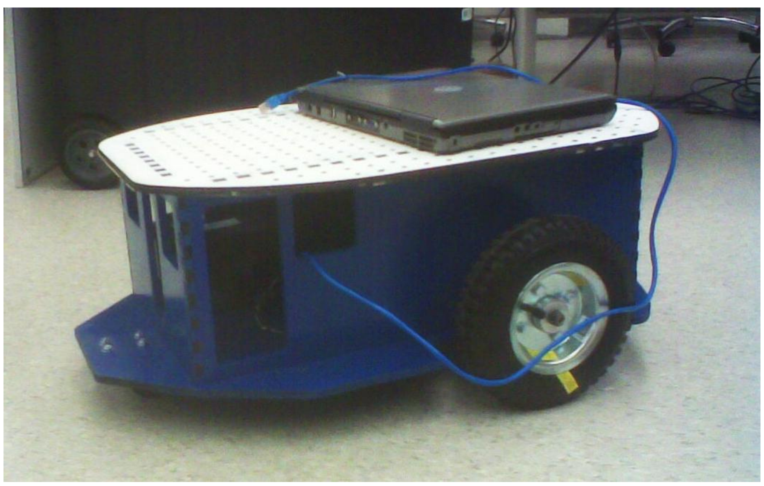
ME 450
Design Review 4
Team 1: Rapidly Manufacturable Robot
Date: April 21, 2009

Section Instructor:
Prof. Hong Im.

Sponsor:
Prof. Edwin Olson, EECS

Members:
Yitao (Tom) Zhuang,
Richard Lacroix
Steven Kuplic
Anand Nageswaran Bharath



Abstract
Using robots in academic settings provides great research and learning opportunities for both students and faculty. However, available robots generally fall into one of two categories; small robots that have low versatility reducing their usefulness, or large expensive robots that are not financially practical. A previous design tried to bridge this cost-benefit gap by using available manufacturing methods and relatively inexpensive materials which greatly reduced the cost. However, mechanical problems, specifically with the robot's drive train, needed to be improved as well as improvements to the dynamics of the robot. This project addressed these concerns and designed and built a robot that is an improvement over the current model. This new robot design is still easily manufacturable and maintains its low cost with improved versatility. This new robotic design will allow for improved student research and classroom learning at the University of Michigan and elsewhere in the field of robotics.

ME 450 WINTER 2009 PROJECT 1: EXECUTIVE SUMMARY

Team Members: Anand Nageswaran Bharath, Steven Kuplic, Richard Lacroix, Yitao Zhuang

Design problem: Prof. Edwin Olson of the University of Michigan Electrical Engineering & Computer Science (EECS) Department is working on developing low-cost, rapidly manufacturable multi-purpose robotic platforms that can be used for robotics research and education, due to exorbitant prices of commercially available robot platforms available today. However, critical engineering issues such as mechanical component failures and poor vehicle dynamics negate the benefit derived from the significant reduction in cost, making the robot unsuitable for research. Hence, our task is to redesign the robot such that the new design addresses these engineering issues while maintaining the low-cost and rapid manufacturability of the robot, thereby producing a high quality platform that is suitable for research.

Specifications: The major objective was to improve the robustness of the drive-train connections, as the connections failed frequently in the original robot. The connection mechanisms between the drive-train components had to withstand high torque values during rapid acceleration & deceleration of the wheels during starting and stopping. Other major issues were the low speed of 0.5 m/s which were too low for human-robot interaction research experiments due to the inability of the robot to keep up with humans at such speeds and the high frequency of vertical vibrations that affected the encoder accuracy and hence the experimental results. The speed had to be increased to at least 1 m/s (human walking speed) and a damping mechanism had to be introduced to significantly reduce vertical vibration amplitudes. While addressing all these challenges, the robot should be easily and rapidly manufacturable for researchers with a limited mechanics background, and cost $500 or less to produce.

Selected Design Concept Analysis: 3/8-inch 7-ply Baltic birch plywood was chosen for the chassis due to its ease of manipulation by the laser cutter, high tensile strength and low cost. Aluminum was selected for the bearing housings, motor mounts, and axles due to its ease of machinability and high fracture toughness. The motors chosen for the drive-train were the IG-42 252 RPM planetary gear motors due to their high torque and speed capabilities. Pneumatic wheels and a soft rubber caster were chosen for the wheels due to their compliance that increased damping in the vertical direction, reducing the amplitude of the vibrations. Keyless bushings and shaft clamps were chosen for the motor-wheel connections as they could withstand high backlash torques and hence significantly reduce the probability of drive-train component failure.

Fabrication Plan/Cost Analysis: CAD files of the chassis walls were fed into a laser cutter which rapidly & precisely cut walls from the plywood. The drive-train components were fabricated through traditional machining processes like turning Aluminum rods for the axle and milling of Aluminum blocks & brackets for bearing housings and motor mounts respectively. The total cost of the raw materials such as Aluminum and plywood, and the components such as the motor, keyless bushings and shaft clamps was maintained within the $500 limit.

Test Results: The dynamics and kinematics test results indicated that the IG-42 motors achieved the maximum speed of 1 m/s required for human-robot interaction. The shaft clamps and keyless bushings provided robust and secure mechanical connections that withstood high torques and never failed during sudden deceleration and acceleration. The pneumatic wheels and the soft rubber caster provided sufficient damping to significantly reduce the vertical vibration amplitudes. As a result, our design was successful overall.

Conclusion: The rapidly manufacturable robot had critical engineering problems that were addressed by our design successfully, while the overall cost for the robot components was within the limit of $500. Hence our project was successful since all the design and economic requirements were met.

TABLE OF CONTENTS

1. INTRODUCTION

The goal of our project was to design and build a robotic platform for research and education that is easy to manufacture by students, and is of relatively low cost. The final robotic design discussed in this report was created with an ideal design in mind that would have a maximum speed which will enable it to keep up with a walking person while carrying a payload including; a laptop, sensors, and other additional objects (e.g. robotic arm). The robot would also be able to work both indoors on smooth surfaces and outdoors on semi-rough terrain, with an emphasis put on indoor performance. We believe that our final design robot meets these criteria. As a secondary concern, we have researched the possibility of utilizing a smart bumper, on the robot, that can detect impacts and minimize damage.

Our sponsor for this project is Professor Edwin Olson of the EECS department at the University of Michigan. He researches and teaches robotics at the university and is the Director of the APRIL laboratory. The motivation for our project comes from his desire to have multiple robots for his research as well as for student projects. The potential also exists that these robots might also be build and used at other institutions, since all information concerning this project will be freely available online.

A previous robot design, created by Professor Olson, is the starting point of our project. This previous robot had the same purpose as far as research and teaching, but is of need of improvements in order to better facilitate these academic desires. Our robot is designed to make significant improvements over the previous design and will therefore enhance the research capabilities of robotics at the university.

This report includes CorelDraw files for the body to be laser cut from, CAD files for assembly, and detailed manufacturing instructions which will all be made free to anyone online. This report also includes data collected from tests done on two prototype robots that have been built, validating the success of our final design. Finally, this report will discuss the evolution of our design from the beginning to the current prototype and will discuss recommendations for future work on our project.

2. INFORMATION RESEARCH

Before we generated design concepts for the robot, we had to determine which components/parts of the previous robot had to be changed. We also had to ensure that our engineering specifications clearly addressed the customer requirements, which allowed us to tailor the design concepts to meet customers' needs. The target consumers for this robotic platform are professors and graduate students in areas of robotic study who require a versatile platform for research and teaching purposes. Hence we conducted extensive interviews with professors and thoroughly examined research articles on robotics education to identify the primary customer requirements. This section covers the main findings of our information research process.

2.1 Literature Review

We consulted various literature sources such as patents, research papers from journals and product specification catalogues from robot parts manufacturers to identify potential solutions to the drawbacks in the current model.

2.1.1 Material for the Chassis/Framework

The chassis of the current robot is made from plywood; we researched some of its mechanical properties to determine if it is the best material to use and compared it with other possible materials. Table 1 shows the mechanical properties and material costs of three materials: Aluminum, ABS and Baltic Birch Plywood BB Grade. We obtained this data from references [1] - [4].

Table 1: Comparison of materials Aluminum Alloy 6061-T4, Acrylonitrile Butadiene Styrene, and Baltic Birch Plywood

Material	Aluminum 6061-T4, T651	Acrylonitrile Butadiene Styrene (ABS)	Baltic Birch Plywood (Currently used)
Ultimate Tensile Strength (MPa)	310	70	117
Yield Strength (MPa)	275	75 (average of range 61 - 90)	80
Cost	$511.62 /36x48 in plate	$300 / LEGO Mind-storms (Large set)	$47.50 /60x60 in. board
Laser Cutting	Not Possible	Possible	Possible

Aluminum would be a suitable material for the chassis as it has a high strength to weight ratio, but buying large quantities of this metal can be very expensive, as shown in Table 1 above. Moreover, after checking with the Machine Shop, we were informed that the laser cutter we have access to does not have sufficient power to cut through aluminum thick enough for our design requirements.

Another problem with aluminum is that connecting parts need to be welded or riveted together, making the manufacturing process more complex. Since the goal of this project is to build a robot that can be easily and rapidly manufactured, we want to avoid using either method for the robot chassis.

Many researchers and instructors have used the LEGO (Acrylonitrile Butadiene Styrene blocks) Mind-storms Robot builder kits for research and to teach robotics [5, 6]. While individual LEGO bricks (made of ABS) are inexpensive and can be easily joined to build the particular type of robot required, a large number of bricks are required to construct a sturdy base for the payload, which will substantially increase the cost. Furthermore, attaching the SICK laser pathfinder on a LEGO structure will be a challenge as drilling holes for fasteners would damage the bricks.

We determined that we will use Baltic birch plywood, the material that was used to fabricate the chassis for the previous robot, as the material for our chassis due to its low cost, relatively high strength and easy manipulation with the laser cutter for manufacturing. More information concerning this plywood will be covered in the material selection portion of the report.

2.1.2 Shaft coupling

Shaft coupling is one of the key areas of improvement that our final design addresses. The slip between wheel and shaft introduced errors between the encoder and the actual distance moved by the robot. The previous coupling devices, the cotter pins, are not useful due to the large slip that results from using them. We reviewed existing literature and patents to find out possible substitutions. There are thousands of patents for different shaft coupling design. Considering the size of shaft and the possible shear stress on the coupling, we decided to search the market for existing connections.

Table 2 below shows our analysis of three common coupling mechanisms: cotter pins, keyless bushings, and keyed bushing. We searched for common materials used for the cotter pins and key stock, used CES to find the yield strengths, and calculated the maximum torque they could maintain without yield. The keyless bushing we considered is from McMaster and would fit the previous robot’s motor shaft.

Table 2: Comparison of couplings between 8” wheel and motor with 120 Kg-cm

Shaft-Wheel Coupling	Cotter Pin (AISI 304 Steel)	Keyless Bushing (Trantorque 6202660)	Keyed Stock (6061 Aluminum)
Max Torque (N-m)	11.69	16	52.53
Machining Time	Minimal	None	Moderate
Cost ($)	0.2	25	2

2.1.3 Tires

The previous tire used on the robots was a solid rubber tire from MAXPOWER Precision Parts. The price of each tire is below five dollars; however the tires lack compliance. As a result, the ride of the robot is very bumpy on pavements and the laser sensor on the previous robot did not perform well. It has been decided to switch to pneumatic tires which are more compliant and offer better damping. The change from solid rubber to pneumatic tires can improve the outdoor performance, removing the need for a suspension system.

We examined several documents focusing on the damping and stiffness of pneumatic tires. A paper from NASA included determination of damping and stiffness from static and free-vibration tests [8]. It is possible for us to adapt the results and dimension analysis to predict the performance of the scaled tires on the robots. Another paper [9] about the dynamic response of pneumatic tires on bicycles was also considered in order to predict the behavior of pneumatic tires.

More information concerning the tires that we chose as well as results from tests on these tires can be found in the material selection and testing sections respectively.

2.1.4 Dampers

Damping is required to reduce the amplitude of vibrations on the wheels caused by the rough and bumpy surfaces to ensure a smooth ride. We considered using different types of dampers such as hydraulic dampers, pneumatic dampers and particle dampers. Ultimately, we concluded that dampers would be unnecessary due to the following reasons:

1. Hydraulic and pneumatic dampers are expensive. Although they do offer an improvement in the dynamics, their monetary cost far exceeds their usefulness. Pneumatic tires might not offer the same level of damping, but they cost much less.

2. Particle dampers are cheap, and they can be easily made with low cost materials and parts such as syringes and iron oxide powders. Unfortunately, these dampers are non-linear [10] and do not exhibit a predictable relationship for us to model the dynamics beforehand in our simulations. Therefore, we cannot assess their reliability easily.

2.1.5 Batteries

The battery that powers the motor and circuitry on the pervious robot is a 12V lead acid battery. We will do an environmental analysis on each type of battery to determine the ethical implications. Table 3 below shows our choices of batteries.

Table 3: Comparison of performance and cost of lead acid and Li-ion batteries

Battery type	Lead Acid	Li-ion
Lifetime (amp-hours)	10	8.1
Output Voltage (V)	12	15
Cost ($)	30	200
Weight (kg)	3.6	1

More information regarding our choice in battery can be found in the material selection section.

2.2 Dimensional Measurements and Basic Kinematic Analysis

Using a tape measure, the previous robot was measured to be 65.5 cm long, 41.3 cm wide, and 31.5 cm tall; the wheel diameter was 24.5 cm (10”). The previous model does not have sufficient space on the top to accommodate two pathfinders and a laptop. Therefore, modifications to the previous dimensions on the design concepts were needed to create the appropriate space for the required components.

Measuring the speed of the previous robot on both a semi-rough and smooth surface was calculated by recording the time the robot took to travel 5 meters on each surface. It was observed that the average speed was approximately 0.5 m/s on both surfaces; this is a quarter of the speed that is required from our design specifications of 2 m/s.

2.3 Customer/Expert Interviews

The potential customers for the robot include robotics professors. To ensure that we identified the requirements that our customers felt were crucial; we conducted interviews with three robotics professors: Prof. Brent Gillespie, Galip Ulsoy, and Dawn Tilbury. In addition to providing us with information on what they expect, each of them also provided useful advice on ways to improve the kinematics and the dynamics of the robot, since they have had significant experience in designing and optimizing robots.

Prof. Gillespie mentioned the use of keyless bushings instead of cotter pins to connect the wheels to the motor shaft. He mentioned about having used keyless bushings before and their reliability. He also suggested that we use pneumatic wheels instead of developing a suspension system, since suspension systems and hydraulic dampers are expensive, and it was not worthwhile to spend a large sum for an improvement in the dynamics which could be achieved by simply changing the wheels.

Prof. Ulsoy suggested that we study the dynamics and kinematics of the ROOMBA, a vacuum cleaner mobile robot developed by the iRobot Corporation. Upon a closer inspection of the ROOMBA data [11], we discovered that the dynamics and kinematics were similar to the ideal operating conditions of our robot. The ROOMBA is able to easily transition between smooth and rough surfaces without significant changes in performance however, due to limited time; we did not fully looked at the technical aspects of the data sheet.

Prof. Ulsoy also suggested the use of strain gauges as sensors for the smart bumpers. Strain gauges would be able to measure the magnitude of the impact from a collision, which will be converted into an electrical signal by a transducer giving us an idea of the type of obstacle that the robot encountered, since different obstacles would exert different magnitudes of forces. To reduce the forces on the wheels that cause vibrations, Prof. Ulsoy recommended that we examine the bearings currently used on the wheels, and determine if they should be changed. He suggested that we consider various options such as rollers and ball bearings.

After interviewing Prof. Tilbury, we learned that she would prefer a robot that would be somewhat smaller than the previous robot, so that a demonstration to students would be possible in a standard classroom space. However, since our robot has to withstand a heavy payload, we need to strike a balance between optimal size and payload capabilities to develop an ideal prototype.

Prof. Tilbury also encouraged us to explore the possibility of developing an interface between MATLAB and the robot so that it could be user-friendly to mechanical engineers who can implement commands from a specialized robotics toolbox readily available for MATLAB. This would eliminate the need for intensive coding that mechanical engineers are generally unfamiliar with.

3. CUSTOMER AND ENGINEERING SPECIFICATIONS

This section describes our customer requirements, their related engineering specifications, and how those specifications were developed. Using the information we obtained from the literature reviews and our customer/expert interviews, we created a Quality Functional Deployment (QFD) diagram to enable us to translate the customer needs into engineering requirements, and identify the most important customer needs and the corresponding engineering requirements that relate to those needs. Our QFD is located in Appendix A on page 24.

First, we created columns for the two groups of customers: (1) professors and (2) students. Professors and students have some general differences in their priorities. Students, who would be conducting the hands-on work more frequently than the professors would naturally consider the manipulative factors such as organization of wires as crucial. Professors, on the other hand would be leading their research groups in the investigation and the purchase of equipment, and hence would be more concerned about the performance parameters of the device such as the versatile platform requirement.

We then determined the relationships between the customer requirements and the engineering specifications, assigning a weight to each relationship signifying the relationship strength. We used the following weight distribution:

9 – Strong Relationship
3 – Medium Relationship
1 – Weak Relationship
(Blank) – No Relationship

Finally, we determined the relationships between the engineering specifications themselves. The grey triangle shows the strength of the engineering interdependencies.

Combining the scores for both the professors and the engineering students for each factor, we identified six customer requirements as those with the highest scores. We further divided these requirements into primary and secondary requirements, to emphasize the greater importance of certain customer requirements over others. The customer requirements are shown below in table 6:

Table 6: Summary of customer requirements, both primary and secondary

Rank	Primary	**Secondary**
1	Low cost of production	Smooth ride
2	Can be easily manufactured and modified	Detecting obstacles
3	Can withstand heavy loads	
4	Interact and respond with humans	

The various customer requirements and the engineering specifications we selected to address these requirements will be elaborated in detail in the following subsections.

1. **Low cost of Production – Keep the cost of production within a budget of $500**
   Many commercially available robots today that are used for research purposes are extremely expensive; each research oriented platform requires expenditures in the order of tens of thousands of dollars. In order to allow students and professors to better utilize funding from the university, we want to keep the production cost as low as possible, while producing a robot that is comparable to a commercially available robot. We aim for a cost of $500 per robot.

2. **Ability to withstand large loads – Payload capacity of at least 20 kg**
   The robot will have many components it will carry while it moves, such as a gripper arm, a laptop that will run the program that controls it, two SICK laser pathfinders, motors and any additional sensors. The estimated total mass of all these components will be at least 20 kg. Hence, the robot chassis should be designed such that the material and the geometry will enable the robot to be strong and durable in spite of the heavy payload of 20 kg.

3. **Interact with & Respond to Humans – Attain a speed of 2 m/s**
   Initially, we considered rapid manufacturability and low cost as the two most important primary customer requirements that would influence our design. However, Prof. Olson wanted us to incorporate features that would enable the robot to interact with humans as he planned to investigate the nature of human-robot interaction, in addition using it for robotics education. For the robot to successfully interact with a human, it must be able to move at the same speed as the walking speed of an average human, which is typically 1 to 2 $^{m}/_{s}$. Thus we have to design the robot such that it has a velocity of at least 1 $^{m}/_{s}$, with the potential to go as fast as 2 $^{m}/_{s}$.

4. **Easily and Quickly Manufactured – Manufacturing Time of approximately 2 working days**
   Electrical Engineering and Computer science students and research investigators should not have to deal with a complicated manufacturing process for the robot, as manufacturing is not their field of expertise. Hence, we need to develop a design that would enable students not familiar with Manufacturing to save considerable time in manufacturing and assembling the parts of the robot. From our previous experiences with operating laser cutters and building an assembly from laser-cut parts, we estimate the required manufacturing time not to exceed two day, with the understanding that additional time may be need for painting, especially drying time.

Secondary Requirements

1. **Smooth Ride – Decrease the vertical acceleration and vibrations of the chassis by 30 %**
   Due to rough terrain and the lack of proper suspensions to introduce damping, the previous robot and its components undergo vertical oscillations with large amplitudes. Such vibrations could result in damage to components due to the continual impact of these components with one another or the chassis. Furthermore, a lack of damping is bad for the encoders on rough surfaces, which is important for path sensing and obstacle avoidance. Therefore, we have to introduce damping into the system to reduce the magnitude of vertical accelerations by at least 30 %.

2. **Detecting and Avoiding Obstacles – Physical Sensors for Smart Bumper to detect at least 0.5 N force for control algorithm to execute motion planning**
   The robot should be able to detect obstacles and change its path once it has come into contact with an obstacle. This requires the use of physical sensors such as strain gauges that will measure the force of impact with the obstacle. Once the desired force has been achieved, a transducer to the control system, which will then determine the new path, will send a signal. The sensors should be able to detect small forces, around 0.5 N so that the robot is sensitive and can quickly respond to obstacles, especially if these obstacles are humans. A small force also ensures that there is no damage to the point of impact.

Combining the scores for both the professors and the engineering students for each factor, we identified six primary customer requirements as those with the highest scores (in order of decreasing importance) shown if Table 7 below. Please refer to the QFD in Appendix A for a more detailed figure.

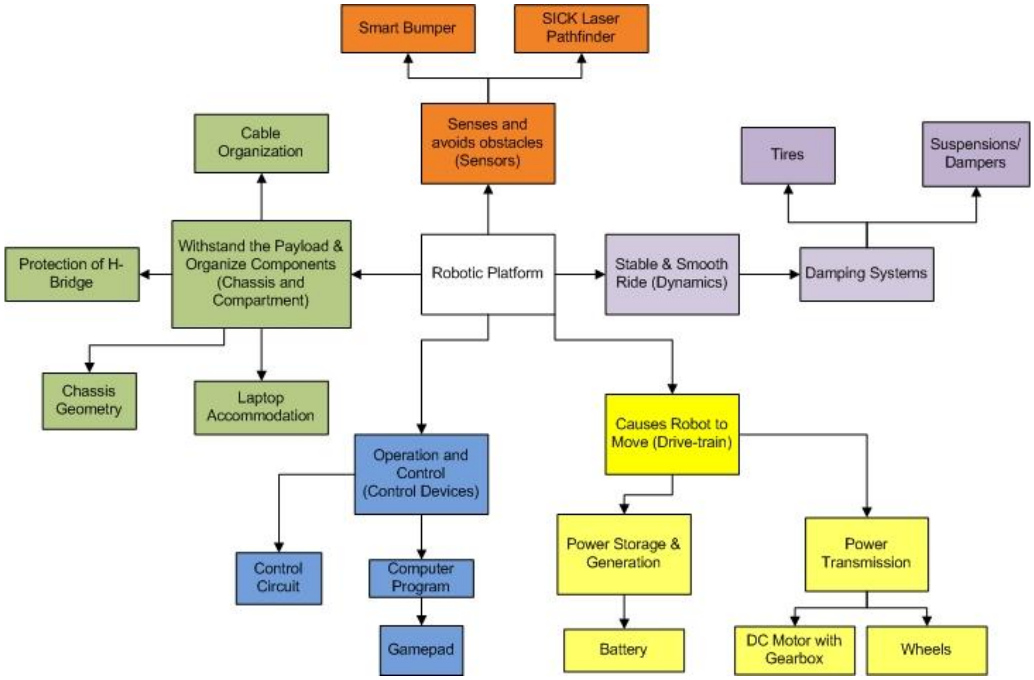
Table 7: **Changes in engineering specification rankings which reflects customer requirements**

Rank	Original	New
1	Price relative to commercial products	Price relative to commercial products
2	Maximum payload (>20Kg)	Maximum payload (>20Kg)
3	Top speed (>=2m/2)	Top speed (>=2m/2)
4	Number of parts	Time to manufacture (<15 hours)
5	Time to manufacture (<15 hours)	Accuracy of odometry
6	Accuracy of odometry	Number of pieces

4. FUNCTIONAL DECOMPOSITION AND CONCEPT GENERATION

We carried out a functional decomposition based on the function of each of the systems of the robot, and our customer requirements. The robot can be divided into five main functions; the control devices, drive-train, dynamics, sensors, and the chassis & compartments, each of which needs to perform a unique function for an ideal operation of the robot, and requires optimization to meet the needs of the customer. Each of these system functions can be further decomposed into specific sub-functions representing the mechanical and electrical components such as the motors, batteries and wheels. A visual representation of the functional decomposition is shown below.

Figure 2: Functional decomposition detailing parts of the robot we are most concerned with



4.1 Drive-train

The drive-train provides the power to move the robot and to run both sensors and control circuit. We divided the drive-train into 2 main parts: the electrical parts which include Batteries and motor, and the mechanical part that contain wheels and gearbox.

4.1.1 Electrical part

We have considered several designs of battery configurations, evaluated their pros and cons and chose the available model meeting the specifications and budget. A single battery configuration is lightweight, however; it cannot provide a voltage higher than 12V and current more than 3A, which may be a concern if large motors are used. On the other hand, 2 batteries offer a greater power capacity. We preferred to use 2 batteries over 1 battery.

The motors are the other key component in the electrical part. We will use only two motors because of the limitation of the control circuits. Stall torque and top speed are two parameters which are closely related to the requirements of robot speed, the choice of gearbox, and the wheel size. Also, the digital encoder is important because the accuracy of the odometer depends on the resolution of encoder. We also have to make sure that the size of the motor is small enough to fit into the robot.

4.1.2 Mechanical part

Because the gearboxes come with the motors we have chosen, we don’t have many choices on gearbox ratios. However, we do have several designs for gear ratio. One of the designs is a tall gear ratio, which means smaller wheels are desired. This design restricts the clearance of the platform and the big gearbox occupies more internal space. Another design is using a big wheel and a short gearbox. Compared with the first design, we believed the second one is better.

The other issue is the wheel and hub connection. The wheel connection is crucial to the accuracy of the encoder and there are several different options. We have considered a basic cotter-pin design, which is easy to manufacture and low cost. We have also thought about the key connections, which can couple wheel and hub very well but require additional machining. Using keyless bushings is a third option, it provide great coupling and is easy to install. We will use keyless bushings in our prototype.

4.2 Dynamic Component
We decided to add compliance and damping to improve the dynamics of the robot and decrease the vertical vibration for more accurate odometry. We designed chassis with swing arms, fully adjustable springs and shock absorbers to find the best setup. A simpler design that uses pneumatic tires and a caster instead of springs and dampers may give us a better tradeoff between cost and performance.

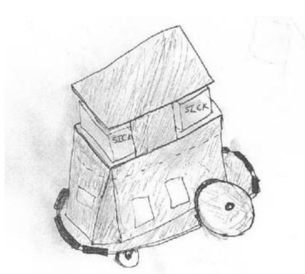
4.3 Sensors
There are two types of sensors on robots, the main sensor to locate the robot and a secondary sensor for collisions. We will not change the current design of main sensor, the laser sensor. We also tried to add a sensing bumper to avoid collision. We are still deciding on how to best implement a secondary sensor for collision avoidance and/or feedback

4.4 Control System
We determined to continue using the current circuit and the whole control system including the laptop and wireless game pad.

4.5 Discussion on Chassis Design
This section will cover several design ideas that we have come up with. These designs were our preliminary designs and show a starting point from which our final design was created. We evaluated the pros and cons of each design both qualitatively and quantitatively and used the results along with other design considerations from the engineering specification.

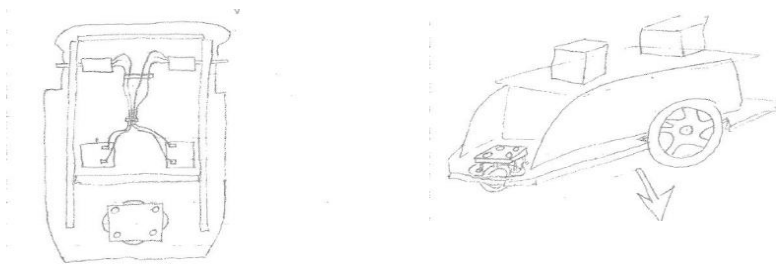
Essentially, the chassis and compartment should be designed such that the geometry will be able to withstand the large payload, provide sufficient space for the storage of components such as the laptop, batteries and motors with minimal compromises in the dynamics of the robot, and accommodate a functional smart bumper.

Figure 4: A preliminary concept drawing – Concept A



<u>Concept B: Caster Mounting Plate Offset</u>
The mount height of a viable pneumatic caster is around 15cm. This mount height is bigger than the height of 9.5 cm that is on the previous robot. Hence, to maintain the clearance height, the base platform has a hole that allows the caster to turn. The mount plate is also offset by cm to maintain the same height. Wire organizers are attached to the compartment interior to organize the cables for easier identification and better maintenance.

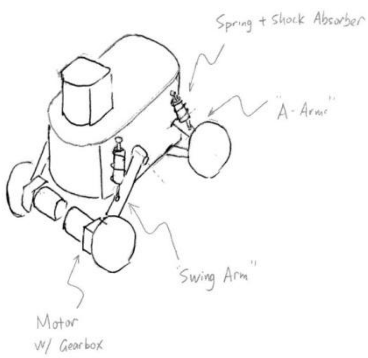
Figure 5: A preliminary concept drawing – Concept B



Unfortunately, the method of attaching the mounting plate with a vertical offset is very complicated and could cause a considerable increase in the assembly time. Furthermore, there might be regions of stress concentrations along the edge which could weaken the structure and cause fracture.

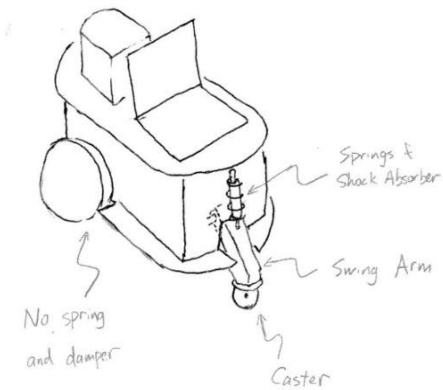
<u>Concept C: Drive-train with axles & Hydraulic Damper</u>
This particular design has a drive-train similar to that of a car; an axle is used to allow the robot to turn. Damping is provided by the hydraulic damper which is attached to each of the wheels. Hydraulic dampers are very effective and can reduce the vertical acceleration by a large amount, which provides a smooth ride, even on rough surfaces. However, hydraulic dampers are very expensive, and assembly will become time-consuming due to the complexity of the axle.

Figure 6: A preliminary concept drawing – Concept C



<u>Concept D: Spring/ Shock Absorber attached to a swing arm connected to caster</u>
In this design, the caster is connected to an arm that provides support for the caster, and allows the connection of the caster to the damper. The hydraulic damper will reduce the magnitude of the vertical vibrations significantly and only one damper is required, which is significantly cheaper than using more than one damper as presented in the previous design; however, the swing arm takes up space in the compartment and hence less space will be available for the components such as batteries and motors. Furthermore, the arm is more rigid and hence the maneuverability will be poor.

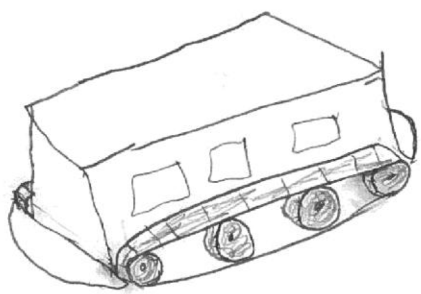
Figure 7: A preliminary concept drawing – Concept D



Concept E: Tank Treads

The idea behind using tank treads is to maximize outdoor performance. Tank treads work great for traversing rough terrain, but is not the best for keeping the encoders accurate due to their roughness and the fact that they turn on a number of underlying wheels making it difficult to know the exact pivot point of the robot.

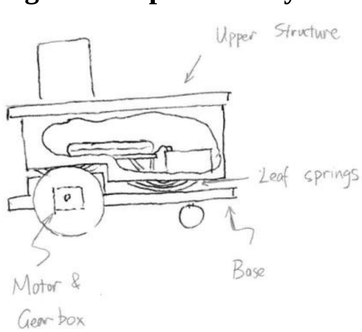
Figure 8: A preliminary concept drawing – Concept E



Concept F: Leaf Springs to absorb vibrations of the compartment and chassis

Leaf springs are what most cars use to dampen vibrations so we came up with a concept that would utilize them. Leaf springs allow for the main body of the robot to be suspended but do not provide suspension to the motors themselves which is a drawback. This design will also increase the complexity of the robot which will increase manufacturing time which is undesirable.

Figure 9: A preliminary concept drawing – Concept F



5. CONCEPT SELECTION

In carrying out concept selection, we first identified three systems for modification: the chassis & compartment, the damping sub-system and the wheel connections. For each system, we first created a concept selection matrix where we listed our major selection criteria that would meet the customer requirements. We compared each concept against the datum, which is part of the system that makes up the current robot. Based on how good the concept was relative to the datum, we assigned it a +, 0 or -:

1. + : Better than Datum
2. 0: Same as Datum
3. - : Worse than Datum

With this preliminary analysis, we were able to identify the best contenders for each system. After this, we continued on with a more detailed scoring matrix to determine exactly how much better each finalized concept was with respect to the datum in meeting the selection criteria. We assigned scores as follows:

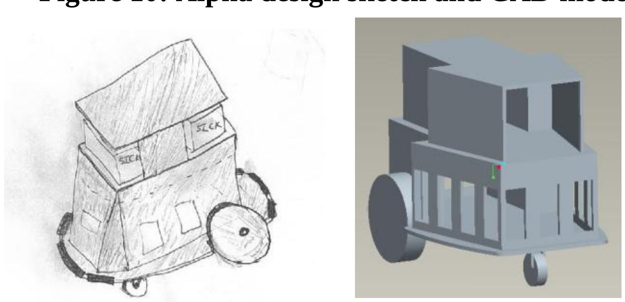
- 1-Much worse than Datum
- 2-Worse than Datum
- 3-Same as Datum
- 4-Better than Datum
- 5-Much Better than Datum

It is important to note that for the scoring matrix, we had to decide the relative importance of each selection criterion to the others, because some criteria would have more weight than others in determining the score. We then incorporated the concept with the highest score into our alpha design. Please refer to appendix C for the various concept selection and scoring matrices.

6. ALPHA DESIGN DESCRIPTION

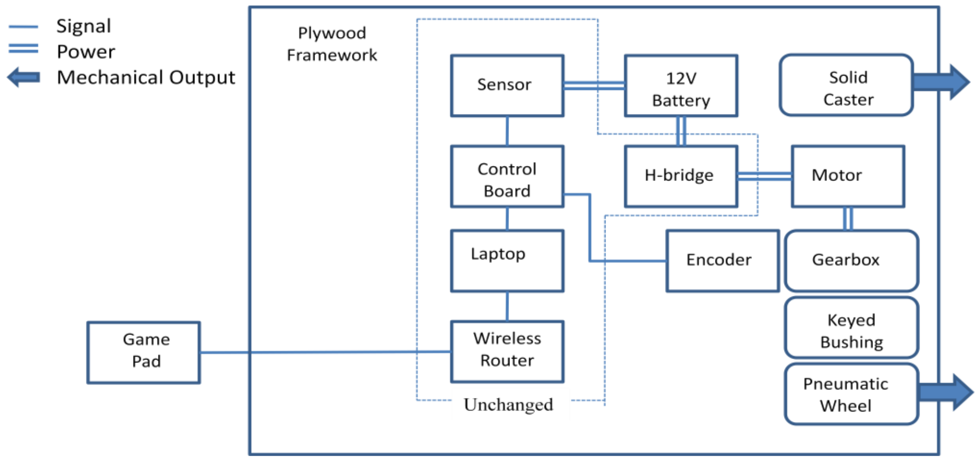
The alpha design was our next step in the process of creating our final design. The alpha design used ideas generated from the preliminary chassis drawing along with the engineering requirements, and functional decomposition. The concept selection process narrowed down the different concepts into our alpha design. The structure of the robot is described below, which is concept A.

Figure 10: Alpha design sketch and CAD model



The basic structure of the robot consists of mechanical and electrical components interacting together. The modes of information transfer in the robot are wireless and electrical signals, electrical power, and mechanical outputs. Figure 4 below shows a block diagram of how the different components interact together.

Figure 11: The basic structure of the robot showing information flow



In our Information Sources, Concept Generation, and Concept Selection sections we detailed different components and why they will suit our design needs. Table 8 below summarizes our part choices so far.

Table 8: Key component specifications and cost of Alpha Design

Part description	Product code	Cost	Comments
Solid caster	22785T61 (MC)	$3.43x1	2" dia,2-5/8" height, rubber
Pneumatic wheels	0061 (slgtools)	$6.00x2	10" dia, 5/8" axle dia
Keyed Bushing	N/A	0	Hand made
Motor	IG42GM01	$44x2	8mm dia,12V, 8kgf radial load
Gearbox	IG42GM01	0	24:1, 248RPM,10kgf-cm, come with motor
Encoder	IG42GM01	0	2-Channel 10-Pole, come with motor
Battery (Lead Acid)	AP-12120F2	$30.59x1	12V,12Ah, 3A, 8lbs
Framework (Plywood)	02-21160	$35.50x1	4'x4', 3/8", 4 piles

In our design, we don't change the sensor, control board, or the H-bridge from the original since they will work with our new design. The total cost of all new key components is under $200. The performance and discussion of each component will be included in Engineering Analysis. Our budget costs do not include the SICK laser sensors, Laptop, or circuit board. A list of all parts is detailed in Appendix B.

7. FINAL DESIGN DESCRIPTION & EVOLUTION

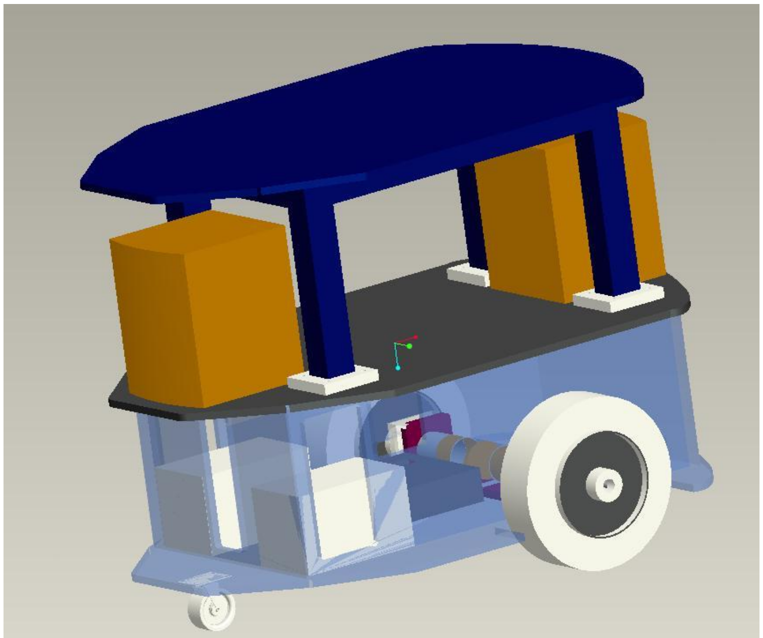
In this section we will present our final design concept and describe its evolution from the α-design. This will be done by explaining what changes were required to the α-design so that the engineering requirements could be met.

7.1 A DESCRIPTION OF THE FINAL DESIGN

Figure 12 below shows what our final design will look like. The robot is 710 mm in length, 450 mm in width and 540 mm in height with the 2nd platform. Without the platform, it is approximately 250 mm tall. This is similar to the length and width of the current robot, which is 653 mm and 410 mm. By keeping the length and width of both the robots as similar as possible, we have tried to ensure that the maneuverability of this new design is similar to that of the current robot. The clearance height for our final design is 5.874 cm, less than the 9.5 cm clearance height on the current robot. This will lower the center of gravity and enhance the stability of the robot and reduce the likelihood of tipping over.

Our final design has been significantly improved over the previous design. Specifically; our design will have a more robust drive train that will not be subject to wear under normal use, tires that reduce vibrations, a lower center of gravity and a wider wheel base to prevent tipping, an additional platform for mounting sensors and apparatus such as robotic arms and cameras, and be able to move about 4 times faster than the current robots. Our design requirements were determined through engineering analysis of each main component and our design was shaped by the available products that meet our needs. While the current design does not have a smart bumper we will continue to research potential ideas and recommend our findings in the final report.

Figure 12: Final design assembly in CAD



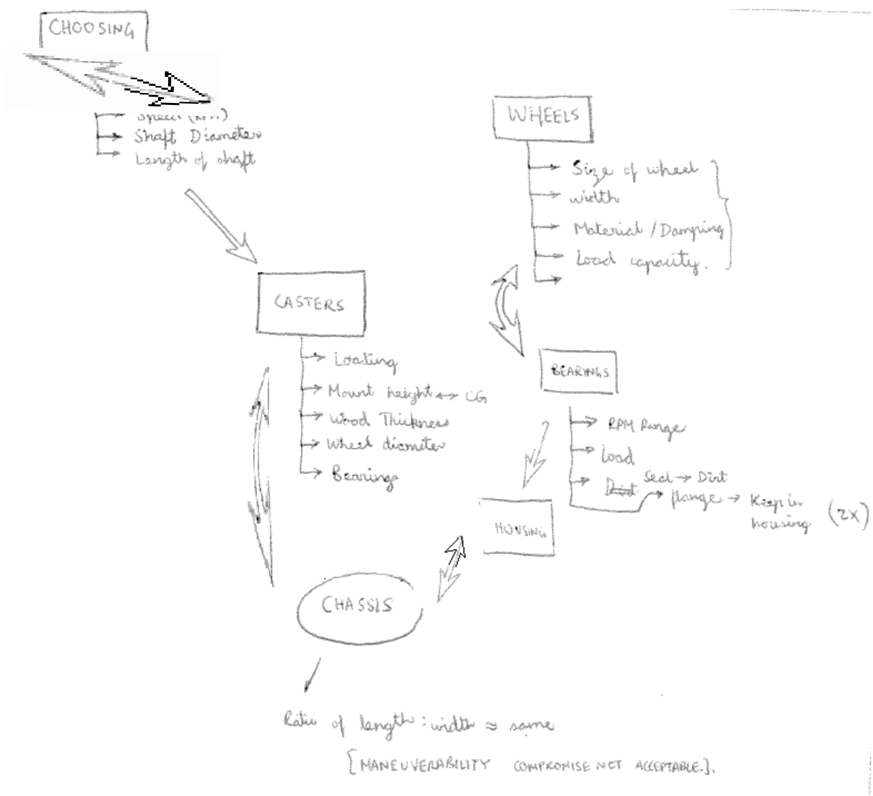
7.1.1 Components: Final Design choice summary

The drive train components were chosen based on engineering analysis and by the characteristics of available parts to meet our needs.

The necessary speed and torques as well as the cost and size determined the two motors we have considered. Since the motors that meet these requirements had shafts too short to connect a wheel to, shaft extenders and connections are needed. The motors shafts have a length of 20mm, a diameter of 8mm, and a stall torque of 60Nm. This determined the size and strength of the connections needed between it and the shafts.

The 8” tires of our design allow for a lower center of gravity over the original robots 10” wheels and allows for a broader base to help prevent tipping. Our design also calls for pneumatic tires to reduce vibrations. Since most of the 8” pneumatic tires had an inner diameter of 5/8” this determined the outer diameter of our extension shaft and keyless bushing. This diameter, the necessary speed, low maintenance, and the robot weight determined the size and type of bearing. The ½” width of the bearings, 3-3/4” length of the wheel hub, 3/8” thickness of the wall between the bearing and wheel determined the minimum shaft length needed and the width of the robot needed to contain the drive train. The part and material choices were done carefully by taking into account not just the engineering requirement for individual parts but how the parts will interact with each other to form the finished product.

Figure 13: Summary of the interactions between engineering requirements and available parts to meet them



7.2 EVOLUTION OF FINAL DESIGN FROM α DESIGN

In this sub-section, we will explain how we derived the final design and engineering specifications from our α-design, and how we modified the α-design in a way that our engineering specifications were met.

The top platform of the α-design was supported by plywood walls on both sides. However, the plywood walls would "box" up the area within the middle platform, resulting in a loss of space on the middle platform. As a result we would not have gained any benefit of adding the top platform. Moreover, 3/8 inch thick walls are not strong enough to withstand the weight of any manipulators or sensors, and the structure would not be sturdy. We therefore decided to use eight wooden posts with 2 in. by 2 in. square cross sections to reinforce the top platform by attaching these posts to its underside and using them as pillars to connect the top platform to the rest of the robot. To further reinforce the structure, we attached these posts to wooden pads with bolt holes.

From our engineering analysis in the previous sections, we determined for our α-design that keyed bushings would be the ideal wheel connections that would provide a durable and strong link between the wheels and the motor shafts. Although the keyed bushings are cheaper and can withstand the same torque range as that of the keyless bushings, we decided to switch back to keyless bushings for our final design after numerous design iterations because of the large amount of machining that needs to be done to manufacture the keyed bushings. Since our aim is to manufacture a rapidly manufacturable robot, we want to cut down as much machining time as possible so that researchers and students with little or no mechanical engineering background do not need to get bogged down with the tedious task of machining. We therefore decided that the benefit of a reduced manufacturing time far outweighed the drawback of a significantly higher price for the keyless bushing, and decided to use the keyless bushing for the final design.

Finally, the α-design had no angled edges, and as a result, there was no accommodation for a smart bumper. Since the smart bumper is supposed to detect collisions in as many directions as possible and act accordingly to those collisions, angled edges where the smart bumper sensors could be attached were required. When a particular edge of the robot collides with an obstacle, the smart sensors will be actuated which will in turn send a control signal to the actuators for the robot to change its direction of travel. A more thorough engineering analysis on the final design is presented in the next section.

8. PARAMETER ANALYSIS & COMPONENT SELECTION

This section will discuss all of the considerations we undertook in order to select the individual materials and components on the robot. A detailed table showing the bill of materials is located in Appendix B

8.1 Chassis

In this section we will discuss the process we took in deciding the materials that will be used to build the robot. The primary focus of this material selection comes from using the 2008 version of the CES material selector software program and from the literature review discussed previously. The CES program allows us to compare many different materials under a vast array of material specifications and characteristics.

The first step for selecting the chassis material is to first decide what the material properties need to be considered. Next we set parameters for each of those properties, assigning lower and upper bounds that we felt were minimum requirements for the material to be viable. Then, using the software we narrowed down the list of possible materials. From there we looked at each material individually and chose the one we felt was the best.

We came up with a list of material properties and characteristics that include; density, relative cost, tensile strength, machine-ability, and water resistance. Table 4 the parameters we set for each of these material characteristics and the importance that the material meets these criteria. In the table 4 an importance of 9 is of the highest priority. Table 5 gives a closer look at different kinds of materials that CES suggested. Figure 1 shows our CES search.

Table 4: The range of characteristic of a desired material and importance

Material Characteristic	Desired range	Importance
Density	500-1000kg/m^3	3
Machinability	Excellent	9
Cost	< $5/kg	6
Tensile strength	>10 MPa	6
Weather resistance	moderate	3

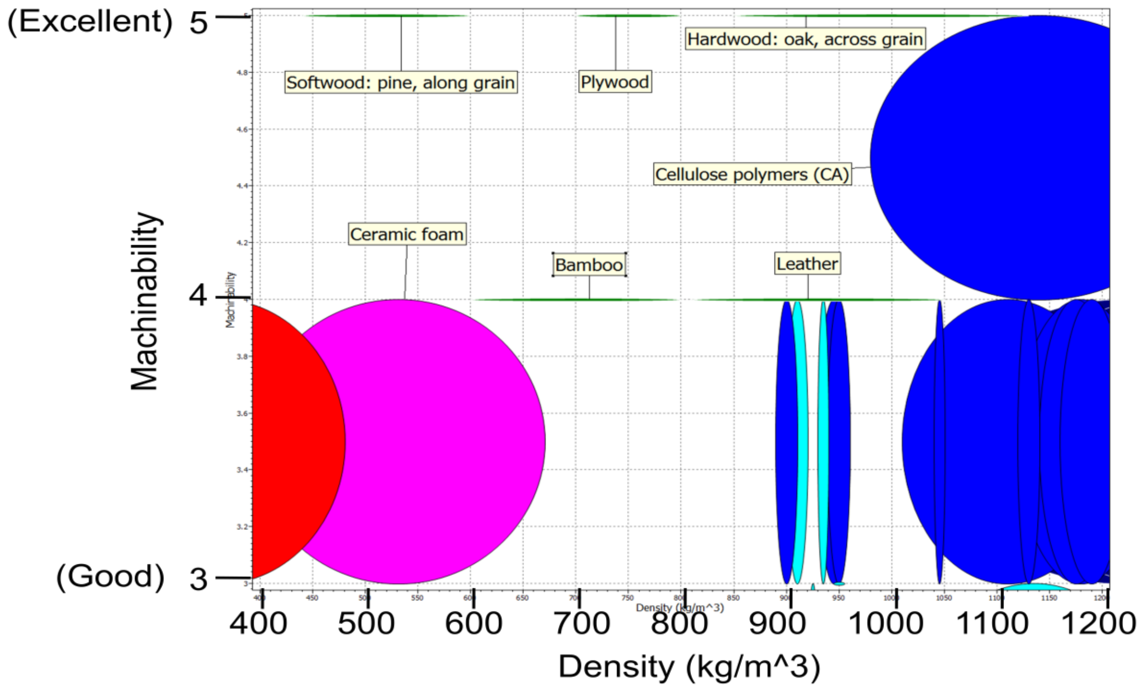
Using CES we set bounds on each characteristic, which narrowed the choices of materials down to four. These four choices included soft pinewood, plywood, hard oak wood and thermoplastics. The table below compares the material characteristics of the four materials choices.

Table 5: Comparison between different materials

Material	Density	Machinability	Cost	Tensile Strength	Weather resistance
Softwood	440-600kg/m^3	Excellent	$2/kg	60MPa	Average
Plywood	700-800kg/m^3	Excellent	$2/kg	40MPa	Average
Hardwood	850-1030kg/m^3	Excellent	$3-$4/kg	>100MPa	Average
Thermoplastic	1000kg/m^3	Great	$3-$4/kg	10-20MPa	Average

After analyzing each of the four materials separately we felt that Plywood would be the best choice for our robot. This came from the factors listed above as well as other consideration. Plywood met all of the material requirements that we felt were needed for the robot chassis. In particular we feel that Baltic Birch 3/8" plywood would be what we will use. This type of plywood is high quality and will more than likely be better than the general plywood used in the CES program.

Figure 1: Plywood provides a combination of lightness and high machine-ability



This is a graph from the CES program shows machine-ability versus density and some materials that are within the desired ranges.

A similar process was used to determine the type of material to be used for the axel, motor mounts, and bearing housing. Through the use of CES we determined that aluminum would be the best choice for these components. For specific information regarding this selection processes see Appendix H.

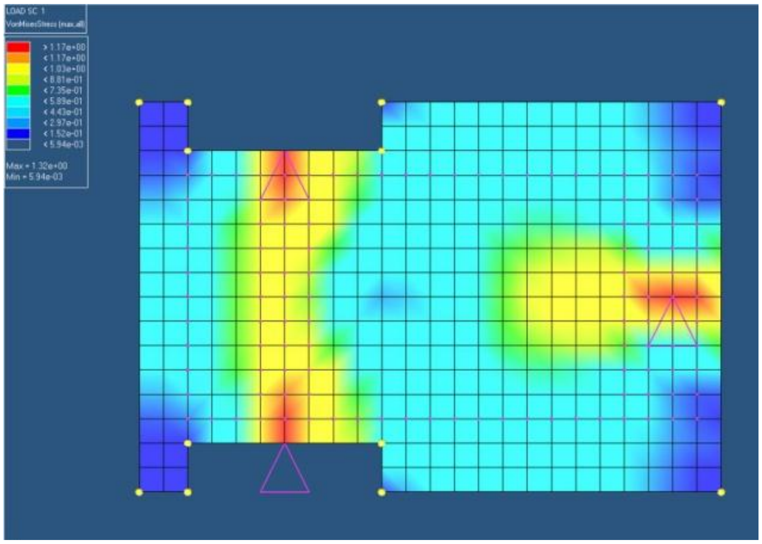
8.1.1 Stress and Load Analysis on Chassis

We have conducted FEA (finite element analysis) to analyze the stress distribution on the chassis and the reaction force on the caster and wheels to make sure the components we chose can survive the payload (20kg).

As shown in Figure 5, the maximum von Mises stress is 1.3 MPa. Even if we are going to punch holes in the boards like in the current robot, which will enhance the stress by a stress concentration factor of 3, the von Mises stress is still less than the yield stress. So the chassis is strong enough to hold the payload.

We have also determined the reaction forces on the wheels and caster. The load on each wheel is 54N and the gearbox can stand 8kg force or 78N, which give us a safety factor of 1.4 on smooth terrain. On rough terrain vibrations can greatly increase the forces that the motors and gears must handle though, which are described in our challenges section. The caster can withstand 70lbs or 311N load and the predicted load on caster is 78N.

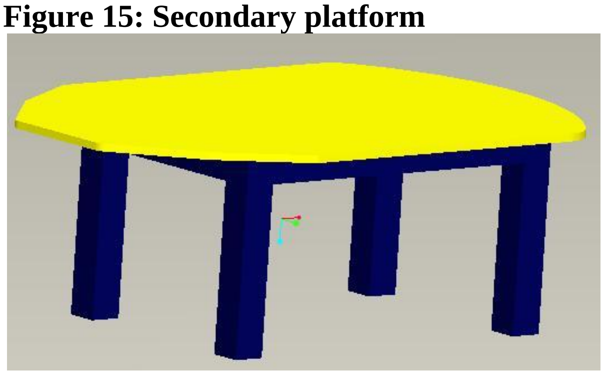
Figure 14: The finite element analysis of the stress distribution and reaction force on the chassis, the maximum stress is 1.3 MPa which is shown by the red zones near the triangular points representing the wheels



8.1.2 Secondary platform

This platform will provide extra space for equipment and sensors. This platform is an optional platform that can be securely attached to the top of the primary platform. The secondary platform will be supported by a frame made from 2x2 wood posts and a platform with the same dimension as the primary platform will be placed on top of the frame. The bottom of the wood posts will be connected to blocks of plywood which will have holes in them that are spaced such that they will line up with the holes on the primary platform. This will allow bolts to connect the secondary platform to the primary platform. Below is a CAD picture of the final design platform; the two different colors are used to distinguish the frame and the platform.

Figure 15: Secondary platform



8.2 DRIVETRAIN: WHEELS

We have narrowed the wheel choices down to two: the semi-pneumatic wheel and the fully pneumatic wheel, each of which has a diameter of 8 inches, a metallic hub and is made of rubber with air filled in the space between the tire and the hub. The air filling in the rubber tires in these wheels decreases the spring constant and increases the damping ratio of these wheels, which improves the ability of the wheel to perform as a shock absorber and energy dissipater, thereby introducing damping effects that reduce the vertical oscillations of the robot on a rough surface and provide a smooth ride.

Figure 16: (a) Semi-pneumatic wheel (b) Pneumatic wheel

We chose to reduce the wheel size from 10 inches to 8 inches so that the clearance height of the robot can be reduced, which will lower of the center of gravity making the robot more stable. Moreover, since the wheel diameter is reduced, the wheels can be pushed further back, which will result in…

The metallic hubs on the wheels also have a higher tensile strength than that of the plastic hubs on the wheels of the current robot and are hence more durable. Hence, they will not fracture as a result of the torsion stresses caused by the torques on the wheel connections, unlike the plastic hubs which have fractured easily after three experiments.

Testing has been done on both the pneumatic and semi-pneumatic wheel. From our tests it is shown that both of these wheels provide significantly more damping over the wheels on the previous robot. The pneumatic wheel did provide more damping than the semi-pneumatic as expected. For more information on the tests and for specific quantitative results see the Testing and Validation sections in this report.

The final design incorporates both types of tires in that it allows the wheels to be interchangeable using the keyless bushing. This will allow for either wheel to be used depending on the preference of the user. More information on the wheel connections can be found in section 8.6.2.

8.3 H-BRIDGE MOTOR CONTROLLER BOARD HOUSING

We designed a 130 mm by 130 mm by 40 mm box made from plywood to house the H-Bridge motor controller board. Currently, the board is placed on a flimsy sheet of cardboard and is exposed to the surroundings which could result in damage due to settling of dust on the board, or damage due to accidental impact on the board during component handling. By isolating the board in the box, we will provide a sturdy structure that will keep the board out of harm's way so that any damage can be prevented.

Fabrication of this housing has yet to be done do to concerning of circuit board over-heating. Our sponsor has informed us that a more permanent housing for the circuitry will be implemented in the near future, but that for this project it should not be one of our primary concerns.

8.4 GEAR MOTORS

This section describes our motor selection analysis. In order to decide on the motors we looked at the customer and engineering specifications. Then we looked for motors that meet these specifications.

Our customer requirements regarding motion are that robot must be able to keep up with a human walking pace, carry a payload of sensors, and be maneuverable. The related engineering specifications are that the robot must be able to move at least1 $^{m}/_{s}$ with a 20 kg payload, be able to turn, and be able to stop. The motors will be driven using two motors in series, which using these specifications and equations 1-4 below we determined the torque required to accelerate the robot at least 0.1 $^{m}/_{s}{}^{2}$ with 8" diameter wheels.

$$F = ma \quad (1)$$
$$T = Fr \quad (2)$$

Next we determined the motor speed that would be necessary in order to move at 2 $^{m}/_{s}$. Since we had decided on the wheel size we used that to determine the RPMs necessary to move the robot. We used the two below equations to determine the frequency (f) that the motors:

$$v = rw \quad (3)$$
$$f = w/(2\pi) \quad (4)$$

After calculating the required motor specifications we conducted a search for products to match our needs. We looked for motors that included an encoder since one will be needed to calculate the robots odometry. The engineering requirements of the motors and two motors that meet them are given below in table 9.

Table 9: Motor requirements and specifications, 42 and 32 are the diameters of the motors in mm. The required torque is for an acceleration of 0.1 $^{m}/_{s}{}^{2}$

	Speed (RPM)	Torque (Kg cm)	Cost ($)	Encoder Sensitivity (poles/rev)
Required	188	1.0		
IG32	270	1.0	22.20	N/A
IG42	305	7.4	53.95	38

Each motor has a planetary gear box with a 19:1 ratio, the output of which produces the speed and torque values listed above. Both of the motor choices have benefits and drawbacks. The IG32 motor costs less, weighs less, and would take up less space within the robot compartment However, its torque rating is just sufficient to provide the required acceleration to reach human walking speed relatively fast and it does not have an encoder. An encoder could be added to the IG32 although this would raise the cost closer to that of the IG42 and it would slightly increase the manufacturing time. Since the torque is low the IG32 might not meet our requirements when we consider the additional friction from the bearings and any other losses in the system. The IG42 exceeds our torque requirements and has a higher speed than the IG32, both of which may be useful for expanding the capabilities of the robot. Some downsides of the IG42 are the cost and length of the motor. Since it is longer than the IG32 it is more difficult to design enough space for it within the robot. Given so many factors we tested the motors to determine which one best meets our needs. The results of the tests are found in the Testing and Validation section.

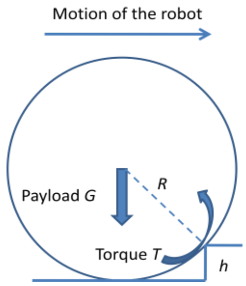
The stall torque of the IG 42 is 60 kg cm. This will allow the robot to climb or stop on a 17.2^{o} slope. Using the IG32 the motor robot will only be able to go up a 2.52^{o} slope without any initial velocity.

$$\sin(\theta)\, Fr = T_{stall} \quad (5)$$

8.4.1 Further discussion on motor torque

The robot is designed to run on both smooth indoor surface and semi-rough outdoor surface. As a result, we do the modeling for the wheel to climb a step and predict the maximum height it can overtake. The model is illustrated in Figure 17.

Figure 17: The physics model of the wheel climbing over a step



IG42 motor and 8 inch wheel with about 20kg payload

$$G\sqrt{R^2 - (R-h)^2} = T \qquad \text{Eq. 6}$$

R=8 inch; G=25Kg; T=0.74Nm

The only force to push the robot over the step is the torque from motor. The balance between the torque and momentum of vertical load give the maximum height of the step it can climb. Doing simple calculation, we come to the maximum height of about .2m. We noted that the deflection of the wheel will help climb the step. The pneumatic tire, which is expected to use on the rough surface, offer great compliance and can pass much higher obstacles than predicted by the rigid tire model. Besides, the model calculated does not take the contribution of speed to pass-ability into consideration. As a result, the model gives us an underestimated result. However the model still shows that a softer tire and massive torque is the ingredient to good off-road performance.

8.5 COMPONENT DESIGN: STRESS ANALYSIS OF SHAFT EXTENDER

Since the shaft on the motor chosen is too short (20 mm in length), we need to fabricate a shaft extender to transmit the motor torque to the wheels. The minimum diameter of the extender is 6 mm. As a result, the stress in the extender is of concern. There are two major loads on the shaft extender; the axial torque and the bending moment due to the payload. The torque rating of the motor restricts the torque transmitted and the possible maximum torque output is about 1Nm. However, the bending momentum depends on the vertical force on wheels. As a result, the bending momentum can be magnified during vertical oscillations, when the actual vertical load on the wheels can be several times larger than the static load. To avoid the possible failure on the shaft extender and the bowing due to excessive dynamic bending momentum, a bearing is used to decouple the momentum and torque.

Using basic mechanical equations of the stress, we calculated the normal stress from the torque (σ) of momentum and shear stress (τ) from the torque.

$$\sigma = \frac{My}{I} \qquad (7)$$

$$I = \frac{\pi r^4}{4} \qquad (8)$$

$$\tau = \frac{Tr}{J} \qquad (9)$$

$$J = \frac{\pi r^4}{2} \qquad (10)$$

The maximum normal stress is estimated to be 19MPa where the bearing is attached assuming the payload is 20kg. The shear stress is estimated to be 29MPa where the motor is connected, assuming the motor running at no speed load or the maximum axial torque possible. As a result, the possible maximum Von-Mises Stress is about 36MPa. The material of shaft extender, aluminum alloy 6061, has a yield stress of at least 275MPa. As a result, the design is believed to be strong enough to hold the load. However, such calculation is based on static load and the actual dynamic load depends on the vertical response of the robot, or more specifically, the vertical acceleration. As we measured before, the maximum acceleration we can get on the asphalt surface is about 3g. Consequently, the actual stress can be greater than 108MPa.

The other issue is fracture at the stress concentration point. Due to the short duration of high acceleration (typical less than 0.1sec), the load will behave like an impact load, resulting in fracture other than pure yield as the possible failure mode. We tried to estimate the possibility of fracture at the extender. However, the exact value depends on both geometry and actual toughness of the aluminum alloy. Besides, the initial crack length is needed to do calculation. Both of them are unknown. Given tested dynamics of the robot with increased damping due to pneumatic wheels we feel that the shaft extender should not fail under any normal situation.

8.6 DRIVE-TRAIN COMPONENT CONNECTIONS

There are two types of connections in our drive-train design; the connections between the motors and the shaft extenders, and the connections between the shaft extenders and the wheels. This sub-section explains the engineering requirements for these connections and our choices for these connections.

8.6.1 Motor-shaft connection

The function of the motor-shaft connection is to transmit the torque from the motor shaft to the wheel. Since we decided to use an extra bearing across the shaft extender in addition to the bearings in the motor, the connection will only need to endure a fraction of the bending moment. As a result, we do not need to place any restriction on the radial load or shear stress ratings for the connection. The connecting mechanism should firmly grip the motor shaft and the shaft extender such that the connection is secure and strong and there is low chance of slip. Other general customer requirements such as; cost, ease of manufacturability and assembly, and ease of maintenance must also be taken into consideration in the selection process.

Table 10: Comparison between two connection requirements: the C-clamp and the set screw.

	Requirement	**C-clamp**	**Set Screw**
Torque rating (Nm)	3	~50	High,>3
Machinery	As low as possible	no	drilling
Cost	As low as possible	~$10	~$1

As shown in table 10, we have two candidates for the motor-shaft extender connection mechanism: the C-clamp and the set screw. While both meet the torque rating requirements and can offer firm and secure connections, the C-clamp does not require any machining processes, while using a set screw requires drilling or milling, adding to difficulties in the manufacturing process. Besides, the lifetime of the set screw is also a concerned. The possible groove on the shaft due to the limited contact area of the screw may loosen the connection. Even if the cost of set screw is far lower than clamp, we are still going to use a c-clamp.

8.6.2 Wheel-shaft extender connection
We use a keyless busing to couple the motion between shaft extender and wheel. The connection is expected to take the torque transmitted from the motor shaft and the bending momentum from the wheel. Also, the axial and radial reaction force should be taken into consideration. As for motor-shaft connection, general customer requirements such as low cost, simple manufacturing and assembly and quick maintenance, are also the criteria in selection.

Table 11: Comparison between connection requirement, the keyless bushing and keyed bushing and shaft

	Requirement	Keyless bushing	Keyed bushing
Torque rating (Nm)	3	~15	High,>15
Thrust (kN)	±0.3	±3.2	+10,one way
Machinery	As low as possible	no	grooving
Cost	As low as possible	~$20	~$5

As shown in table 11, we have two candidates in the connection between wheel and shaft extender, the keyless bushing and keyed bushing. Both meet the requirement of torque rating. Keyless bushing can take thrust of 3kN in both directions while the keyed can only take axial load in one direction. The other advantage of using keyless bushing is that it is easy to assemble the connection, which makes the wheel changeable. Even though the keyless bushing is about four times more expensive than a keyed bushing, we still decided to use the keyless bushing as the means to connect the axle to the wheels.

8.7 COMPONENT SELECTION: CASTER WHEEL
This section will outline the reasons for deciding on the caster wheel chosen to be used on our final design. First we created a list of engineering specifications, presented in table 12, which encompasses the needs that a successful caster must fulfill. Next, we searched for caster wheels that met these requirements and identified potential candidates. Finally, from the list of potential candidates we selected the caster we felt would work the best for our prototype.

Table 12: Caster wheel engineering requirements

Requirements	Specific target
mount height	2" - 3"
wheel diameter	1/2" - 1"
load rating	60lbs or greater
wheel damping/material hardness	60A - 80A (Durometer)

The engineering requirements stated in the table above come from the overall design requirements. The mount height was determined from the size of the drive wheels and the likely ground clearance required of the prototype. The wheel diameter was specified to maximize maneuverability and sturdiness of the robot. Load rating was determined based on the maximum projected weight of the robot and the percentage of that weight the caster is likely to support with a safety factor of 2. The hardness rating was determined based on maximizing the damping potential of the caster with the ease of caster rolling; a hard caster wheel will provide easier rolling but less damping.

In our preliminary search for a caster wheel we came across many different types from several different manufactures/distributers. It became clear that we could narrow the list of possible casters, without the need of the engineering requirements, based on the basic necessities for the caster. The following characteristics were also identified; the caster had to be a swivel caster to allow for the maneuverability that the robot required. The caster needed to have a top mounting plate as oppose to a stem, this allows the caster to be mounted directly to the chassis without the need of another component. Finally, it would be ideal that the caster have ball bearings which would improve the durability and provide maximum maneuverability.

Three distributors were used in our selection process; the first was McMaster Carr, second was Caster City, and third was Great Lakes Caster. McMaster Carr had swivel caster wheels with a top mounting plate that met our engineering requirements; however the casters within the desired mount height did not have ball bearings. Caster City had no caster wheels that met our mount height requirements; the smallest caster had a mount height of 4". Great Lakes Caster has two casters that meet all our requirements and have double ball bearings. One of these casters had a mount height of 2.3" and the other had a mount height of 2.6" with all other specifications being identical. Great Lake Caster is also comparable in price to the McMaster Carr. Therefore, we decided to go with the caster, from Great Lakes Caster, with a 2.3" mount height for our prototype. It will give us more flexibility, than the 2.6" mount height caster, with the motor mounts; since it is easier to add height, via washers or adding a piece of ply board, to the caster. Our plan is to level the platform of the robot by adjusting the caster mount height to equal the height between the platform and the bottom of the drive wheel. This will ensure that the prototype is level and the sensors on the prototype will be able to work properly.

Figure 18: Mount Height

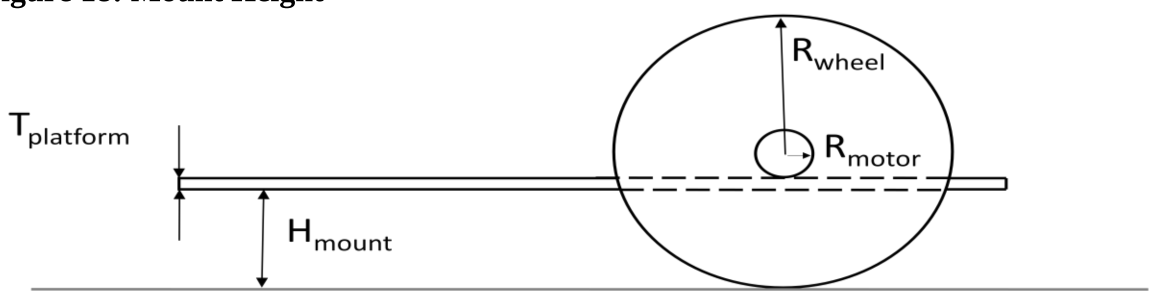


Figure 18 is a diagram that shows how the target mount height was calculated. Taking the radius of the drive wheel and subtracting it by the radius of the motor and the thickness of the plywood gives an approximate caster mount height..

8.8 COMPONENT SELECTION: BEARING

This section will discuss about the requirements and the engineering specifications of the bearings that will be used in our final design. Due to the short shaft of the motor we chose, the bearing in the motor cannot support more than 5kg or about 50N radial load. Using the shaft extender leverages the load on the motor by a factor of 3. As a result, the static load on the motor bearing under designed maximum payload will be 25Kg, which is much larger than the rated load. Furthermore, the shaft extender itself may yield and bow due to the dynamic load. The deflection at the end is estimated to be negligible. The large deflection will affect the accuracy of the encoder as well as increase the possibility of drive-train failure due to misalignment of components. Hence, an extra set of bearings is attached to the shaft extender to decouple the bending moment exerted by the payload and the axial torque transmitted by the motor.

We have come up with several requirements to narrow down the list of possible bearings to choose from. the first requirement is the size of the bearing. To simplify the production and assembly, we chose the inner-diameter of 5/8", same as the aluminum rod used as the shaft extender, as the required size. Then we desided that the axial load capacity of the bearing should be more than 50lbs, which gives us a reasonable safety factor for dynamic loads and possible impacts. The maximum rotating speed is also a concern. According to the datasheet of the motor, 252rpm is its maximum rotating speed. Therfore, the bearing speed rating needs to be at least 300rpm. It would also be beneficial that the bearing be sealed so that no extra lubrication is required. The bearing will be flanged for simple assembly and secure connection to the bearing housing. From all these requirements, we have decided on a ball bearing (Part Number: 6384K365, McMaster-Carr) that meets all our requirements and offers a good balance between performance and price. Table 13 lists all of these particular bearings specifications.

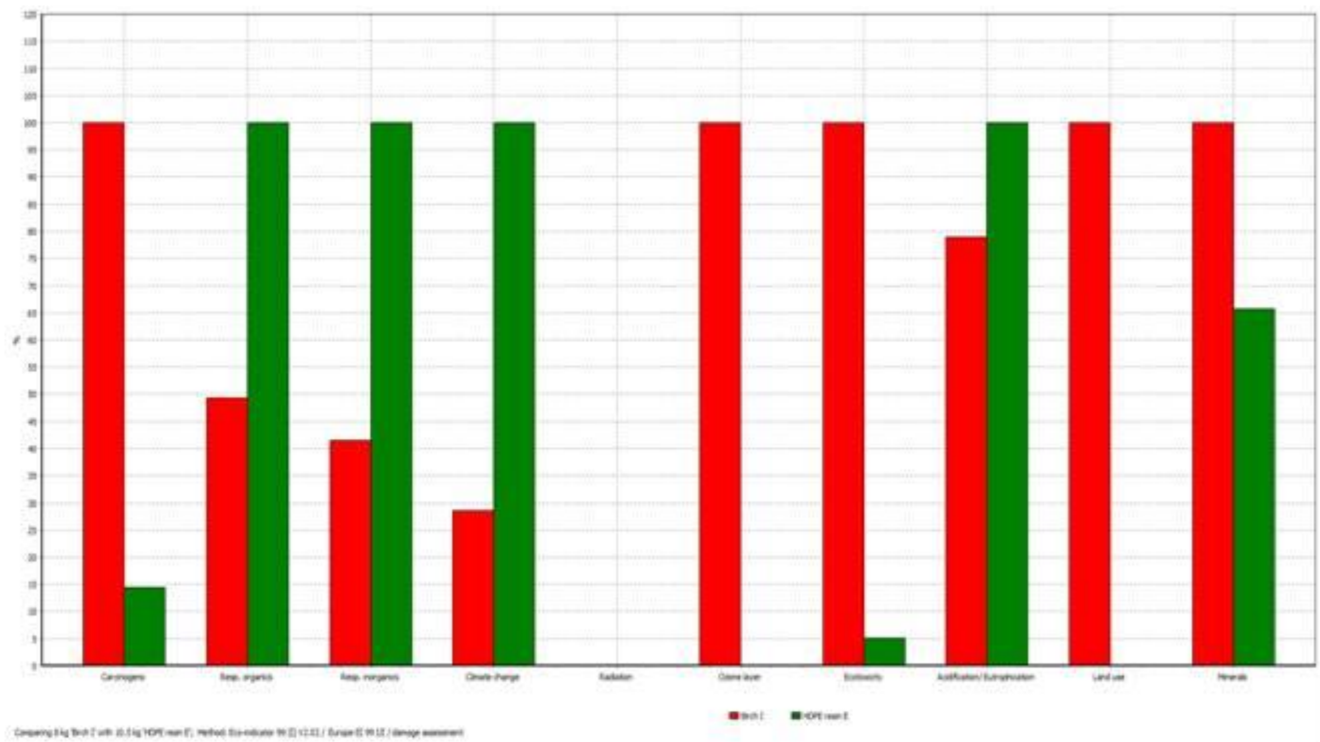
Table 13: Requirement of the design and the engineering specification of the chosen bearing

	Requirement	**Specification of Bearing**
Type	NA	Ball Bearings
Style	Flanged Double Sealed	Flanged Double Sealed
Shaft Diameter	5/8”	5/8”
Outside Diameter	<1-1/2”	1-3/8”
Width	NA	1/2”
Load Capacity	50lbs	352lbs (dynamic)
Maximum rpm	300	1000
Price	<$15	Around $10

8.9 SUMMARY OF DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

From the DFES assignment, we learnt how to analyze the environmental impact that our design would cause to the surroundings, and how we can take this into consideration in our engineering design and analyses. We also learnt that quantitative comparisons of environmental impact between two materials are not always sufficient to allow us to arrive at a decision on which material we should use. This is due to the fact that certain environmental consequences might be of higher importance than others in our selection criteria based on our desired purpose of our design, and as a result, the material that causes more damage to a particular aspect of the environment might not necessarily be worse than the material which has a lower impact. Moreover, we need to consider other factors that influence our decision such as cost, machinability, material physical properties and availability of materials, which might have significantly greater importance than just environmental impact alone. In addition, SIMAPRO, the software used to perform the Life-cycle Analysis, does not consider sustainable practices such as recycling in the determination of the overall impact of the materials on the environment. Recycling and other sustainable processes have the potential to significantly reduce wastes and hence the materials we choose might have a significantly lower environmental impact than the calculations given by SIMAPRO.

As an example, let us consider our analysis of the chassis material selection process. (More details about the analysis can be found in the appendix on the DFES process.) As shown in the figure below, birch wood, which we plan to use for our chassis emits a greater amount of carcinogens as compared to High-Density Polyethylene (HDPE). A large amount of land use is required as well because of the clearing of forests to obtain the wood from birch trees. However, the impact that the wood has on climate change is significantly less than the impact that the HDPE has on climate change, since HDPE is manufactured from petroleum (which contains carbon that has “escaped” the carbon cycle due to metamorphosis of plant and animal remains over millions of years) and this would require processing of petroleum that gives out greenhouse gases such as carbon dioxide and methane that would cause global warming and disturb the equilibrium rate of carbon removal and replenishment in the carbon cycle. On the other hand, if we practice sustainable logging through reforestation and limit the cutting of trees to a particular regulatory cap that must be met, the land use impact due to birch could be significantly minimized. Moreover, from a machining/manufacturing standpoint, HDPE melts easily and therefore deformities could develop during re-solidification, rendering it a poor material. HDPE also has poorer material properties than those of birch. As a result, we determined that birch was the more suitable material of the two for the chassis. A similar analysis for the drive-train components can be found in the appendix **??** as well.



9. PROTOTYPE DESCRIPTION

This section will discuss how we used a prototype in order to implement and fine tune our final design. We will also discuss the nature of the prototype and its purpose in the overall project.

One of the components of our project is to manufacture two full scale robots. Our goal is to be able to build the first robot to the specifications of our current final design and use this robot as a prototype to carry out validation and testing. The nature of our project is such that some of the final modifications of the second robot came from the testing results of the prototype robot. Information that was gained from the testing was used to make modifications to our final design.

Through conversations with our sponsor, we have already come up with some aspects that will be considered in our prototype design and testing. This includes; the size of the overall robot, in order to maximize the use of space and maneuverability. The caster size and the location of the motors are also important, in order to have sufficient ground clearance and insure that the robot can perform on uneven surfaces.

Some of the prototype testing was performed prior to the full assembly of the first robot. Testing the motors, wheel connections, and robot wheels did not necessarily require a fully assembled robot, especially when we are isolating a particular component in the testing process. However, we fully assembled the first robot before we started manufacturing the second robot. The purpose of this was to make certain that the first robot is fully functional and to ensure that we knew exactly what changes need to be made to the second robot.

Overall, the initial prototype will end up as one of the two finished robots that will be delivered at the conclusion of this project. The prototype will be built using the CAD files in this report and will be manufactured in the same way as our final design. In the next section we will discuss the testing we performed on the prototype and the results from those tests.

10. PARAMETER VALIDATION AND EXPERIMENTATION

Before we fully manufactured a robot, we needed to determine if the components and devices we selected meet the engineering requirements. We did this by testing the first robot we build with the different components we ordered and by performing dynamic tests on it. To do this we will not need to construct the entire robot, so once the drive-train is assembled we will perform our tests. Then, we will compare the results we obtained from these dynamic tests with the results from the dynamic tests of the current robots to evaluate how well we were able to achieve our engineering targets.

10.1 OBJECTIVES OF THE EXPERIMENTS

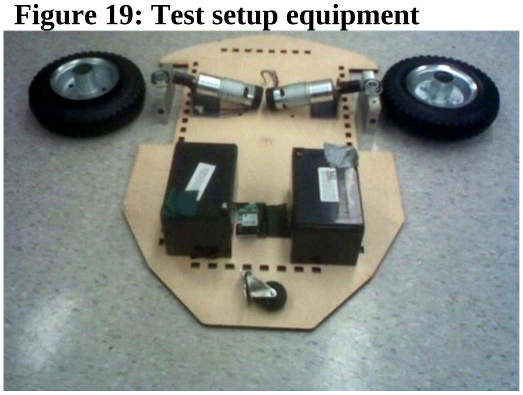
The specific objectives of our experiments are as follows:

- To compare the IG-32 & IG-42 motors and select the one that best enables us to achieve the torque and speed ratings required
- To identify the limitations/benefits of the semi-pneumatic and pneumatic wheels and the rubber & polyurethane caster wheels (with regards to achieving a smooth ride with minimal vibrations)
- To evaluate the motor-wheel connections and choose the one that is the most durable
- Determine the speed of the robots after they have been assembled to validate their maneuverability

10.2 TEST SETUP & APPARATUS

Figure 19 shows the components that were used in the test setup, and their approximate locations. (Note that the side walls are not shown here to provide a view of the components.)

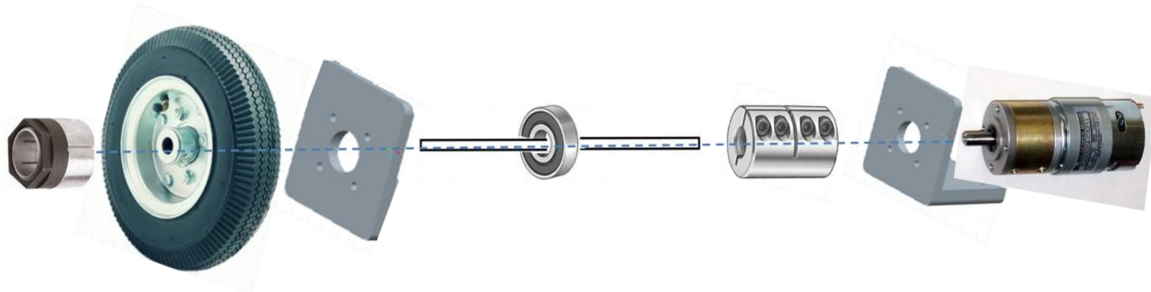
Figure 19: Test setup equipment



10.2.1 Mechanical setup

The drive train was set up as shown below in figure 20. Each robot has two of these assemblies, one for each drive wheel. From left to right are the keyless bushing, wheel, bearing housing, axle, bearing, c-clamp, motor mount, and motor.

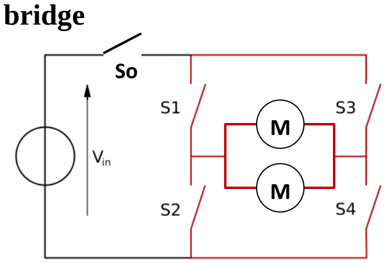
Figure 20: Drive train assembly showing each component, bolts were omitted



10.2.2 Electrical circuit Setup

We used the circuit board's H-bridge to control the motors for our tests and will construct the motor power/control circuit as follows. The one 12V batteries will be connected in to provide power to the motors. The motors were both placed in parallel with the battery which allows them to both receive 12 volts. Figure 21 below shows the electrical circuit with the circuit board and H-bridge; V_{in} is provided by the battery.

Figure 21: Motor power and control circuit. V_{in}=12V, M=motors, S=switch, S1-S4 represent the H-bridge



The accelerometer was attached to the base and was used to measure the vertical accelerations that occur due to the vibration of the robot during motion. There is a port connecting the accelerometer to the laptop (which will have a program that obtains acceleration data) for data recording. The accelerometer measured the vertical and horizontal accelerations, which in turn can be used to find the wheels damping and horizontal velocity respectively.

The base was fabricated by laser cutting of the 9mm thick Baltic birch plywood. Please refer to the manufacturing process plan in Appendix D for more details on the laser cutting process.

10.3 PROCEDURE

Overall, six experiments were executed. The list of experiments and the variables being tested is given below in Table 14.

Table 14: Experiments to test

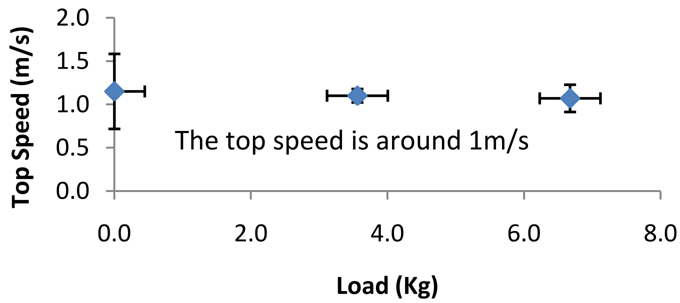
Experiment Number	Description	Motor		Wheel Type	
		IG32	IG42	Semi-Pneumatic	Pneumatic
1	Maximum motor speed without loading	x		x	
2			x	x	
3	Wheel vibration damping		x	x	
4			x		x
5	Keyless bushing strength		x	x	
6			x		x

10.3.1 Motor Speed Analysis

This test will be used to determine which of the two motors can move the robot with a velocity of at least 1m/s with a payload of 20Kg. During the motor and gearbox selection, we have conducted an estimation of maximum speed for the data sheet of the selected components. However, the actual top speed, also dependent on unknown drag and resistance, is undetermined unless we run the real test.

We conducted a 5 meter drag test indoors (on carpet) and measured the time to cover the whole distance. Because it takes about one sec for the robot to accelerate to its top speed, negligible to the total time, we used the average speed of the total distance as the top speed. However, due to the limitation of the circuit and H-bridge, only one battery (12V) is used other than the rated voltage of the motor (24V), as a result, the robot can move only at a lower speed than predicted.
We performed five test runs and calculated the top speed of each test. We then added loads to measure the top speed under different load condition. The total result is plotted in Figure 22.

Figure 22: Top speed under different loading condition, with 12V power input.

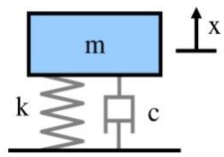


10 m speed test	
IG32	IG42
.85 m/s	.95 m/s

As shown above, the load has limited effect on the top speed, which maintains at 1 m/s. If two power resources in series (24V) are adapted, a higher speed is feasible. However, even under 12V, the robot can still keep up with human walking speed and the customers’ requirement is met.

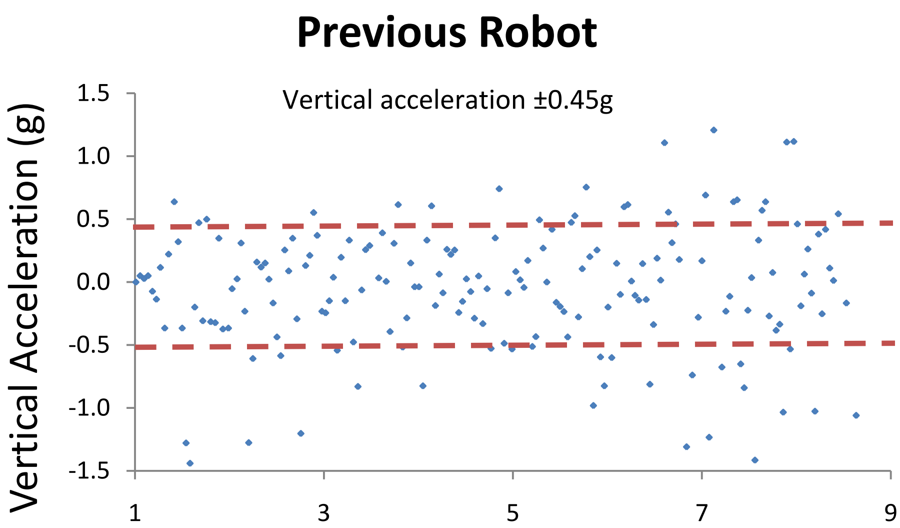
10.3.2 Damping Analysis
For this test we will drive the robot over some rough terrain outside; including sidewalk bumps and pot holes, as this is the most rugged terrain the robots will experience. We will use the accelerometer data and our visual analysis of the robot over this terrain to compare the maximum accelerations present for each wheel. The robot can be simplified to a simple mass-spring-damper system. The wheels will act as a spring and damper while the rest of the robot will act like the mass. This is shown in Figure 23 below.

Figure 23: This figure shows the behavior of the robot is like that of a mass-spring-damper system



We measured the vertical acceleration of the current robot running full speed on asphalt surface of a parking lot. The results are shown in Figure 24.

Figure 24: The vertical of acceleration of the old robot



We used time-averaged acceleration magnitude as the parameter to compare the severity of vertical oscillation. The dynamics of the robot chassis is complex: there are traditionally 18 degrees of freedom of a three-wheel chassis and even more if there is compliance between chassis and wheels. To simplify the system, only the vertical translational acceleration on the geometric center of the base is used to describe the motion of the whole robot. The less smooth the ride is, the higher the acceleration will be. The time-averaged value is adapted to eliminate the difference of time scale of each test and the directional effect. As shown in Figure 24, the averaged acceleration of the old robot is 0.45g.

We also tested the prototype robot with both pneumatic and semi-pneumatic tires, shown in Figure 25.

Figure 25a: The vertical acceleration of the new robot with pneumatic tires

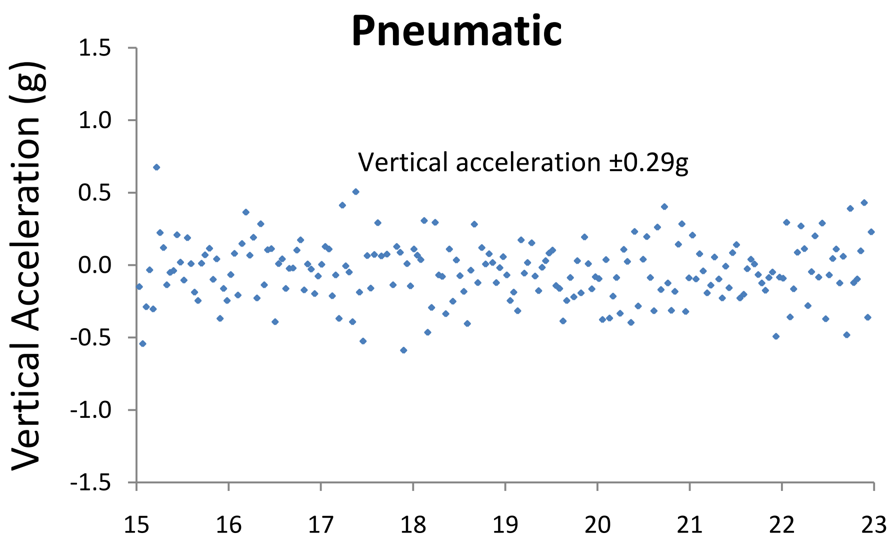
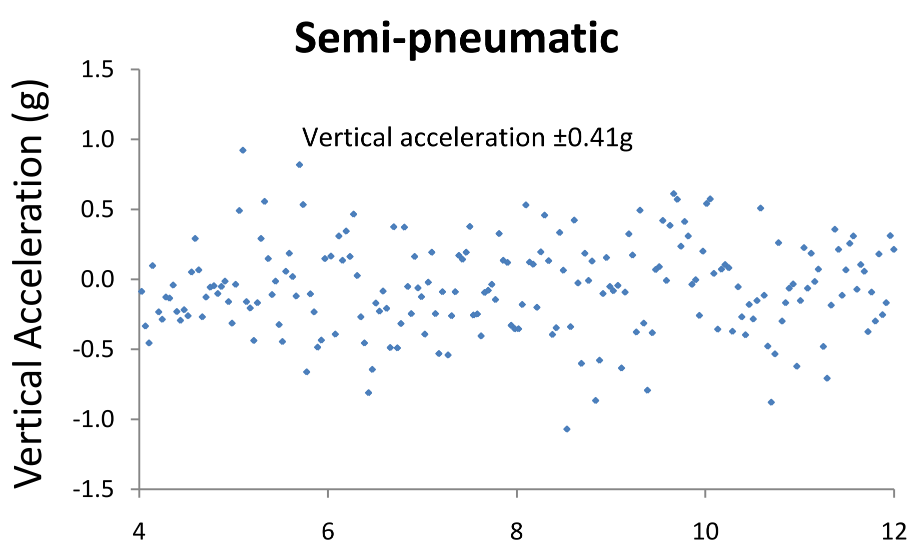


Figure 25b: The vertical of acceleration of the new robot with semi-pneumatic tires



Using fully pneumatic tires, we reduced the averaged vertical acceleration by 36% to 0.29g while using semi-pneumatic decreases it by 16% to 0.41g. It is not a surprise that the pneumatic tires, which provide a better compliance and damping, ride smoother than the semi-pneumatic tires. Also, the optimal weight distribution and smaller wheel size contributes to the smooth ride as well.

10.3.3 Wheel Connection Testing

Another requirement is to find a solution to improve the current wheel connection, the cotter pin that breaks about every 5 minutes. As in design description, keyless bushings are used as wheel and shaft coupling. It is pretty hard to measure the life span of the connection.

During the design Expo, the robot was in use for several hours and the wheel connection survived all the test drives. Considering the duration of lab study on the robot in future is under an hour, we can conclude that the improvement on wheel connection meet the customers' requirements and engineering specifications.

Besides, using keyless bushings make it possible to change the wheels with ease. We can change one wheel less than 1 minute with a wrench. As a result, the interchangeable wheels make it possible for researchers to choose the right wheels for better compliance and more accurate odometry.

10.4 SAFETY ISSUES

Safety precautions must be observed when conducting the experiments and during the handling of equipment. The lead-acid batteries should not be over-charged, as overcharging can cause explosion. Always connect it to a volt-meter during charging to determine the voltage, and disconnect if the maximum voltage has been reached. A better option would be to use a programmable power supply, which automatically controls the supply of current depending on the battery voltage.

Since at sometimes two batteries are used, the total voltage is at 24 V, so there is a voltage hazard. It is therefore important to use safety gloves if possible while handling equipment. Ensure that the insulation in the wires is intact so as to prevent any direct contact between the wire and skin. Skin should be dry as water reduces the body internal resistance, increasing probability of current flowing into the body.

The experimentalist must ensure that the battery terminals are connected to the corresponding terminals of the components so that there will be no potential hazards.

The voltage through the motor should not exceed the voltage rating set by the manufacturer since such carelessness would damage the motor. It would be wise to use a resistor in the circuit to allow a potential drop so that the voltage through the motor is always less than the maximum, which is safer (even though the power extracted might be less).

11. CHALLENGES

There are several challenges for this project. First, is the compromise among the rapid manufacturability, low cost, and multipurpose function aspect of the robot design. Second, the balance between outdoor and indoor performance will be an issue. Specifically, the robots wheels need to be able to absorb as much of the vibrations as possible while keeping an accurate odometry. A durable wheel attachment is also a challenge because none of our team members have experience in this field. We may also face some difficulties in designing and building the sensing bumpers, which requires a background in dynamics, signal processing and electrical control.

12. DISCUSSION

This section details improvements that can be made to our design. There are several challenges for this project. First, is the compromise among the rapid manufacturability, low cost, durability, and multipurpose capabilities of the robot design. Second, the balance between outdoor and indoor performance was a consideration. Specifically, the robots wheels need to be able to absorb as much of the vibrations as possible while keeping an accurate odometry. Since the odometry is based on the wheel diameter having soft wheels that deform would reduce the quality of the readings. A durable wheel attachment is also a challenge because none of our team members have experience in this field.

12.1 Design Critique

Although we put much thought into the concept of our design there were some things that we feel could be improved upon. Our sponsor has mentioned some design changes he would like made, including putting the bearings in the walls instead of external housings and using a larger caster.

Machining of the bearing housings could have been simplified. The bearing housing transmits the load from the axle to the chassis. They were machined from aluminum blocks which took much time. It may be possible to cut them from remaining plywood scraps we had which will decrease the cost of the robot and greatly reduce the machining time as the laser cutter cuts wood much faster than the mill cuts through aluminum. This would not reduce our part count or assembly time but it would greatly simplify our manufacturing process and reduce cost. We considered this design option before but thought that the bearing housings should be made extra durable so as to be extra durable and strong. We also considered cutting holes in the walls to use as the bearing housings. We decided against this as the bearings are wider than the walls and because the limited space (from the maximum size of laser cut pieces) required that the bearing sit outside the main chassis, so an additional part had to be made to facilitate this.

It may also be possible to make motor mounts out of wood as well instead of aluminum. If the motor mounts were to be made using wood cut in the laser cutter they would need to be made from multiple pieces glued together instead of one aluminum bracket.

Another improvement that could be made is using a caster with a larger wheel size and mount height. This would allow the robot to clear more obstacles and reduce the chance that it would get tuck. This could be done by a few methods. The motors could be mounted underneath the robot instead of inside it, which would increase the clearance under the robot by the motor diameter and wood thickness (5.5cm). It could be difficult to mount the bearing housings underneath the robot as they are attached to the walls. Mounting them could have been achieved by having a section of the walls protrude under the robot from the main chassis. Since we were able to just fit a number of walls on one piece of plywood this design would require more wood to be purchased for each robot as each of the longer wall sections would need its own piece of wood. Using a larger caster could also be done by having the motors rest on the base of the robot (so the mounts are not under it and not space is left between it and the chassis). This would give about a half inch of space for a slightly larger caster. Alternatively the caster could be mounted on a surface that is higher than the main base of the robot.

While there are some changes that could simplify our design we made a number of critical improvements to the previous version of the robot that will provide researchers and students a much better robot platform to use.

13. RECOMENDATIONS AND FUTURE WORK

This section details our recommendations for the final robot design based on our tests and discussion with our sponsor. From our experiences with this project we have come up with some recommendations for our sponsor. We suggest a test simplification of the bearing housings, a larger caster that is mounted higher than the chassis base, use of the IG42 motors, pneumatic tires, keyless bushings, shaft coupling clamps, and aluminum motor mounts; all of which are detailed earlier in this report. All these recommendations should be carefully considered before fabricating any more robots.

After running tests on the IG42 and IG32 motors we recommend the IG42 with the 28 poles per revolution encoder, and a 19:1 gear ratio planetary gear box. The IG42 with this configuration gives the robot a higher speed, better acceleration, allows it to clear larger obstacles, ability to carry a greater load at reasonable speeds, and better odometer over the IG32 (smaller size leads to less encoder poles. The speed is also improved over the design of the old robots.

We recommend sticking with the lager chassis size and shape of the first prototype. This will allow the use of the IG42 motors as it gives more room for the components.

For the tires we recommend using the 8” pneumatic tires. Using these gives the robot good vibration damping and as long as the tire is inflated (25-30 psi) properly the odometer accuracy should not be affected by wheel deformations. They give a
Keyless bushings are recommended due to their durability and prevent the wheel from slipping on the drive shaft.

As stated above in the Discussion section, the bearing housings could be made from scrap pieces of wood instead of aluminum. Two pieces of We recommend that this design change is tried. It will not take too much work manufacture the parts, (about 1 hour of CorelDraw and laser cutting). They can then be tested on the current prototype to see how they function. Also once the CAD is done for them they can easily be re-produced in a few seconds along with the other wood components. This will decrease manufacturing time and cost. We don’t believe that making the walls act as the bearing housings is viable as there is no space to do this.

The motor mounts were not too difficult to make and we do not recommend making them out of wood due to increased parts and assembly times. We recommend making them from aluminum as in the prototypes.

As for mounting the motors under the robot we believe this would raise the center of gravity too much and require such a large caster that the maneuverability will be compromised by. We recommend testing the IG42 motors mounted underneath the robot with the larger casters.

We recommend that a larger caster be used in the final design than in the first prototype and smaller than that in the second prototype. A caster size of 2.625” should work well. This size should be tested and implemented in future robots if it suits our sponsor’s needs. This can be implemented by raising the platform where the caster is mounted.

We also faced difficulties in designing and building the sensing bumpers, which requires a background in dynamics, signal processing and electrical control. We recommend that this be looked into further by future groups either in ME450, UROP, or another group.

We recommend anyone making future robots should follow our safety guidelines and manufacturing instructions for the best results and safe manufacturing.

After considering these recommendations and making any wanted improvements the desired number of robots can be made to facilitate further research and education. Also at that point, as stated in the project definition, the files associated with the robot should be made “free source” to give students and researchers at other universities and schools the ability to increase robotics education and research.

We will be editing the prototypes over the remaining part of the semester in order to make some more improvements before delivering them to Prof. Olson.

14. SUMMARY AND CONCLUSIONS

We worked with our project sponsor, Prof. Olson, to improve the current robot design in order to create a better robotics platform for research and education. Our man objectives were to improve the dynamics and structural integrity of the robot while making it easy to rapidly manufacture and keeping a relatively low cost for its capabilities, around $500 per robot. We identified our primary and secondary goals, conducted literature searches, interviewed professors, tested the prototype, and have come up with a final design. We have determined to stick with wood for the body of the robot because of its east to make parts out of using the laser cutter, strength, and light weight. We optimized the general features to meet the criteria of manufacturing. We chosen the type of motor and wheels and found the right caster for our design. We have designed the shaft extender to transmit torque form motor to wheel. An extra bearing is used to decouple the load. C-clamp and keyless bushing are the components for drive-train connection respectively. We have manufactured two robots and provided CAD and assembly instructions online so that Prof. Olson and anyone else can easily produce their own robots.

15. ACKNOWLEDGEMENTS

We would like to thank our sponsor Professor Edwin Olson and our section advisor Professor Hong Im for their time and support with this project. Their help was crucial to the completion of this project and it was much appreciated. We would also like to thank Professor Skerlos for leading this term’s ME450 section. Finally we would like to thank Professor Gillespie, Professor Tilbury, and Professor Ulsoy for sharing their expertise in robotics and Dan Johnson for being a helpful GSI during the course.

16. REFERENCES

[1] Burton, T., Sharpe, D., Jenkins, N., & Bossanyi, E. (2001). Properties of wood laminates, wind energy handbook. *Wind energy handbook* (pp. 378) John Wiley & Sons.
[2] Kipp, D. O. (2004). *Plastic material data sheets* MatWeb - Division of Automation Creation, Inc.
[3] Kutz, M. (2006). *Mechanical engineers' handbook - materials and mechanical design (3rd edition)* John Wiley & Sons.
[4]The Wood & Shop Inc. "Baltic birch plywood, Russian, Finland, craft plywoods".http://www.woodnshop.com/Hardwood/Baltic_Birch_Plywood.htm, Jan 28, 2008
[5] Zhang, H., Baier, T., Zhang, J., Wang, W., Liu, R., Li, D., et al. (2006). "Building and understanding robotics - A practical course for different levels education." *2006 IEEE International Conference on Robotics and Biomimetics, ROBIO 2006*, 61-66.
[6] Jeschke, S., Knipping, L., Liebhardt, M., Muller, F., Vollmer, U., Wilke, M., et al. (2008). "What's it like to be an engineer? Robotics in academic engineering education". *2008 Canadian Conference on Electrical and Computer Engineering - CCECE*, 000941-6.
[7]Fenner Drives, "Products Specification", p6, 2009
[8] Robert K. Sleeper and Robert C. Dreher, "Tire Stiffness and Damping Determined from Static and Free-Vibration Tests", NASA technical paper 1671, 1980
[9] PHANS B. PACEJKA, "Approximate Dynamic Shimmy Response of Pneumatic Tires", Vehicle System Dynamics, 1973.
[10] J.A. Rongong. The design of particle dampers for suppressing resonant vibrations. *ENGINEERING INTEGRITY*, *16*(JULY 2004), 24-30.
[11] "iRobot: Robot Roomba Vacuum Cleaning Robot", 2008, http://store.irobot.com/category/index.jsp?categoryId=3334619&cp=2804605&ab=CMS_RobotSuper_Roomba_102308
[12] McMaster-Carr, "Keyless bushings", "cotter pins", "key stock". http://www.mcmaster.com, Feb 16, 2008
[13]Masaki Sekine, Toshiyo Tamura, Toshiro Fujimoto et al, "Classification of walking pattern using acceleration waveform in elderly people", 22nd Annual Engineering in Medicine and Biology Society, July 2000

APPENDIX A

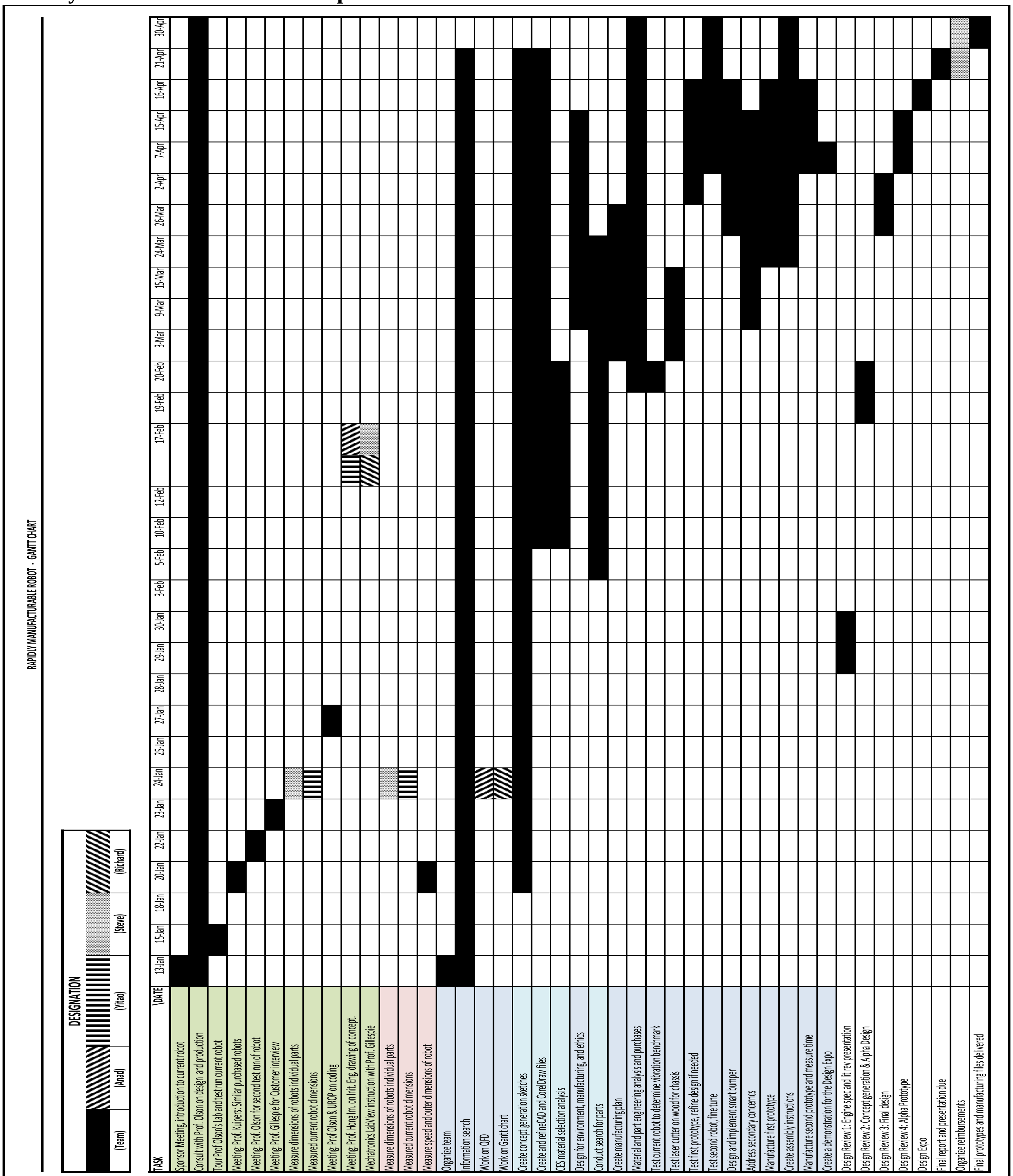
Figure A1: QFD diagram detailing importance of and relations between customer requirements, engineering requirements, and their interrelations

Engineering parameters	Number of Parts	Time for Manufacturing (< 15 hrs)	Top Speed (>= 2 m/s)	Turning Radius (m)	Frictional Torque on Wheel Connection (N-m)	Maximum Payload (> 20 kg)	Center of gravity	Accuracy of Odometer (%)	Price relative to commercial product (%)	Surface area of platform (m^2)	Obstacle Sensing Distance (m)	Wire Labels (A,B,C,etc.)	Interna space
Number of Parts													
Time for Manufacturing (< 15 hrs)	9												
Top Speed (>= 2 m/s)													
Turning Radius (m)													
Frictional Torque on Wheel Connection (N-m)	1		9	1									
Maximum Payload (> 20 kg)			3										
Center of gravity	1		3			1							
Accuracy of Odometer (%)					3		3						
Price relative to commercial product (%)	3	3	3			3		3					
Surface Area of Platform (m^2)		1	1	3		1	3		1				
Obstacle Sensing Distance (m)								9					
Wire Labels (A,B,C,etc.)	1	3							1				
Internal space		1		3		3	1		1	3	1	1	

Quality Functional Deployment

Customer Specifications	Professors	Students	Number of Parts	Time for Manufacturing (< 15 hrs)	Top Speed (>= 2 m/s)	Turning Radius (m)	Frictional Torque on Wheel Connection (N-m)	Maximum Payload (> 20 kg)	Center of gravity	Accuracy of Odometer (%)	Price relative to commercial product (%)	Surface area of platform (m^2)	Obstacle Sensing Distance (m)	Wire Labels (A,B,C,etc.)	Interna space
Low Cost of Production	9	3	9	9	9			1		1	9	1	3	1	3
Easy to manufacture	9	9	9	9	1			1			3	1	1		3
Easy to reconfigure	3	3	3	3	1			1			3	1	1		3
Well-organized Wires for easy access during maintenance	1	3		3							3			9	1
Able to keep up and interact with humans	9	9	1	1	9	3		1	3	3	9		3		1
Versatile platform	9	3	1	3	1			9	3		9	3			3
Robust motor/wheel connection	3	3	3		3		9	3		9	1				
Interchangeble wheels	3	3	3		1					3	1				
Stable ride	1	1			3			3	9	3	1	3			
Smooth ride	3	3	1		3			3	9	3	1		1		
Can withstand bulky and heavy loads	3	3			3			9	3		1	3			3
Maintain Performance regardless of surface	9	9			9			3	3	3	1				
Highly manuverable	3	3	1			9		3	3	1	1	3			
Braking	1	1	1				3	3	3	3	1				
Emergency stopping	3	1	1				3				1			1	
Durable	1	1	3	3							1				
Low maintenance	3	3	3	1	1		3				1				3
Predicts and avoids obstacles accurately	9	9				3				9	9	3	9		
STUDENT			167	150	240	81	42	138	120	192	292	72	132	31	84
PROFESSOR			229	216	300	81	48	198	138	198	396	96	150	21	118
Total			396	366	540	162	90	336	258	390	688	168	282	52	202

Figure A2: Gantt Chart detailing our tasks, who will perform them, and the times in which they will be conducted and completed



APPENDIX B

Table B1: Part List for current robot detailing quantities, dimensions, and other specifications.

Category	Part #	Part Name	Function	Qty	Unit Cost ($)	Material	Color/Finish	Size	Manuf. Process	Notes
Materials		Plywood for body	To make chassis components	4	11.95	7 ply Baltic Birch Plywood boards	Wood	3/8"x24x39	Laser cutter, filed, drilled, painted, glued	
		Tight bond 3	To attach chassis components	1	7.95	Wood glue	White	16 oz	Connect chassis components	
		Aluminum L-beam	Motor mounts	2	5.00	Al 6061	Silver	5cm x 5cm x 0.5cm thick x 5cm long	Milled	
	6750K173	Multipurpose Al 6061 rod	Axle	2	9.79	Al 6061	Silver	36"x5/8" diameter	Cut, lathed	
		Aluminum round stock	Wheel hub	2	7.00	Al 6061	Silver	1-3/4" x 6"	Lathed, drilled, press fit	
		Almuminum bar stock	Bearing housings	2	10.00	Al 6061	Silver	55mmx64mmx18mm	Milled	
		Bolts, washers, nuts for motor mounts	Bolt motor and bearing mounts to chassis	24	0.10	Steel	Silver	1/4-20 x 1"	Bolted	
		Bolts, washers, and nuts for bearing housings	Bolt bearing housings to side walls	24	0.10	Steel	Silver	1/4-20 x 1-1/4"	Bolted	
		Bolts, washers, and nuts for bearing housings	Bolt caster to base of chassis	12	0.10					
		Small bolts for motor attachment	Attach motors to motor mounts	8	0.10	Steel	Silver	M4 x 10mm	Screwed into motor	
Parts	TD-044-252	IG42 Motors, planetary gear box, and encoder	Provide torque to wheels, measure distance traveresed	2	53.95	Permanent magnet, steel housing, copper widing	Black/Silver	44cm diam	Bolt, clamp	T=60kg-cm, w=250RPM, Geared 19:1
	PRE16113TZ-3R	Soft rubber swivle caster	Bearing mounts	1	12.95	Aluminum/Rubber	Black/Silver	1.625" high	Attached with bolts	70 lb capacity
	18923	8 in. Pneumatic Wheel	Drive wheels, vibrations damping	2	14.99	Rubber tire with steel hubs	Black/Silver	8" diam x 2" wide	Press fit, keyless bushings	250 lb capacity
	9658T4	Shaft coupling		2	11.99	Al 6061	Silver	inner diam=5/16" x 5/8" long	Clamped down on axle and motor	
	6202660	Keyless bushings		2	25.40	Steel, zinc coated		ID=6mm, OD=16mm, L=	Expanded onto wheel hub and axle	
	0200667722 84	Spray paint can	Water resistance and robot differentiation	3	3.25	Paint	Blue	can	Paint chassis	
	ILA1212000	12 V Lead acid battery	Power robot	1	40.00	Plastic exterior, lead acid	Black	15"x9.7"x9.5"	Connected with slide on wires	
	6384K365	Roller bearings, double sealed, flaged	To transmit loads from the drive train to the chassis	2	9.66	Steel	Black/Silver	5/8" ID 1-3/8" OD 1/2' wide	Placed in bearing housing, axle pushed through	300lb load capacity
	TOTALS:			93	400.28					

ID #	Item Number	Material Name	Material Des
1	131402	Baltic Birch Plywood, 9mm	9 mm ply Baltic Birch Pl dimensions: 0.375
2	6750K173	Multipurpose Al 6061 T6 rod	5/8" diam, 36" long. W extension for both robo
3	S1847KH1	2x2" square hardwood posts	2"x2"x8' To be used for platform support frame

ID #	Item Number	Part Name	Part Descri
1	9908T12	Cart King Dual Wheel Caster	Swivel caster with 2 rub supported by double ba carrying capacity of 200
2	PRE16113TZ 3R	1.625" Soft Rubber Swivel Caster	1.625" Soft Rubber Swi with 70 lb load carrying
3	TD-044-252	IG42 24VDC 252 RPM Gear Motor with Encoder	42 mm Gearbox Planet with 252 RPM maximum velocity & encoder for s measurement
4	TD-015-265	IG32P 24VDC 265 RPM Gear Motor	32 mm Gearbox Planet with 265 RPM Maximum Velocity
5	[illegible]-CCDCBL	Cable Caddy Organizer	Cable Caddy Desktop C
6	C-200-10AHB	10 A+ Dual H-Bridge	Dual H-Bridge Controlle Controlling Motors
7	SKU-432595	1NXA4 Semi-Pneumatic Wheel	8 inch diameter semi-p for lawn mower with lo lb
8	SKU-61819	2G345 Light Duty Lawn Mower Wheel	8 inch diameter semi-p for lawn mower with lo lb
9	18923	8 in. Pneumatic Wheel	8 inch diameter Pneum 250 lb load carrying cap
10	6384K365	Flanged ball bearings, sealed	Inner diam= 5/8", oute
11	9658T4	Shaft coupling	inner diam=5/16" , 5/8
12	61005K3	Shaft coupling	inner diam=5/16" , 1+3
13	6202660	Keyless bushings	Inner diameter 6mm, o length 19.1mm

APPENDIX C: Concept matrices

Figure C1: Selection matrix

	CHASSIS CONCEPTS						
Selection Criteria	A	B	C	D	E	F	Current Model (Datum)
Ease of Assembly	+	-	-	-	0	0	0
Cost of Development	0	-	-	-	0	0	0
Ability to withstand Payload	+	+	+	+	+	+	0
Dynamic Response Capability	+	+	+	+	+	+	0
Maneuverability	+	+	+	-	-	0	0
Sum +'s	4	3	3	2	2	2	0
Sum 0's	1	0	0	0	2	3	6
Sum -'s	0	2	2	3	1	0	0
Overall Sum	4	1	1	-1	1	2	0
Rank	1	3	3	7	3	2	6
Continue?	Yes	No	No	No	No	Yes	No

Figure C2: Concept scoring matrix

		A		F	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Ease of Assembly	0.3	4	1.2	3	0.9
Cost of Development	0.1	3	0.3	3	0.3
Ability to withstand Payload	0.3	5	1.5	4	1.2
Dynamic Response Capability	0.2	4	0.8	4	0.8
Maneuverability	0.1	4	0.4	3	0.3
Total Score			4.2		3.5
Rank		2		1	
Continue?		No		Yes	

Figure C3: Selection matrix

Selection Criteria	Coil Spring	Particle Damper	Leaf Spring	Hydraulic Suspension	Pneumatic Suspension	Pneumatic Tire	Solid Robber Tire (Datum)
Monetary Cost	0	+	+	-	-	0	0
Linearity/Predictability of Behavior	+	-	-	+	+	+	0
Amount of Damping provided	+	+	-	+	+	+	0
Ease of Installation	-	-	-	-	-	0	0
Sum +'s	2	2	1	2	2	2	0
Sum 0's	1	0	0	0	0	2	4
Sum -'s	1	2	3	2	2	0	0
Overall Sum	1	0	-2	0	0	2	0
Rank	2	3	7	3	3	1	3
Continue?	Yes	No	No	No	No	Yes	No

Figure C4: Concept scoring matrix

		Coil Spring		Pneumatic Tire	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Monetary Cost	0.35	3	1.05	3	1.05
Linearity/Predictability of Behavior	0.25	4	1	4	1
Amount of Damping provided	0.15	4	0.6	4	0.6
Ease of Installation	0.25	2	0.5	3	0.75
Total Score			3.15		3.4
Rank		2		1	
Continue?		No		Yes	

Figure C5: Selection matrix

	CONCEPTS		
Selection Criteria	Keyless Bushing	Keyed Bushing	Cotter Pin (Datum)
Maximum Torque	+	+	0
Minimum Machining Time	+	0	0
Purchase/ Manufacturing Cost	-	+	0
Sum +'s	2	2	0
Sum 0's	0	1	3
Sum -'s	1	0	0
Total Sum	1	2	0
Rank	2	1	3
Continue	Yes	Yes	No

Figure C6: Concept selection matrix

		Keyless Bushing		Keyed Bushing	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Maximum Torque	0.35	4	1.4	5	1.75
Minimum Machining Time	0.2	5	1	3	0.6
Purchase/ Manufacturing Cost	0.45	1	0.45	2	0.9
Total Score		2.85		3.25	
Rank		2		1	
Continue		No		Yes	

APPENDIX D: MANUFACTURING/FABRICATION PLAN

D1. GENERAL SAFETY PRECAUTIONS

The following general safety precautions apply to all machining processes and must be strictly followed:

1. Wear safety glasses, close toed shoes and long pants. Do not wear any loose clothing.
2. Tie back any long hair that might get caught in any machinery. Tuck in any shirt or t-shirt into pants.
3. Do not wear any jewelry, watch or anything on the wrist or fingers as they can get caught in machinery.

D2. CUTTING SPEED CALCULATIONS

The Machinery Handbook was used to determine the required cutting speeds. The cutting speeds will depend on the size of the tool used for milling and drilling, and the initial diameter of the work piece and the feed rate for turning. For the band-saw, the value of 275 RPM for the blade oscillation is the recommended value that is used in the machine shop for cutting aluminum.

The equation used to calculate the cutting speed is as follows:

$$N = \frac{12 \cdot V}{\pi \cdot D}$$

Where:

- N is the cutting speed in revolutions per minute (RPM).
- V is the linear velocity in ft/min.
- D is the diameter of the tool or the work piece, depending on the machine under consideration.

For cold drawn 6061-T651 Aluminum alloys, the optimal cutting speed is 165 ft/min. for drilling. For turning, the linear velocity will be slightly modified to account for the feed rate we plan to use as well as the depth of cut required. The modifications are carried out by multiplying the optimal speed with the feed factor F_f and the Depth-of-cut factor F_d as shown in the following equation:

$$V = V_O \cdot F_f \cdot F_d$$

These are the following values of the depth of cut, the feed rate and the corresponding factor values for these machining parameters we will use:

Machining Parameter	**Value of Parameter**	**Factor Value**
Feed Rate (in./rev) *(i=f)*	0.020	0.80
Depth of cut (in.) *(i = d)*	0.375	0.86

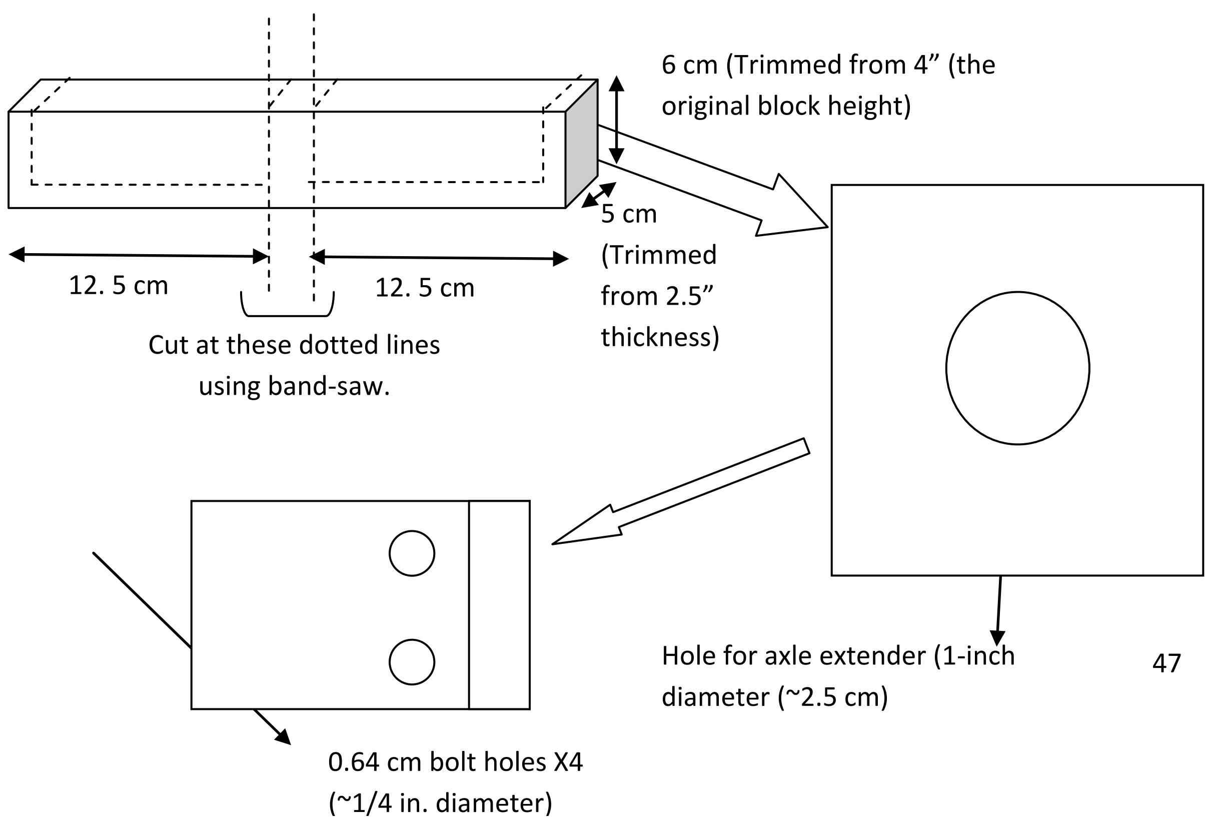
The linear velocity recommended for turning 6061-T651 Aluminum is 500 ft/minute. Using these correction factors, the linear velocity we will get is 344 ft/min.

D3. MOTOR MOUNT

The motor mount will be fabricated according to the drawing shown in section 2.1. Manual machining will be used to fabricate the mount. The cutting tool used will be high speed steel, which is the standard tool material used in the machine shop. The stock used will be a 6061-T651 Aluminum Alloy Block with dimensions of 12” by 4” by 2.5”.

The specific operations and any special safety precautions that are required are given in the table below:

Step	Operation	Machine/ Tool	Cutting Tool	Cutting Speed	Notes	Additional Safety Precautions
1	Cutting Block to required dimensions	Band-saw	Steel Blade	275 RPM	Feed Rate at 50 ft per min. See diagrams for exact cutting operations	Push block using a vise saw to avoid hands from getting cut by the blade
2	Milling to create the hole for axle extender	Milling Machine	1” end mill tool	600-700 RPM	See diagrams for exact cutting operations.	N/A
3	Milling to create bolt holes	Milling Machine	1/4” end mill tool	2,500 RPM	See diagrams for exact cutting operations.	N/A
4	Filing to round edges	File	N/A	N/A	Scrape along sharp edges of block to remove material & obtain smooth surface	Sharp edge could abrade skin and cause bleeding. Try to avoid skin contact with sharp corners.



D4. AXLE EXTENDER

The axle extender will be fabricated according to the drawing shown in section 2.2. Once again, manual machining will be used for fabrication. The cutting tool material will be high speed steel, and the stock used will be a 1 foot long 6061-T651 Aluminum rod with a diameter of 1 inch.

The specific operations and any safety precautions are given below:

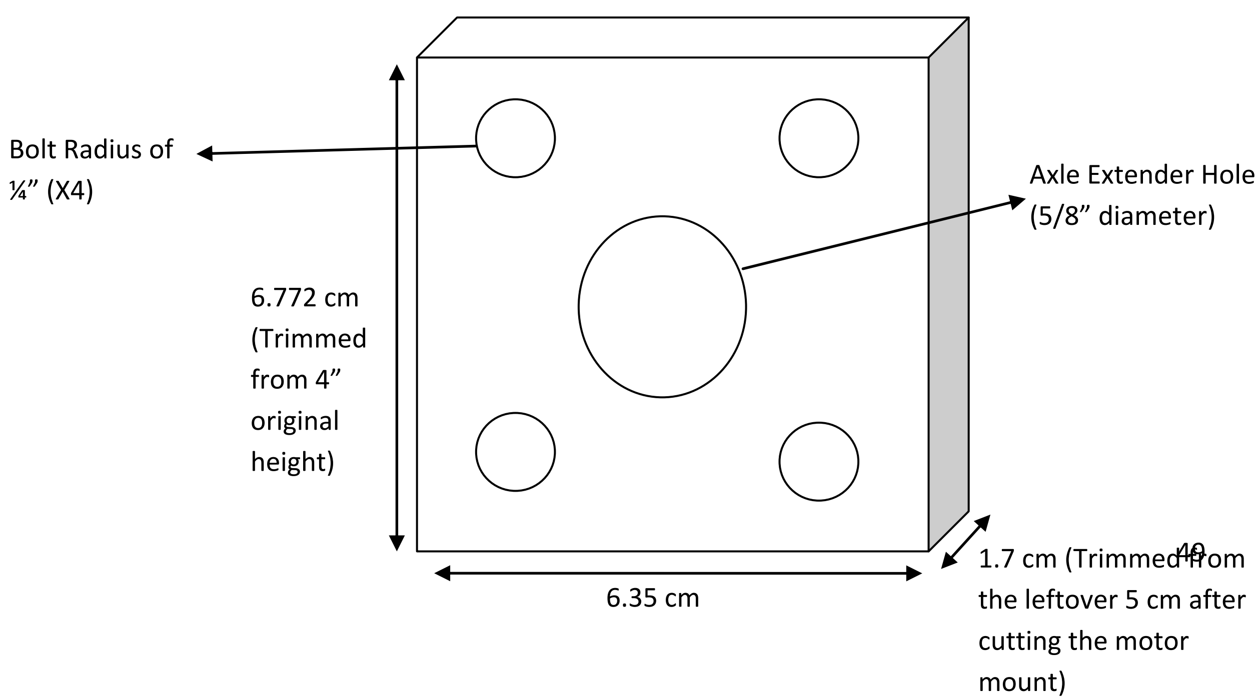
Step	Operation	Machine	Cutting Tool	Cutting Speed	Notes	Additional Safety Precautions
1	Turning to obtain the required axle diameter	Lathe	High Speed Steel Turning tool	1,300 RPM	Using a depth of cut of 0.375 in. to obtain the required diameter. Feed rate at 0.02 in./rev.	N/A
2	Drilling to obtain the shaft slot	Lathe	Center drill, 3/8” drill bit	1,000 RPM	Feed Rate at 0.02 in./rev	Use cutting fluid to cool metal as heat is produced by friction.
3	Turning to obtain the diameter for keyless bushing	Lathe	High Speed Steel Turning tool	2,000 RPM	Using a depth of cut of 0.375 in. to obtain the required diameter. Feed rate at 0.02 in./rev.	N/A
4	Cutting Rod to required length from the 1 foot long rod.	Band-saw	Steel Blade	275 RPM	Feed Rate at 50 ft per min.	Push rod using a vise saw to avoid hands from getting cut by the blade

D5. BEARING HOUSING

The bearing housing is made up of two parts: the slot block where the bearing is placed, and a 1-mm thick plate which is used to seal the face of the block with the flanged side to prevent the bearing from slipping. Each

D5.1 Housing Block

Step	Operation	Machine	Cutting Tool	Cutting Speed	Notes	Additional Safety Precautions
1	Cutting Block to required dimensions	Band-saw	Steel Blade	275 RPM	Obtained from remaining material after cutting material for the motor mount. See diagrams for exact cutting operations.	Push block using a vise saw to avoid hands from getting cut by the blade
2	Milling to create the hole for axle extender	Milling Machine	5/8” end mill tool	1,000 RPM	See diagrams for exact cutting operations.	N/A
3	Milling to create bolt holes	Milling Machine	1/4” end mill tool	2,500 RPM	See diagrams for exact cutting operations.	N/A
4	Filing to round edges	File	N/A	N/A	Scrape along sharp edges of block to remove material & obtain smooth surface	Sharp edge could abrade skin and cause bleeding. Try to avoid skin contact with sharp corners.



D5.2 Face Plate
The most efficient way to fabricate the face plate is given by the following steps:

1. First, the 5-cm thick block left after cutting the material for the motor mount will be subject to the operations mentioned in section 3.5.1.
2. Then, two 18 mm thick blocks are cut using the band-saw at a rate of 275 RPM (feed rate of 50 ft/min).
3. From the remaining 14 mm thick block, two 1.5-mm thick blocks are cut at the same rate and feed rate.
4. After these plates are obtained, they will be filed using a file to remove any rough and bumpy surfaces and to reduce their thickness to 1 mm.

The safety precautions one has to take would be the following:

1. Use a vise to push work-piece through the band-saw to avoid any injuries to the hands.
2. Try to avoid skin contact with sharp corners during filing so as to prevent bleeding.

D6. CHASSIS BASE, WALLS & PLATFORMS
The chassis base will be manufactured using the laser cutter. The stock will be the 9-mm thick 24" by 30" Baltic birch plywood.

1. From the drawings that were created, the chassis base will be re-generated in Bob-CAD software from scratch due to compatibility issues with the CAD software in the CAEN computers. Bob-CAD is currently only available in the X50 machine shop.
2. It is important to check that the geometry is correct and parts should be fitted as close together as possible.
3. Protective coating paper should be placed on top of the wood before cutting.
4. Material will then be placed on the cutting surface. Care should be taken to ensure that it is flat.
5. Close top door on the laser cutter.
6. After file is sent, go to file/print. Then check to make sure that it is configured as follows:

    6.1 The scale should be 1:1
    6.2 Now go to setup menu.
    6.3 Makes sure selected printer is X2-600 and in landscape mode.
    6.4 ***Now go to properties menu***.
    6.5 Red should be used for cutting- make sure you see Rast/Vect
    6.6 Set power 90% speed 1.2% gas assist High.
    6.7 Blue should be used for engraving.
    6.8 Set for Rast/Vect, power 40% speed 40% gas assist High.

7. When all of the above is completed press start button.

D6.1 Safety Precautions

1. The laser is very powerful, and direct eye contact could cause serious eye injury. Hence it is important to avoid any exposure of the eye to the beam.

2. Baltic birch plywood uses formaldehyde as the adhesive to join the layers of wood. During the laser cutting process, heat generated by the laser will cause evaporation of the formaldehyde. Since

formaldehyde is a carcinogen, care must be taken when working with it so as not to inhale the fumes.

3. Do not use material thicker than the thickest possible material that can be used. Thicker materials will not clear the cutter head and cause a crash, rendering the machine useless for the remaining projects.

APPENDIX E: ASSEMBLY INSTRUCTIONS

Upon the request of our sponsor, we were required to build two robots. The robots are slightly different from each other in the following ways:

1. One of the robots is 710 mm by 450 mm in length and width respectively, while the other one is 653 mm by 410 mm. Initially, we decided to build the larger robot to increase space while still maintaining maneuverability of the robot. However our sponsor wanted a robot that had the same dimensions of the original robots, and hence we will reduce the dimensions to satisfy his request.

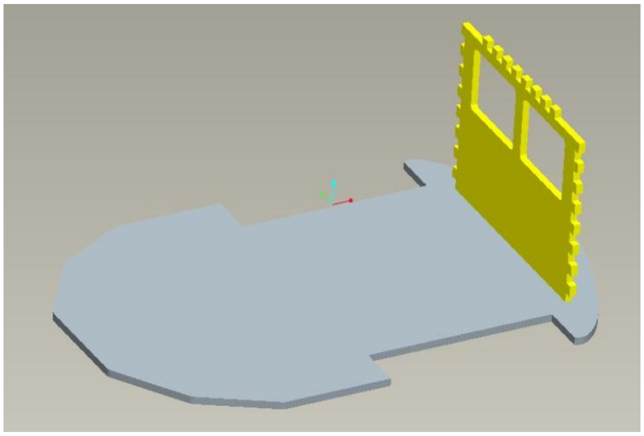
2. The IG-32 gear motor has a smaller gearbox (32 mm diameter) than that of the IG-42 gear motor. Hence the mounting location of the gearbox will change which will in turn change the mount height of the caster. While the IG-42 motor can be mounted to the base by placing it in the interior compartment, the IG-32 motor has to be mounted to the bottom of the robot outside the compartment. As a result, a larger caster is required when the IG-32 motor is mounted to the bottom of the robot.

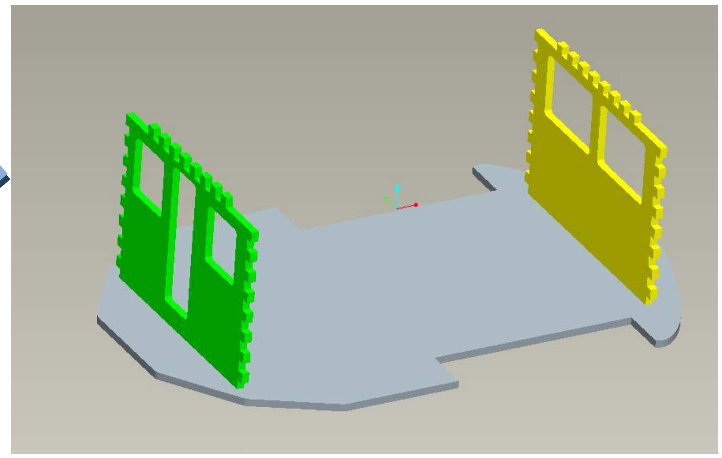
The assembly instructions presented here will therefore include the pictures for both these robots, and any special instructions for the robot with the IG-32 motor mounted to its bottom.

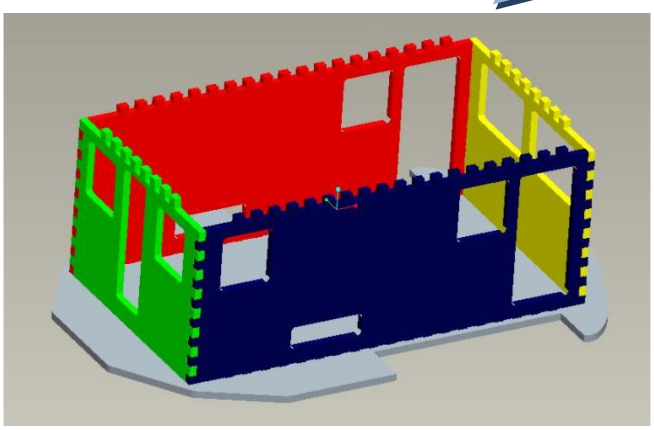
Before the walls are assembled together, they will have to be painted using water-based spray paint. First sanding has to be carried out using 60-grit sandpaper to remove any rough edges or irregularities caused by machining and the laser cutter so that the surface is smoother and the paint coats will be more even. A layer of primer is first sprayed onto both sides of the walls, and left to dry for about 30-45 minutes. Then more sanding is carried out, but this time 120-grit sandpaper is used to produce an even smoother surface than before by removing less material per scrape. After this, a first coat of the paint is sprayed onto both sides of each piece and left to dry for 30-45 minutes, followed by sanding using 150-grit sandpaper to further improve smoothness. This combination of the painting and sanding processes is repeated until a smooth and even finish is obtained.

The water-based spray paint cans contain xylene and toluene as solvents for spraying. Xylene and toluene are extremely volatile, toxic and hence are health hazards. As a result, the painting should be done outdoors (to allow good ventilation), and safety masks are required so that one does not accidentally inhale these solvents. The MSDS sheets for xylene and toluene are given with this safety report.

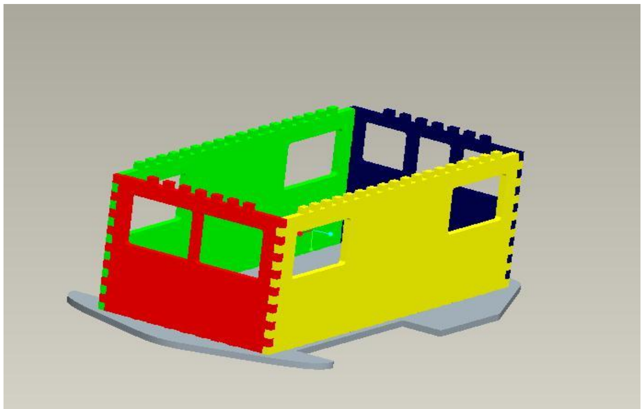
STEP 1







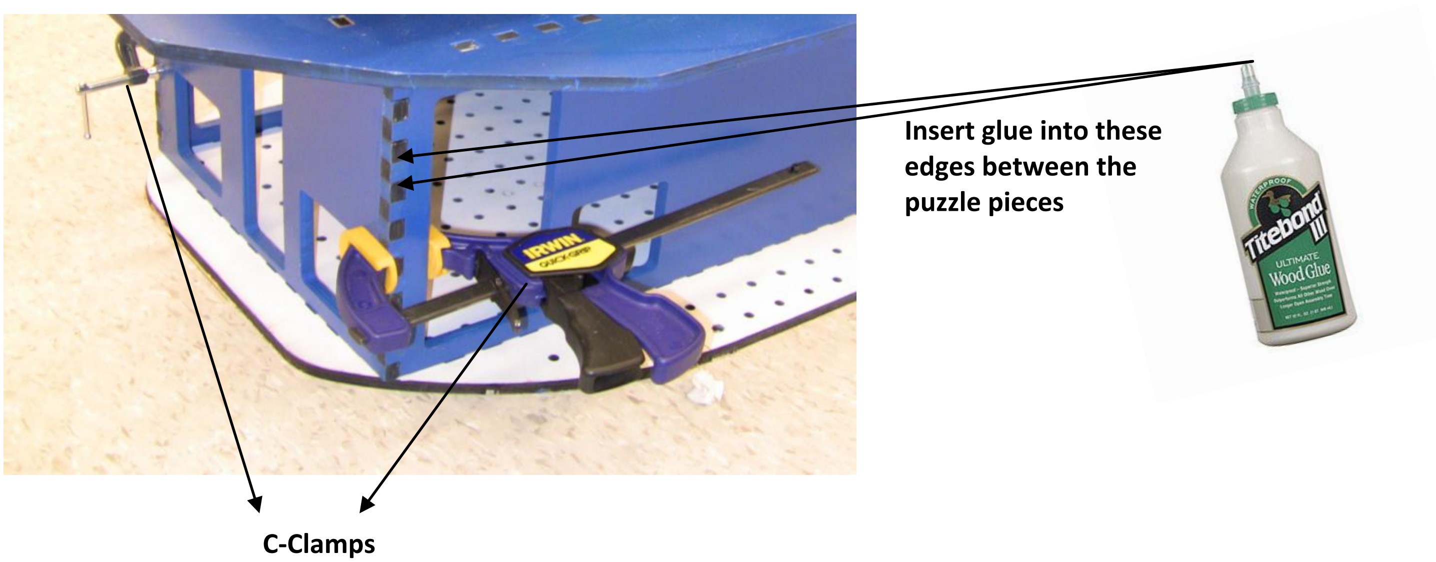
To the base of the robot, attach the back wall by inserting the puzzle piece extrusions of the back wall into the slots on the back of the base. Then add the front wall and finally the two side walls using the same procedure, slotting the puzzle pieces of the walls through the slots. The diagram to the left shows the order of assembly.



The same steps have to be repeated for the 653 mm by 410 mm robot with the smaller walls. The smaller robot chassis will look like the picture on the left after assembly.

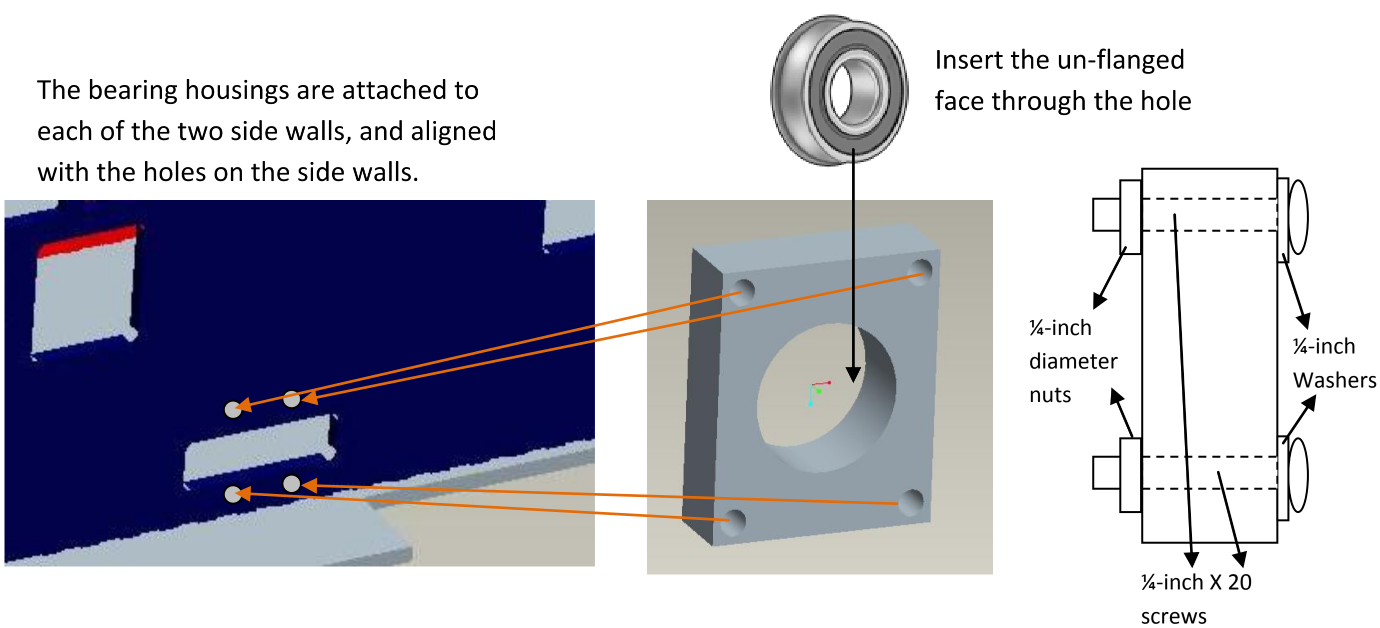
STEP 2

Now, flip the chassis upside down and add wood glue to the edges of the walls and the puzzle pieces. Then, clamp the walls together using C-Clamps (on the front and back) as shown in the diagram below. Allow the setup to dry overnight.



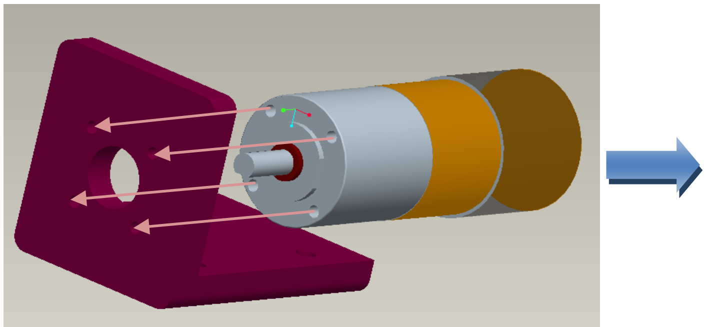
STEP 3

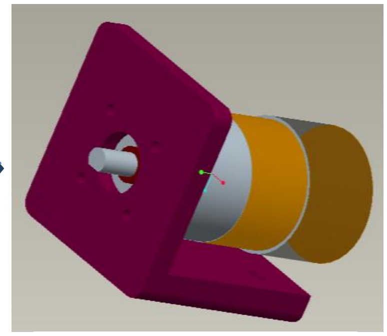
Insert the bearings into the bearing housings. Remove the clamps and mount the bearing housings using ¼ -inch X 20-inch screws, ¼ -inch diameter washers and ¼-inch diameter nuts.



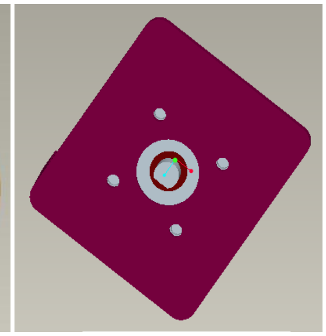
STEP 4

Align the IG-42 & IG-32 motors with their respective motor mounts, and connect the motors and the mounts using screws. Use M4 screws to connect the IG-42 motors with their motor mounts. For the IG-32, use the M3 screws.





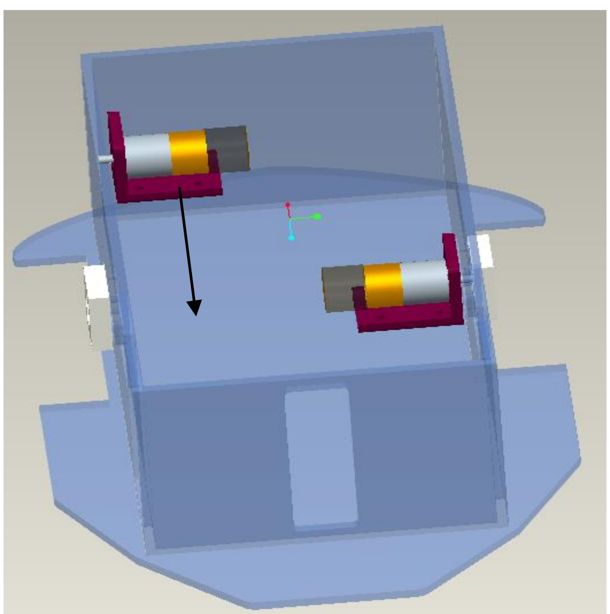
Side view of the motor mount assembly



Front view of the assembly

STEP 5

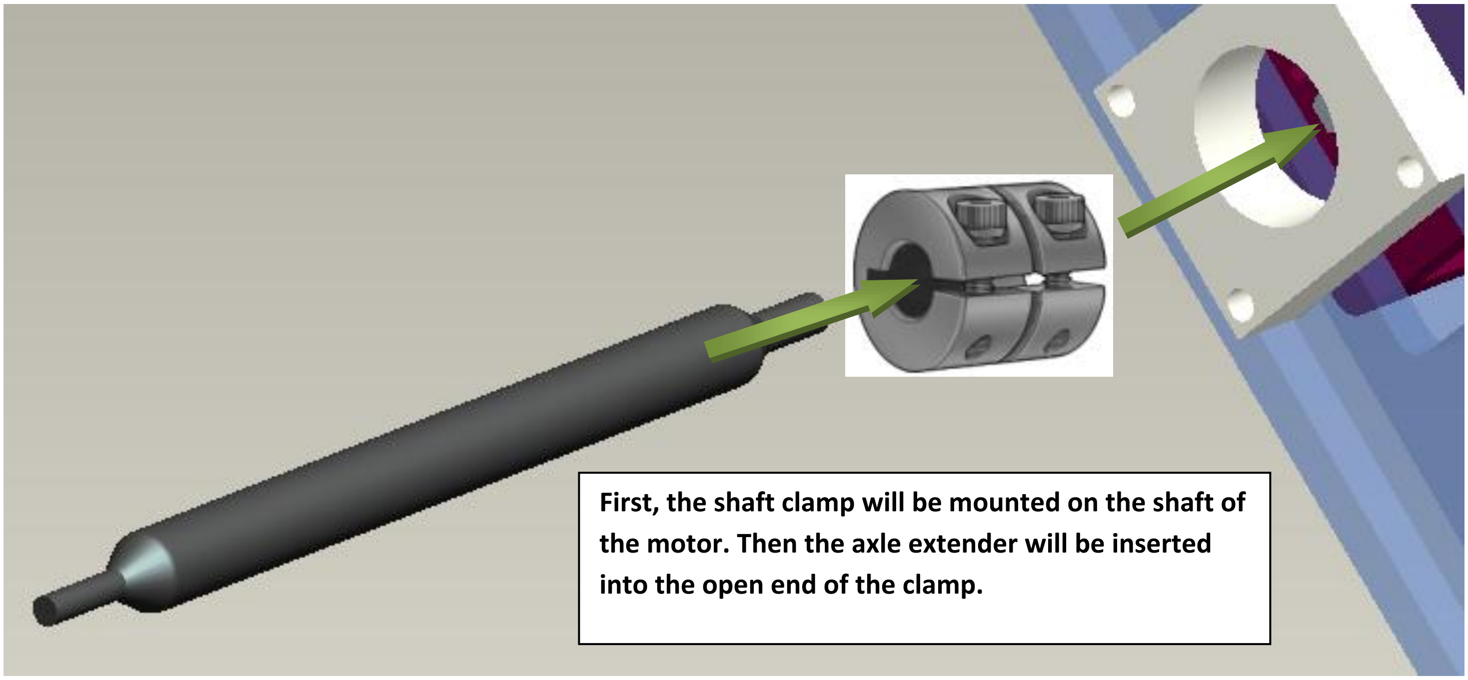
Attach the motor mounts to their respective chassis assemblies. The IG-42 mounts will be attached to the top of the base within the compartment of the chassis. The IG-32 mounts on the other hand will be attached to the underside of the base.



Place motor assembly as indicated by arrow. (Aligned with the other motor assembly). (IG-42)

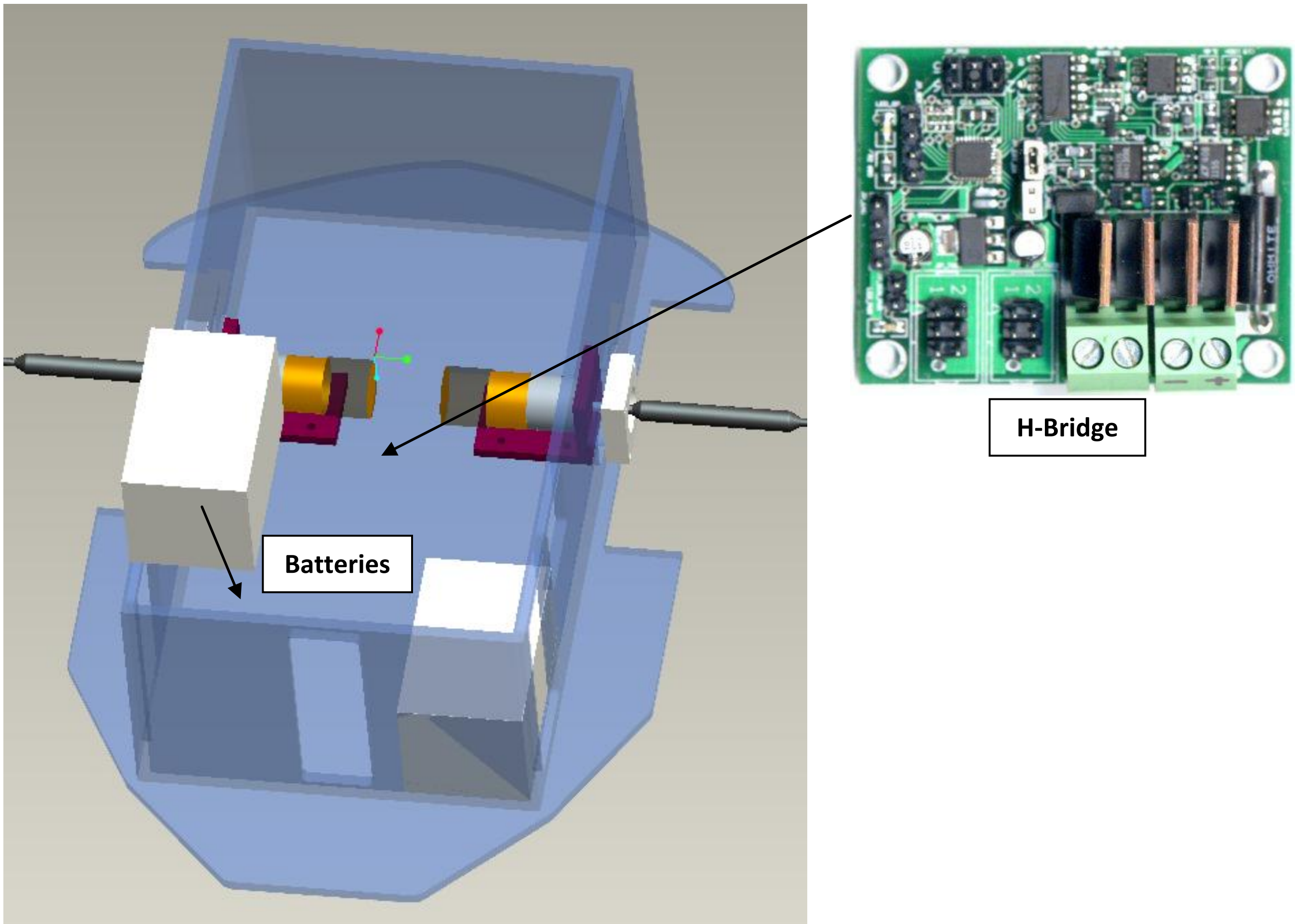
STEP 6

Now, connect the axle extenders to the motor shafts using the shaft clamp. Use the order as shown in the diagram below. The Allen wrenches will be used to loosen the screws to insert the extenders and shafts, and re-tightened again.



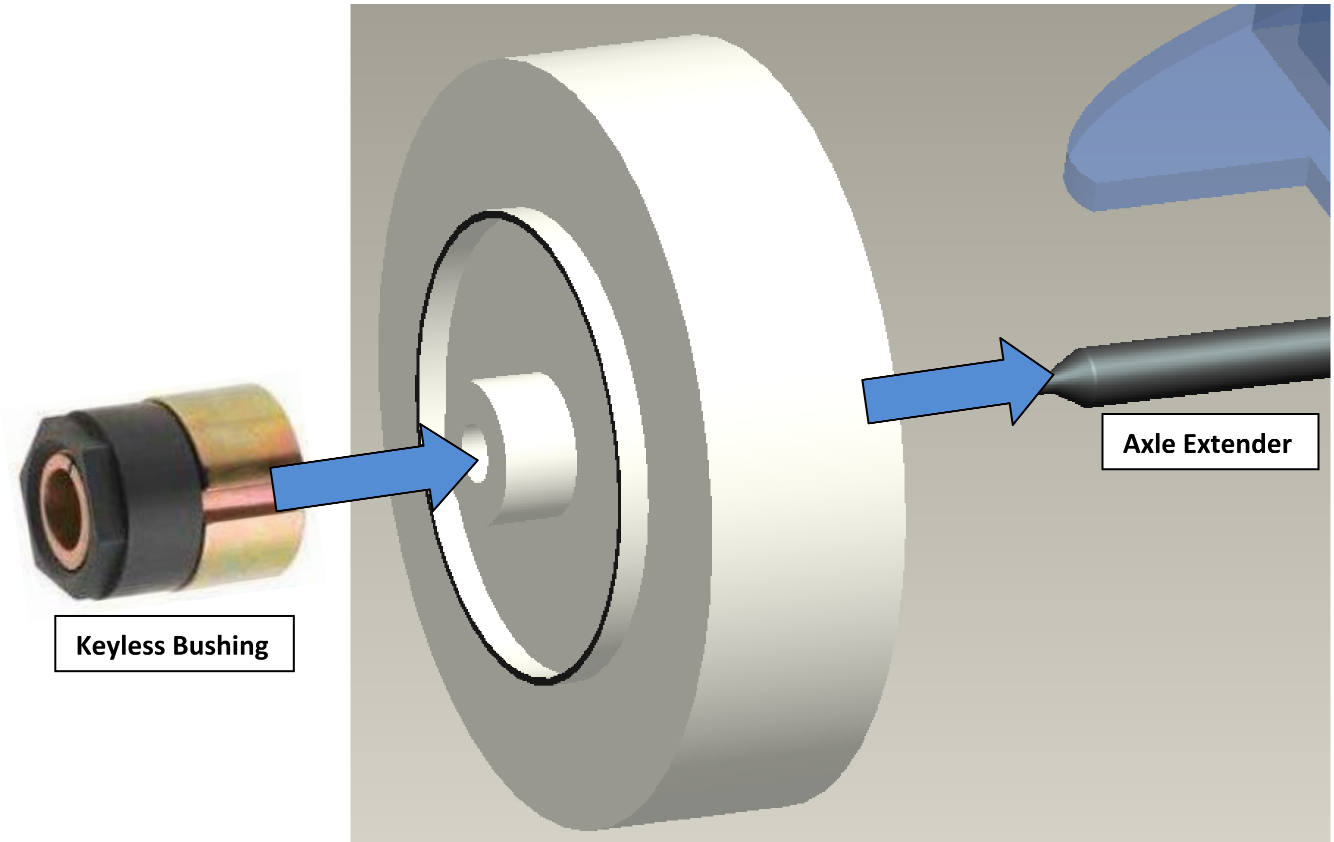
STEP 7

Add the lead-acid batteries and the H-Bridge circuit board as shown in the diagram (1 or 2 can be added, depending on power needed.):



STEP 8

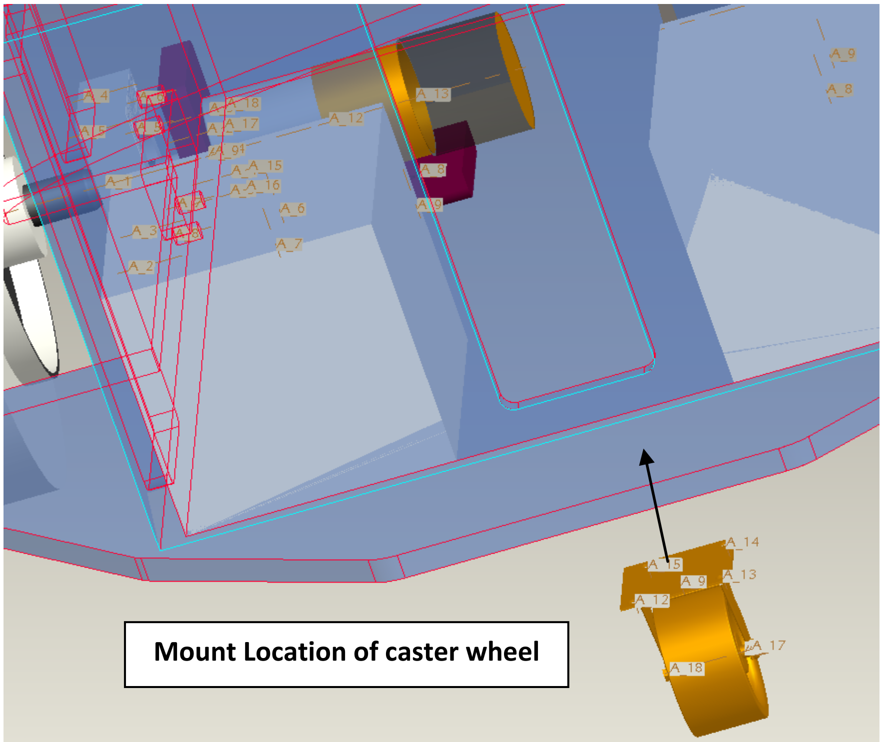
Connect the pneumatic wheels to the axle extenders, and use the key-less bushings to connect them securely to the shafts:

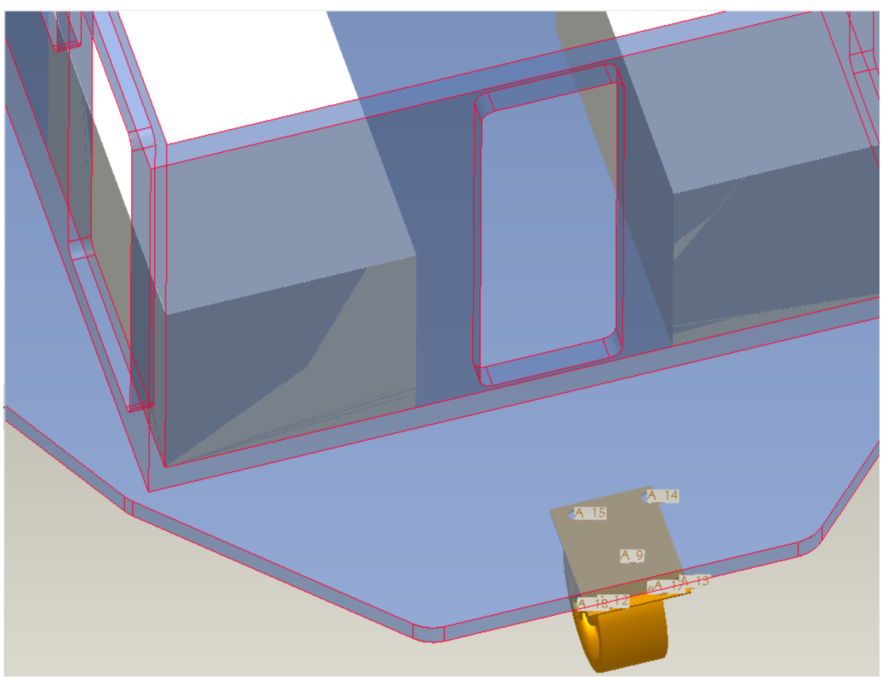


Pneumatic Wheel

STEP 9

Attach the caster wheel to the base of the robot at the front end. Use four of the ¼-inch X 20 screws with washers and nuts to fasten the caster wheel to the base.



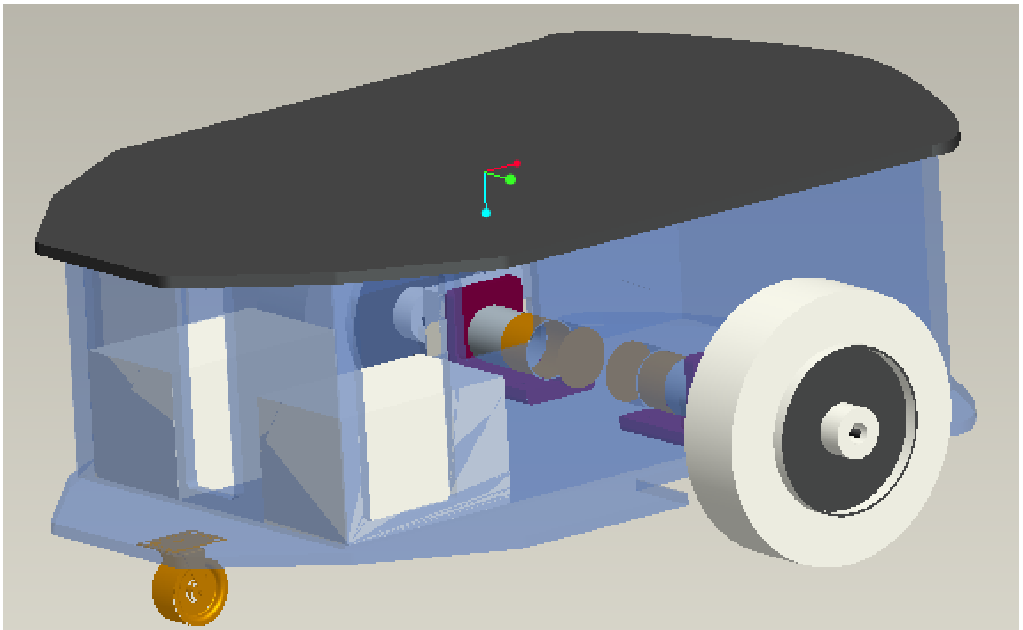


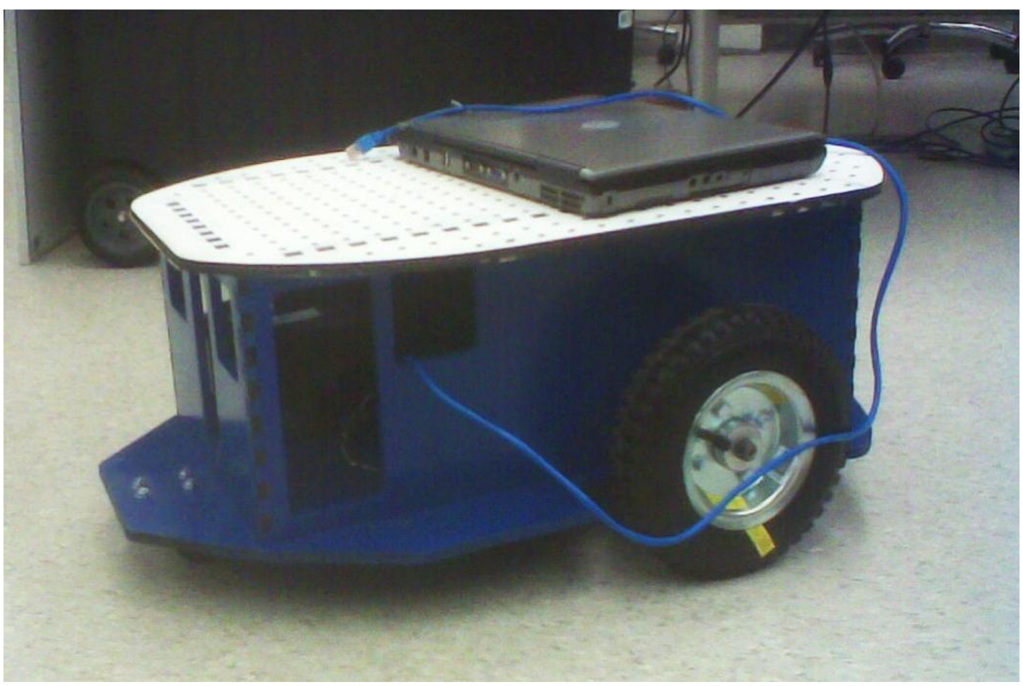
Another view showing the mount location more clearly

STEP 10

Finally, add the middle platform to the top of the chassis, once again connecting the platform to the four walls (front, back and 2 sides) through the use of the mating puzzle pieces and corresponding slots.

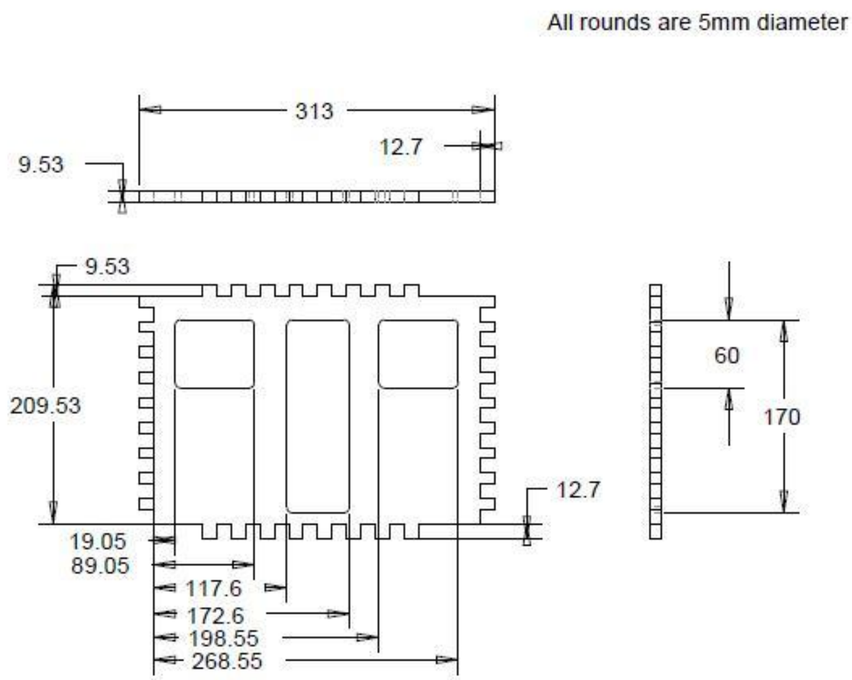
NOTE: DO NOT GLUE THE MIDDLE PLATFORM TO THE REST OF THE CHASSIS! THIS HAS TO BE MADE REMOVABLE FOR EASY MAINTENANCE AND CHANGE OF BATTERIES!



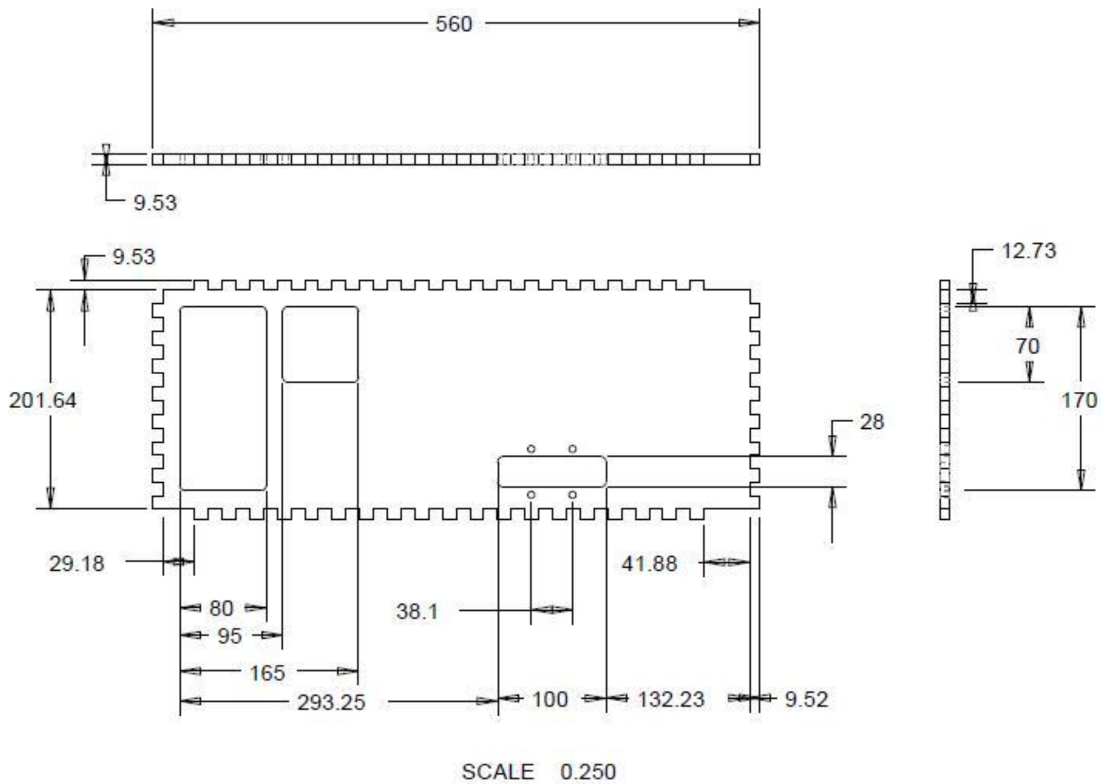


APPENDIX F: ENGINEERING DRAWINGS

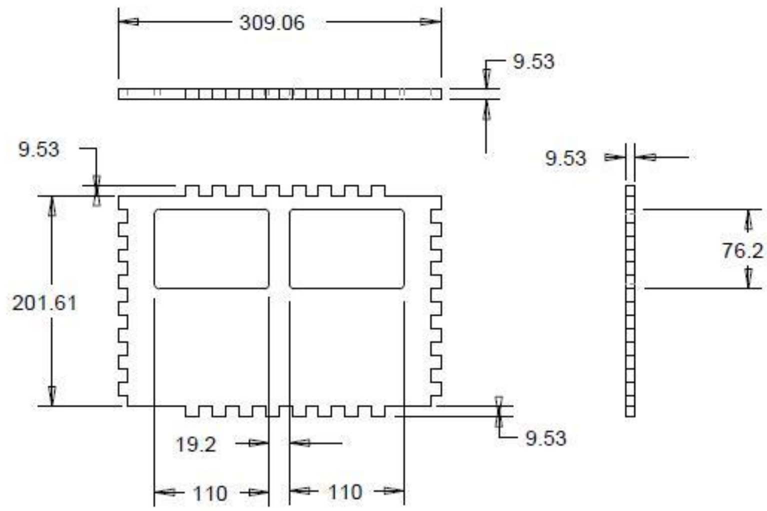
Front Side Wall	Drawn By: Steven Kuplic
	Date: March 27 2009
Team: ME 450 Team 1	Version: V1.0



Side wall	Drawn By: Steven Kuplic
	Date: March 27 2009
Team: ME 450 Team 1	Version: V1.0

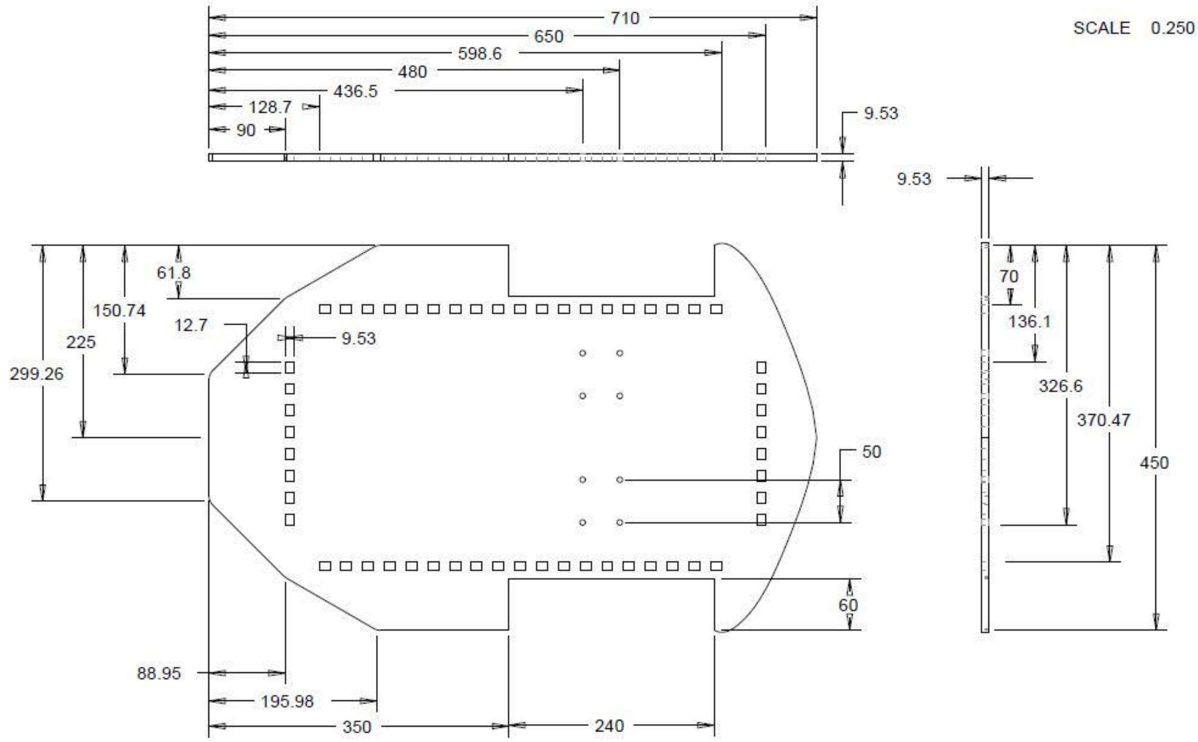


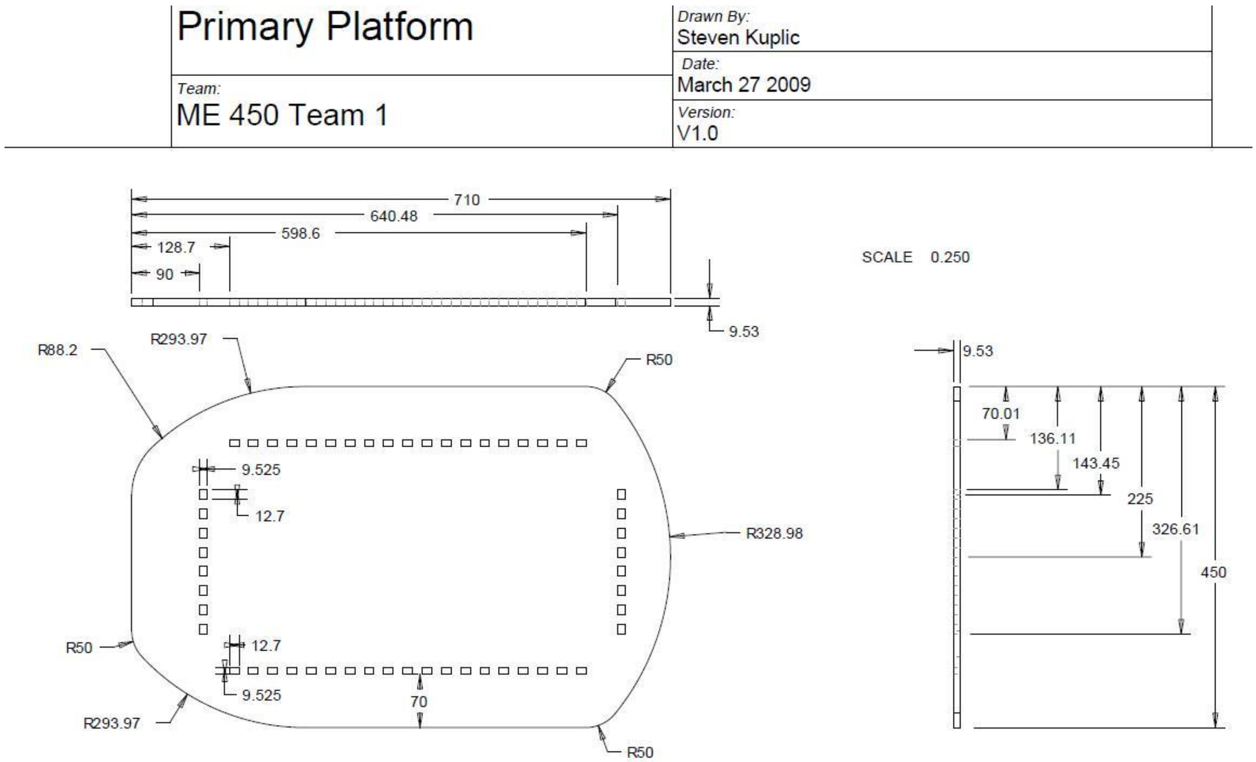
Back side wall	Drawn By: Steven Kuplic
	Date: March 27 2009
Team: ME 450 Team 1	Version: V1.0



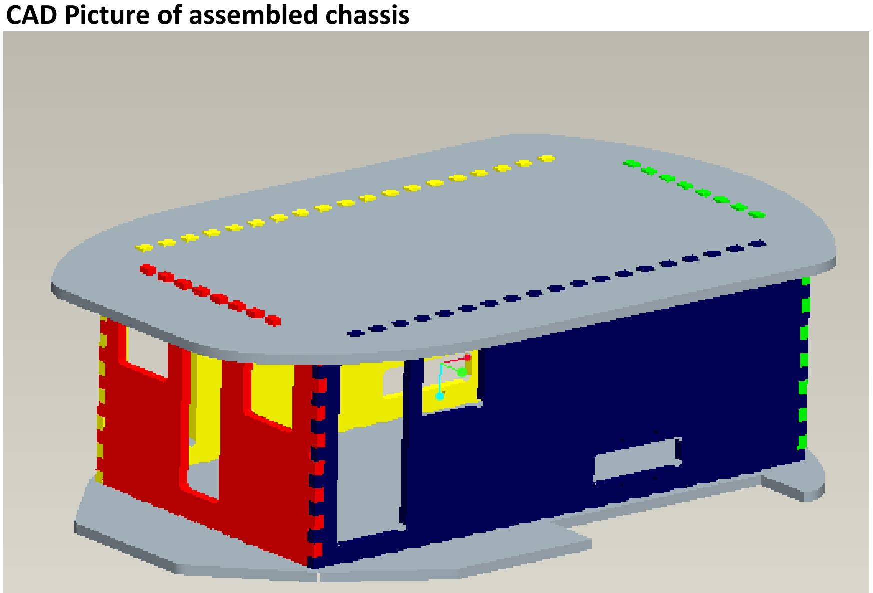
Chassis Base

Team: ME 450 Team 1	*Drawn By:* Steven Kuplic
	Date: March 27 2009
	Version: V1.0

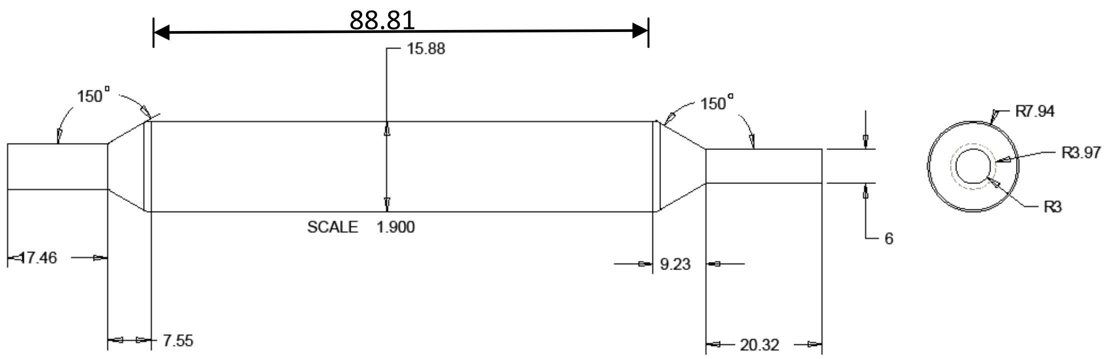




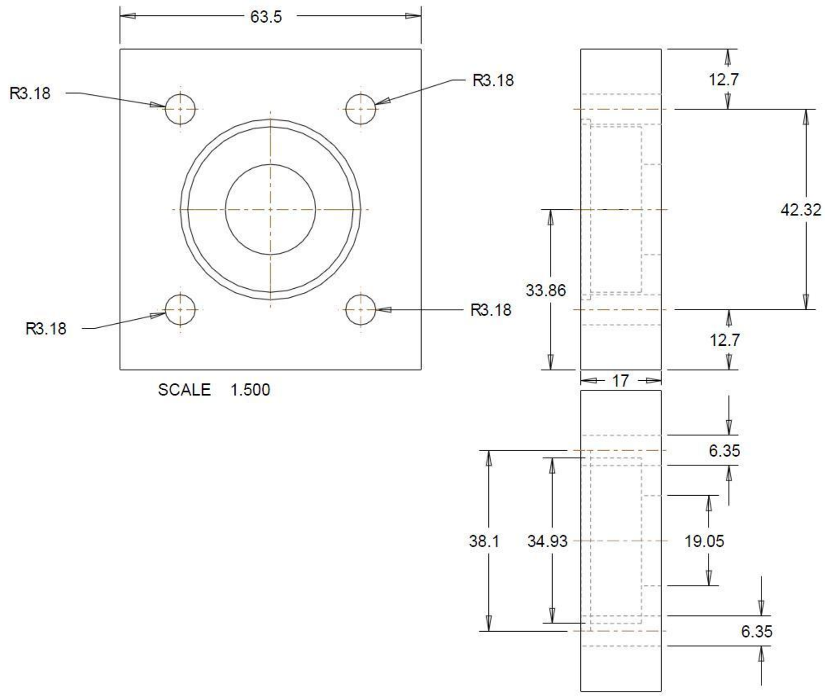
CAD Picture of assembled chassis



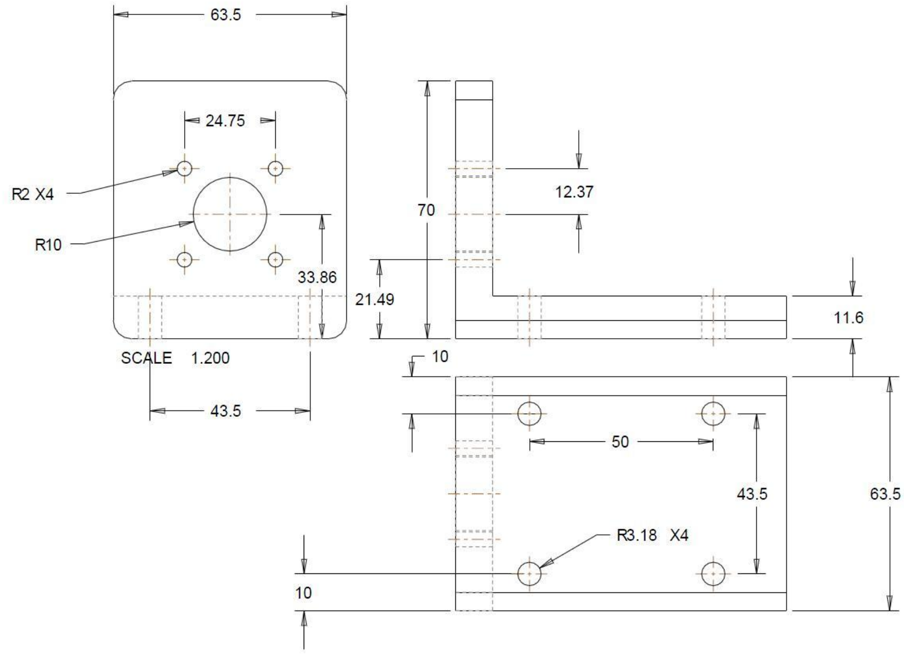
Originally Drawn: March 27th 2009	# Axle Extender	*Drawn By:* Anand Nageswaran Bharath
Revision Made: April 3rd 2009		*Revision made by:* Anand Nageswaran Bharath
	Team Name: ME 450 Team 1	*Version:* V4.0 FINAL



Bearing Housing	*Drawn by:* Anand Nageswaran Bharath
	Date: March 16th 2009
Team Name: ME 450 Team 1	*Version:* V1.0



Motor Mount	Drawn by: Anand Nageswaran Bharath
	Date: March 23rd 2009
Team Name: ME 450 Team 1	Version: V2.0



APPENDIX G: FMEA

FMEA: Proj 1, Motors

Description of system and mode of operation	Key Contact / Phone	Date of Initial FMEA
System Subsystem X Component	Core Team: Zhuang Yitao Steve Kuplic Anand Nageswaran Baharath Richard LaCroix	Date of Initial System Demonstration Review Board Approval / Date
	Location:	

Potential Failure Modes and Hazard Identification

Categorize: Identify subsystem and mode of operation	Potential Failure Mode and 5 Whys [1]	Potential Effect of Failure [2]	SEV	Potential cause(s)/ Mechanism(s) of Failure [3]	OCC	Current Controls for Detection / Preventio	DET	RPN	Recommended Action [5]	Person Responsible & Completion	Action Results: Action Taken [6]	SEV	OCC	DET	RPN
Motors (2) IG42 TD-044-252 24vDC Provide motion, turning and odometry to robot	Short circuit	Destroy motor functionality	9	Too much current/voltage melting wire insulation	2	Fuse	2	36	Use batteries with correct voltage, no more than two 12 V batteries	All	Check battierie s with a volt meter	10	1	1	10
				Motor overheat and ambient heat causing melting of wire insulation		Fuse		0	Monitor heat (touch) during test runs of robot. Keep motor area open for convection cooling	All					0
	Wear or breaking of motor gears	Destroy motor functionality	9	Too much load on gear box from robot payload	2	High load bearings	1	18	Impliment bearings to take the weight of the payload	All	Yes	10	2	2	40

Discussion

1. Discuss root cause of the failure mode (based on the 5 whys, hypothetical situation)

The two most likely modes failure of the robot are melting of the insulation of the wires making up the motors windings and the failure of the gear box from loading being higher than what it is made for

W1 Why are the motors not turning the axles? Because they are damaged

W2 Why were they damaged? Because they short circuited

W3 Whay did they short circuit? Because too large a voltage source was connected

W4 Why was too large a voltage source connected? Batteies with a combined voltage of more than 24 volts was connected

W5 Why were the wrong batteries connected? Because their voltages were not checked prior to connection

Based on the 5 whys we conclude that the batteies should be checked before connection

2. Discuss/justify the severity rating (SEV)

If the insulation on the wires melted the motor would be short circuited and would not produce a magnetic field needed to turn. If the motors gear box is damaged from too much loading it may not be able to transmit the motor motion to the wheel. If either of these conditions happened a new motor would be needed, hence 10. If the odometry were compromised due to wear on the motor axle to axle extension connection or from too much loading then the odometry from the motors tachometer could loose percision and this would reduce the quality of the robot

3. Discuss/justify the rating for probability of occurrence (OCC)

The motors are made to withsatand continuous running at room temperatures and above. So as long as the motors are not in a tight inclosure that will allow heat to build up they should not overheat. Since we are adding bearings to our design to take most of the loading on the robot the motors should not be overloaded unless the robot is loaded to much more weight than it is required to carry

4. Discuss/justify the rating for the probability of detecting a "failure imminent" condition and avoiding the failure (DET)

If the motors fail it will be aparent during test running the robot and will be detected.

5. Recommended actions: Make specific recommendations for action and include some discussion of the alternatives considered.

It is reccommended that the motors are not insulated or tightly inclosed so that they will not overheat. It is also reccommended that we use bearings to trake the load so that the motors do not have to.

6. Notes on Actions taken:

Both reccomendations have been implemented in our design plan.

FMEA: Proj 1, Batteries

Description of system and mode of operation	Key Contact / Phone	Date of Initial FMEA
System Subsystem X Component	Core Team: Zhuang Yitao Steve Kuplic Anand Nageswaran Baharath Richard LaCroix	Date of Initial System Demonstration Review Board Approval / Date
	Location:	

Potential Failure Modes and Hazard Identification

Categorize: Identify subsystem and mode of operation	Potential Failure Mode and 5 Whys [1]	Potential Effect of Failure [2]	SEV	Potential cause(s)/ Mechanism(s) of Failure [3]	OCC	Current Controls for Detection / Prevention [4]	DET	RPN	Recommended Action [5]	Person Responsible & Completion Date	Action Results: Action Taken [6]	SEV	OCC	DET	RPN
Batteries (2): 24v lead acid RB-sum-22 Provides power to robot's circuitry and motors	Overheating of battery	Ignition/explosion of battery	10	Connecting the battery to an improper voltage source or short circuiting	2	Insulation cover over atleast one battery lead at all times to prevent short circuit.	2	40	Always check the voltage rating on the battery and test the charging device for a match. Keep the area around the batteries open to allow for heat disipation	All		10	2	1	20
	Damage or corrosion of battery housing	Acid leak	10	Corrosion and surface damage to battery housing	2	The batteries are placed in the robot in a way that keeps them from being damaged under normal operation	3	60	None	All					0

Discussion

1. Discuss root cause of the failure mode (based on the 5 whys, hypothetical situation)

If batteries are overcharged or overheat they may set on fire or explode.

W1 Why did the batteries catch on fire? They overheated

W2 Why did they overheat? They were shorted

W3 Why where the batteries shorted? Because a conductor conneced both the positive and negative battey leads

W4 Why were both leads exposed? To make it easier to connect wires

W5 Why do we need to make it easier to connect the battery? To recharge it

A safe* charging station is being developed by UROP students to charge the batteries without disconnecting the wires and keeping atleast one lead is always covered

2. Discuss/justify the severity rating (SEV)

If a battery sets on fire the entire robot may catch on fire destroying different components and causing a safety hazard. Leaking of the lead acid would pose a safety risk as well. This is why the seerity rating is a 10

3. Discuss/justify the rating for probability of occurrence (OCC)

Since all of us working on the robot know not to short circuit the batteries and there is a charger for the robot that should prevent overcharge, the chance that this will happen is minimalized. Also on the current robot has a fuse as our robot will. The batteries are made to last a long time before corrosion. So there is only a small chance failure will occur

4. Discuss/justify the rating for the probability of detecting a "failure imminent" condition and avoiding the failure (DET)

Fuses will help us detect if there is a problem with too much voltage in the system

5. Recommended actions: Make specific recommendations for action and include some discussion of the alternatives considered.

It is reccommended that the wireing be such that the batterie can not be easily short circuited and will not be closed in to allow for heat disipation.

6. Notes on Actions taken:

FMEA: Proj 1, Pneumatic Wheels

Description of system and mode of operation	Key Contact / Phone	Date of Initial FMEA
System Subsystem X Component	Core Team: Zhuang Yitao Steve Kuplic Anand Nageswaran Baharath Richard LaCroix	Date of Initial System Demonstration Review Board Approval / Date
	Location:	

Potential Failure Modes and Hazard Identification

Categorize: Identify subsystem and mode of operation	Potential Failure Mode and 5 Whys [1]	Potential Effect of Failure [2]	SEV	Potential cause(s)/ Mechanism(s) of Failure [3]	OCC	Current Controls for Detection / Prevention [4]	DET	RPN	Recommended Action [5]	Person Responsible & Completion Date	Action Results: Action Taken [6]	SEV	OCC	DET	RPN
Pneumatic Wheels: (2) 8" diameter	Tire bursting	Injury to persons	10	Tire filled to to high an air pressure	2	Pressure limits listed on tire and the air pump has a pressure gage on it.	3	60	Keep watch on the air pressure while filling the tire, DO NOT over inflate the tires.	All		10	2	1	20
	Loss of air pressure	Reduce the accuracy of the robot's odometry and decrease the quality of motion	2	Sharp object puncturing the tire of loss of air through the valve or a small hole developed from ware	2	The air containing part of the tire has a durable rubber cover that will help protect it during use	2	8	Check time pressure periodically and fill air as needed. DO NOT over inflate the tires.	All					0

Discussion

1. Discuss root cause of the failure mode (based on the 5 whys, hypothetical situation)
   Improper inflation may cause loss of pressure or bursting of tire.
   W1 Why did the tire burst? There was too much air pressure.
   W2 Why was there too much air pressure? Tire was over inflated?
   W3 Why whas it over inflated? Because there was not read during inflation.
   W4 Why was the pressure not taken during iflation? There was no pressure gague.
   W5 Why was there not a presusre gague to check the pressure? We thought we could tell when the tire was properly inflated.
   We purchased a pump with an attached pressure gage to take readings during inflation. This will m inimize the chance of damage or injury.
2. Discuss/justify the severity rating (SEV)
   If the wheels are over inflated a leak may form or they may burst causing possible injury.
3. Discuss/justify the rating for probability of occurrence (OCC)
   Since all of us working on the robot know not to short circuit the batteries and there is a charger for the robot that should prevent overcharge, the chance that this will happen is minimalized. Also on the current robot has a fuse as our robot will. The batteries are made to last a long time before corrosion. So there is only a small chance failure will occur
4. Discuss/justify the rating for the probability of detecting a "failure imminent" condition and avoiding the failure (DET)
   Fuses will help us detect if there is a problem with too much voltage in the system
5. Recommended actions: Make specific recommendations for action and include some discussion of the alternatives considered.
   It is reccommended that the wireing be such that the batterie can not be easily short circuited and will not be closed in to allow for heat disipation.
6. Notes on Actions taken:

APPENDIX H: CES ALUMINUM

In addition to using CES for the chassis walls, which was incorporated into the report in section 8.1, we also used the software program to help us determine the appropriate material for other robot components.

Aluminum is the principal material other than wood that was used to manufacture the robot. Specifically, aluminum was used for the axel, motor mounts, and bearing housing. The paticular type of aluminum used was 6061. This is a common type of age-hardened wrought aluminum used for structural components. This section will discuss why we chose aluminum over other materials, in part through the use of the CES computer program.

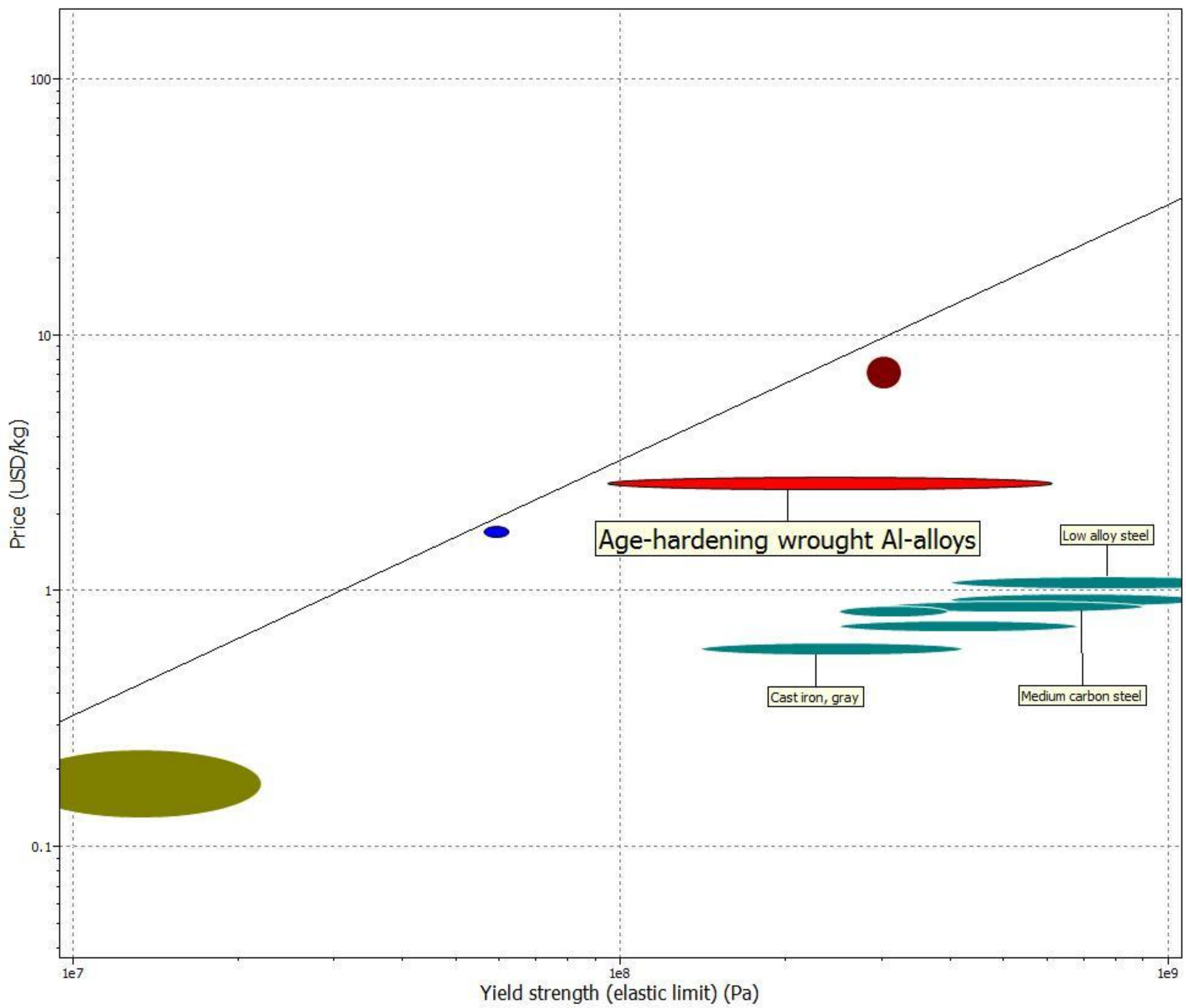
In order to use CES to help us select a material for those parts, we first had to determine applicable engineering requirements. It was determined that all three of these parts had the same engineering requirements, which included; material strength, machineability, density, and cost. Considering the overall requirements of our project, it was determined that machineability and cost were the most important, and material strength and density were somewhat less important. An exception to this was the axel; due to the torque that the axel has to transmite there was extra importance placed on the material strength. There was also a desire to use one material for all the components, this would make the cost of the parts less expensive because we would be able to buy larger, more economical, pieces of material. The requirements were quantified and the target values for each requirement are presented in the table below.

Requirement	Target
Machinability	Excellent
Cost	< $5/kg
Strength	> 1E7 Pa
Density	< 3000kg/m^3

From these requirements we desided to focus on metals for the components. Metal is great from a strength to cost ratio. Also, most metal is easily machineable and is widely available. Overall, using metal for these components seemed to be the best choice. Using CES we narrowed down the choices of metals by comparing them to our requirement targets.

The graph below shows yeild strength vs. cost. It was important that the cost did not become too expensive so we narrowed down the possibilities by limiting the cost relative to yield strength. Any materials above the diagonal line on the graph were deemed too expensive relative to their strength. The line is upward sloping because as a material becomes stronger we were more willing to pay extra for it.

H1: CES GRAPH YIELD STRENGTH VS. PRICE PER KG



From this graph we narrowed down our search to; age-hardened wrought aluminum, cast iron, low alloy steel, and medium carbon steel. Using CES we researched each of these materials and compared them against our requirements. Below is a table showing the material properties of each of these materials.

Requirement	Aluminum	Cast Iron	Low alloy steel	Medium carbon Steel
Machinability	Excellent	Good	Good	Good
Cost	$2.6/kg	$0.6/kg	$1/kg	$0.9/kg
Strength	1E8 Pa	2E8 Pa	1E9 Pa	6E8 Pa
Density	2700kg/m^3	7000kg/m^3	7800kg/m^3	7800kg/m^3

From this table we selected aluminum. First, aluminum was the only material that had an excellent manufacturability rating and met all other requirements. It was significantly more expensive than the other materials, but it was still relatively cheap overall so that wasn't a big concern. It was also much lighter than the other materials, which is important since one of our objectives was to make sure the robot does not become too heavy.

APPENDIX I: DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

OVERVIEW

Recently, environmental degradation has become a serious problem due to the excessive release of pollutants into the atmosphere as a result of human activities. Moreover, the widespread practices of natural resource extraction today are depleting the world's supply of natural resources at an alarming rate, in addition to polluting the environment. As a result, it is essential for every engineer to consider the environmental impact of material extraction and processing before finally choosing the ideal material for fabrication. This will enable the engineer to make a more sound decision in selecting materials as he/she can now select a material which is able to offer the same performance characteristics as the materials used in previous designs, while minimizing environmental impact. This practice will in turn allow us to develop products that are beneficial to mankind while respecting the environment by reducing the damage we cause in our product development.

It should be noted that even after a careful environmental assessment, the engineer might end up selecting the material that might have a greater environmental impact if the alternative materials (the ones that would cause a lower environmental impact) do not possess the material characteristics required for the application the engineer has in mind. This can happen when environmental impact might not be an important factor if the emissions are minimal, or there are other more important factors to be considered such as material properties. In addition to this, the software used, SIMAPRO is a static database that does not consider the novel techniques for material extraction and use that are developing everyday and are more sustainable than the techniques used in the past. Nevertheless, it does make one aware of the footprint that he/she leaves on the environment in choosing materials and hence think about steps that can be taken to minimize environmental impact.

For our project, we identified two major subsystems: the chassis and the drive-train components. We performed a material selection process using CES and narrowed down to birch wood & High Density Polyethylene (HDPE) for the chassis, and Aluminum & Steel for the drive-train components. In this section, we present an environmental impact assessment using SIMAPRO for these materials, and present our conclusions.

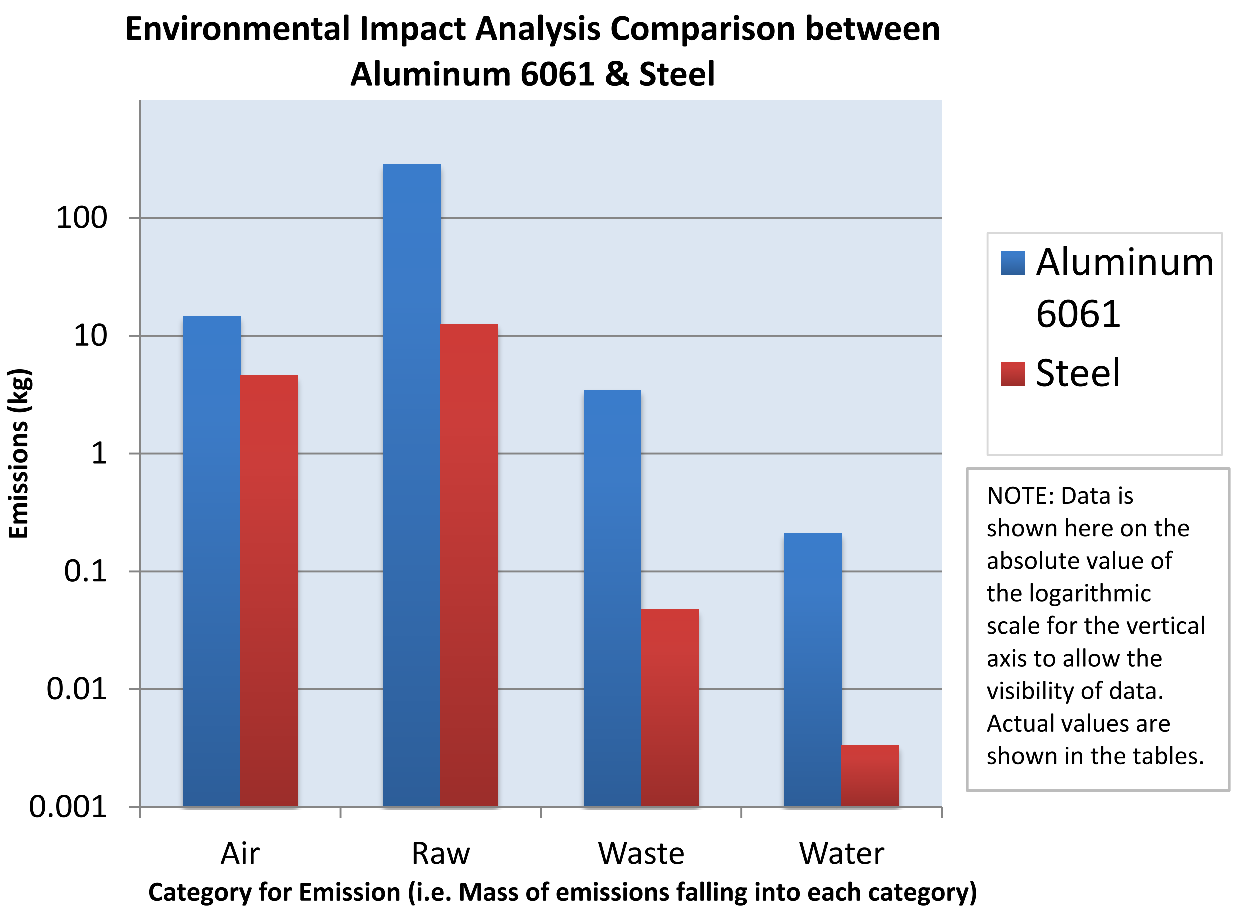
PROCEDURE
Using the SIMAPRO software, we used the Eco-Indicator 99 (I) Europe EI 99 method for calculations to generate a number of graphs. We then generated a number of graphs which we used to perform the analysis. More details will be provided on these graphs in the upcoming sections.

DRIVE-TRAIN COMPONENTS
For the drive-train components, we narrowed the suitable materials down to 6061 Aluminum and Steel (Fe 470) using CES, and performed the environmental analysis. The total mass of aluminum used is 1.5 kg. (for the axle extenders, bearing housings and motor mounts.) By doing some simple density calculations (assuming volume of parts fabricated is exactly the same for both materials), we calculated about 4.4 kg required for the steel. The table and bar chart below give the quantitative characterization of impact for the four categories: raw, air, water and waste.

I1: Emission levels for Aluminum 6061 and Steel (Fe 470).

Emissions (kg)							
Air		Water		Raw		Waste	
Aluminum 6061	Steel (Fe470)	Aluminum 6061	Steel (Fe470)	Aluminum 6061	Steel (Fe470)	Aluminum 6061	Steel (Fe470 I)
14.6	4.59	0.21	0.0033	283.3	12.6	3.46	0.047

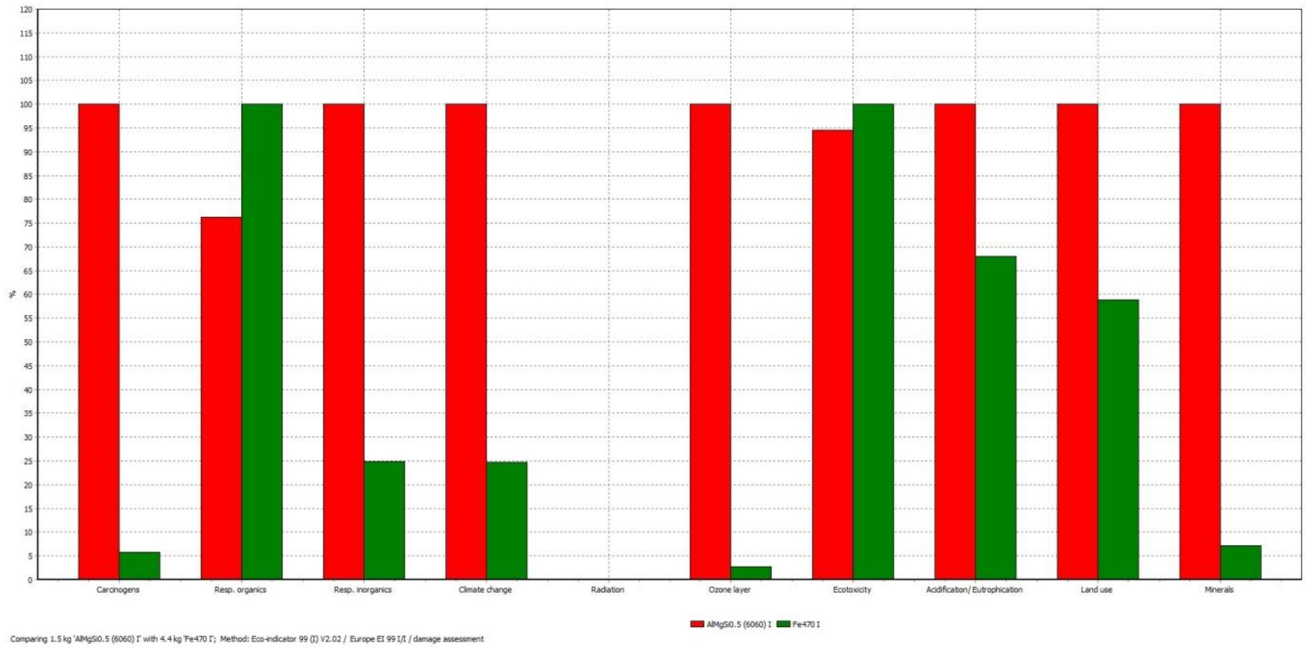
I2: Aluminum and Steel Impact Comparison



The chart shows that aluminum produces more emissions than steel for all the categories, indicating that aluminum extraction produces more waste, more air pollution, more water pollution and requires more raw material than steel for the amounts we want to use. More graphs are given below from the SIMAPRO database in the following pages.

The characterization chart below allows us to make a comparison in terms of the impact that each material has on climate change and the ozone layer, as well as the amount of carcinogens released. Once again, aluminum has a greater impact than steel in all categories, with large discrepancies in minerals, carcinogens and climate change.

I3: Characterization Chart for Aluminum 6061 and Steel (Fe 470)



Aluminum has a greater impact in all these areas mainly due to its chemical nature. It is a more reactive metal than iron, and hence it tends to form very stable compounds in the form of minerals. A large amount of energy is required to extract aluminum from its minerals by electrolysis of its components such as bauxite, and this has to be done at extremely high temperatures as well (around 950 degrees Celsius). Iron on the other hand requires much less energy as its compounds are less stable, and hence only a smaller amount of energy is required through smelting. Due to the graphite electrodes used that burn away, carbon dioxide is produced that causes global warming and hence climate change. This is much less in comparison to the carbon dioxide produced in the smelting of iron ores since the ores are smelted at lower temperatures resulting in less carbon dioxide produced.

However, as we mentioned earlier, SIMAPRO results may not necessarily be valid all the time due to any sustainable practices that could exist in the extraction of these materials. Moreover, SIMAPRO does not consider the activities of recycling, which will significantly reduce the amount of climate change and carcinogens released into the atmosphere. There is also less energy usage, and hence less raw emissions and waste are produced.

We still prefer to go with aluminum as our main choice even though environmentally, it will have a greater impact. The reasons are that aluminum weighs a lot less than steel as compared to that of steel, as we mentioned in the section on the CES analysis. As a result, the robot will be significantly lighter if the drive-train components were made out of aluminum than of steel. Moreover, aluminum is easier to machine than steel, and this is an important consideration, since our main aim of the project is to create a rapidly manufacturable robot. Since aluminum enables us to meet our goal better, we will use it for the drive-train components. We will however, be sure to take into account the environmental impact caused, and hence make it a point to only use recycled aluminum to minimize our environmental footprint.

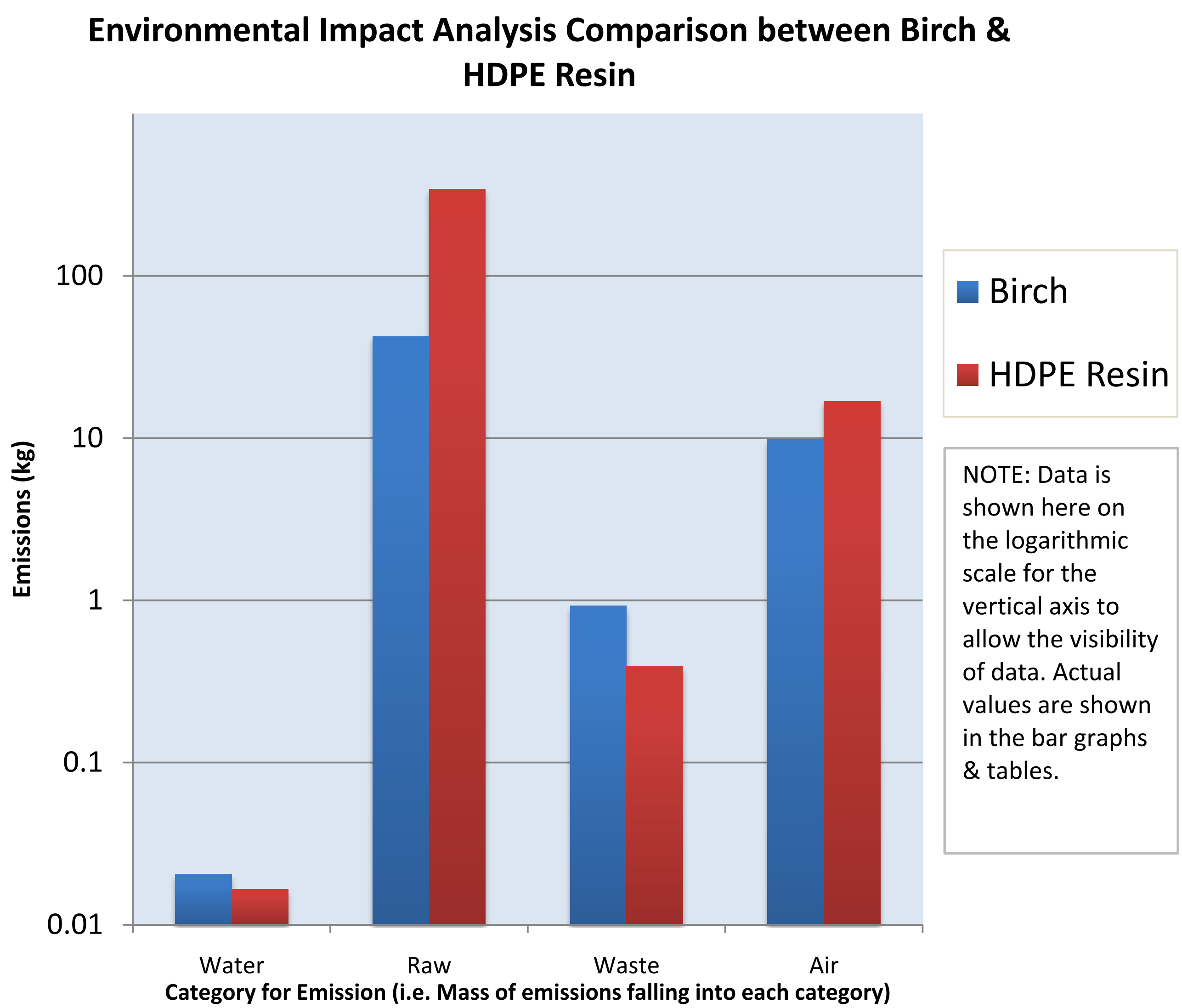
CHASSIS

For the chassis, we narrowed the materials down to birch and HDPE. The total mass of wood required was 8 kg, and the mass of HDPE required based on accounting for density was10.5 kg (assuming the same volume was used for both materials in the fabrication of the chassis.) Once again, the table and the bar chart give an idea of the emissions.

I4: Emission levels for Birch and HDPE Resin.

Emissions for the various categories (kg)							
Air		**Water**		**Raw**		**Waste**	
Birch	**HDPE Resin**	**Birch**	**HDPE Resin**	**Birch**	**HDPE Resin**	**Birch**	**HDPE Resin**
9.87	16.86	0.02	0.017	42.2	343.8	0.92	0.39

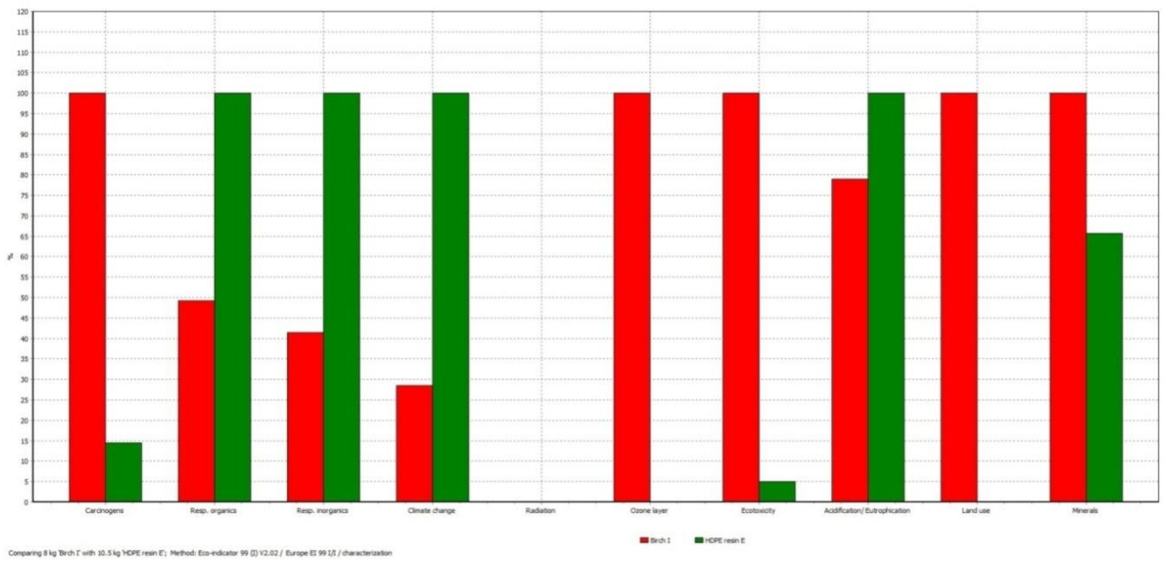
I5: Birch and HDPE Resin Emissions Comparison



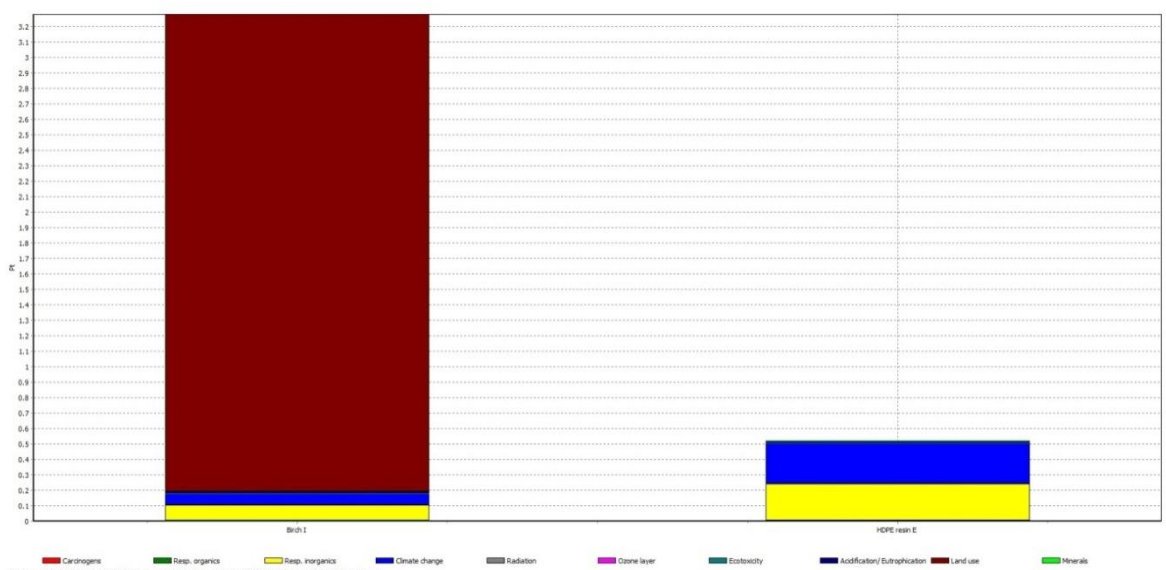
Except for the impact caused by emissions that will cause water pollution (whose values are very close to each other), birch produces way less emissions than HDPE that will have an impact on the air, and less emissions that will have an impact on the water resources as well as less waste.

According to the characterization chart, birch produces more carcinogens than HDPE, and requires a larger area of land than HDPE. It also requires more minerals and has a strong tendency to deplete the ozone layer when extracted. HDPE on the other hand does not cause ozone depletion.

I6: Characterization chart for Birch and HDPE Resin



I7: Single score chart for Birch and HDPE Resin



As further clarified by the single score chart, Birch does indeed require extensive land use, as large areas of forests have to be cleared to supply wood. Removing trees depletes the ozone, because the major source of oxygen that is used to form ozone in the stratosphere comes from trees, and hence the replenishment rate of ozone from oxygen is reduced. However, the single score chart gives a poor picture, because even though large areas of land have to be cleared, there are certain effects that HDPE has on the environment too that cannot be ignored. HDPE has a large environmental impact, as there is a large amount of raw materials that need to be supplied to extract ethylene from petroleum, and more raw materials are required to polymerize ethylene. Moreover, processing of petroleum to obtain ethylene gives out greenhouse gases such as carbon dioxide and methane that would cause global warming and disturb the equilibrium rate of carbon removal and replenishment in the carbon cycle, since petroleum consists of carbon that has “escaped” the carbon cycle by becoming trapped for millions of years under the ground. Many toxic chemicals are also produced that if released, could cause water and air pollution in the processing of HDPE. Wood on the other hand produces less toxic chemicals when processed.

Comparing the environmental impact of the two materials, birch certainly is a better choice overall, although it fails significantly in such categories as ozone depletion and land use. In addition, from a machining/manufacturing standpoint, HDPE melts easily during the laser cutting process and therefore deformities could develop during re-solidification, rendering it a poor material. HDPE also has poorer material properties than those of birch. Being a polymer, HDPE has values of elastic modulus and tensile strength lower than those of birch (a wood), which means that rigidity and strength of the structure would be compromised if we chose polyethylene. The tensile strength of HDPE is about 29 MPa, while that of birch is no less than 40 MPa. As for the elastic modulus, HDPE has a value of about 1.4 GPa while birch has a value of about 20 GPa.

Although birch is a good choice based on environmental reasons, we still have to find ways to reduce the environmental impact caused by deforestation, such as the large land use and the depletion of the ozone layer. One way to do this is to buy birch wood from loggers who practice sustainable logging. This means than we will purchase wood from only those loggers who carry out reforestation after cutting out an area of the forest, and allow fallow periods so that the forests are able to replenish themselves over time, ensuring a sustainability of natural resources.

CONCLUSION

In this section, we have analyzed the environmental impact caused by the materials we selected using CES, and we have narrowed down the initial group of materials to aluminum for the drive-train components, and birch for the chassis. We used SIMAPRO, a life cycle assessment software to do the analysis. Although SIMAPRO gives a lot of useful information, it still has drawbacks as it does not incorporate information about sustainable practices. Hence it is essential to consider those in determining the environmental impact as well. Most importantly, environmental impact might not be an important factor in the analysis, so it is necessary to carefully identify the application and determine the importance of other factors before performing the material selection.