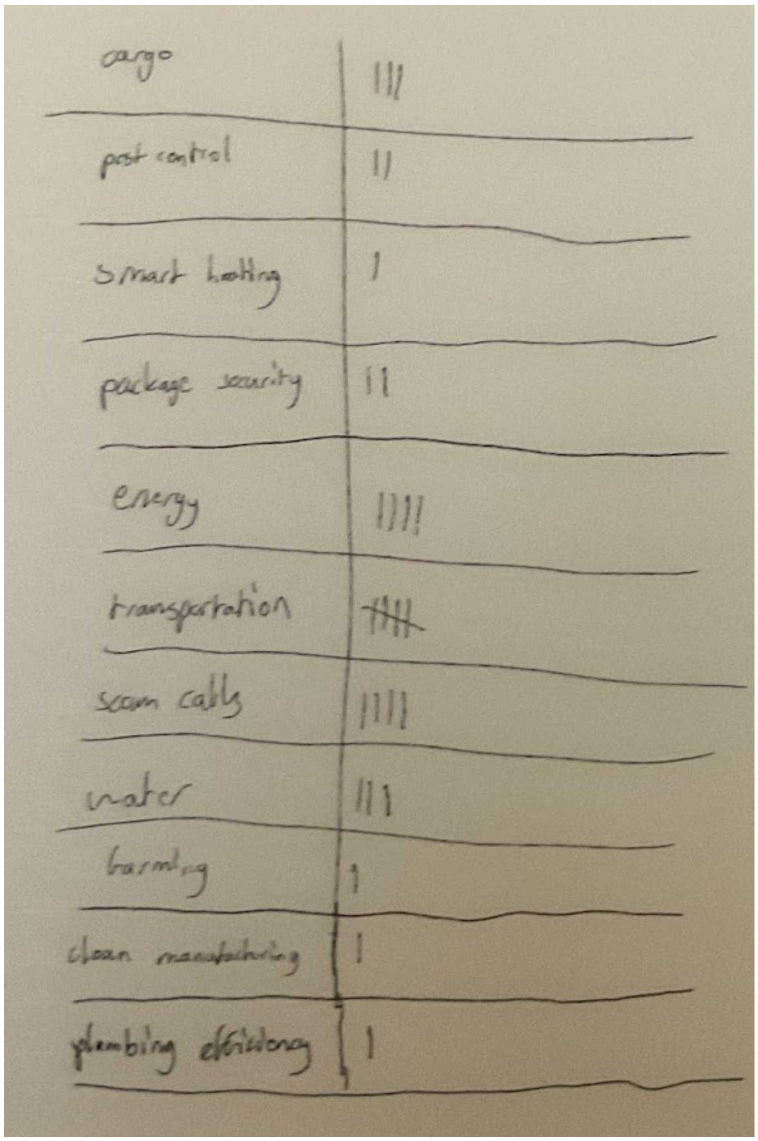


Figure 10.1: Problem Area Level of Interest

Following this assessment, four were selected to be put through a screening matrix, basing the decision to pursue whichever area ended up being chosen on concrete criteria. This can be seen in Table 10-1.

Table 10-1: Problem Area Screening Matrix

	Concepts			
	A	B	C	D
Selection Criteria	Transportation	Energy	Cargo	Water
Ability to have working prototype	1	0	1	0
Current market price	0	-1	1	0
Correct number of subsystems	1	0	1	1
Complexity	-1	-1	0	0
Personal interest	1	0	1	0
Sum of +1's	3	0	4	1
Sum of 0's	0	0	0	0
Sum of -1's	-1	-2	0	0
Net Score	2	-2	4	1
Rank	2	4	1	3
Continue?	N	N	Y	N

Based on the results of the screening matrix, the team pursued the “Cargo” problem area.

11 Appendix B: Customer Requirements, Technical Specifications, and Benchmarking

Table 11.1: Full Customer Requirements

Customer Need	Requirements (aka Technical Specifications)	Target Value / Range of Values
Can lift all types of warehouse cargo	*Lift Capacity*	*100-200 lbs*
	Can Lift & Handle Cardboard Boxes	*Yes*
	Be able to hold the weight of itself and the cargo	*0 structural failures*
	Cargo dimensions	*< 4’ x 4’ x 4’*
Can grab boxes off of a shelf	*Degrees of Freedom*	*≥ 3*
	Fully Extended Span	*4’ - 8’*
	Position Accuracy	*< 0.6 degrees of variation*
Be able to transport a package successfully	*Packages do not fall off the robot*	*< 0 dropped packages during transportation*
Can be easily stored	*Retracted length*	*< 4’*
	All of the parts are stored internally	*No unnecessary parts outside the chassis*
Can support warehouse cargo at full extension	*Holding Torque*	*> 4000 lb-ft*

Size – can move things throughout a warehouse	*Width x Depth x Height (pertains to the robot frame perimeter)*	*< 6’x8’x10’*
Can be used by a minimally trained worker	*Number of inputs*	*<5 inputs*
	Training to Operate	*<½ day*
Many can be operated by one worker	*Worker to Robot Ratio*	*1:5*
Sensors are quick enough to navigate while moving	*Speed of sensor readings*	*< 1 ms*
Operate in all seasons	*Temperature of operation*	*32-100 deg. F*
Can carry out tasks quickly	*Speed*	3-5 mph
Can’t run into things	*Braking Distance*	< 1’
	Obstacle Detection	>5’
User Comfort/Safety	*Noise Level*	*70db Max*

Figure 11.1: Boston Dynamics' Handle Robot (The Robot Report, 2021)

Figure 11.2: ***Amazon's Kiva Robot (reinformation.tv, 2021)***

Figure 11.3: ***Runtx's FD40T Forklift (Alibaba, 2021).***

12 Appendix C: Gantt Chart

Project Legion Schedule

Atlis Innovations

Project Start Date: 06/21/2021   Display Week: 1

Project Manager: Kris Riordan

Gantt Chart Template © 2012-2020 by Vertex42.com: Licensed for private use only. Do not p

WBS [1	Task [2]	Lead	Start [4]	End [5]	Days [6]	% Done [7]	Work Days [8]
1	**Milestone 1 - Overview**		06/21	07/11	21	100%	15
1.1	Determining Problem Area		06/21	06/23	3	100%	3
1.2	Gathering Customer Needs		06/24	06/27	4	100%	2
1.3	Interpreting Needs into Measurable Specs		06/24	06/27	4	100%	2
1.4	Decide on System Level Design		06/27	06/28	2	100%	1
1.5	Determine Subsystems		06/27	06/28	2	100%	1
1.6	MS 1 Presentation		06/29	06/30	2	100%	2
1.7	MS 1 Memo		06/29	07/11	13	100%	9
2	**Milestone 1 - Concept Generation and Selection**		06/28	07/18	21		15
2.1	Drivetrain Concept Generation	JA	06/28	07/14	17	100%	13
2.2	Chassis/Structure Concept Generation	CW	06/28	07/14	17	100%	13
2.3	Actuation/Pneumatics Concept Generation	KR	06/28	07/14	17	100%	13
2.4	Manipulator/Gripper Concept Generation	CJ	06/28	07/14	17	100%	13
2.5	Energy/Power Concept Generation	KD	06/28	07/14	17	100%	13
2.6	Sensors and Controls Concept Generation	FD	06/28	07/14	17	100%	13
2.7	Drivetrain Concept Selection	JA	07/15	07/17	3	100%	2
2.8	Chassis/Structure Concept Selection	CW	07/15	07/17	3	100%	2
2.9	Actuation/Pneumatics Concept Selection	KR	07/15	07/17	3	100%	2
2.10	Manipulator/Gripper Concept Selection	CJ	07/15	07/17	3	100%	2
2.11	Energy/Power Concept Selection	KD	07/15	07/17	3	100%	2
2.12	Sensors and Controls Concept Selection	FD	07/15	07/17	3	100%	2
2.13	System Level Design Review	KR	07/18	07/18	1	100%	0
3	**Milestone 2 - Prototyping and Testing**		07/18	08/12	26		19
3.1	Drivetrain Concept Prototyping/Testing	JA	07/18	08/12	1	100%	19
3.2	Chassis/Structure Concept Prototyping/Testing	CW	07/18	08/12	1	100%	19
3.3	Actuation/Pneumatics Concept Prototyping/Testing	KR	07/18	08/12	1	100%	19
3.4	Manipulator/Gripper Concept Prototyping/Testing	CJ	07/18	08/12	1	100%	19
3.5	Energy/Power Concept Prototyping/Testing	KD	07/18	08/12	1	100%	19
3.6	Sensors and Controls Concept Prototyping/Testing	FD	07/18	08/12	1	100%	24
4	**Milestone 3 - Final Report**		08/12	10/10	60		42
4.1	Design Presentation/Report		08/12	10/10	60	60%	42

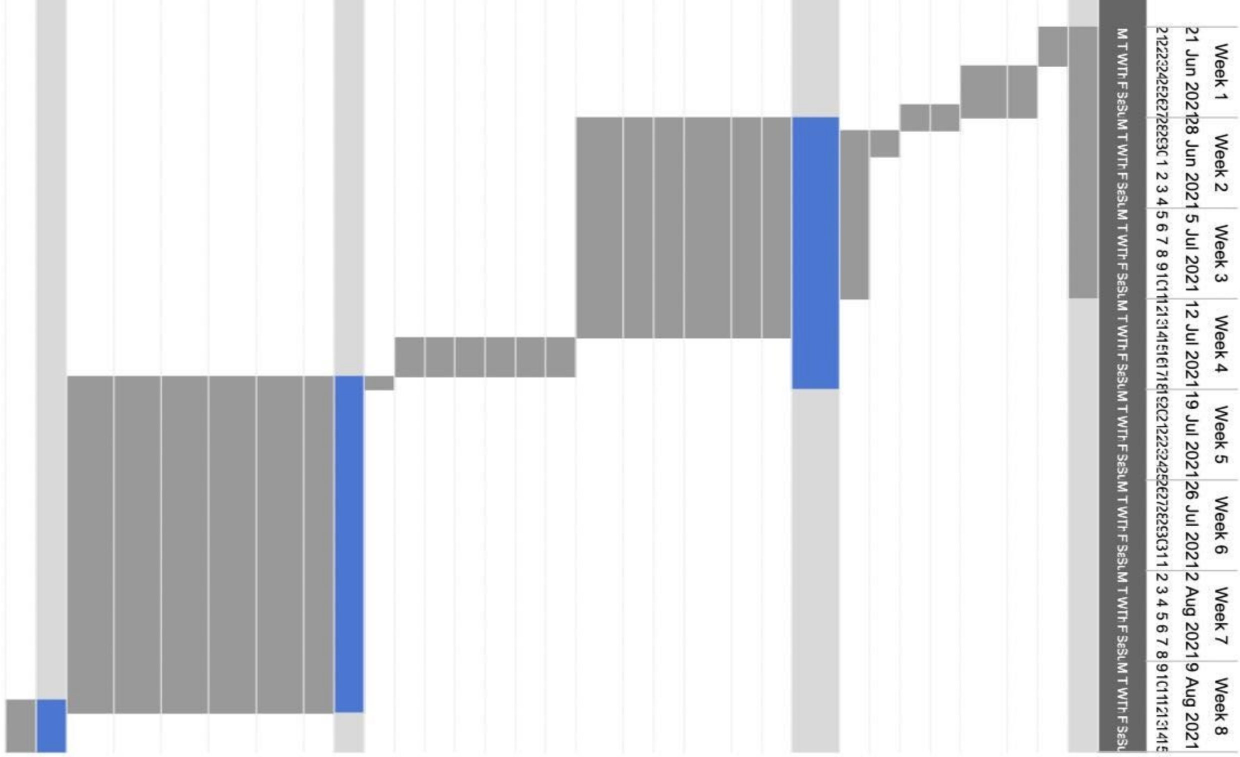


Figure 12.1: Ghantt Chart

13 Appendix D: Expense Report

Table 13.1 - Project Expenses

Item	Quantity	Unit Price	Subtotal
6” DuraOmni Wheel	2	$35.00	$70.00
HiGrip Wheels	2	$12.00	$24.00
Greartisan DC Motor	3	$11.99	$35.97
DC Stepper Motor STP-MTRAC-34156D	3	$265	$795
AC Microstepper Driver	3	$199	$597
SureStep Encoder	3	$56	$168
3" x 6" Aluminum Rectangle Bar 6061-T6511-Extruded	1	$140.36	$140.36
HT Cort-20E Series Cycloidal Gear Robot Arm Reducer Low Backlash 121:1	3	$1,200	$3,600
FAG 54211 DOUBLE DIRECTION THRUST BALL BEARING	1	$477.71	$477.71
1/4" Steel Plate Hot Rolled (24”x48”)	6	$129.60	$777.60
1/4" Steel Rods	2	$26.15	$52.30
Suction Cups (pack of 10)	1	$19.16	$19.16
Vacuum Pump	1	$168.00	$168.00
Steel Plate	1	$13.64	$13.64
FES Disk	1	$21/kg	$163.2
Inductive Magnets			
Passive Stabilizer Magnets	12	$10.94	$122.52
Total			

Appendix E: Team Members and Their Contributions

Team Member 1: Jenna Ackerson

My non-technical contributions included attending and contributing to group meetings, discussions, and decision making. I also assisted with the presentation slides for Milestones 2 and 3 and I worked on the memos for Milestones 1 and 3. Technically, I was responsible for the Drivetrain subsystem. I researched the components needed for this design, purchased the parts needed for the demo, and assembled them as needed, while coordinating to implement it into the structure.

Team Member 2: Frantz Doerrer

Non-technical contributions: Giving advice on the concept selection to team members based on research and understanding of the constraints of the control subsystem.

Technical contributions: completing the design for the control subsystem, which included selecting the software and sensors that the ATLIS robot would use to navigate the warehouse and retrieve packages effectively, and manipulating the physical structure through the motors.

Team Member 3: Kessler Dupont-Teevin

Lead designer for the power delivery subsystem.

Team Member 4: Christian Johnson

My non-technical contributions included contributing to team discussions to continue the conversations. I also was a part of assisting others with making decisions on their individual subsystems. Additionally, I contributed to the presentation slides and the decisions behind Milestone 2.

Technically, I was responsible for the Manipulator subsystem as well as the final CAD assembly of the Actuation and Manipulation subsystems. For my subsystem I performed an analysis of customer needs and generation of different concepts. I then chose which concept to use and the best ways to implement the system. I researched all of the necessary components needed for the final design and chose the components that I would purchase for the prototype. I then 3D modeled the manipulator system and assembled the prototype individually.

Team Member 5: Kristopher Riordan

My non-technical contributions included scheduling team meetings and enforcing deadlines by sending reminders in the Webex Teams space. Additionally, I created and shared the outlines for major project documents, such as: MS1 Memo, MS2 Slideshow, MS3 Memo. When preparing these documents I often led the creation of outlines, and delegated tasks outside of documenting individual subsystems. This ensured that sections such as “Introduction” and “Technical Specifications” had one person who was responsible for getting them done.

Technically I was responsible for the creation of the system level design sketches, basing them off of group discussion and individual system sketches. I then created the System I/O Diagram to show what inputs drove each subsystem to perform its desired outputs. Primarily, my work was focused on my subsystem: Actuation. I performed the analysis of customer needs to generate and select the concepts for the actuation system. All of this is outlined in the section detailing the design of the Actuation subsystem (the entirety of which I wrote). I researched and selected all of the necessary tools to create the fully functional prototype based on the mathematical model so that Frantz could control the motion using simple commands from the Raspberry Pi microprocessor. I also designed the arm with a consideration of being integratable into the chassis for the demo. I designed, CAD modeled, 3D printed, ordered, and machined the necessary components and assembled the prototype individually, spending many hours in the Forge, Processes Shop, and IED shop in order to assemble, test, and improve upon the prototype leading up to it’s showcase during the demo.

Team Member 6: Catherine Worthington

My non-technical contribution included contributing to team discussion to help facilitate the progress of the team. Also, I contributed to the presentation slide creations and made considerable contributions to the MS1 memo. Technically, I focused on the structure's subsystem. I used the engineering design process to create the base in which all the other subsystems were connected to. I was able to complete a prototype of the structure that helped to provide a physical demonstration for milestone 2. Finally, I put time into the final CAD drawing that visualized half of the overall system design.

14 Appendix F: Statement of Work

Table 15.1: Statement of Work

Semester Objectives	- Design and build a device that helps autonomously move cargo throughout a warehouse. - Perform engineering analyses and tests to guide design of a second phase, allowing the device to be controlled with few user inputs to maximize warehouse efficiency. - Design and construct a comprehensive prototype that can demonstrate lifting and transporting capabilities.
Approach	Worked as a team to iteratively design an autonomous warehouse robot. Focused on creating a pragmatic, tightly integrated design that is testable and readily manufacturable on a large scale.
Deliverables & Dates	Milestone 1: System Concept Presentations - 07/01/21 Milestone 2: Demonstrations - 08/12/21 Milestone 3: Design Presentation - 08/19/21

15 Appendix G: Professional Development - Lessons Learned

From a professional development viewpoint, the team project helped show our group how to work well in a team and what to change differently in the future to make the team dynamic even better. Something that worked well for our team and we would use again in the future was our meeting organization. In our team standards, we set the guidelines: everyone must attend at least one of the two group meetings each week, a 15 minute progress report should be held at the beginning of each meeting, All members must come prepared to discuss at least one task that progress has been made on since the last meeting. Setting these standards allowed for each member to stay accountable for meeting attendance and forward progress in the project. Without the meeting organization our team would not have been as successful. Also from this team project, we have learned that a variety of personality traits are needed to make a successful team. We had a positive project experience because we had the right balance of personality traits. For example, we had extroverted people who easily spit out ideas, and we had introverts who listened to and analyzed these ideas to pick out the useful ideas.

One area that could have been improved was time management. For this project, every person's design depended on at least one other person's design. Occasionally, there would be standstills where one person could not make progress on their subsystem design without information from another subsystem. If the information was not quickly delivered, then there would be some delay in the overall progress of the team. Instead of just waiting for the answer, in the future we could try as a team to find something else to help with or work on while waiting for the information. Also, to improve time management as a team, we could try starting big assignments much sooner to eliminate stress before big deadlines.

16 Appendix H: Software / Technology Used

Collaboration Among Team Members

- Cisco WebEx Teams and Meetings
- Google Drive

Subsystem Design

- Siemens NX
- AutoCAD
- 3D printer

Programming

- Python
- Curses

Subsystem Testing/Simulation/Emulation

- Siemens NX
- SAP2000
- 3D printer
- Laser cutter

17 Appendix I: User Manual

In order to operate the ATLIS robot, a technician will have to give commands that indicate the location to retrieve and place packages in the warehouse. The steps for doing that in the GUI will be detailed in this section.

Selecting the shelf

Upon connecting to the robot, the user should be greeted with the following UI:

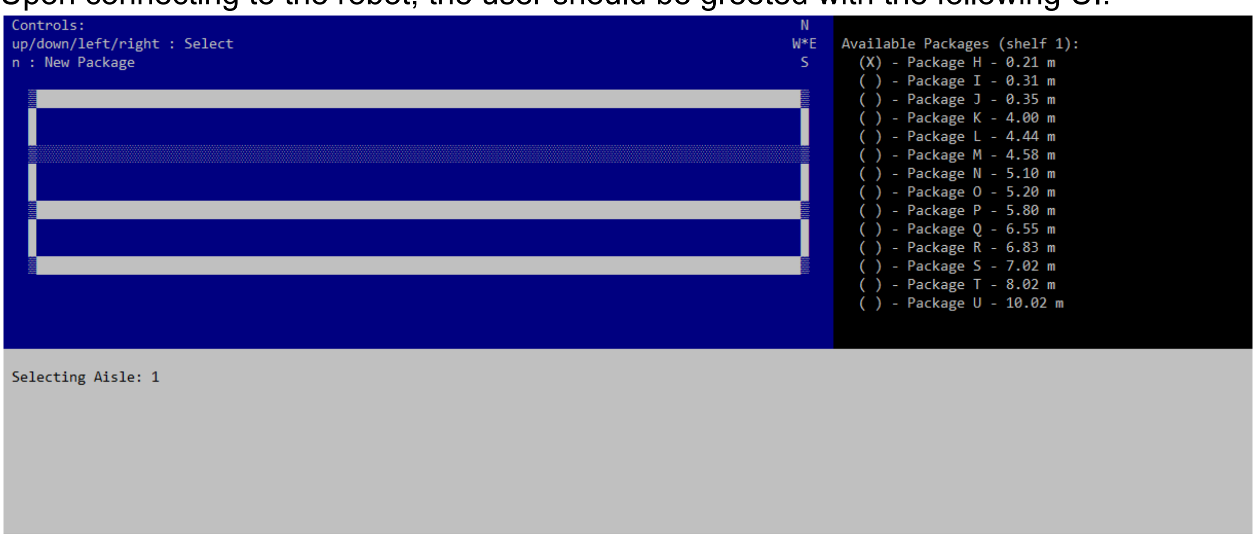


Figure 18.1: Console GUI with aisle 1 selected

The top left is a representation of the allies between each shelf, assuming there are in this case 3 shelves with 2 sides on each.

The user first needs to select which shelf they want the robot to navigate. Here, the southern aisle of the northmost shelf is selected, as indicated by the blue shading of the aisle in the top left pane. To change the aisle selected, use the up and down arrow keys. Press the right arrow key to select which package on that shelf the ATLIS robot will retrieve.

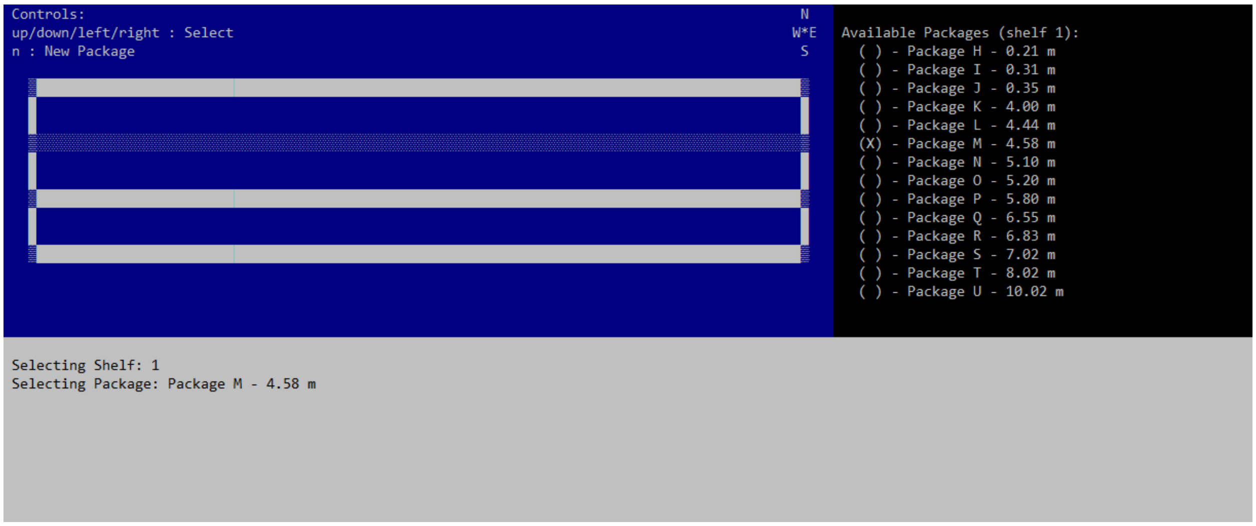


Figure 18.2: Console GUI with package M selected

Once the user selects the shelf, the console on the bottom will indicate that a shelf and package have now been selected, to adjust the package selection, use the up and down arrow keys and then press the right arrow key to finalize the selection, which the console will ask to confirm.

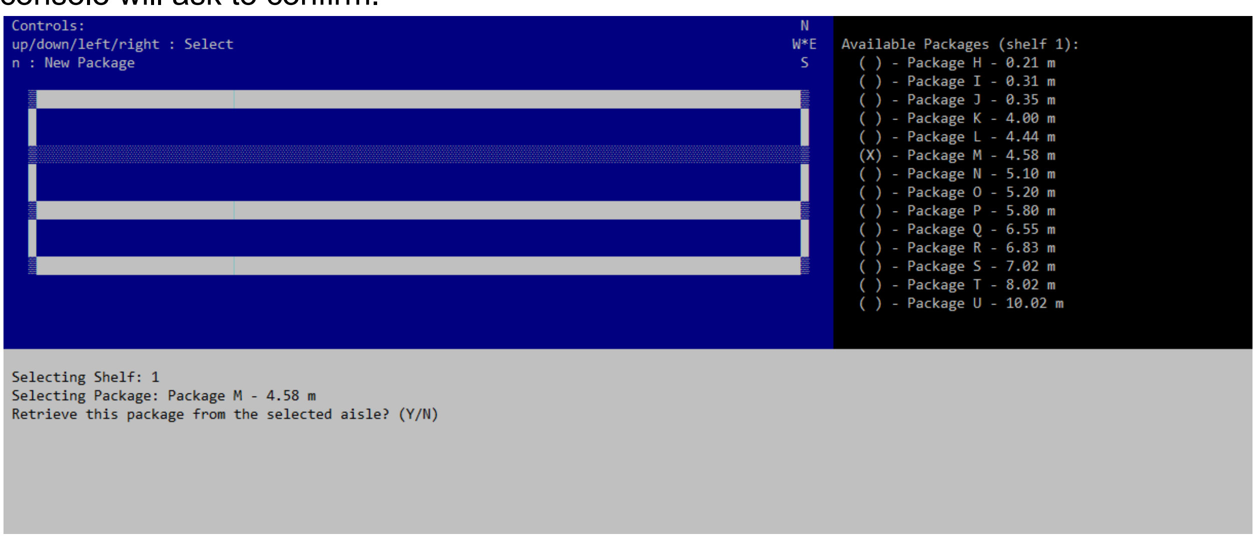


Figure 18.3: Confirmation dialogue of GUI console

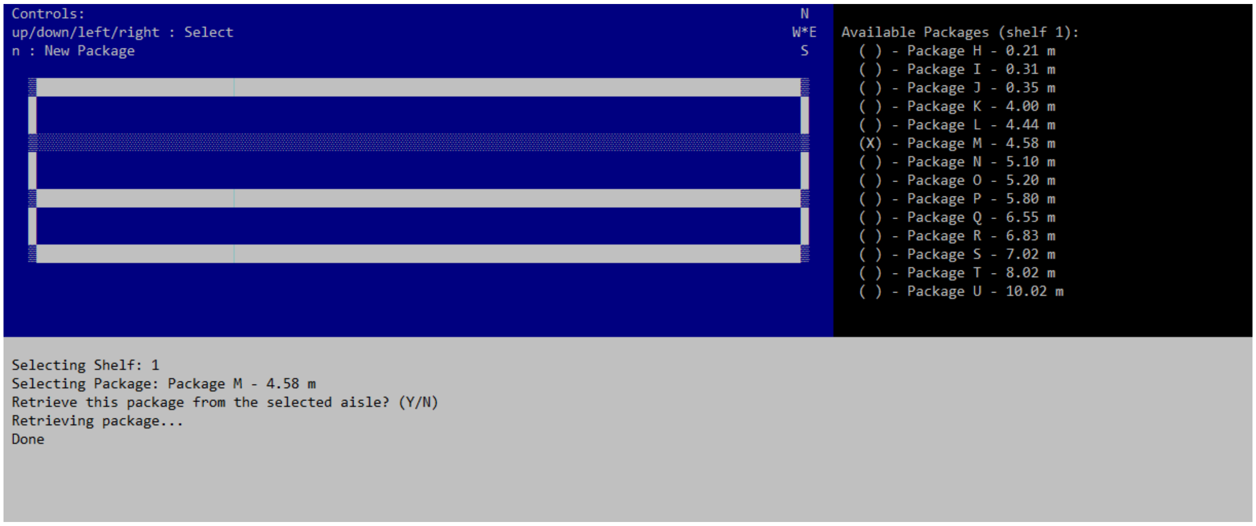


Figure 18.4: Console once package retrieval finishes

Once the confirmation dialogue pops up asking to retrieve the package, press Shift+Y to begin the pickup process or Shift+Y to reselect the package and aisle. Once the pickup is complete, the console will print "Done" and the GUI will reset.

18 Appendix J: Figures and Calculations

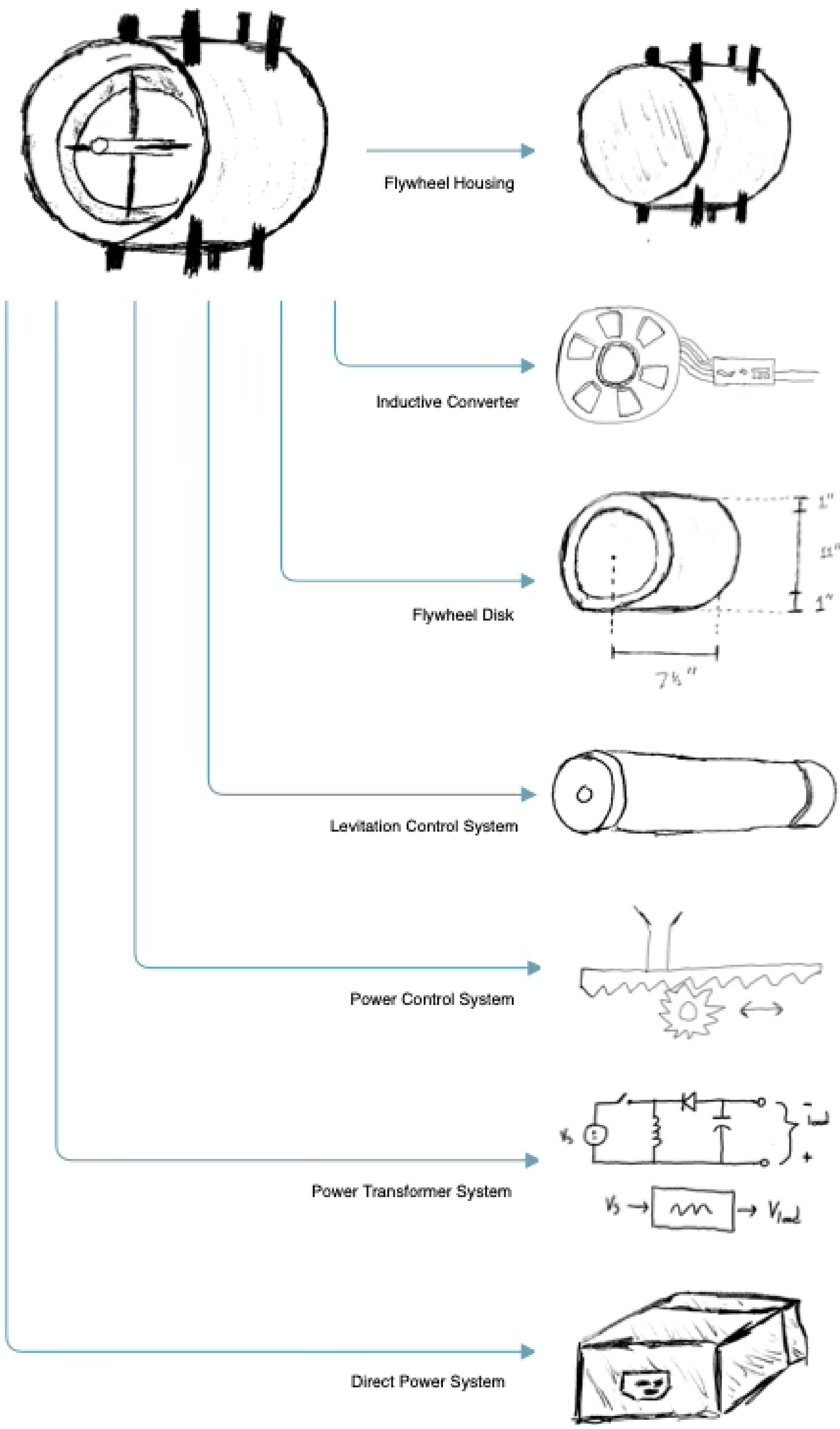
Controls and Navigation

Table 19.1-1: Concept Selection Matrix

Weight	Selection Criteria	Infrared Receivers	QR Codes	Line Following	Gyroscope
2	Cost	-1	1	0	0
2	Ease of Implementation	-1	-1	0	0
1	Efficiency	1	0	1	0
1	System Weight	1	1	1	1
1	Size	1	1	1	1
1	Practical	-1	1	1	0
1	Safety	1	1	1	1
1	Mobility Precision	1	-1	1	0
2	Durability with Average Usage	0	1	1	0
1	Versatility	1	-1	-1	1
1	Reliability	-1	1	1	0
1	Potential Speed	1	-1	1	1
	Net Score	1	4	9	5
	Rank	4	3	1	2
	Continue?	**N**	**Y**	**Y**	**Y**

Power

18.1.1Breakdown of the Power Delivery Subsystem



18.1.2 Concept Selection Matrix for The Power Delivery Subsystem, Condensed

Storage System Selection												
Type	Sa	Si	P	E	D	Rc	Rl	C	Rp	Cn	Ei	Score
Weight	3	1	3	3	3	2	3	2	1	2	3	
Li-Ion	0	1	0	0	1	0	0	1	0	1	-1	5
SSB	1	1	0	0	1	0	0	0	0	1	-1	6
Reactor	-1	1	0	1	1	0	-1	-1	-1	0	-1	-5
Thermal	0	0	0	0	0	-1	0	0	0	0	1	1
FES	0	-1	1	1	0	1	1	0	0	1	1	15
Petroleum	0	1	1	-1	1	1	0	0	0	1	-1	5

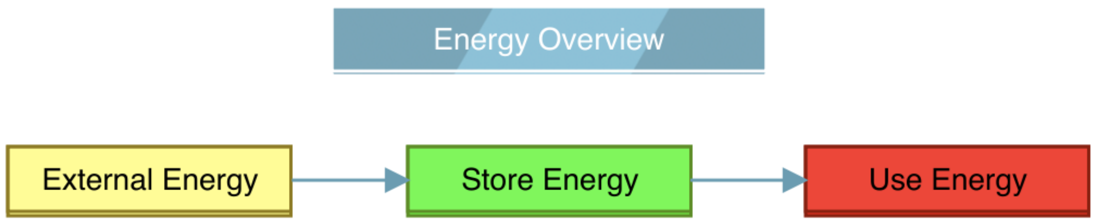
18.1.3 Concept Selection Matrix for The Power Delivery Subsystem

Storage System Selection												
Type	Safety	Size	Peak Power	Efficiency	Density	Rechargeability	Reliability	Cost	Repairability	Control	Environmental Impact	Score
Weight	3	1	3	3	3	2	3	2	1	2	3	
Li-Ion	0	1	0	0	1	0	0	1	0	1	-1	5
SSB	1	1	0	0	1	0	0	0	0	1	-1	6
Reactor	-1	1	0	1	1	0	-1	-1	-1	0	-1	-5
Thermal	0	0	0	0	0	-1	0	0	0	0	1	1
FES	0	-1	1	1	0	1	1	0	0	1	1	15
Gasoline	0	1	1	-1	1	1	0	0	0	1	-1	5

18.1.4 Concept Combination Table for The Power Delivery Subsystem

Power Input	Power Storage	Power Regulation	Power Transmission
Wireless Induction Charger	Lithium Ion Battery	Buck/Boost Converter	Copper Wiring
Direct Power AC1	Solid State Battery	Voltage Divider	Aluminum Wiring
Direct Power DC2	Nuclear Reactor	Battery Regulator Circuit	Transmission Lines
Replacable Battery	Thermal Storage		
	FES		
	Gasoline / Petroleum		

18.1.5 Flow of Energy in The Power Delivery Subsystem



18.1.6 Results of Tensile Stress Analysis for Various Disk Material Candidates

Material Vetting for FES Disk				
Scenario	Carbon Fiber	Titanium	Steel	Aluminum
Heavy	Y	Y	N	N
Medium	Y	Y	N	N
Light	Y	Y	N	N

18.1.7 Tensile Stress Analysis for Various Disk Material Candidates

Scenario	Diam. (in)	Mass (lbs)	RPM (1000's)	Power (kJ)
Heavy	13	25	12.05	246.9
Medium	12	22	14	249
Light	11	18	16.8	246.7

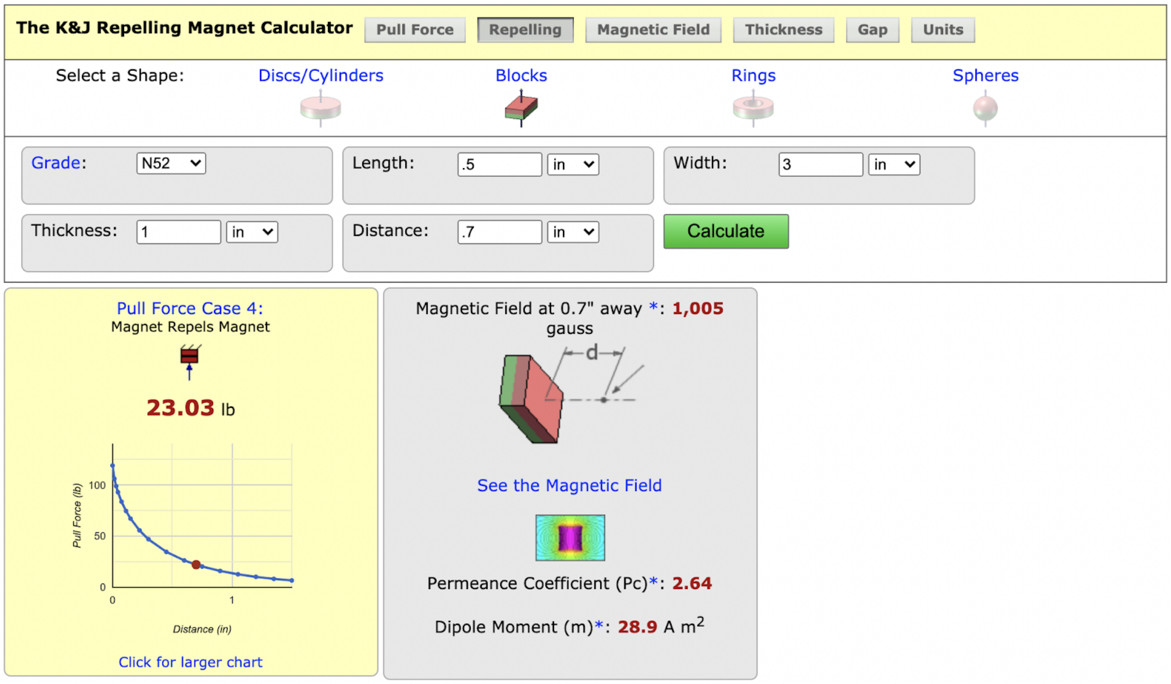
Scenario	Carbon Fiber	Titanium	Steel	Aluminum
Heavy	7.56E+07	1.89E+08	3.38E+08	1.13E+08
Medium	8.69E+07	2.18E+08	3.89E+08	1.30E+08
Light	1.05E+08	2.63E+08	4.71E+08	1.58E+08

Scenario	Radius (m)	Mass (lbs)	RPS (Hz)	ω
Heavy	0.1625	25	201	1261
Medium	0.15	22	233	1465
Light	0.1375	18	280	1758

Material Vetting for FES Disk				
Scenario	Carbon Fiber	Titanium	Steel	Aluminum
Heavy	Y	Y	N	N
Medium	Y	Y	N	N
Light	Y	Y	N	N

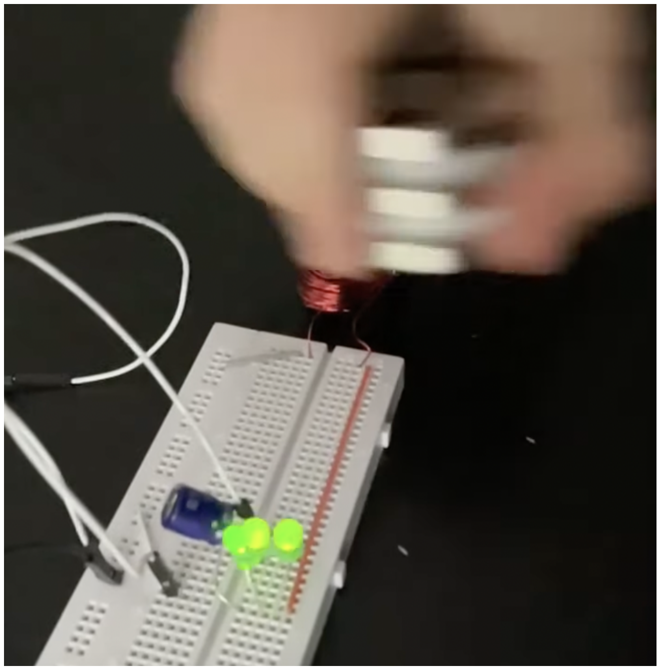
Scenario	Radius (m)	Mass (kg)	Volume (cubic meters)	Volume (cubic feet)	Volume (cubic in)
Heavy	0.1625	11.3	0.0064	0.23	392
Medium	0.15	9.9	0.0057	0.20	345
Light	0.1375	8.1	0.0046	0.16	282

18.1.8 Calculation of ring



18.1.9 Demonstration of Magnetic Levitation

18.1.10 Demonstration of Magnetic Induction



18.1.11 Calculation of FES Disk Dimensions

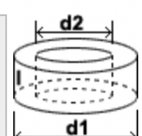
Tube Volume Calculator

Result

$$\text{Volume} = \pi \frac{d_1^2 - d_2^2}{4} l$$
$$= \pi \times \frac{13^2 - 11^2}{4} \times 7.5$$
$$= 90\pi$$
$$= \mathbf{282.74333882308\ inches^3}$$

Outer Diameter (d1)	13	inches
Inner Diameter (d2)	11	inches
Length (l)	7.5	inches

Calculate



Drivetrain

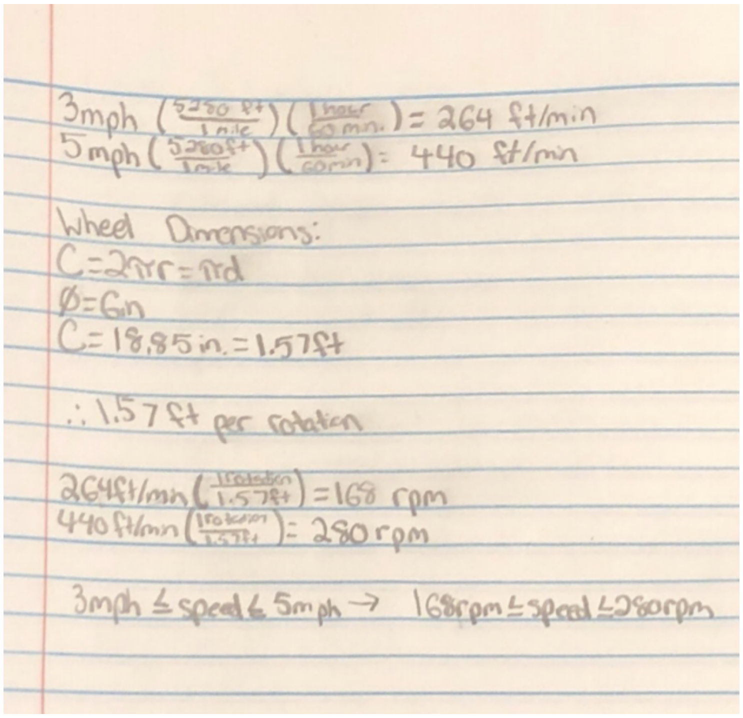
Table 19.3-1: Drivetrain Specific Customer Requirements

Customer Requirement	Technical Specifications	Target Values
Can Carry Out Tasks Quickly	Speed	3-5 mph
Can Lift Most Warehouse Cargo	Critical Load	100-200 lbs

Table 19.3-2: Wheels Selection Matrix

		Concepts					
		Omni		**Caster**		**Mecanum**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Size	10%	3	0.3	3		3	0.3
Precision	25%	3	0.75	1	0.3	2	0.5
Stability	20%	2	0.4	1	0.2	2	0.4
Cost	10%	2	0.2	3	0.3	1	0.1
Durability	15%	1	0.15	1	0.15	2	0.3
Strength	25%	2	0.5	3	0.75	1	0.25
	Total Score		2.3		1.7		1.85
	Rank		1		3		2
	Continue?		Yes		No		No

Figure 19.3-1: Drivetrain Motor Speed Calculations



Manipulation

Tables

Table 19.4.1: Manipulation Customer Requirements

Customer Requirement	**Technical Specification**	**Target Value / Range of Values**
Can handle standard warehouse cargo	Lift Capacity	100-200 lbs
	Can lift & handle cardboard boxes	Yes
	Be able to hold the weight of itself and the cargo	0 structural failures

	Cargo dimensions	<4' x 4' x 4'

Table 19.4.2: Manipulation Decision Matrix

		Concepts			
		Suction cups		**Gripper**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Size	5%	2	0.1	3	0.15
Ease of Manufacture	15%	2	0.3	3	0.45
Durability	20%	3	0.6	2	0.4
Cost	10%	2	0.2	2	0.2
Ease of Maintenance	15%	2	0.3	3	0.45
Weight	5%	2	0.1	3	0.15
Strength	30%	3	0.9	1	0.3
	Total Score		2.5		2.1
	Rank		1		2
	Continue?		Yes		No

Figures

Figure 19.4.1: Gripper w/ Gear Train & Motors

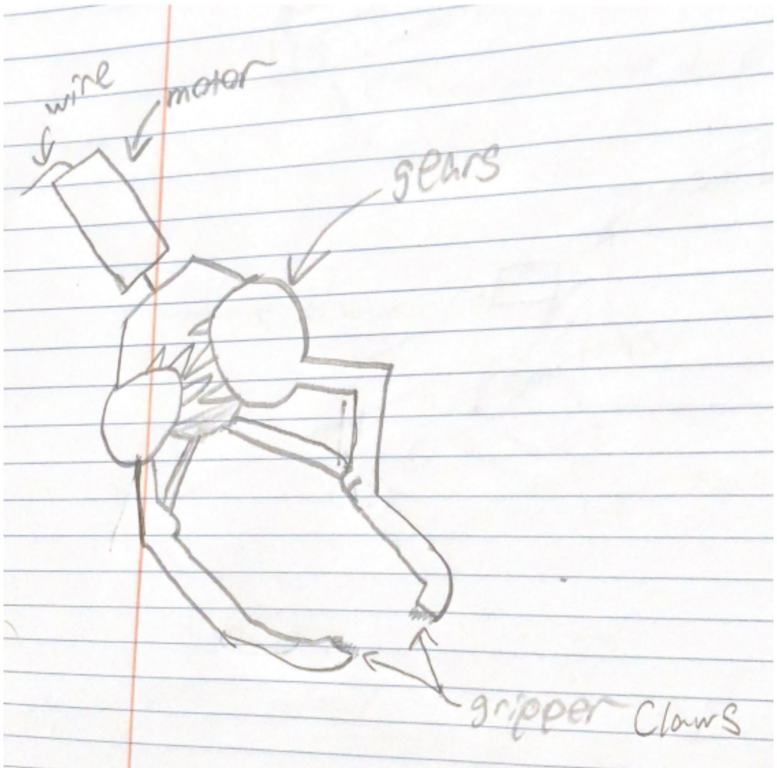


Figure 19.4.2: Suction Cup Manipulator

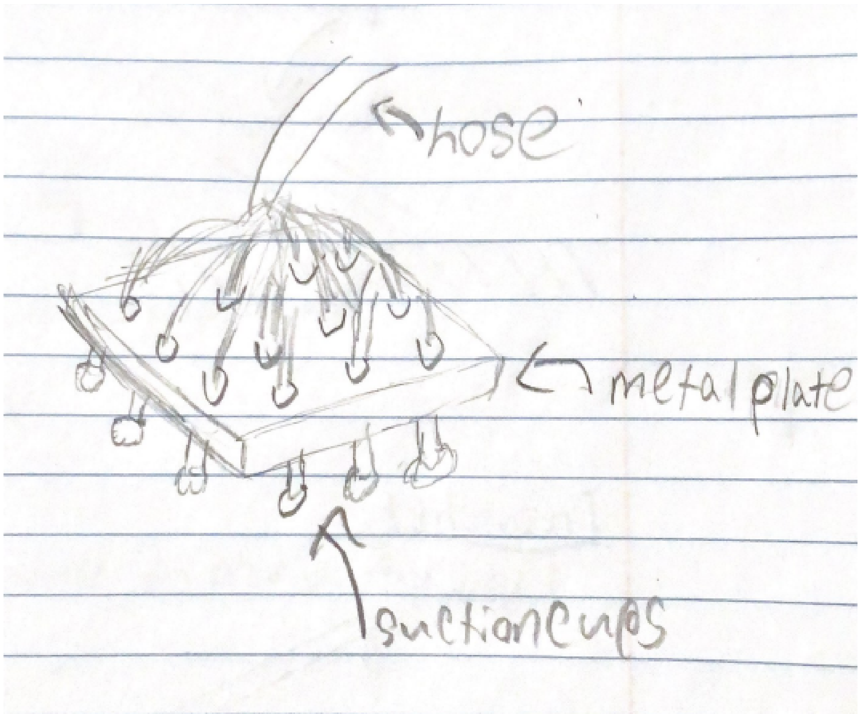
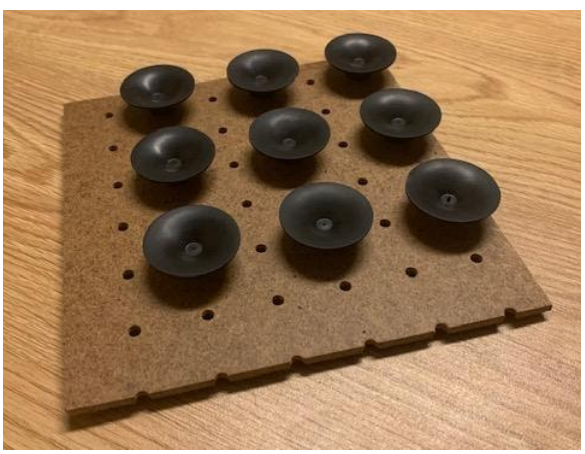


Figure 19.4.3: Suction Cup Prototype



Actuation

Tables

Table 19.5-1: Actuation Specific Customer Requirements

Customer Requirement	Technical Specification	Target Value / Range of Values
Can grab boxes off of a shelf/place boxes in desired locations	Degrees of Freedom	≥ 3
	Fully Extended Span	4' - 8'
	Position Accuracy	< 0.6 degrees of variation/command
Can be easily stored	Retracted length	< 4'
Can support warehouse cargo at full extension	Holding Torque	600 - 4000 lb-ft

Table 19.5-2: Turret Mechanism Weighted Scoring Matrix

		Concepts							
		Direct Drive w/ Gearbox		Direct Drive w/o Gearbox		Indirect Driven w/ Gearbox		Indirect Driven w/o Gearbox	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Size	5%	2	0.1	3	0.15	2	0.1	3	0.15
Ease of Manufacture	15%	3	0.45	3	0.45	2	0.3	3	0.45
Durability	20%	3	0.6	2	0.4	3	0.6	2	0.4
Cost	10%	2	0.2	3	0.3	2	0.2	3	0.3
Ease of Maintenance	15%	2	0.3	2	0.3	1	0.15	2	0.3
Weight	5%	2	0.1	3	0.15	2	0.1	2	0.1
Strength	30%	2	0.6	1	0.3	3	0.9	2	0.6

	Total Score		2.35		2.05		2.35		2.3
	Rank		1		4		2		3
	Continue?		Yes		No		No		No

Table 19.5-3: Arm Mechanism Weighted Scoring Matrix

		Concepts			
		Direct Drive w/ Gearbox		Indirect Driven w/ Gearbox	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Size	15%	2	0.3	2	0.3
Ease of Manufacture	10%	3	0.3	1	0.1
Durability	10%	3	0.3	2	0.2
Cost	5%	3	0.15	2	0.1
Ease of Maintenance	10%	2	0.2	1	0.1
Weight	10%	3	0.3	2	0.2
Mobility	20%	2	0.4	2	0.4
Strength	20%	2	0.4	2	0.4
	Total Score		2.35		1.8
	Rank		1		2
	Continue?		Yes		No

Table 19.5-4: Motor Selection Weighted Scoring Matrix

		Concepts					
		Servo		Stepper		DC Brushless	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Torque	25%	3	0.75	2	0.5	2	0.5
Max RPM	5%	2	0.1	2	0.1	3	0.15
Power Requirement	25%	3	0.75	3	0.75	2	0.5
Cost	10%	1	0.1	2	0.2	3	0.3
Maintenance	10%	1	0.1	3	0.3	2	0.2

Position Control Accuracy	25%	3	0.75	3	0.75	1	0.25
	Total Score		2.55		2.6		1.9
	Rank		2		1		3
	Continue?		No		Yes		No

Table 19.5-4: Competitive Benchmarking

Competitive Product	Title / Description	Relation to this project
PincherX 100 Robot Arm	High torque, servo driven robotic arm using positional feedback to intelligently position the end effector (gripper) in the desired location. Has 4 degrees of freedom with full 360 degree rotation. (Trossen Robotics, n.d.)	This robotic arm provides torque at high speed with servo motors. It is also precise in its commands. Lastly, it exceeds the lower limit for degrees of freedom set in the project metrics.
Handle Robot	Three jointed robotic arm mounted onto a two-wheeled robot. Capable of using suction based end effector to pick up and place cardboard boxes. Fully autonomous, aware of the environment. (Youtube, 2019)	This robot can navigate a warehouse setting, lifting and placing boxes in a precisely stacked manner. Meets the lower limit for degrees of freedom.

Table 19.5-5: Patent Benchmarking

Competitive Product	Title / Description	Relation to this project
Six-degree-of-freedom humanoid robot arm	Versatile, precise robot arm resembling that of a human. Joints driven by multiple	Greatly exceeds the degrees of freedom set by the metric. Active status leaves us limited in how

	actuators about multiple axes. Six total degrees of freedom.	higher degrees of freedom may be addressed without infringing.

Table 19.5-6: Required Output Torque for Specification Extrema

Primary Motor		
Max Length	**Cargo Weight**	
	150lbs	*500lbs*
4'	680 lbf-ft	2080lbf-ft
8'	1360 lbf-ft	4160 lbf-ft
Secondary Motor		
Max Length	**Weight**	
	150lbs	*500lbs*
~2'	315 lbf-ft	1015 lbf-ft
~4'	630 lbf-ft	2030 lbf-ft

Figures

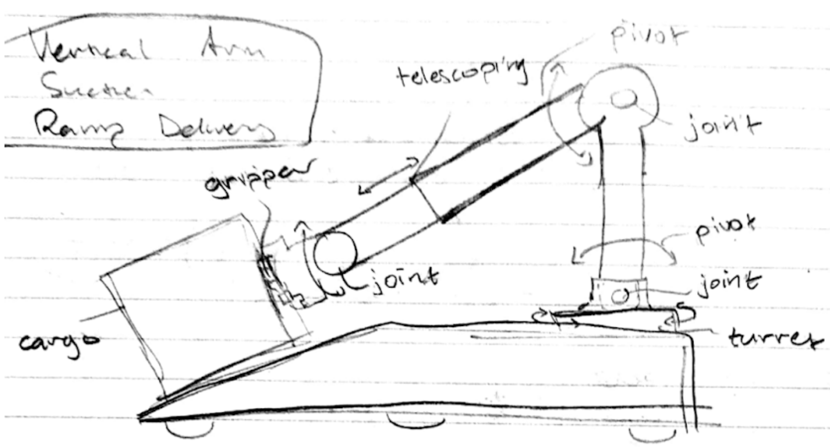


Figure 19.5.1: Arm with Ramp Assisted Lifting

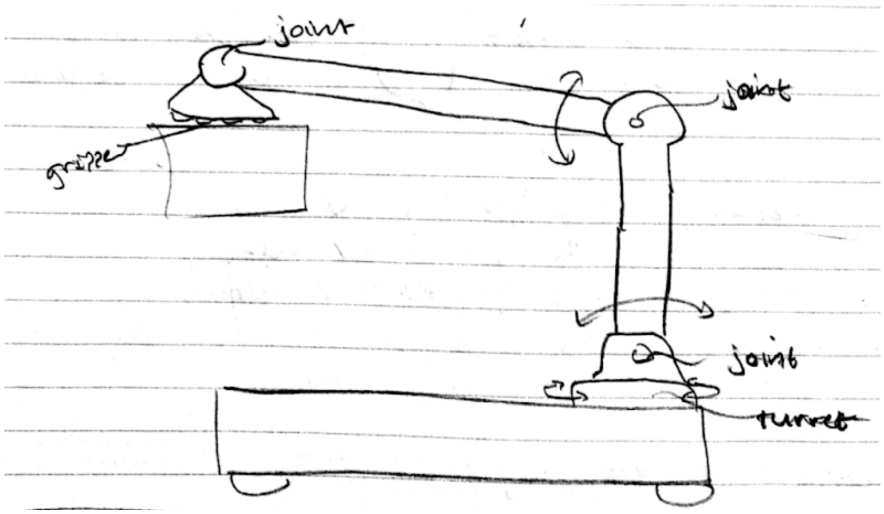


Figure 19.5.2: Three Jointed Arm with Turret

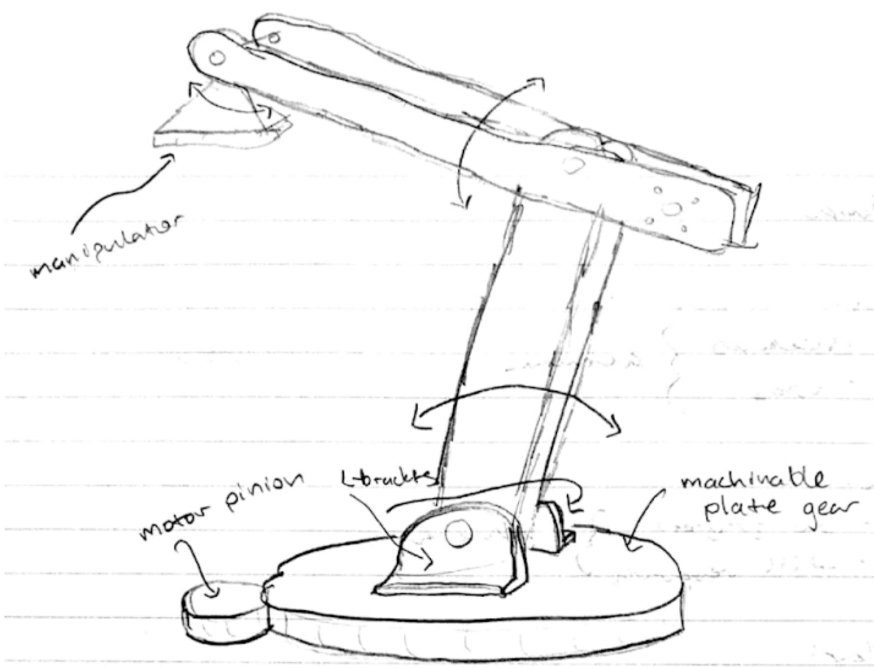


Figure 19.5.3: Arm with Gear Driven Turret

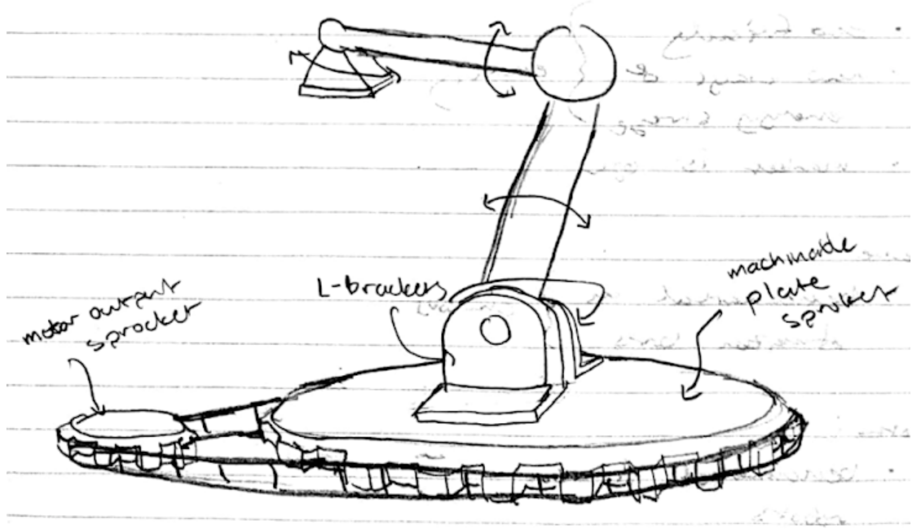


Figure 19.5.4: Arm with Sprocket Driven Turret

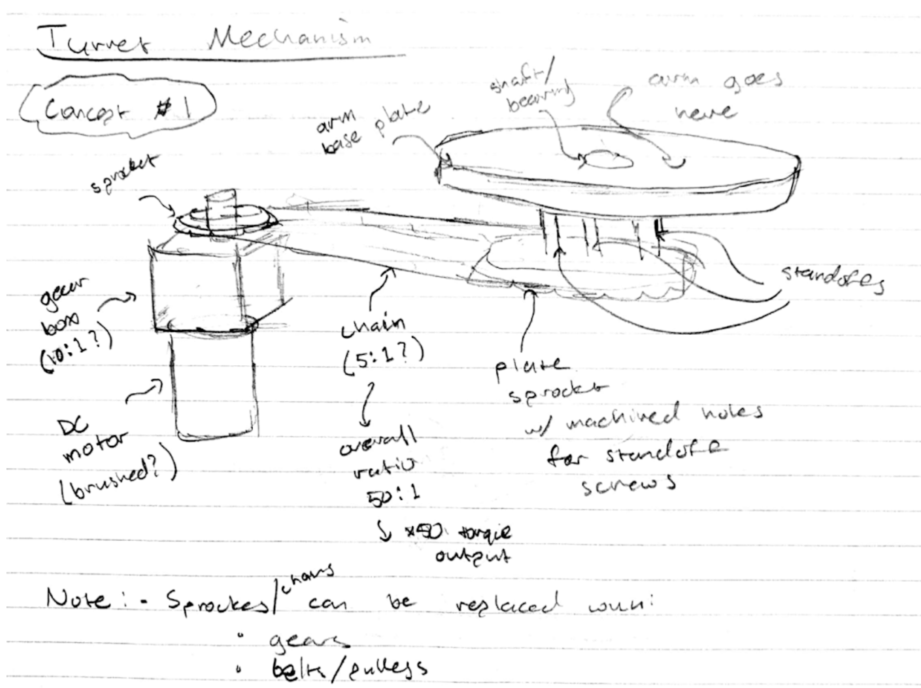


Figure 19.5.5: Sprocket Driven Turret with Gearbox Reduction

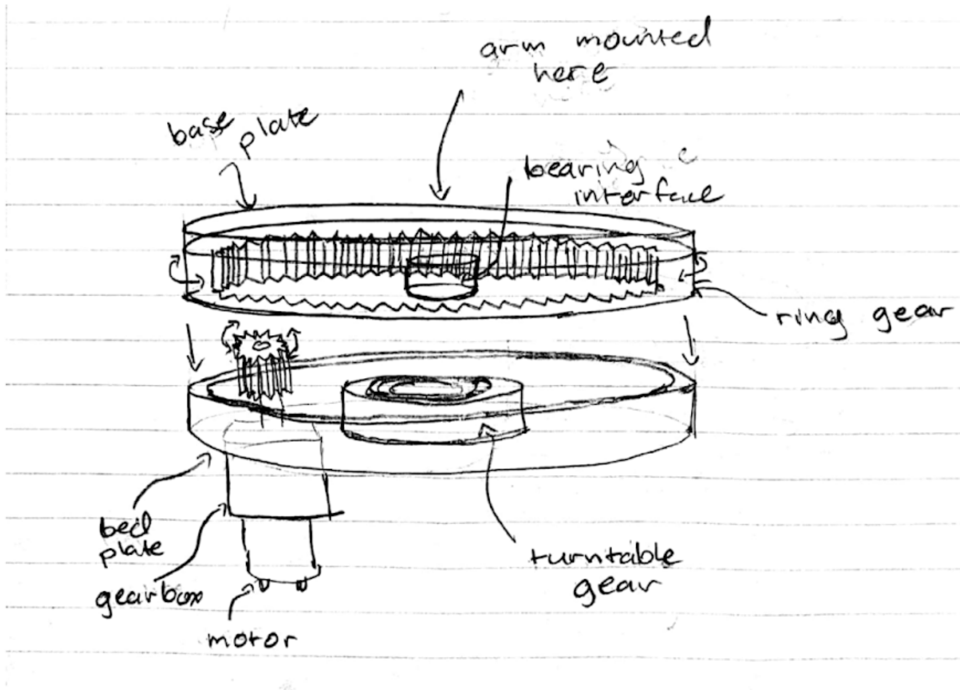


Figure 19.5.6: Ring Gear Driven Turret with Gearbox Reduction

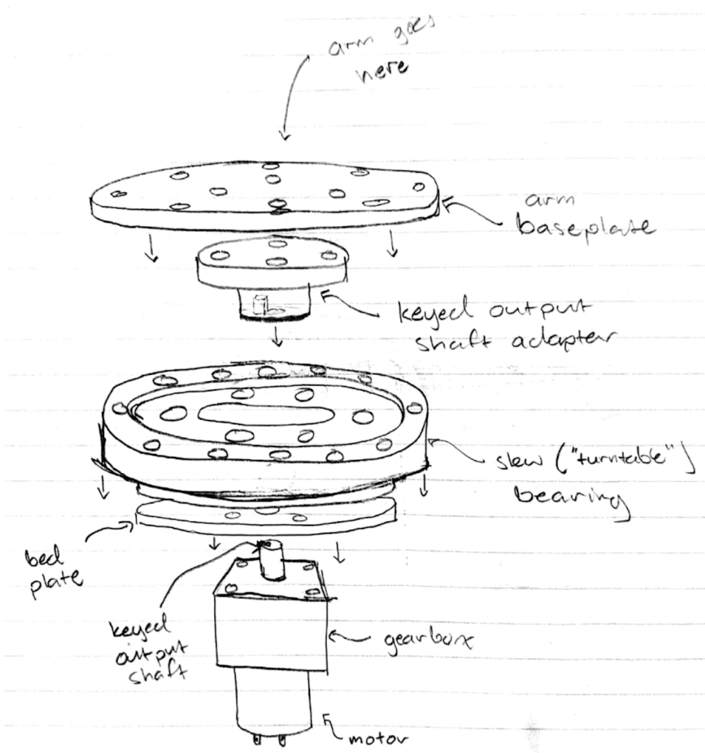


Figure 19.5.7: Directly Driven Turret with Gearbox Reduction

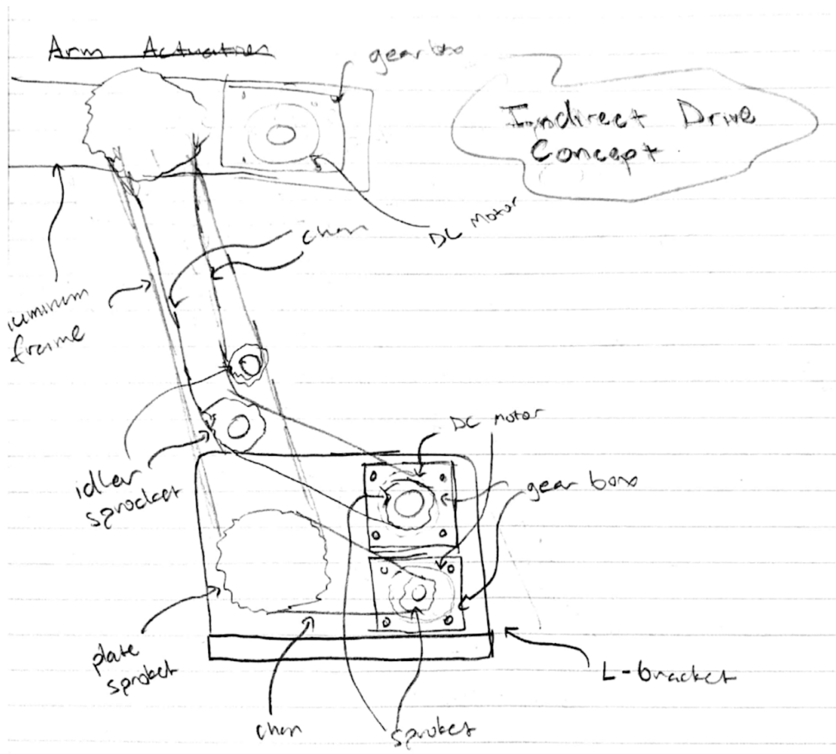


Figure 19.5.8: Sprocket Driven Arm Joints with Gearbox Reduction

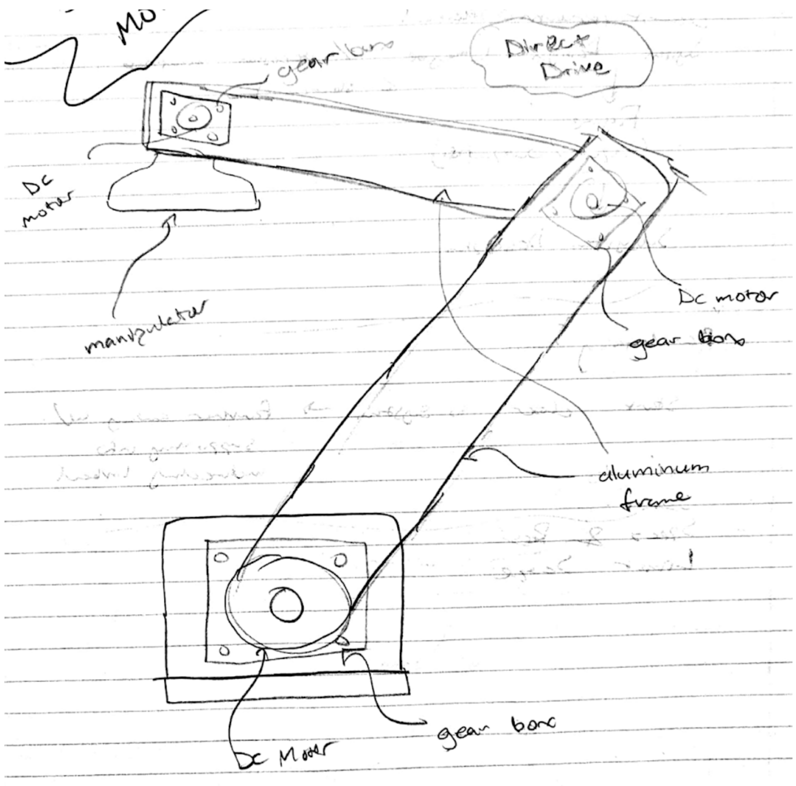
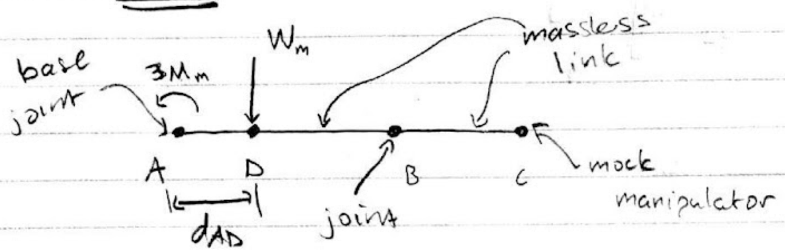


Figure 19.5.9: Direct Driven Arm Joints with Gearbox Reduction

Arm Prototype Model

- Depicts arm fully exended horizontally (max torque on system)

FBD – Static

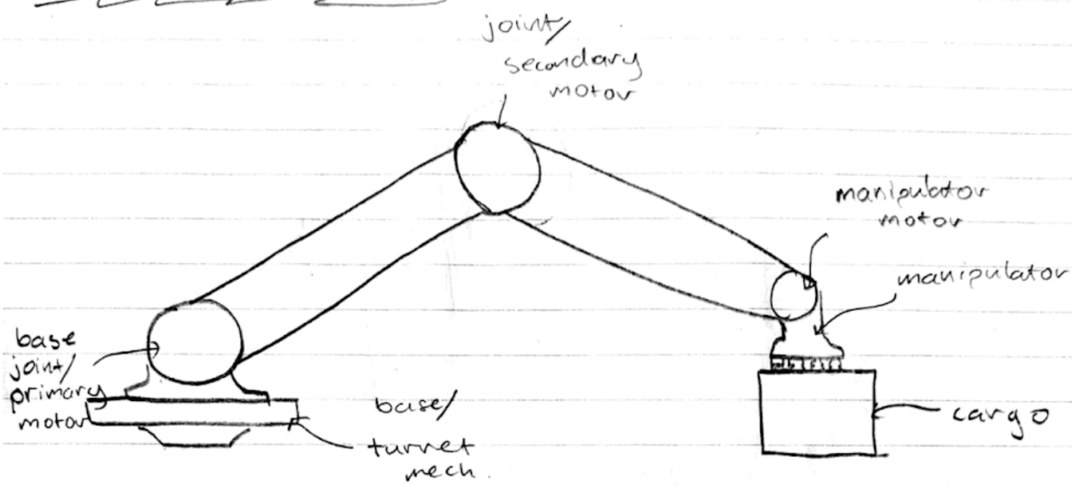


$$\Sigma M_A = M_m - W_m d_{AD} = M_m - (7.744\ \text{ozf})(2.48\ \text{in}) \geq 0$$

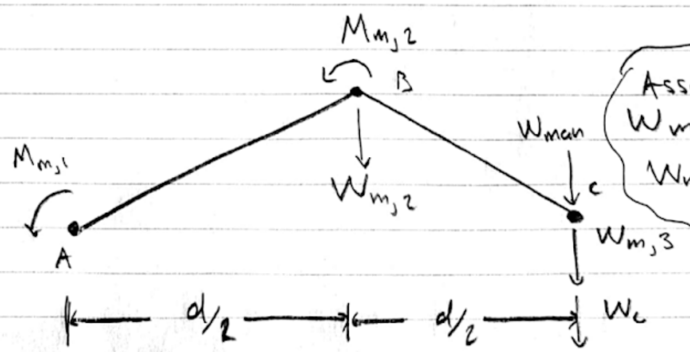
$$3M_m \geq 19.2\ \text{oz-in}$$

Figure 19.5.10: Mathematical Model for the Prototype

Fullscale Arm Model



FBD - Static



Assume:
$W_{m,i} = 10\,\text{lbs}$
$W_{man} = 5\,\text{lbs}$
$M_c \equiv W_c \cdot d$ (seen in tables)

In general, for primary motor:

$$\Sigma M_A = -M_c - W_{m,2} \cdot \frac{d}{2} - W_{m,3} \cdot d - W_{man} \cdot d + M_{m,1} = 0$$

$$\therefore \quad M_{m,1} = M_c + d\left[1.5 W_{m,i} + W_{man}\right]$$

for secondary motor:

$$\Sigma M_B = -M_c - W_{m,3} \cdot \frac{d}{2} - W_{man} \cdot \frac{d}{2} + M_{m,2} = 0$$

$$\therefore \quad M_{m,2} = M_c + \frac{d}{2}\left(W_{m,i} + W_{man}\right)$$

Figure 19.5.12: Mathematical Model for Full Scale

Structure

Tables

Table 19.6-1: Structure Specific Customer Requirements

Customer Need	Requirements	Target Value / Range of Values
Can lift most warehouse cargo	*Critical Strength*	*150 - 500 lbs* *68 - 227 kg*
	Be able to hold the weight of itself and the cargo	*< 0 structural failures*
Be able to transport a package successfully	*Packages do not fall off the robot*	*< 0 dropped packages during transportation*
Can be easily stored	*All of the parts are stored internally*	*No unnecessary parts outside the chassis*
Size – can move things throughout a warehouse	*Width x Depth x Height (pertains to the robot frame perimeter)*	*< 6’x8’x10’* *< 1.8 x 2.4 x 3 m*

Table 19.6-2: Chassis Shape Decision Matrix

		Concepts			
		Rectangular Chassis		Triangular Chassis	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Ease of Integration	30%	2	0.6	1	0.3
Ease of Maintance	10%	2	0.2	1	0.1
Ease of Manufacture	10%	3	0.3	2	0.2
Strength	10%	2	0.2	2	0.2
Weight Distribution	25%	3	0.75	1	0.25
Mobility	15%	2	0.3	1	0.15
	Total Score		2.35		1.2
	Rank		1		2
	Continue?		Yes		No

Table 19.6-3: Framing Decision Matrix

		Concepts					
		Criss Cross Framing		*Diagonal Bracing*		*X Bracing*	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Strength	30%	1	0.3	2	0.6	3	0.9
Ease of Manufacture	15%	2	0.3	3	0.45	2	0.3
Durability	25%	1	0.25	2	0.5	3	0.75
Cost	5%	2	0.1	3	0.15	2	0.1
Ease of Maintenance	15%	2	0.3	3	0.45	2	0.3
Weight	10%	2	0.2	3	0.3	2	0.2
	Total Score		1.45		2.45		2.55
	Rank		3		2		1
	Continue?		No		No		Yes

Table 19.6-4: Internal Placement Decision Matrix

		Concepts			
		Power in the Center		Power on the edge	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Ease of Integration	35%	3	1.05	2	0.7
Ease of Maintance	20%	2	0.4	3	0.6
Ease of Manufacture	10%	2	0.2	2	0.2
Weight Distribution	35%	3	1.05	1	0.35
	Total Score		2.7		1.85
	Rank		1		2
	Continue?		Yes		No

Figures

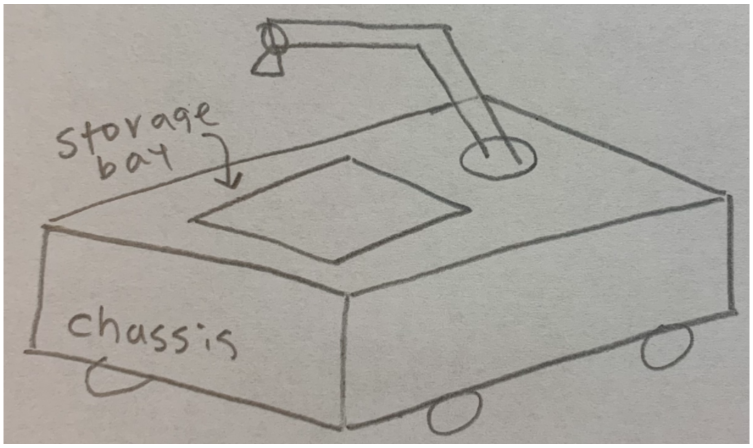


Figure 19.6.1: First Generated Concept

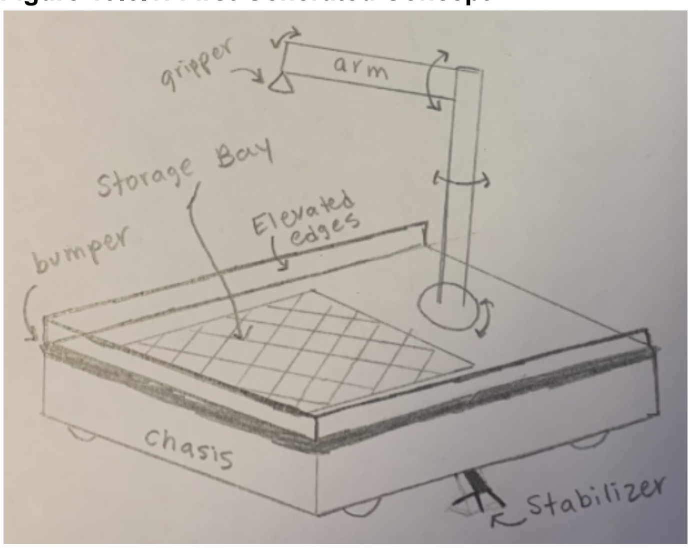


Figure 19.6.2: Exterior Stability Consideration

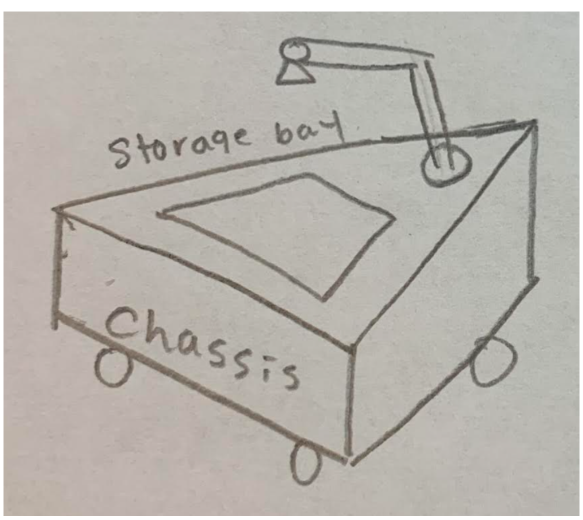


Figure 19.6.3: Triangular Prism Chassis Concept

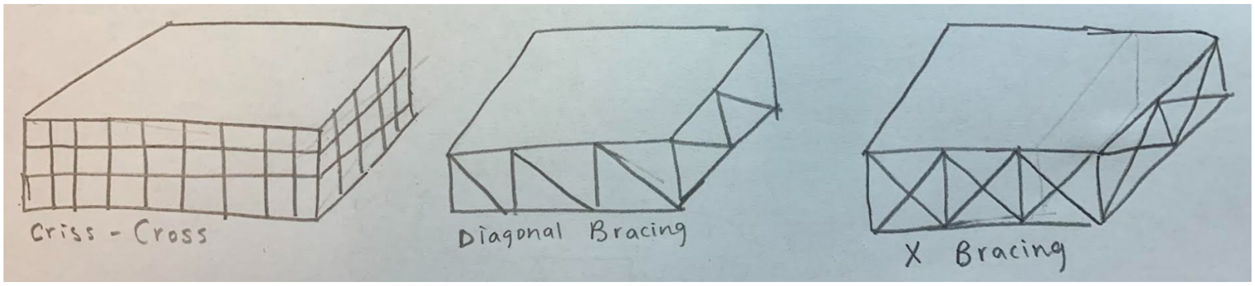


Figure 19.6.4: Internal Framing

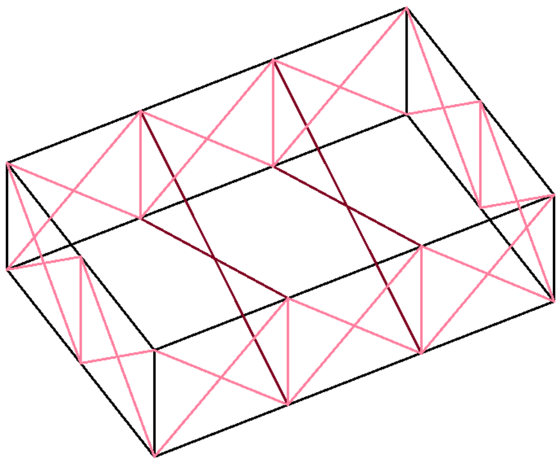


Figure 19.6.5: Final Internal Framing Cad

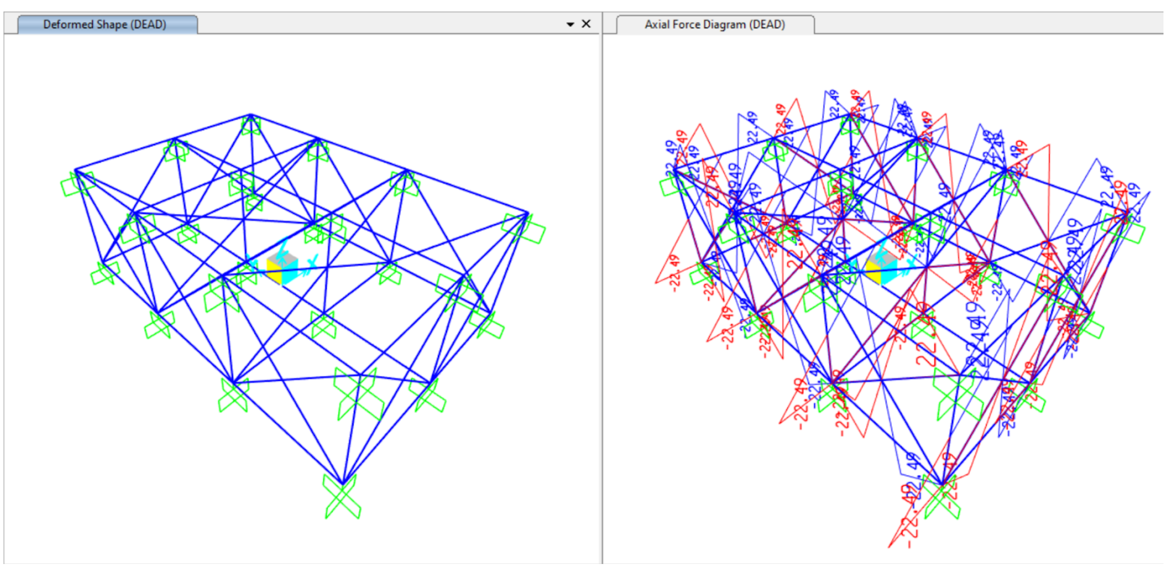


Figure 19.6.6: Modeling Force Applied to the Structure

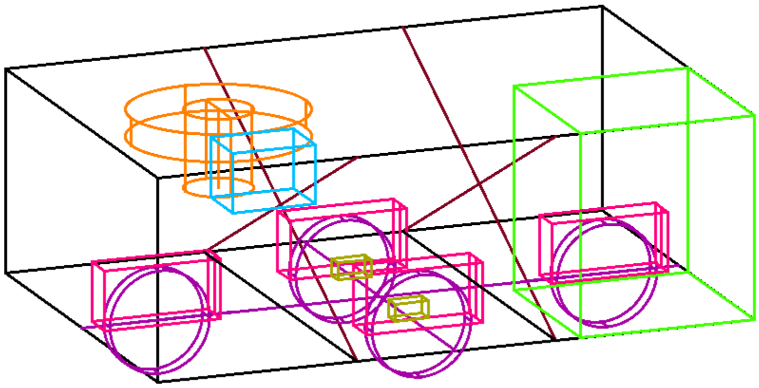


Figure 19.6.7: Side View of Internal Placement with Power on the Side

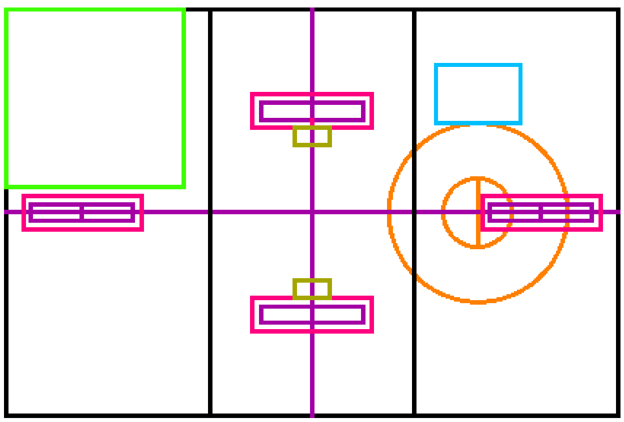


Figure 19.6.8: Top View of Internal Placement with Power on the Side

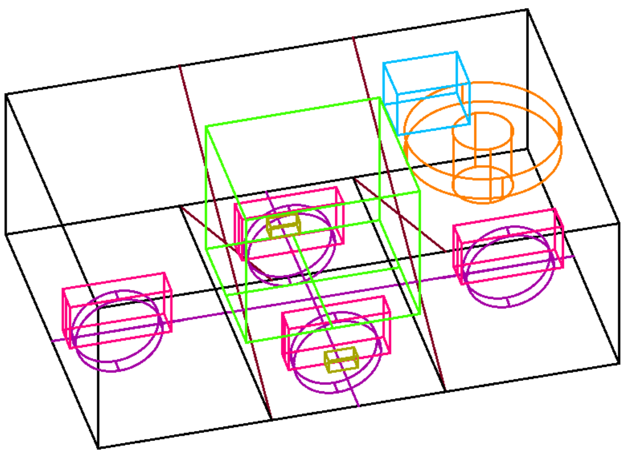


Figure 19.6.10: Side View of Internal Placement with Power in the Middle

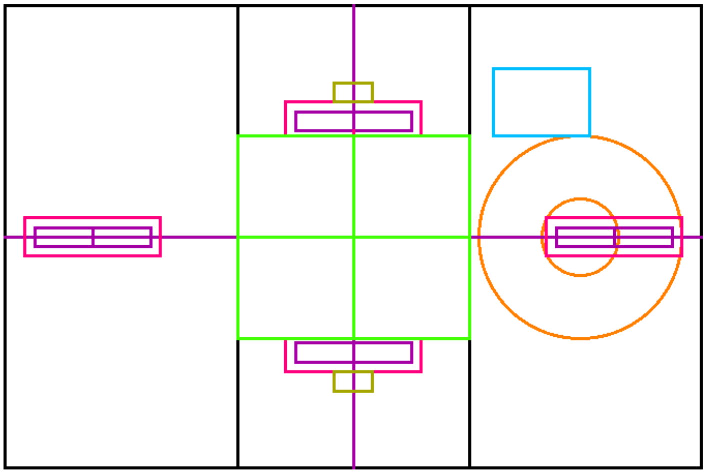


Figure 19.6.9: Top View of Internal Placement with Power in the Middle