Final Report for a Material Transportation Robot

ME 492 Final Report – Year 2014

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Due

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Executive Summary

Axiom Electronics is a manufacturer of high-end electronic circuit boards which are used in new assemblies as well as older machines that require board replacements. During the production process, valuable time is wasted because an assembler must push a cart filled with circuit board from inspection to packaging. Axiom would like to free up the assembler by having a robot do this job. To fulfill Axiom's requirements, the robot would have to be fully autonomous and be able to avoiding colliding with employees and other obstacles. This group was tasked with the job of design and building a robot according to Axiom Electronics' specifications. After the complete of a remote-controlled prototype of the robot, a graduate student was assigned to make the robot fully autonomous.

After an extensive external search, this capstone team designed and manufactured a chassis and selected the motors, wheels, batteries, and other components that were needed for the completion of a fully functional remote-controlled robot. This report outlines the design and manufacture of the robot and includes the mission statement, the product design specification, the top level design, the work and analysis involved in the external and internal research, and the process of component selection. Each decision is tied back to its ability to fulfill the robot's PDS requirements.

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1 – Introduction and Background Information

Axiom Electronics is located in Tigard, Oregon and is a producer of Printed Circuit Boards. They currently manufacture boards used in medical, scientific, and defense products. They are a proponent of lean manufacturing and have identified several ways that time is wasted during their manufacturing process. One major area of waste is the transportation of finished products from testing to packaging and shipping. Currently, an assembler pushes a cart about 100 feet to deliver the product to packaging. Axiom has investigated purchasing and installing a commercial robotic system to perform this and other delivery tasks. All existing commercial solutions, however are too expensive. Furthermore, many robotic options require a taped line the robot must follow, a necessity that Axiom feared would hinder employees' movements. Due to these cost-related and navigational concerns, Axiom concluded that only a fully autonomous robot would meet the company's needs. Axiom contacted Portland State University's Mechanical and Materials Engineering Department to see if a more economically viable solution could be found. In January, the team met with Dolly Blanda, Vice President of Axiom Electronics for an initial discussion regarding the depth of the project. After consulting with Dr. David Turcic, the faculty advisor for this project, it was decided that this team would focus on the mechanical aspects of the project and a graduate student was assigned to deal with the necessary programming and hardware required for an autonomous robot. The full project had a budget of $10,000, but the group aimed to only use 33% of the budget for the mechanical aspects of the project.

2 – Mission Statement

The goal of this project was to design and build a robot frame that is capable of transporting electrical circuit boards around Axiom Electronics' manufacturing site. The robot had to be able to carry 80 pounds of material at a speed of 50 feet per minute. The robot also had to be remote-controlled and have a loading platform consisting of a 24" x 36" shelf that will be capable of holding two 22.5" × 17.5" rectangular holding bins. Finally, the cost of the project had to be less than $3,300.

3 – Product Design Specification

The PDS requirements were created using a list of product requirements provided by Axiom Electronics. The requirements were further developed through group brainstorming to determine the most important criteria for project completion. The product requirements sheet can be found in Appendix A – Product Requirements

Some key PDS requirements are shown below. For the full PDS table, see Appendix B – Product Design Specification Table

- **Velocity -** The robot must have a speed between 50 and 100 feet per minute.
- **Payload** - The robot must be capable of carrying at least 80 pounds on a 36" x 24" shelf.
- **Maneuverability -** The robot must be able to maneuver in a 35 inch hallway.
- **Environment** – Given that the environment is a semi-clean room factory setting, no hazardous materials can be used in the construction and implementation of the robot.
- **Costs** – The total budget for this aspect of the project is $3,300.

4 – Top Level Design

The group conducted an external search to find existing solutions that would fulfill the design requirements. The results of this search can be found in Appendix C - External Search. The external search focused on three options: purchasing a pre-built robot, modifying an existing robot, or manufacturing a new robot. After the external search, it was decided to manufacture a new robot due to the cost of the other options.

The group also conducted an internal search, which can be found in Appendix D - Internal Search. The internal search focused specifically on the design ideas regarding the chassis, wheel placement, material selection, motor selection, wheel type, and the electrical and control design. The flowchart in Figure 1 was then developed to help the team navigate the design process. As it can be seen, Wheelbase Selection and Material Selection were deemed imperative to the design of the chassis and are interdependent of each other.

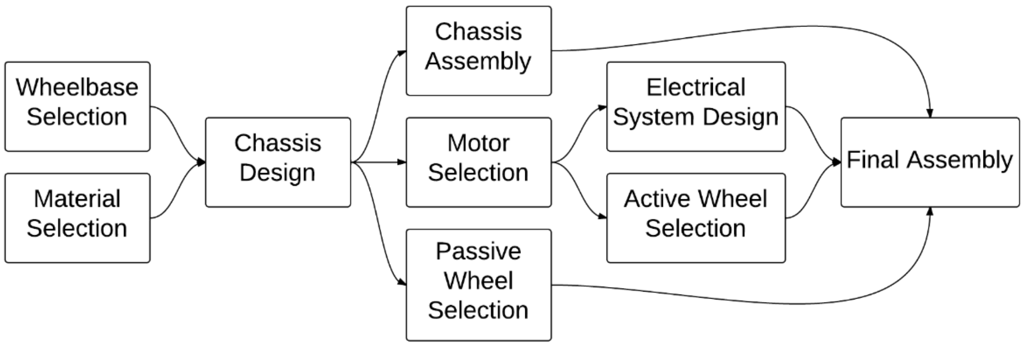
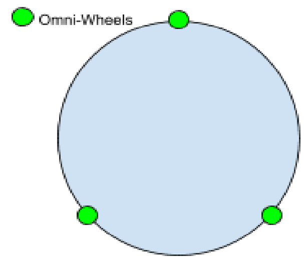
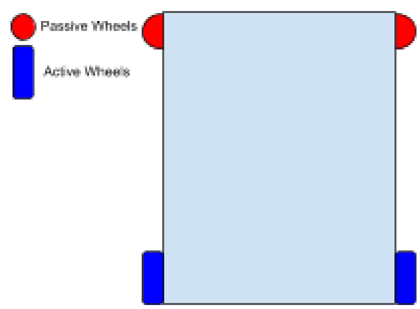
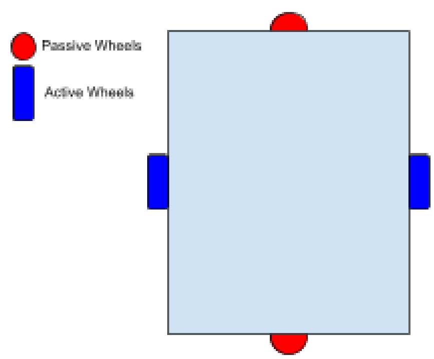
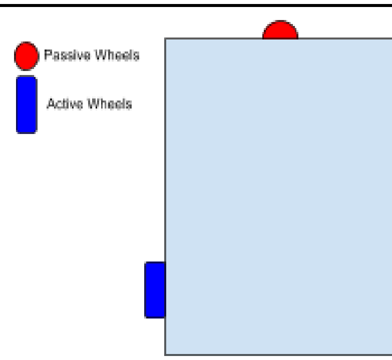


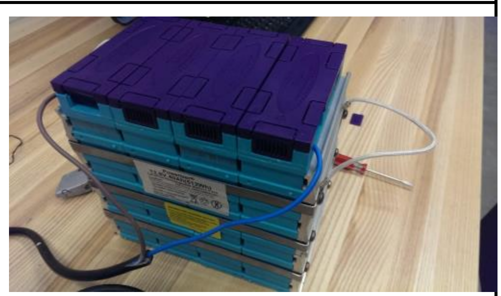
Figure 1 - Robot Design Process

Due to the cleanliness standards maintained in Axiom's work environment, battery selection was another important aspect of this project. Table 1 (next page) details the advantages and disadvantages of each wheelbase geometry, material, and battery that was evaluated.

To assist with the selection process, the group created concept scoring matrixes for each decision which can be found in Appendix E – Concept Scoring Matrix. After using the concept scoring matrixes, the group decided to use the Trapezoidal wheel base, selected steel for the main chassis material, and chose the lithium ion phosphate battery.

Table 1 - Advantages and Disadvantages Table for Wheel Placement, Material Selection, and Battery Selection

Design	**Advantages**	**Disadvantages**	**Images**
Wheel Base			
Omni-directional wheels	• High maneuverability	• Complex programing • Expensive • Not stable	
Rectangular	• High stability	• Large turn radius • Suspension system required	
Trapezoidal	• Able to move back and forth easily • Tight turn radius	• Suspension system required • Not quite as stable as the Rectangular Wheelbase	
Triangular	• No need for a suspension system • Only need 3 wheels	• Low stability • Large turning radius	

Design	**Advantages**	**Disadvantages**	**Images**
Material			
Steel square tube	• Inexpensive • Can withstand high load with small deflection • Easy model and analyse.	• High specific weight • Need skills to weld, difficult to adjust	
Aluminum 80/20	• Light-weight • Can withstand high load • No welding needed	• High cost (~$500 total) • Complicated to model and analyze.	
Battery			
Sealed lead battery	• Inexpensive • High capacity	• Not safe for clean room environment. • Low cycle life	
Lithium Ion Phosphate Battery	• High capacity • High cycle life (~2,000) • Safe for environment	• High cost	

5 – Detailed Design

The following sections outline the detailed design decisions made in reference to the PDS requirements. A bill of materials for the robot can be found in Appendix F – Bill of Materials.

5.1 – Material

The frame of the chassis was primarily composed of 1.00” × 1.00” × 0.083” hot-rolled steel square tubing. 0.75” × 0.75” × 0.065” hot rolled steel square tubing and 0.5” diameter steel round bar were also utilized to secure the totes at the top of the chassis. The main advantages of hot-rolled steel square tubing was the low cost of the material. Moreover, the steel tubing met all of the requirements in the PDS table. Table 2 lists the physical properties of the grade of steel chosen. Additionally, ⅛” thick aluminum plating was also used as a base for the top and the bottom of the chassis.

Table 2 - Physical Properties of Hot Rolled Steel

Modulus of Elasticity	Poisson's Ratio	Density	Yield Strength
30,000 ksi	0.29	0.285 lb/in	35 ksi

5.2 – Chassis

After the trapezoidal wheelbase was selected, the chassis was modeled in Solidworks as shown in Figure 2. Complete drawings of the chassis can be found in Appendix G – Chassis Drawing. Once the Solidworks model was completed, the design was transferred to Abaqus and finite element analysis was performed to verify the strength of the design. For the purpose of this analysis, the active wheels were considered to be stationary and the passive wheels were limited to transverse movement only. The chassis was modeled using 1” × 1” × 0.083” steel tubing. Figure 3 shows the results with respect to the

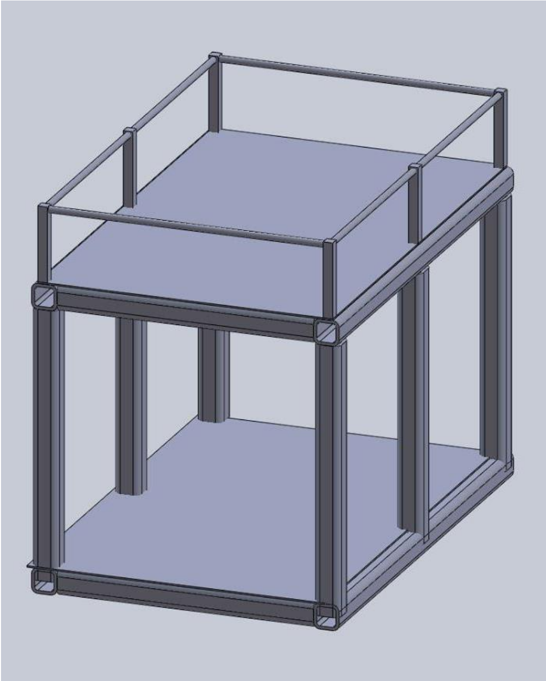


Figure 2 - Solidworks Model of the Chassis

Von Misses Stress. As the figure shows, the maximum stress in the material is 637 *psi*. Further analysis revealed that the maximum deflection is 0.00328 inches. From this it was concluded that the frame was strong enough to handle the necessary loading with a large factor of safety. Further finite element analysis, showing the magnitude of deflection, can be found in Appendix H – Finite Element Analysis.

To provide a surface for the components and materials to rest upon, ⅛” thick aluminum plating was pop-riveted to the top level and base of the chassis. Additionally, a fence was welded around the edge with uprights of 0.75 x 0.75 x 0.065 inch steel and cross bars of ½ inch steel round bar.

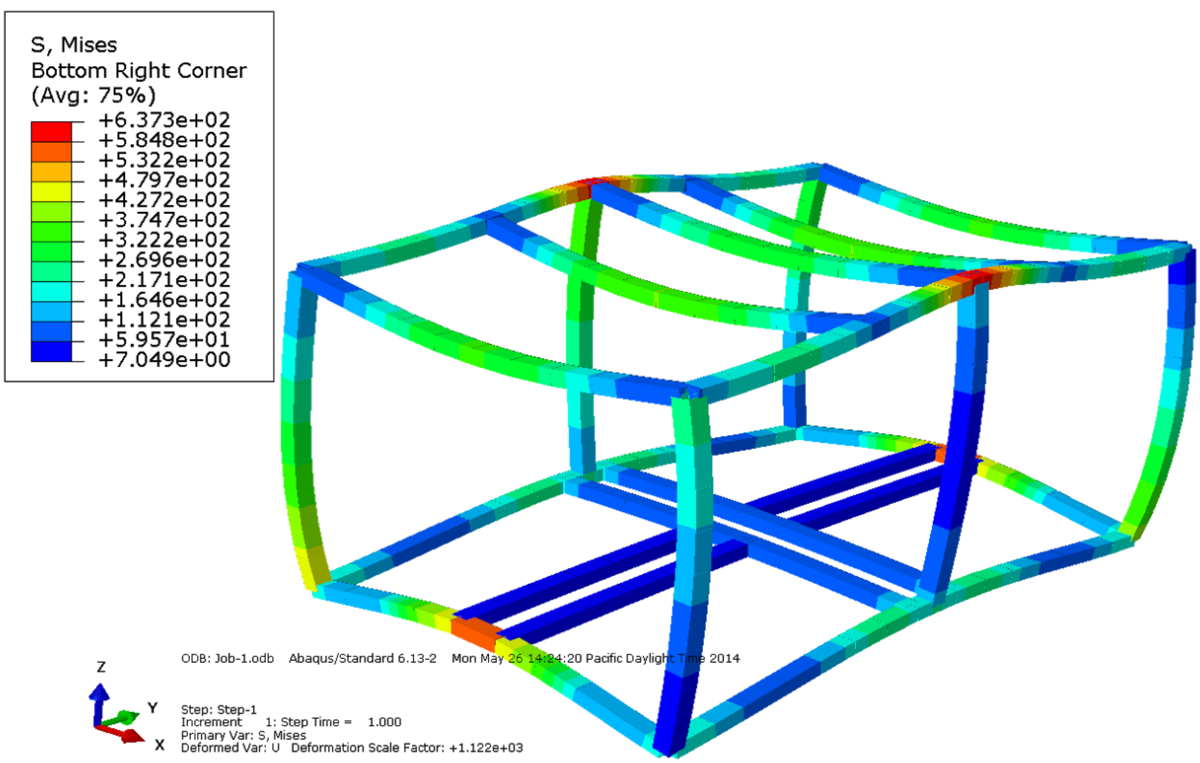


Figure 3 - Finite Element Analysis Showing the Von Misses Stress in the Chassis

5.3 – Motor

Figure 4 - 42A5-FX Parallel Shaft DC Gearmotor Model 5073

A thorough calculation of the required motor torque based on the weight of the robot, speed profile, and supplied power is presented in Appendix I – Motor Torque Requirements. With these calculated values, a search for a suitable motor and gearhead was conducted with the assumption that the motors and gearheads would be connected directly to the driving wheels. To satisfy this requirement, the 42A5-FX Parallel Shaft DC Gearmotor Model 5073[1] was selected and can be seen in Figure 4. Its speed vs torque diagram is shown in Figure 5 together with the calculated torque. As can be seen, the calculated torque stays within the normal operation area of the motor and ensures the motor will work as expected under normal working condition as well as in overload.

To attach the motor to the chassis, two 6-inch angled steel brackets were purchased and bolt holes machined. Half inch spaces were used to ensure that the motor would be at the correct height. The drawing for the brackets can be found in Appendix K – Motor Bracket Drawing

[1] 42A5-FX Parallel Shaft DC Gearmotor Model 5073 - http://www.bodine-electric.com/Asp/ProductModel.asp?Context=13&Name=42A5-FX%20Parallel%20Shaft%20DC%20Gearmotor&Model=5073&Sort=11923

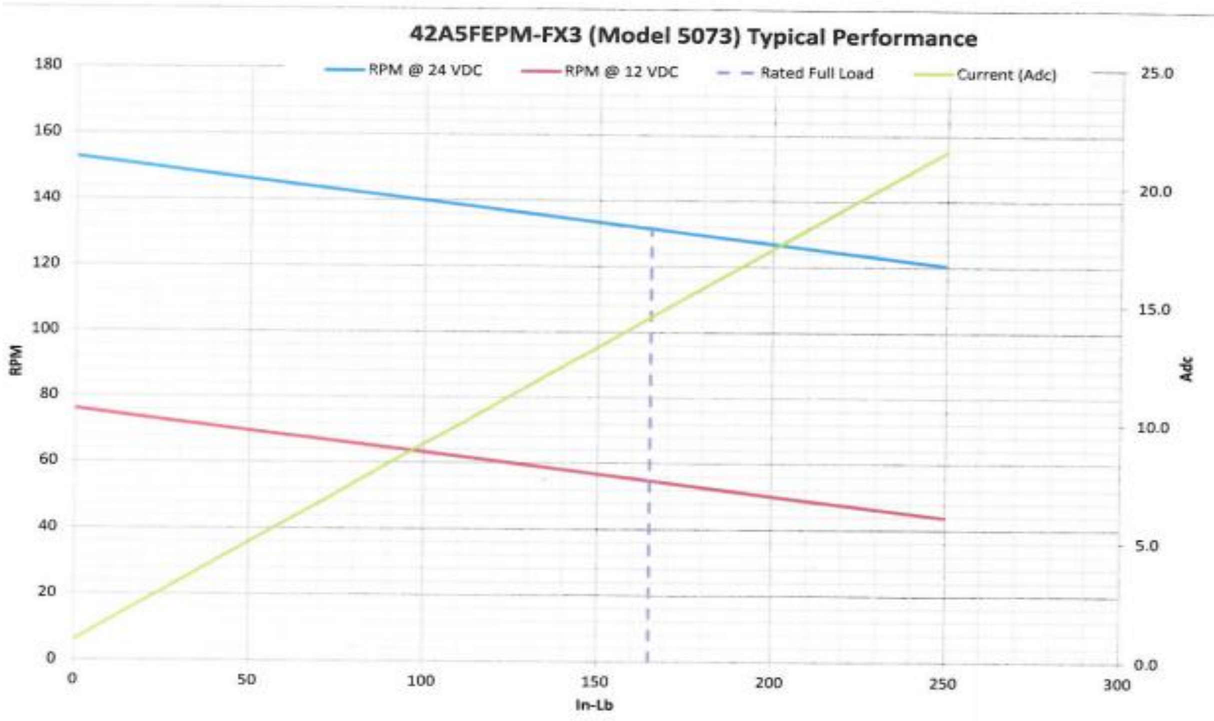


Figure 5 - Speed vs. Torque Graph for a Bodine DC Gearmotor Model 5073

5.4 – Wheels

The wheel selection process is divided into two sections: driving wheels and caster wheels.

5.4.1 – Motor Wheels

Rubber, flat-proof tires were chosen for the driving wheels because of their ability to grip the floor. Moreover, it was desired that the tires selected would not need routine maintenance, risk getting a flat tire, or leave scuff marks on the floor. The size of the wheel was also important. A balance was sought so that the wheel would overcome small obstacles yet not require more torque than the motors could overcome. A 10 inch diameter, solid rubber wheel was selected for use. A drawing of the wheel used can be found in Appendix L - Wheel Drawings

A wheel hub was purchased to attach the driving wheels to the motors. At the time of assembly, it became apparent that the hub did not have a set screw to fix the hub to the motor shaft. This meant that the hub would not resist forces along the axis of the shaft. To solve this problem, a Climax, C200-075 Keyless Bearing was purchased with an outer diameter of 1.85 inches to secure the wheel to the motor shaft. Drawings for the keyless bushings can be found in Appendix J – Keyless Bushing Drawing. The wheel hubs were then machined to attain the required inner diameter and were assembled as seen in Figure 6. Drawings of the modified hubs can be found in Appendix M – Modified Wheel Hub Drawing

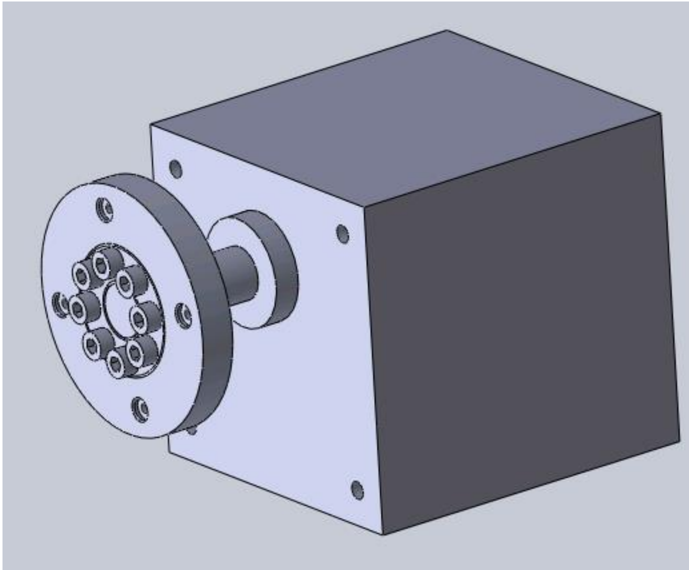


Figure 6 - Keyless Bushing Assembly. The Keyless Bushing Was Used to Connect the Wheel Hub to the Motor Shaft

5.4.2 - Caster Wheels

Due to the expected load and the need for a smooth ride, caster wheels with built-in suspension were required. An analysis of the expected vibration due to travel and the necessary spring and damper system required to keep the robot moving smoothly was conducted and can be found in Appendix N – Vibration Analysis. The results of this analysis was unsatisfactory and after consultation with caster-manufacturer RT Laird and with the project's advisors, it was decided that excessive vibrations would not be a major concern with a velocity of 50 feet per minute. 6-inch diameter caster wheels were chosen because they could easily be aligned with the height of the driving wheels

5.5 – Battery

For ease of management, the power supply for the motors was separated from the power supplied to the other electrical components. Batteries for the motors were selected based on the 8-hour work cycle life and clean room environment specified by Axiom. Two 12V, 40A, 40Ah LiFePO4 batteries were selected for each motor as can be seen in Figure 7. This battery was selected because it had a large capacity compared to the lead acid battery and because it will full Axiom's cleanroom standards. Moreover, its life cycle is ten times greater than the equivalent (same voltage and amp hours) lead-acid battery.

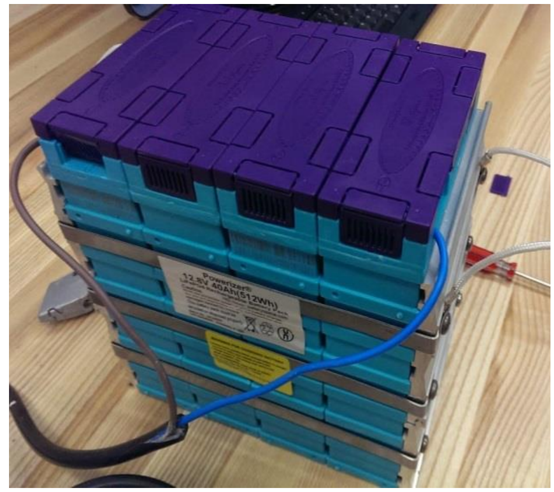


Figure 7 - 12V, 40Ah, LiFePO4 Battery

6 – Evaluations & Future Design Considerations

The success of the robot design and assembly was evaluated using the PDS requirements. The complete PDS table can be found in Appendix B. The following sections compare the outcomes of the different sections in comparison to what was required for performance as well as budget constraints.

6.1 - Material

The criteria for material dictated that the chassis weight would be less than 50 pounds. The chassis weight has been estimated to be approximately 50 pounds. To help improve the PDS requirements, a thinner gauge of aluminum should be used for the top and the base.

6.2 - Chassis

There is one PDS requirement for the chassis. It dictates that the size of the chassis must be 24" x 36" x 30". The final dimensions of the robot fully assembled are 24" x 36⅛" x 30⅛". Note that the height given is from the floor to the top of the shelf. Given the method of assembly, it is doubtful that the chassis could obtain a tighter tolerance than the current model.

6.3 - Motor

There are two performance metrics that relate to the motor: first, the motors must work as required with a torque of 6,772 mN-meters; second, the motors must move the chassis at a rate of 50 feet per minute. The motors fulfill these criteria as proven by the motor data sheet and calculations.

6.4 - Wheels

The wheel size and material composition was never specified by Axiom. As a result, it was the responsibility of the group to determine these criteria. One important consideration was that the chassis did not vibrate incessantly. This was dealt with by purchasing caster wheels with built-in suspension to keep vibrations at a minimum. The wheels also had to maintain proper traction with Axiom's production floor. By choosing treaded rubber tires, the robot was proided with the grip necessary for its work.

6.5 - Battery

There were two PDS requirements that related to the battery. The first was that the batteries would last for a full, eight hour workday and the other was that the batteries would not violate Axiom's cleanroom standards. The battery selected fulfilled both of these requirements.

6.6 - Budget

The total budget for this project was $10,000. Initially, the team estimated that the mechanical aspects of the project would use approximately 33% of the budget. At this point, the team has spent $3,189.87, an amount that represent only 32% of the total budget. This leaves 68% for the controller, sensors, and other equipment needed for the automatization of the robot.

7 - Conclusion

Over the past six months, this group has worked efficiently to design and manufacture a robot to meet the specifications of Axiom Electronics. Careful consideration was put into every aspect of the robot's creation, from the design and configuration of the wheels to the selection of the materials and batteries. Before any purchases were made, an analysis was carried out on the overall design to ensure that the final product could carry the desired load. The end result is a robot that is fully operational, aesthetically pleasing, and built in accordance to the specifications set forth by Axiom Electronics.

During this project, the team learned several important skills. We learned how to work well together, how to weld and machine steel, and how to communicate effectively with each other, our advisor, and our sponsor.

Appendix A – Product Requirements

The following are the product requirements from Axiom Electronics.

1. Hold 2 totes - each tote 22.5 x 17.5" (Self - Length 36", width 24")
2. Shelf height from the floor - 30"
3. Cary 80 pounds
4. Battery powered, charges from a standard wall outlet
5. Speed: 50 ft/min
6. Obstacle Detection System - Must be safe around humans
7. Alerts personnel of its presence
8. Autonomous Navigation - drive around mapping with laptop/iPad, no separate server/database, not racks of any kind required.
9. Small footprint - navigate in 35" hallways

Optional requirements:

1. Ability to add another shelf
2. Ability to pull a 36x24" separate car with a weight capacity of 100 pounds
3. Speed: 100 ft/min

Appendix B – Product Design Specification Table

The following is the PDS table that was created with team meetings and in conjunction with the Product Specifications in Appendix A – Product Requirements.

Table 3 - Product Design Specification table

Criteria	Requirement	Customer	Metrics	Target	Basis	Verification
High						
Environment (navigation)	Ability to Navigate around obstacles	Axiom Electronics	Collisions and accidents	No Collisions or accidents	Interview with AE	Testing and Validation
Laws, Codes, and Standards	Environmentally Responsible	State	Standards	Clean Room	Regulations	Careful study
Documentation (customer)	A Users Manual	Axiom Electronics	Instructions	Well Written	Capstone Decision	Careful Validation
Time Scale	Finish work based on the timeline given	Capstone Group	Date	Finish before June 10.	Discussed within group	
Performance (battery)	The battery lasts for a work period	Axiom Electronics	hours	8	Axiom Electronics	Testing
Performance	Motor works as required	Capstone Team	mN-meters	6,772	Calculations	Testing and Validation
Performance	Robot doesn't excessively vibrate	Capstone Team	Cycles of Vibration	<3	Group Decision	Testing and Validation
Size and Shape	Follow prescribed dimensions	Axiom Electronics	Inch	36" x 24" x 30"	Axiom Electronics	Measurement and Design
Retail and production costs	Remain within Budget	Axiom Electronics	Dollars	$10,000	Axiom Electronics	Budget
Testing	The robot works to specifications	Capstone Group	Robot	Carries weight	Group Decision	Testing and Validation

Criteria	Requirement	Customer	Metrics	Target	Basis	Verification
Medium						
Product Life Span	Continued Operation for the foreseeable Future	Axiom Electronics	Years	5	Interview with AE	Parts and Processes Analysis
Environment (floor)	Ability to work in factory setting	Axiom Electronics	Have grip on floor surface	Be able to turn & stop	Interview with AE	Testing and Validation
Installation	Quick Installation	Capstone Group	Day	<1	Brainstorm Decision	Processes Analysis
Legal	Not conflict with existing patents	Axiom Electronics	NA	NA	Design Decision	Careful Study
Documentation (university)	PDS Document, House of Quality	Capstone Group, Dr. Yi		1 each	Required by the department	Submitted to the professors
Quality and Reliability	Fulfills product expectations	Capstone Group	NA	NA	Brainstorm Decision	Testing
Maintenance	Should be easy to maintained	Axiom Electronics	times per year	2	Axiom Electronics	Checking performance twice a year
Performance	Velocity	Axiom Electronics	Feet per Minute	50	Axiom Electronics	Testing and Validation
Performance	Ability to Navigate narrow hallway	Axiom Electronics	Inches	>35	Axiom Electronics	Testing and Validation
Low						
Materials	Be Lightweight	Capstone Group	Pounds	<50	Brainstorm Decision	Not Applicable
Chassis Weight	Be transportable	Capstone Group	Pounds	Less than 50	Brainstorm Decision	Testing
Aesthetics	Worthy of showcasing	Axiom Electronics	Looks Good	Customer Feedback	Artistic choice	Interviewing the customers
Manufacturing Facility	A place with enough tools and machines to manufacture	Capstone Group	A clean Room	The capstone lab	Group Decision	Not Applicable
Processes	Researching/ Building	Capstone Group	Facility	1	Department Constraints	Visual

Appendix C - External Search

At first, the team conducted a search for existing products that fulfilled the robot's design requirements. From this search process, we discovered some current robot design features that could be utilized in our situation. Packmobile [2]—a company that specializes in automation solutions — showcases an automated guided vehicle (AGV) that is able to transport packages, boxes, or parts inside a manufacturing site. Figure 8 shows the basic structure of this product. While the Packmobile design is a good example to refer to, it requires an invisible fluorescent guidepath that is not applicable to this project since Axiom requires that no guidepath markings be made on their production floor. Another AGV from Savant Automation[3] was also considered. Savant Automation uses inertial guidance which can adjust the floor plan easily by means of software programming. This navigation technology is a close approximation to our project's intended design since it satisfies Axiom's floor specifications.

Figure 8 - The Egemin Packmobile AGV

Our external search involved reading through books such as "Introduction to Autonomous Mobile Robots" published by MIT Press. MIT's "Introduction" gave an overview of the design and manufacturing process for a mobile robot and helped us to develop our detailed design. Specifically, our external search led us to include the chassis design, the material selection, the motor selection, the wheel selection, and the electrical and control design.

One of the most important features of our robot is the ability to self-navigate on the floor. Therefore, we conducted an external search of indoor-positioning technologies. While most of the wireless technologies for positioning are affordable and easy to install, the sensor's accuracy

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[2] "Egemin Packmobile AGVs - Egemin Automation Inc." 2006. <http://www.egeminusa.com/pages/agvs/agvs_packmobile.html>

[3] "Savant Automation." 2004. <http://www.savantautomation.com/>

will only bring the robot within 50 cm of its desired location. Ubisense, a leading company in indoor navigation systems, offers a real-time indoor navigation system with an accuracy of 30 cm. Unfortunately, Ubisense's system requires a 24/7 server and costs $12,500 above our project budget. The inability to utilize Ubisense's technology necessitated exploring other solutions that offered acceptable accuracy at a cheaper price.

Appendix D - Internal Search

Internal research first focused on the feasibility of the project. Given the nature of the programming requirements and the relative inexperience of the capstone team, feasibility was a major concern both to the team and to Axiom Electronics. Thus, a graduate student was assigned to perform the programming and select the robot's necessary electrical components.

The next step in this project was to design the chassis and to select the robot's mechanical components. Before the chassis could be designed, however, wheel arrangement options had to be examined. First, we considered a triangular wheel configuration that relied on three powered, omnidirectional wheels. The triangular design was rejected because the omnidirectional wheels would be difficult to program and because the triangular base would be unstable. Second, we considered a rectangular shape with four wheels, two of which were powered and two of which were passive. Because the four-wheel base offered maximum maneuverability and stability, we decided to use this design. The initial configuration of this design is shown in Figure 9. While this design provides maximum stability, maneuverability would be minimal. Figure 10 depicts a configuration in which the active wheels are located in

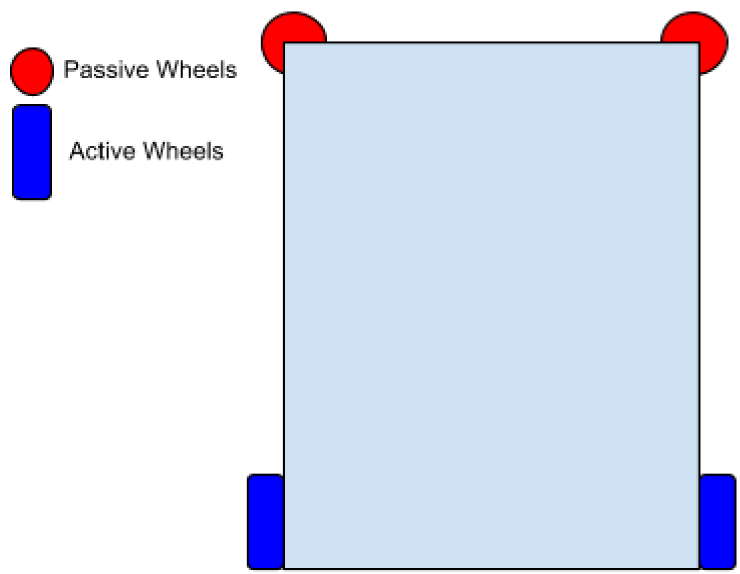

Figure 9 - Schematic of a 4 wheeled robot wheel configuration

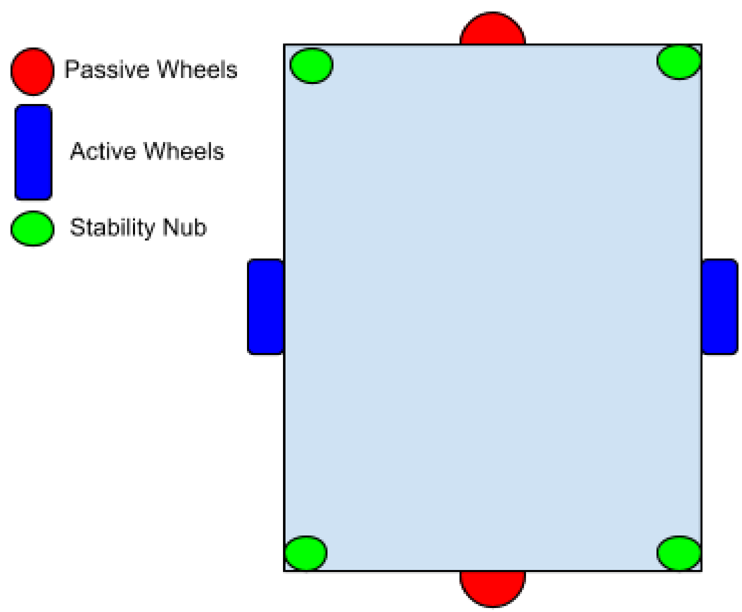

Figure 10 - Final Schematic for the robot

the middle of the chassis, providing maximum maneuverability but less stability than the schematic in Figure 9. To enhance stability, nubs were added to each corner.

Appendix E – Concept Scoring Matrixes

Table 4 is a concept scoring matrix for the chassis design, Table 5 is the concept scoring matrix for the material selection, and Table 6 is the concept scoring matrix for battery selection.

Table 4 - Wheelbase Concept Scoring Matrix

CHASSIS

Concept	Criteria	Weighted Value	Criteria	Weighted Value	Criteria	Weighted Value	
	Stability	5	**Maneuverability**	3	**Ease of use**	4	**Total Value**
Omni-Directional Wheel Base	2	10	4	12	2	8	30
Rectangular	5	25	1	3	4	16	44
Trapezoidal	4	20	5	15	3	12	47
Triangular	3	15	3	9	4	16	40
Total Value		70		39		52	

Table 5 - Material Concept Scoring Matrix

MATERIAL

Concept	Criteria	Weighted Value	Criteria	Weighted Value	Criteria	Weighted Value	
	Cost	6	**Ease of assembly**	2	**Robust**	2	**Total Value**
Hot Rolled Steel	4	24	2	4	2	4	32
8020 Aluminium	2	12	5	10	4	8	30
Total Value		36		14		12	

Table 6 - Battery Concept Selection Matrix

Batteries

Concept	**Criteria**	**Weighted Value**	**Criteria**	**Weighted Value**	**Criteria**	**Weighted Value**	
	Cost	3	**Environmental Concerns**	5	**Life Cycle**	2	**Total Value**
Lead Acid	5	15	2	10	2	4	29
Lithium-Ion	1	3	5	25	4	8	36
Total Value		18		35		12	

Appendix F – Bill of Materials

Table 7 is a bill of materials for all material used for the purposes of the autonomous robot.

Table 7 - Bill of Materials

ASSEMBLY	PART NUMBER	DESCRIPTION	QUANTITY	VENDOR
CHASSIS	10-00	14 G, 1X1X36" STEEL HR TUBING	4	METAL SUPERMARKETS
CHASSIS	10-01	14 G, 1X1X22" STEEL HR TUBING	7	METAL SUPERMARKETS
CHASSIS	10-02	14 G, 1X1X15" STEEL HR TUBING	4	METAL SUPERMARKETS
CHASSIS	10-03	14 G, 1X1X20" STEEL HR TUBING	6	METAL SUPERMARKETS
CHASSIS	11-00	16 G, 0.75X0.75X6" STEEL HR TUBING	6	METAL SUPERMARKETS
CHASSIS	12-00	0.5X22.5" STEEL HR ROUND BAR A36	2	METAL SUPERMARKETS
CHASSIS	12-01	0.5X17" STEEL HR ROUND BAR A36	4	METAL SUPERMARKETS
CHASSIS	12-02	1/8 INCH ALUMINIUM SHEET 24X36	2	METAL SUPERMARKETS
CHASSIS	12-03	5/32 X 1/4 INCH POP-RIVETS	50	HOME DEPOT
MOTOR/WHEEL	13-00	42A5-FX DC GEAR MOTOR MODEL 5073	2	BODINE ELECTRIC COMPANY
MOTOR/WHEEL	13-01	E5 OPTICAL KIT ENCODER	2	US DIGITAL
MOTOR/WHEEL	13-02	NPC-PH804 HUB, WHEEL	2	ROBOT MARKETPLACE
MOTOR/WHEEL	13-03	KEYLESS BUSHING	2	CLIMAX METAL PARTS
MOTOR/WHEEL	13-04	10 IN FLAT-PROOF WHEEL	2	ROBOT MARKETPLACE
MOTOR/WHEEL	13-05	6X6X.375 X 6 HR ANGLE IRON	2	METAL SUPERMARKETS
MOTOR/WHEEL	13-06	MOTOR BOLTS	8	ACE HARDWARE

ASSEMBLY	PART NUMBER	DESCRIPTION	QUANTITY	VENDOR
MOTOR/WHEEL	13-07	1/2 INCH 3 INCH LONG BOLTS	8	ACE HARDWARE
MOTOR/WHEEL	13-08	1/2 INCH NUTS ULTRA FINE	8	ACE HARDWARE
CASTER WHEEL	14-00	SUSPENSION CASTERS	2	R.T. LAIRD
CASTER WHEEL	14-01	5/16 INCH BOLT 2 INCH LONG FINE THREAD	8	ACE HARDWARE
CASTER WHEEL	14-02	5/16 INCH, LOCTITE NUTS	8	ACE HARDWARE
ELECTRICAL	15-00	SABERTOOTH 25A 6V-24 MOTOR DRIV	2	ROBOTSHOP
ELECTRICAL	15-01	10-PIN LATCHING CONNECTOR	2	US DIGITAL
ELECTRICAL	15-02	FUTABA R/C TRANSMITTER	1	AMAZON.COM
ELECTRICAL	15-03	LI-ION 7.4V 6.6AH BATTERY	1	AA PORTABLE POWER CORP
ELECTRICAL	15-04	SMART CHARGER (1.2A) FOR 7.4V	1	AA PORTABLE POWER CORP
ELECTRICAL	15-05	12.8V 40AH LIFEPO4 BATTERY	2	AA PORTABLE POWER CORP
ELECTRICAL	15-06	SMART CHARGER (15A)	2	AA PORTABLE POWER CORP
ELECTRICAL	15-07	LED BALANCE MODULE	4	AA PORTABLE POWER CORP
AESTHETICS	16-00	1X1 14-20 GAUGE CAPS	10	FASTENAL
AESTHETICS	16-01	0.75X0.75 14-20 GAUGE CAPS	10	FASTENAL

Appendix G – Chassis Drawing

Figure 11 is a drawing of the chassis frame complete with dimensions. Figure 12 is a dawing of the fence that was welded around the top of the chassis. Please note that all dimensions are in inches.

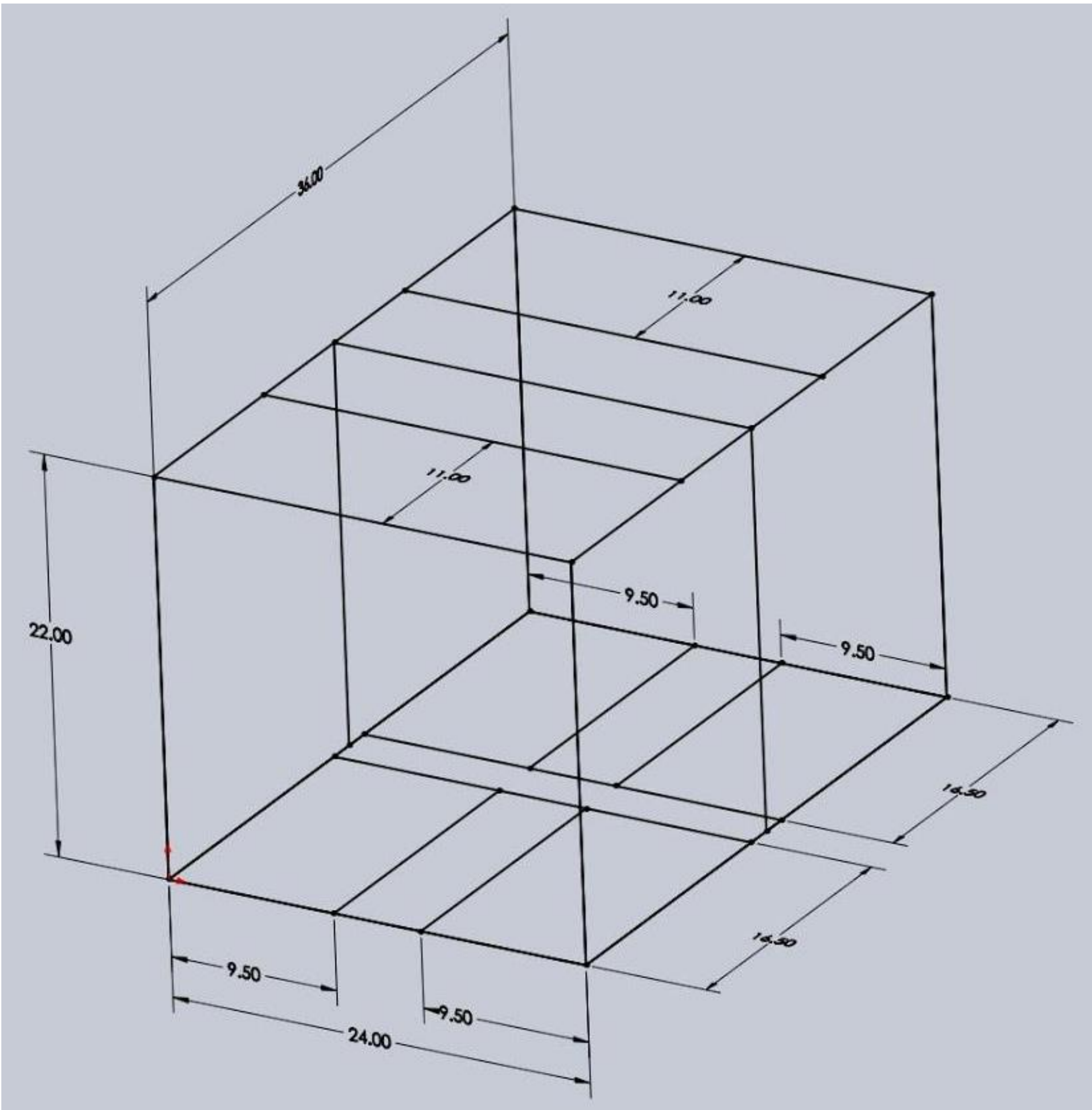

Figure 11 - Chassis Frame Drawing

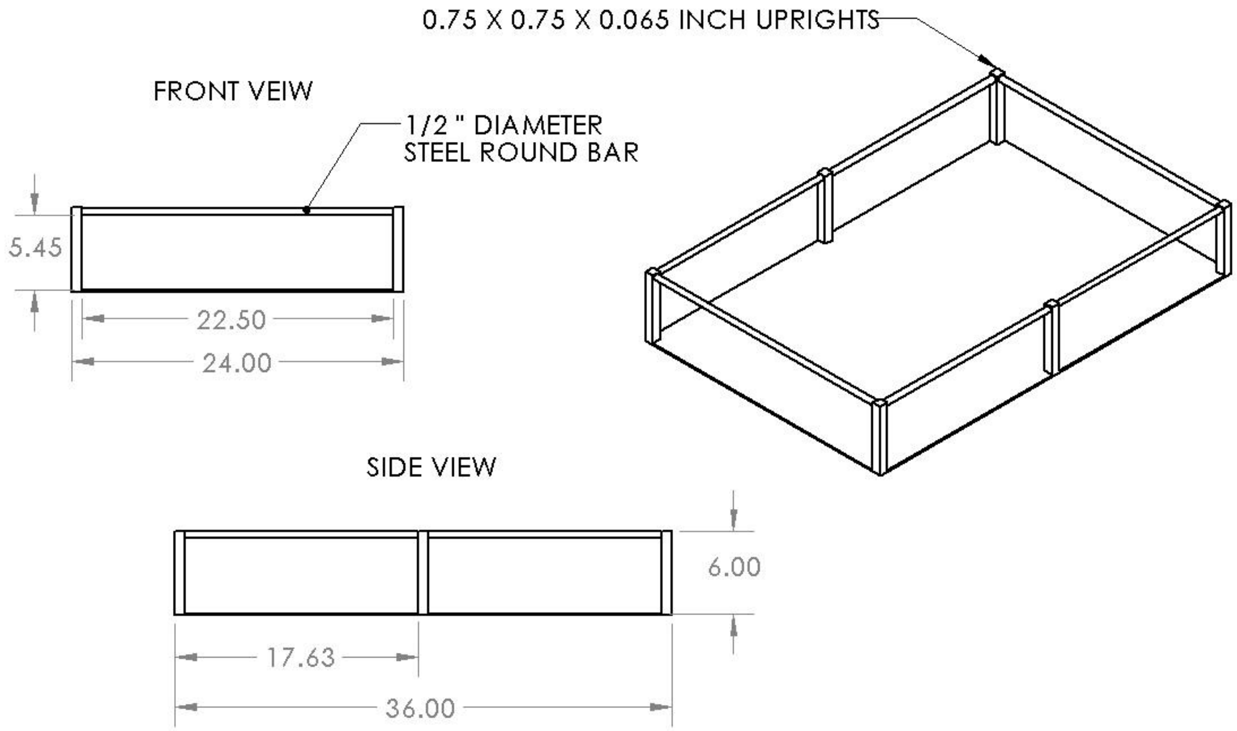

Figure 12 - Chassis Fence Drawing

Appendix H – Finite Element Analysis

Figure 13 are the results from the Finite Element Analysis showing the magnatude of the deflection.

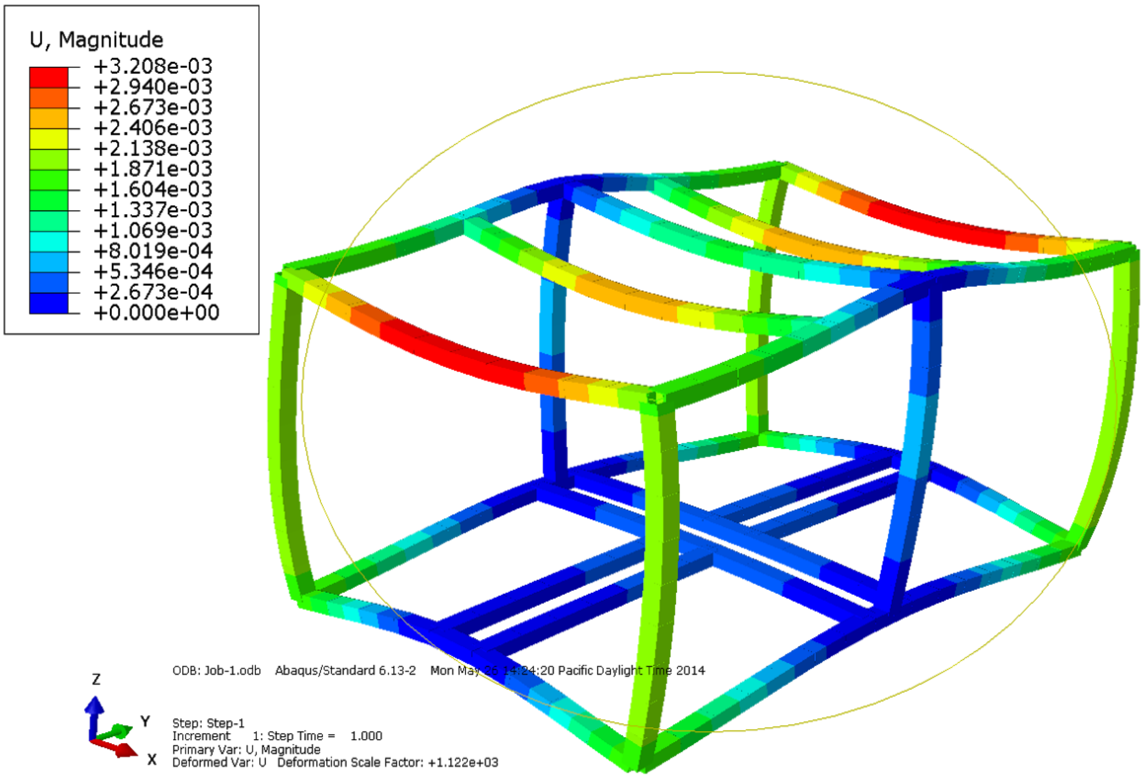

Figure 13 - Finite Element Analysis Showing the Magnatude of Deflection

Appendix I – Motor Torque Requirements

The following is an analysis of the torque output required by the motors selected.

Summary: In order to choose a motor, we calculated the maximum torque and mean torque required. All calculations utilized the procedure from the Department of Mechanical and Aerospace Engineering at the University of Florida.

Given: A robot weighing 140 pounds that needs to be accelerated over 1 second to a velocity of 100 feet per min.

Find: A motor that will fulfill the requirements:

- Weight of the robot: no load - 60 lbf, 100% load - 140 lbf.
- Maximum Speed: 100 fpm or approximately 80 rpm with 6 in diameter wheel.
- Time to accelerate: 1 second.
- Provided voltage: 12V or 24V, battery pack.

Assumptions:

The floor is made of concrete, the wheels are rubber, and the robot is traveling up an incline of 3 degrees (worst case scenario).

Solution:

Figure 14 is a schematic showing the free-body diagram of the forces acting on the robot in motion.

First, the Total Tractive Effort (TTE) was found, which is given in Equation 1.

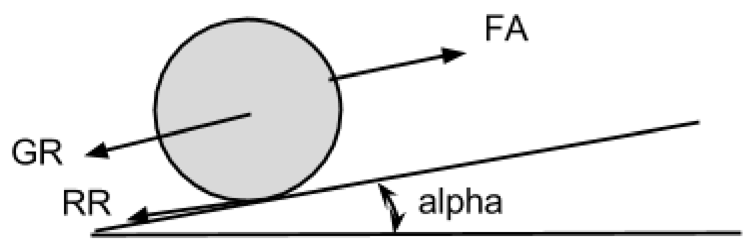

Figure 14 - Schematic of the Different Forces That Will Act on the Robot in Motion

$$\mathrm{TTE} = \mathrm{GR} + \mathrm{FA} + \mathrm{RR} \qquad \text{Eq. 1}$$

where GR is the resistance due to Gravity, FA is the force due to acceleration and RR is the Rolling

Resistance which is defined as

$$RR = GVW * C_{rr} \quad \text{Eq. 2}$$

where GVW is the weight of the robot and $C_{rr}$is the rolling resistance which is defined as 0.02 for rubber on concrete.[4]

The Resistance due to Gravity is defined as

$$GR = GVWsin(\alpha) \quad \text{Eq. 3}$$

where α is the angle of inclination between the robot's direction and the horizontal plane. For the purposes of these calculations, $\alpha$was assumed to be 3^{o}. The floors in Axiom Electronics are flat so this is for a worst case scenario.

The Force due to acceleration is defined as

$$FA = GVW * V_{max} /(gt) \quad \text{Eq. 4}$$

where $V_{max}$is the maximum velocity of the robot, gis the acceleration of gravity, and t is the time taken to accelerate. The Total Torque was then found by

$$T_w = TTE * R_w * RF \quad \text{Eq. 5}$$

where $R_w$is the radius of the wheel and R_f is the resistance factor.

Since there are two drive wheels, the TTE value was calculated using assumption values will be double. With the assumption of V_{max} = 100 ftm, t_a = 1s and incline angle of 3 degree, the torques required during a working cycles is presented in the Table 8.

Different value of V_{max}, alpha and t_a are also evaluated and a torque map has been created as in Figure 15 The map then is compared with motor performance plot to select a suitable motor and gearhead for the robot.

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[4] Gillespie ISBN 1-56091-199-9 p117

Table 8 - Torque Required at Different Loads and Different Phases of the Working Cycle.

	Load (lb)	Phase 1 - Acceleration	Phase 2 - Constant Speed	Phase 3 - Deceleration	Phase 4 - Stand still	RMS Torque [mN-m]	Max Torque [mN-m]
Duration (s)		1	90	1	60		
Speed (rpm)		38.20	38.20	38.20	0.00		
No Load	60	4,837.63	2,819.88	-802.12	3.14	2,206.00	4,837.63
20% Load	76	6,127.67	3,571.84	-1,016.02	3.98	2,794.27	6,127.67
40% Load	92	7,417.70	4,323.81	-1,229.92	4.81	3,382.54	7,417.70
60% Load	108	8,707.74	5,075.78	-1,443.82	5.65	3,970.80	8,707.74
80% Load	124	9,997.77	5,827.74	-1,657.71	6.49	4,559.07	9,997.77
100% Load	140	11,287.81	6,579.71	-1,871.61	7.33	5,147.34	11,287.81

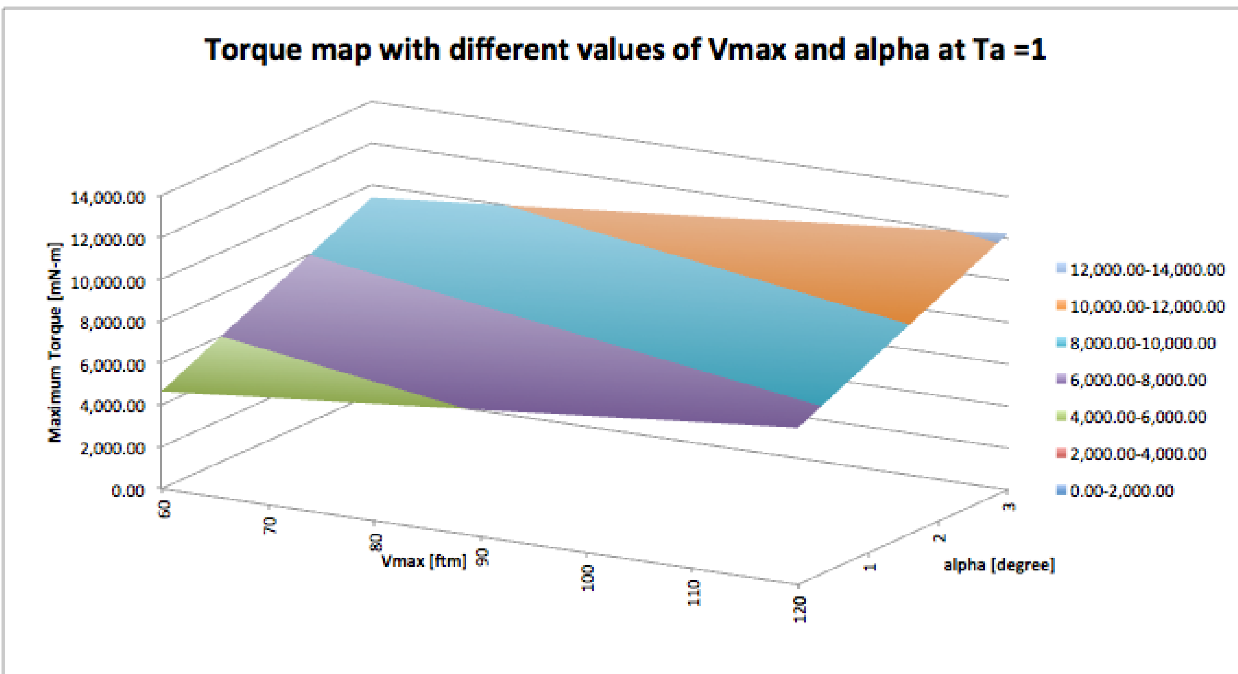
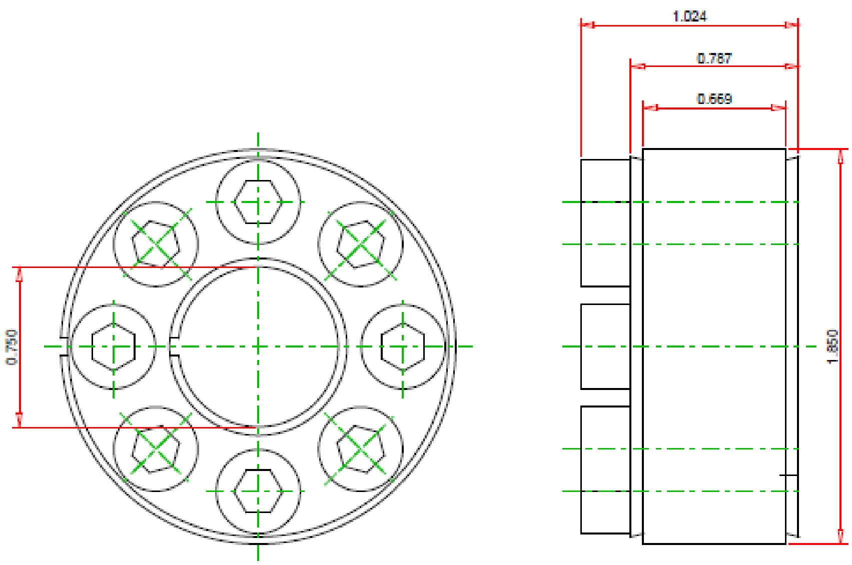


Figure 15 - Maximum Torque at Acceleration Time of One Second and Different Values of V_{max} and α.

Appendix J – Keyless Bushing Drawing

Figure 16 is the drawings for the keyless bushing as provided by Climax Metal Parts.



MAX TORQUE Mt :	223 ft-lbs
MAX AXIAL LOAD Fax :	7135 lbs.F
SHAFT PRESSURE Ps :	37704 psi
HUB PRESSURE Ph :	15282 psi
LOCKING SCREWS :	SOCKET HEAD CAP SCREW, GRADE 12.9, (8) M6 x 18
LOCKING SCREWS TIGHTENING TORQUE Ma :	10 ft-lbs

Figure 16 - Keyless Bushing Drawing

Appendix K – Motor Bracket Drawing

Figure 17 is a drawing of the motor brackets that were used to attach the motors to the chassis

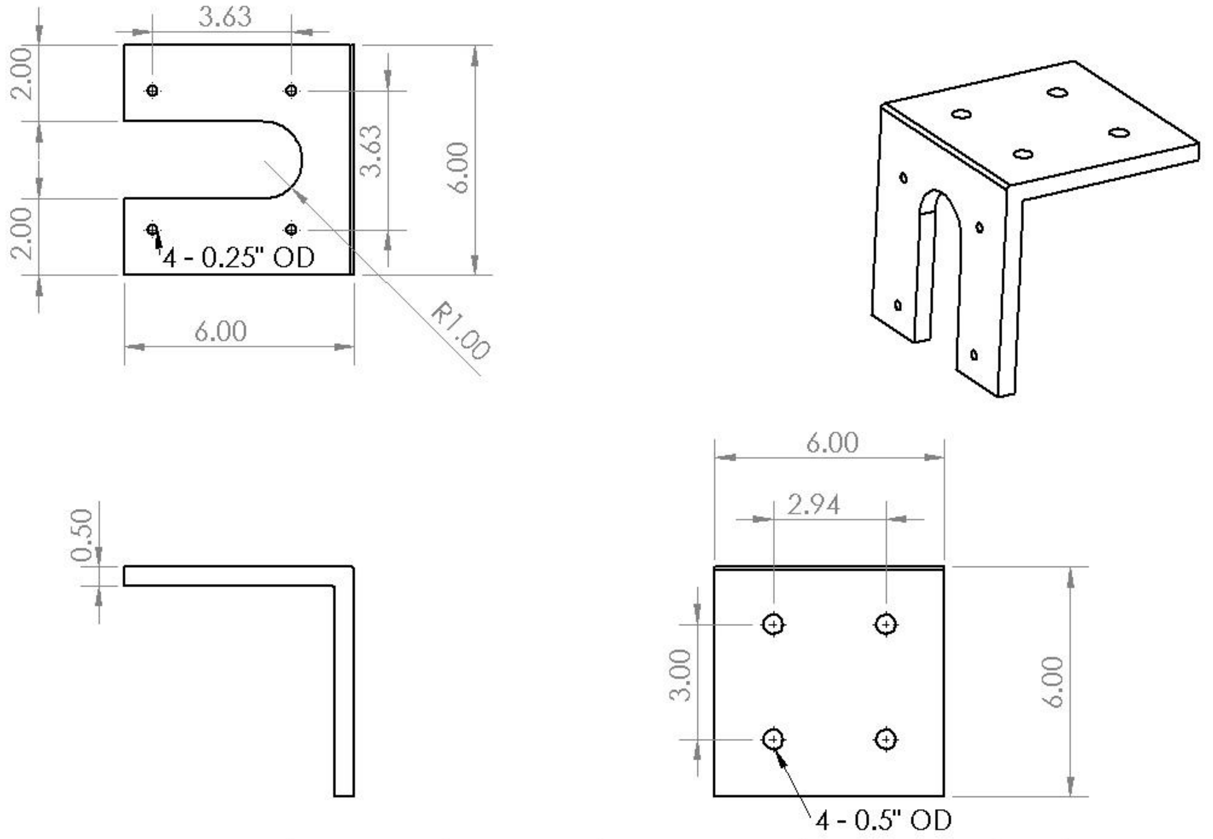


Figure 17 - Motor Bracket Drawing

Appendix L - Wheel Drawings

The following are the drawings for the drive wheels and the caster wheels. Figure 18 is a drawing of the motor wheels, and Figure 19 is a drawing of the suspension caster wheels

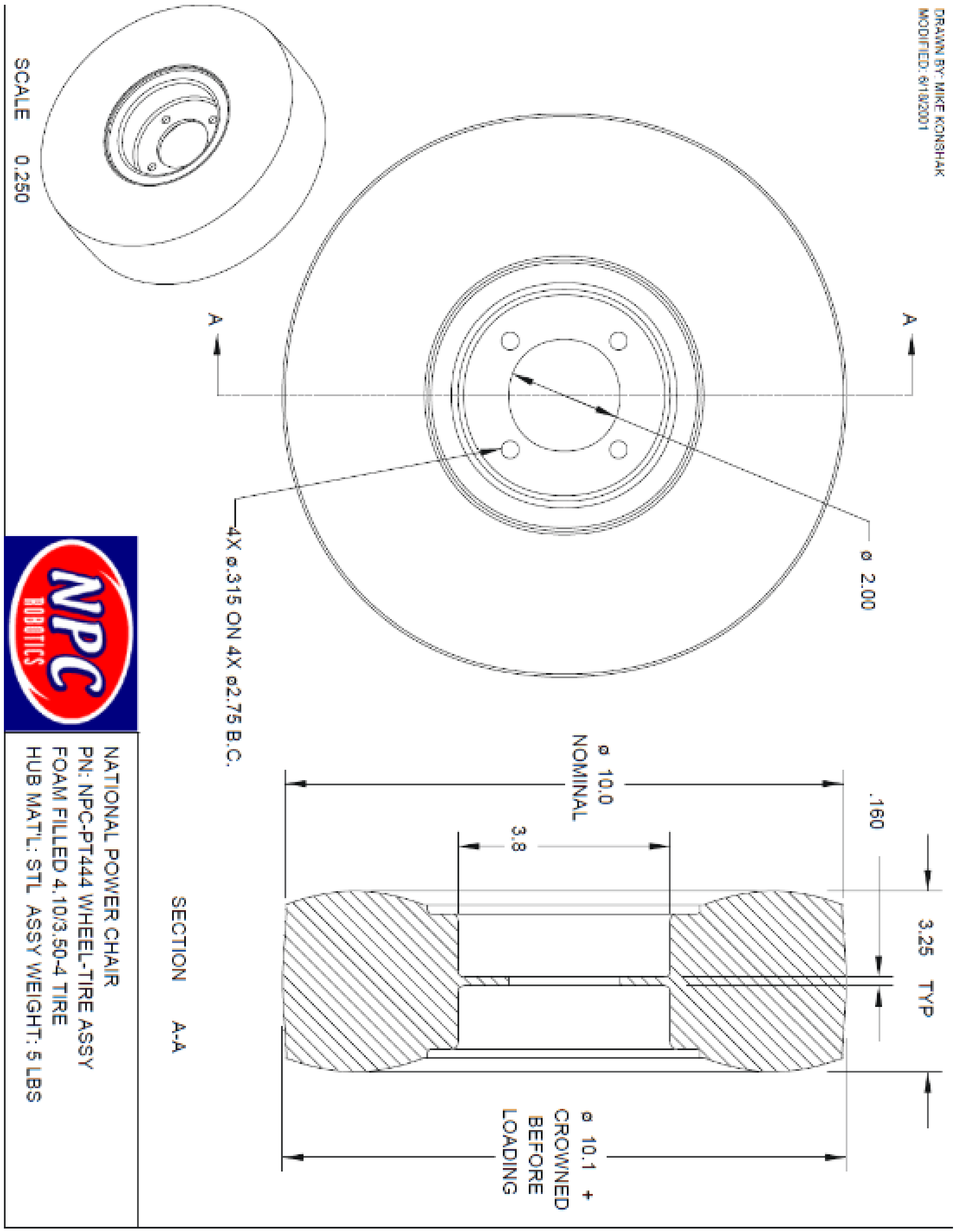


Figure 18 - Motor Wheel Drawing

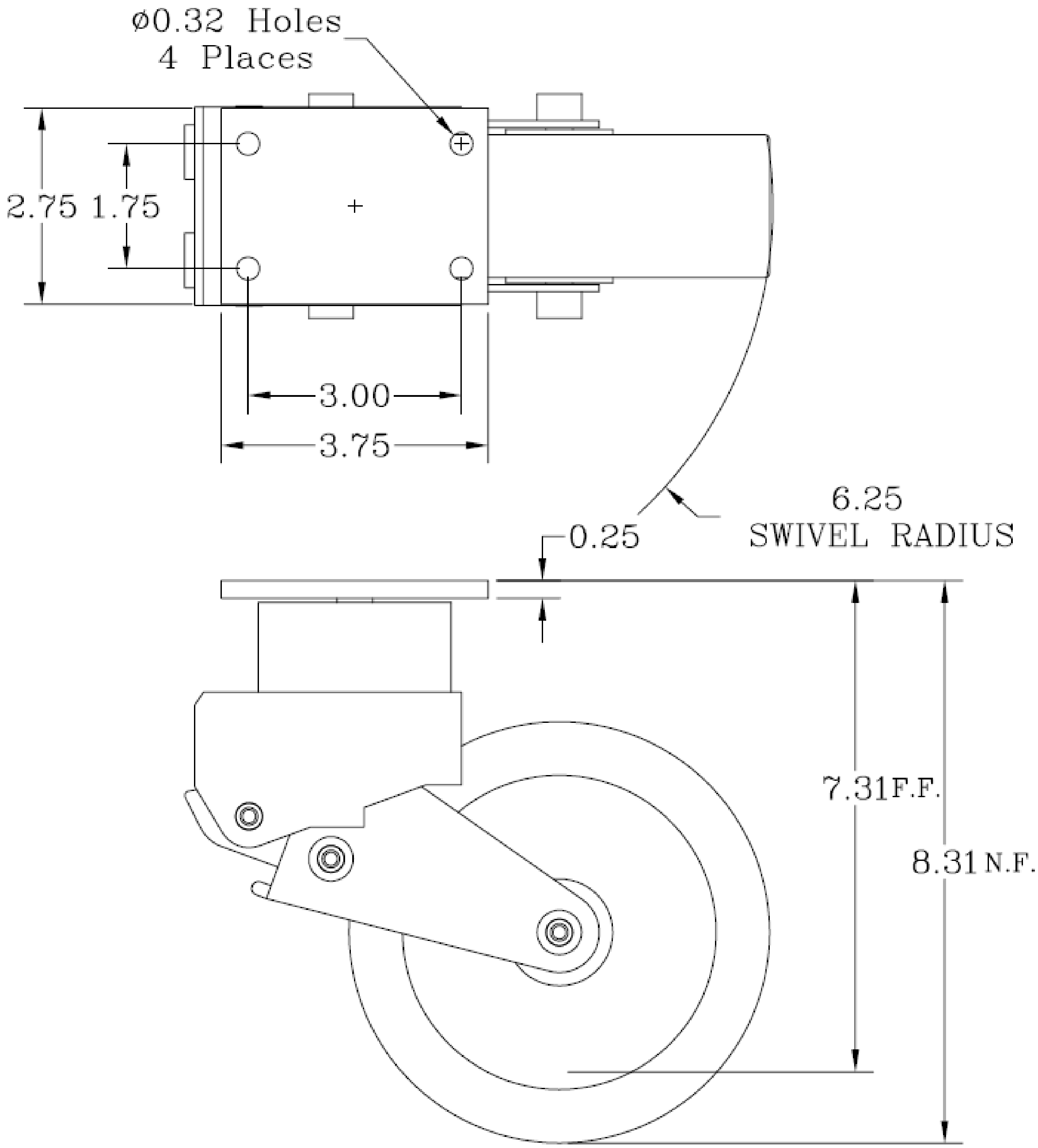


Figure 19 - Suspension Caster Wheel Selection.

Appendix M – Modified Wheel Hub Drawing

Figure 20 is a drawing of the modified wheel hub that was used with the keyless bushing and the wheels.

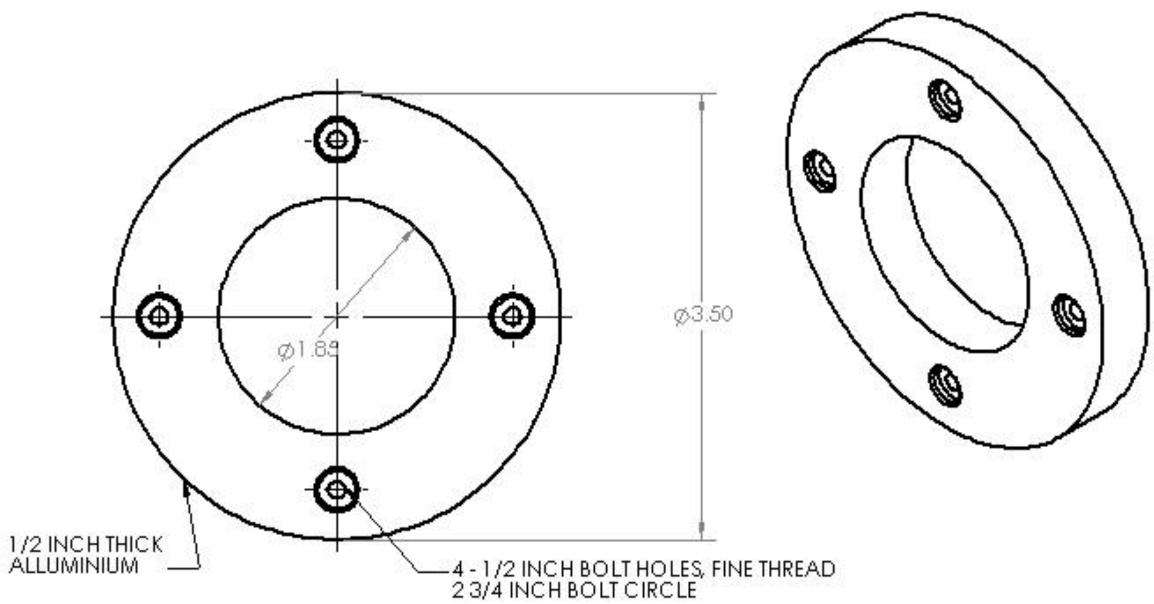


Figure 20 - Modified Wheel Hub Drawing

Appendix N – Vibration Analysis

First, start off with a schematic of the robot with springs and dampers as can be seen in Figure 21.

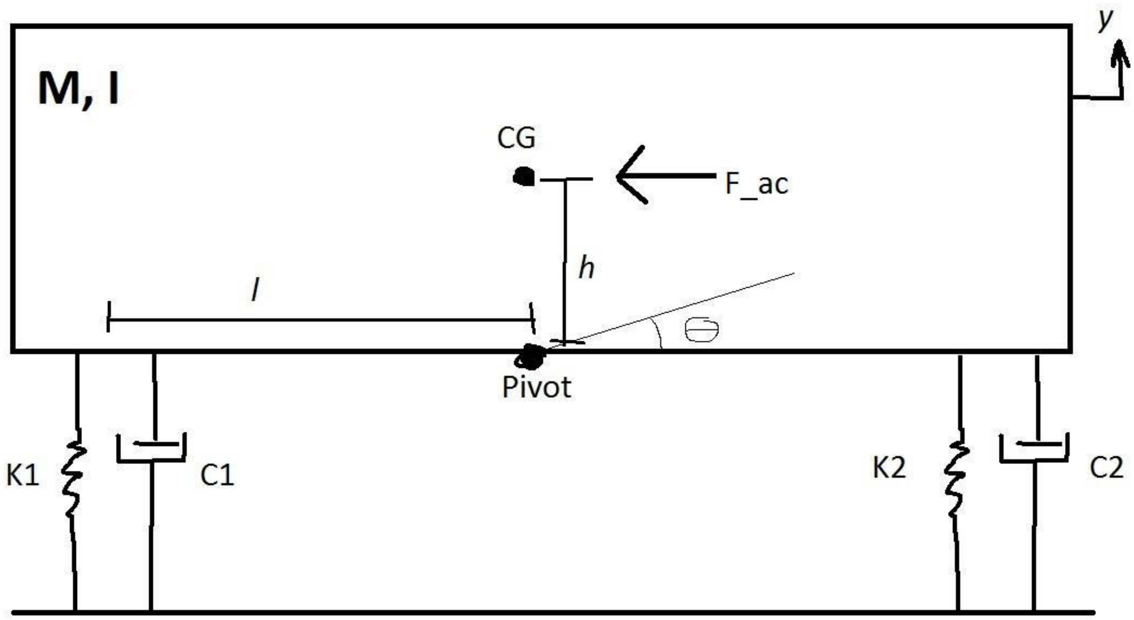


Figure 21 - Schematic of the robot along with the datum planes and direction of analysis

This shows the datum points, the direction that the displacement will be modeled in. Now, split up the analysis into two different segments then super impose them on top of each other. First, analyze y in the positive y direction as can be seen in Figure 22 where F_1 through F_4 are defined as.

$$F_1 = k_1 y$$

$$F_2 = c_1 y'$$

$$F_3 = k_2 y$$

$$F_4 = c_2 y'$$

and $F_{ac} = ma$ where a is the acceleration of the robot.

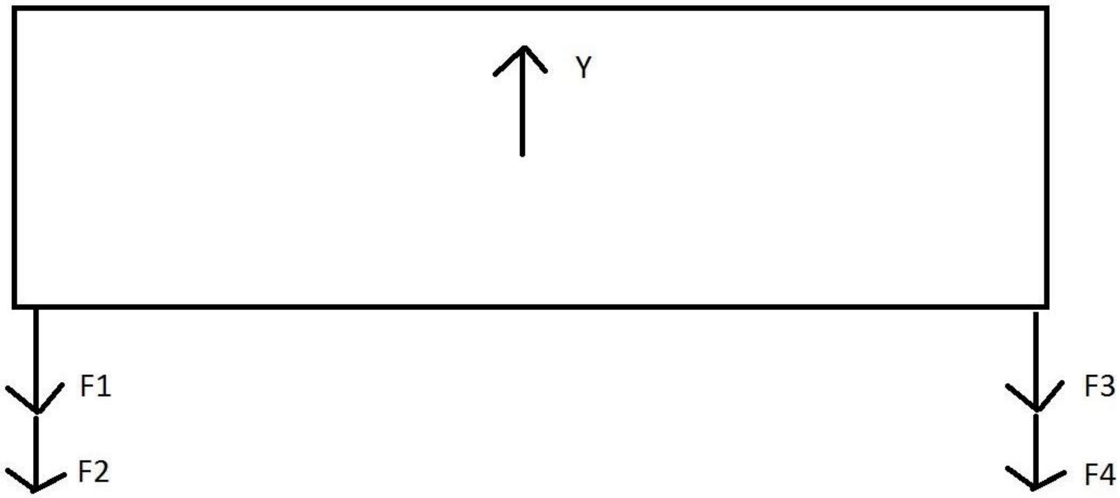


Figure 22 - Free Body Diagram for Displacement in the Y-Axis.

Next, draw the free body diagram for displacement in the positive θdirection as can be seen in Figure 23

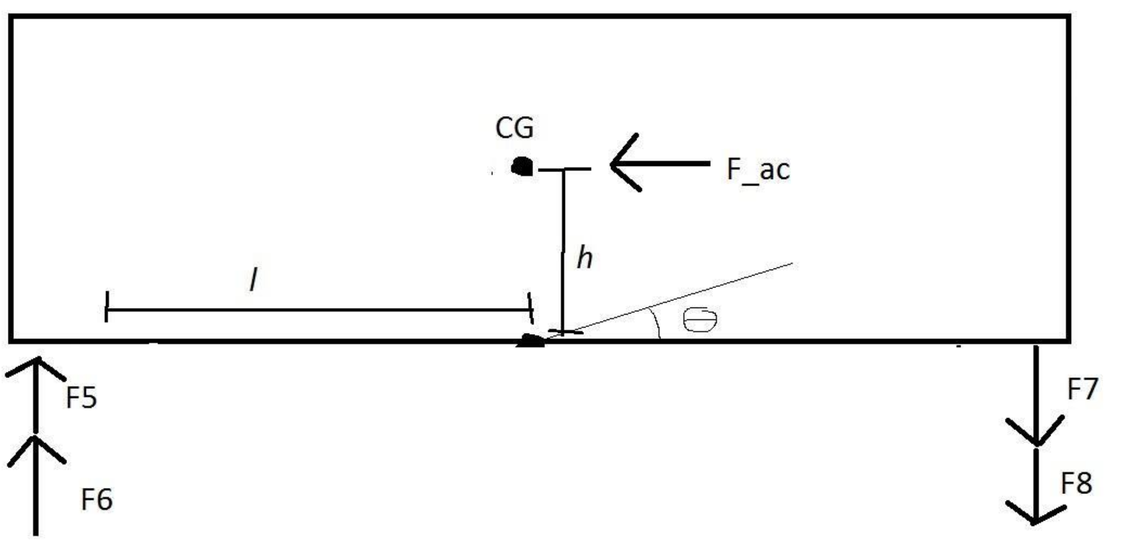


Figure 23 - Free Body Diagram for the Displacement in the θ Direction

where

$$F_5 = k_1 y_\theta$$

$$F_6 = c_1 y_\theta'$$

$$F_7 = k_2 y_\theta$$

$$F_8 = c_2 y_\theta'$$

Define $y_\theta = l * \sin(\theta)$, thus $y_\theta' = l\theta' * \cos(\theta)$. Next, assume small angles, such that $\sin(\theta) = \theta$ and $\cos(\theta) = 1$. Therefore $y_\theta = l\theta$ and $y_\theta' = l\theta'$. Thus

$$F_5 = k_1 l\theta$$

$$F_6 = c_1 l\theta'$$

$$F_7 = k_2 l\theta$$

$$F_8 = c_2 l\theta'$$

Now, sum the two Free body diagrams together to create Figure 24

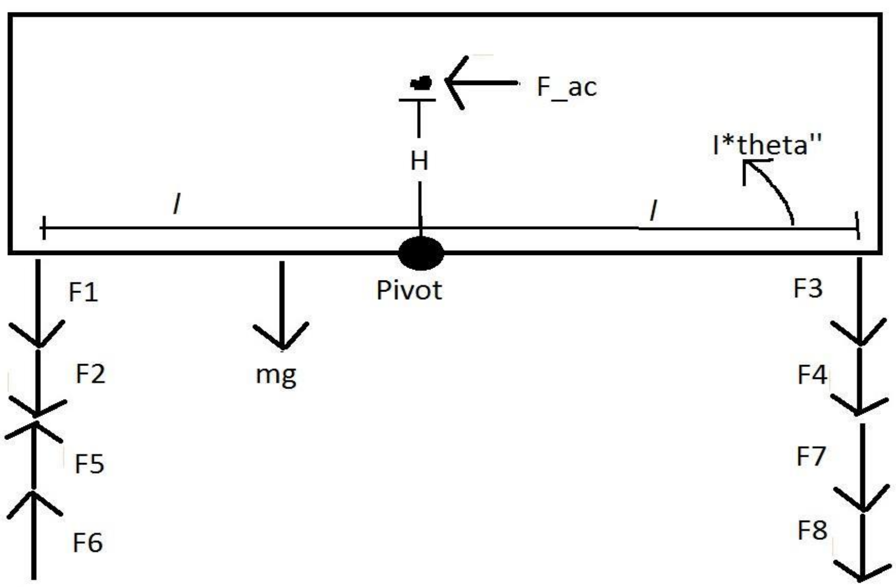


Figure 24 - Free Body Diagram Showing the Sum of the Forces

First, sum the forces in the Y - direction

$$\sum F_y = 0 \Rightarrow mg = F_5 + F_6 - F_1 - F_2 - F_3 - F_4 - F_7 - F_8$$

$$\Rightarrow my'' + F_1 + F_2 + F_3 + F_4 - F_5 - F_6 + F_7 + F_8 = 0$$

$$\Rightarrow my'' + k_1y + c_1y' + k_2y + c_2y' - k_1l\theta - c_1l\theta' + k_2l\theta + c_2l\theta' = 0$$

$$\Rightarrow my'' + (c_1 + c_2)y' + (k_1 + k_2)y + (c_2 - c_1)l\theta' + (k_2 - k_1)l\theta = 0$$

Next, sum forces about the pivot point with counter-clockwise moments in the positive direction.

$$I\theta'' = F_1l + F_2l - F_3l - F_4l - F_5l - F_6l - F_8l - F_8l + F_{ac}H$$

$$\Rightarrow I\theta'' - F_1l - F_2l + F_3l + F_4l + F_5l + F_6l + F_7l + F_8l = F_{ac}H$$

$$\Rightarrow I\theta'' - k_1ly - c_2ly' + k_2ly + c_2ly' + k_1l^2\theta + c_1l^2\theta' + k_2l^2\theta + c_2l^2\theta' = F_{ac}H$$

$$\Rightarrow I\theta'' + l^2(c_1 + c_2)\theta' + l^2(k_1 + k_2)\theta + l(c_2 - c_1)y' + l(k_2 - k_1)y = F_{ac}H$$

However, for this system, the equations should be decoupled, Thus, the two - 1 Degree of Freedom System equations are

$\Rightarrow my'' + (c_1 + c_2)y' + (k_1 + k_2)y = 0$ Eq. 1

$\Rightarrow I\theta'' + l^2(c_1 + c_2)\theta' + l^2(k_1 + k_2)\theta = F_{ac}H$ Eq. 2

Next, write the transfer function for both displacements in the y-axis and in the θdirection.

To define the following coefficients

$$a = m$$

$$b = c_1 + c_2$$

$$c = k_1 + k_2$$

$$d = I$$

$$e = l^2(c_1 + c_2)$$

$$f = l^2(k_1 + k_2)$$

Thus, equations 1 and 2 become

$ay'' + by' + cy = 0$ Eq. 1a

$d\theta'' + e\theta' + f\theta = F_{ac}\,H$ Eq. 2a

Then use the S-operator

$as^2y + bsy + cy = 0$ Eq. 1b

$ds^2\theta + es\theta + f\theta = F_{ac}H$ Eq. 2b

Solve Eq. 1b as a transfer function

$$y = \frac{0}{as^2 + bs + c}$$

And Eq. 2b as a transfer function

$$\frac{\theta}{F_{ac}H} = \frac{1}{ds^2 + es + f}$$

Sub back in the coefficients

$$\frac{\theta}{F_{ac}H} = \frac{1}{Is^2 + l^2(c_1 + c_2) + l^2(k_1 + k_2)}$$