MECH 4240

Critical Design Report

Final Presentation

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Corp 4 (Robotic Lawnmower)

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1.0 Summary

Mechanical Team Beta was formed to aid in the completion of an autonomous robotic lawnmower. The project started as a whole in June 2009, when Mechanical Team Alpha began work designing the mower from a system level. Alpha designed and developed the mower structure, the cutting deck, and the drive train. When Team Beta formed in August 2009, tasked were passed down which included designing a trimmer arm, environmentally protecting the electronics, and mounting sensors.

The scope of the work for Beta became oriented to a few, very well defined subsystems and components. After preliminary meetings with Team Alpha, as well as with the rest of the Automow Team, the requirements for the three subsystems were generated. After receiving and creating requirements, Beta generated concepts for each of the designs to be completed. The environmental package and sensor mount requirements were very well defined and the development of the chosen concept occurred quickly in verbal discussions between Alpha, Beta, and the electrical team lead. The environmental package needed to complete the enclosure of the mower and provide a means of keeping the mower electronics, motors, and batteries cool. Despite knowing what was needed for the sensors, no actual sensors have been chosen yet. Thus, Team Beta generated two concepts to be adapted as needed to support sensor positioning and accuracy.

The bulk of the work has been in the development of the trimmer subsystem. The requirements were well defined and there were many desired functions for the trimmer. These functions include but are not limited to: tracing a path along a flowerbed, having an adjustable height, and being able to be stowed when not in use. After the development and decision on a final trimmer arm concept, some new tasks developed. A geared DC motor with an encoder was chosen for the means to position the trimmer arm. In order to size the motor, a Working Model simulation was developed and is being analyzed for the required torque and rpm needed to choose the desired motor.

This critical design report will detail the design process the team used to attack the problem and the final results of the design process. Calculations were performed to give the team values that were needed to pick out a motor to control the arm, fans to remove heat from the inside of the mower, and spring rates that were needed for the flex sensor on the trimmer head. Very detailed 3D CAD drawings were generated and drafts were made to serve as guides during the manufacturing process. A detailed bill of materials (BOM) was created from assembly drafts. The BOM includes prices for raw materials, fasteners, and manufactured components as well as material information and the quantity of said materials and fasteners. The goal of Team Beta's design is to allow easy modification by teams in the upcoming semester, or by teams that try to improve on the design in the coming years.

2.0 Table of Contents

2.1 List of Figures

3.0 Introduction

A multi-disciplined team of engineers from Auburn University have joined together to design and build an autonomous lawnmower to compete in the 2010 ION Robotic Lawnmower Competition. The team includes electrical, software, computer, and mechanical engineers. The entire team meets biweekly to discuss design and integration, and different tasks have been assigned to each group of engineers. The first set of mechanical engineers, known as Mechanical Team Alpha, were tasked with designing the overall structure, drive train, and mowing deck. Mechanical Team Beta has been tasked with designing a trimmer mechanism to aid the mower in cutting some of the more difficult areas. Beta is also charged with designing an environmental and thermal system. This system is intended to keep the electronics and batteries at low temperatures and free from moisture. Finally, Mechanical Beta was tasked with designing sensor mounts which would provide adjustment while arresting some of the vibrations.

Many of the functions and requirements for the three systems were well defined by Team Alpha during their first phase of design. The main goal of this critical design report is to provide a detailed design of the three systems that were given to Team Alpha at the beginning of the semester.

4.0 Mission Objective

The overall objective of the mission is to provide trimming capabilities, to environmentally protect the motors and mower internal components, and to provide sensor and electronics mounts for the autonomous mowing system designed by Mechanical Team Alpha to compete in the Advanced Autonomous Mowing Field Contest at the Seventh Annual Robotic Lawnmower Competition.

5.0 Concept of Operations

The lawnmower will automatically deploy and retract the trimming arm, while being cooled by fans and protected by the elements. The arm will deploy via a geared DC motor. The motor will respond to an input from a sensor that will detect distance from the obstacle. Once the arm is deployed, the bump sensor will tell the lawnmower when to turn on the Neuton motor that is attached to the arm. Once the trimmer head disengages from a barrier, the trimmer motor will turn off and the arm will be retracted back to its original position. The fans will be running throughout the entire duration of the lawnmower’s operation. Paneling will protect sensitive electronics from as many weather elements as possible including rain, dust, and wind-blown grass.

6.0 Mission Environment

The mower will be operated on the advanced autonomous mowing field which consists of an "L" shaped field with both moving and static obstacles. The moving obstacle is a RC car with a stuffed poodle mounted on top. The static obstacles include a picket fence and a flowerbed. The playing field is laid out as shown below. The main task of Team Beat is to design a trimmer arm to cut Zone Three as shown in Figure 1. This area consists of a one foot wide patch of grass surrounding the flowerbed and the picket fence and is very valuable to cut.

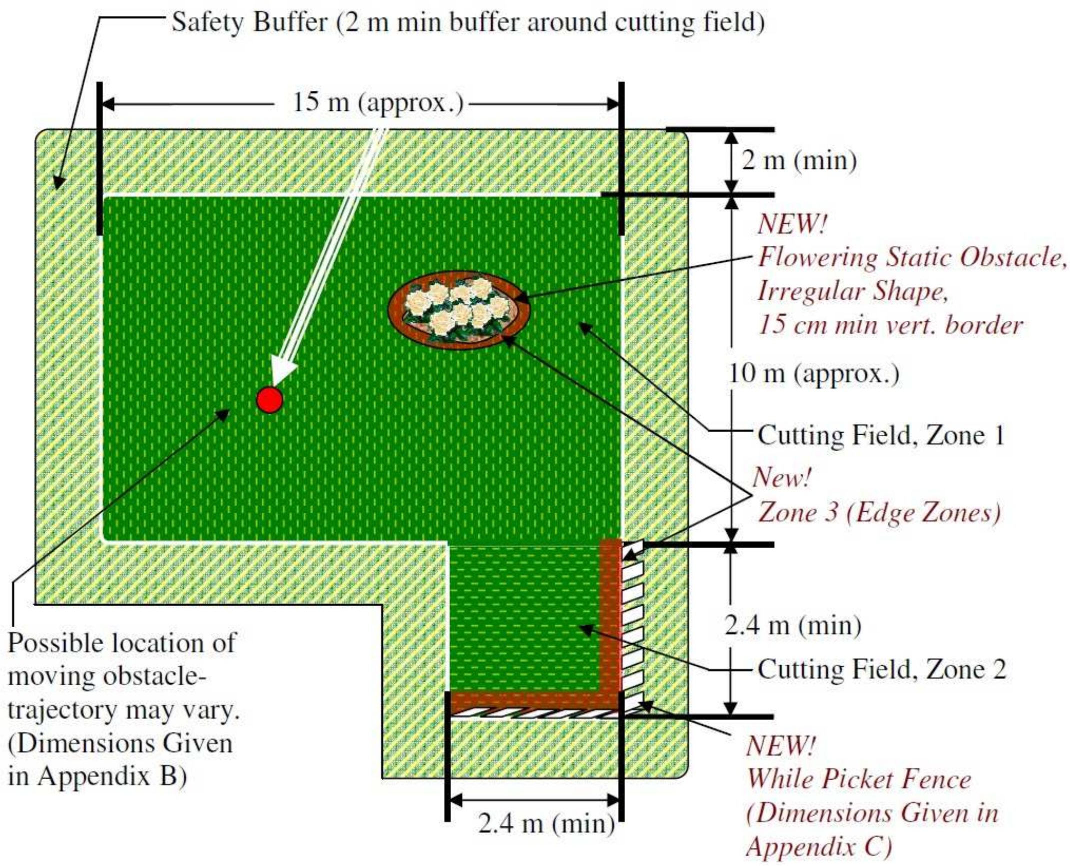


Figure 1: Picture of Cutting Field

The mower must be capable of operating in Ohio at the beginning of June. Part of the design for Mechanical Team Beta involved ensuring the mower doesn't overheat. To do this the last eleven years of weather data for Beavercreek, OH were analyzed. The mean high temperature was 78 degrees Fahrenheit, with a max high of 91 degrees as shown in Figure 2. It rained lightly three out of the last five years and had an average wind speed of 6 knots.

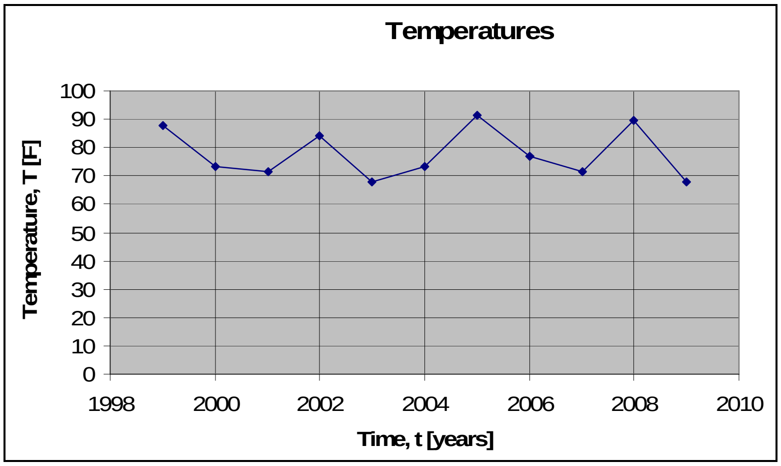


Figure 2: Temperature History of Beavercreek, OH

6.1 Rules

There are several rules affecting the design of each of the systems included. Some of these rules place physical constraints on the team's designs; others help to define requirements that need to be met. The rules and information provided that affect the second stage of the design of the autonomous lawnmower are as follows:

- Trimmer Mechanism

- The trimmer is designed to aid in cutting the areas around the flowerbed and the picket fence. This area is deemed Zone Three and according to analysis done by Mechanical Team Alpha is worth .331% per square foot cut for a total of 30% of the overall performance score. The flowerbed (Figure 3) will not exceed five meters and will contain a concave portion with a minimum radius of two meters. The flowerbed will be surrounded by a plastic border with a minimum height of fifteen centimeters. The flowerbed will be positioned five minutes before the competition starts and its orientation and position may not be programmed into the mower.

Figure 3: Sample Flower Bed

In accordance with the rulebook for the 2009 Ion Lawnmower competition, the mower may not exceed two meters in any dimension. Thus, the trimmer arm must be shorter than two meters minus the lawnmower dimension. It must not travel outside of the safety buffer or the emergency stop will be activated. To avoid disqualifying the mower, the trimmer arm should be retracted when not in use. Otherwise the effective safety zone shrinks by the length of the trimmer arm. The mowing field will not exceed a ten percent grade and divots may be filled prior to competition.

- Environmental Protection System

The environmental protection system which consists primarily of panels, doors, fans, and filters is designed to provide a safe environment for the electronics onboard the mower. It will provide both thermal protection and water resistance. According to the rulebook, mowers should be capable of operating in any weather condition. While it states that the competition will likely be postponed in the event of inclement weather, it is up to the judges, and the mowers must be ready regardless.

- Sensor and Electronic Mounts

While the sensors and electronics to be included on the mower have not been entirely defined, the competition rules do define very specifically where to mount and how big a required emergency stop button. The rules state that it must be accessible from the rear of the mower, must be red, and must be larger than forty centimeters in diameter. As mentioned above, the sensors must be capable of operating in any weather condition. Also, the field may be rough, so the sensors should be durable or mounted in a way to protect them.

7.0 Architectural Design

The following sections provide concepts that were generated for the purpose of accomplishing the mission objective that was stated in Section 3.0.

7.1 Review of Subsystems Concepts

The Mechanical Beta Senior Design Team was given three different design tasks for their senior design project. The first task is to design a trimmer mechanism for the autonomous lawnmower. The second is to design a thermal and environmental protection system for the autonomous lawn mower, and the third is to design a vibration isolation sensor mount system for the autonomous lawnmower. These three design tasks will help aid the autonomous lawnmower win the autonomous lawnmower competition by optimizing the performance of the cutting system, sensors, and electrical system.

7.2 Trimmer Mechanism System

The trimmer mechanism system is a system that is designed to help maximize the amount of points scored during the autonomous lawnmower competition by cutting the area that surrounds the flower bed. The trimmer mechanism system is designed to be able to cut a one foot wide area along an arc with a maximum radius of seventy-eight inches. The swinging trimmer arm concept was chosen for the trimmer mechanism system. This system is broken down into three subsystems, a lawnmower to trimmer arm interface, a trimmer arm to trimmer head interface, and a trimmer head attachment.

Trimmer Requirements:

- Low Power Usage
- Light Weight
- Retractable
- Soft Interface with obstacles
- Easy Attachment
- Outdoor Conditions

The lawnmower to trimmer arm interface will consist of two pieces of the 1010 profile 80/20 mounted to the structure of the autonomous lawnmower, a square piece with a hole cut in the center of it mounted to the two 1010 profile 80/20 pieces, a bearing will be pressed in to the hole of the square piece, a circular piece with a shaft will be pressed into the bearing, a 1020 profile piece of 80/20 will be used as the trimmer arm and it will be mounted to the circular piece, a square piece with a bore cut into it will be mounted onto the trimmer arm, the shaft of the electric motor that will control the trimmer mechanism will be mounted to the square piece by a set screw and key way as shown in Figure 4. This concept will allow the trimmer arm to cut the required area surrounding the flower bed.

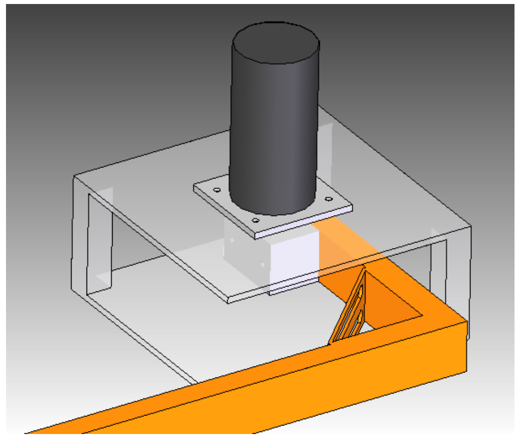


Figure 4: DC Motor with Arm Interface

The trimmer arm to trimmer interface will consist of a circular piece with a hole cut in the center of it for the trimmer motor. Two 1010 profile 80/20 pieces will be mounted at opposite ends of the circular piece. One of these pieces will have adjustment holes cut into the side of it. Another piece of 1010 profile 80/20 will be used to help support the trimmer head and it will be mounted to the two 80/20 pieces that is mounted to the circular piece. The trimmer arm will then be mounted to the piece of 80/20 with the adjustment holes in it. Figure 5 shows how the electric trimmer motor will be mounted to the circular piece and that it contains a threaded shaft that will attach to the trimmer head.

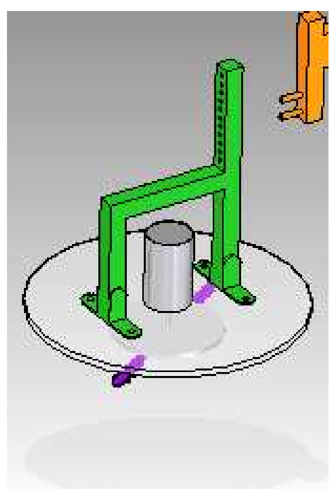


Figure 5: Trimmer Height Adjustment

The trimmer head will consist of a circular piece that will attach to the threaded shaft on the electric trimmer motor. Plastic cutting blades will be attached to the circular piece at opposite ends. This concept will help insure that the trimmer will be able to cut a one foot area that surrounds the flower bed.

Figure 6 shows the completed concept generation for the trimmer arm. The swinging trimmer arm will begin its operation by being retracted and turned off. Once the trimmer arm is in the areas around the flowerbed and the picket fence it will begin its deployment. The trimmer blades are then activated and will begin to cut the desired areas. After completing the cutting mission the cutting blades will be deactivated and the trimmer arm will retract to its initial position. The trimmer is designed so that it will cut even with the cutting deck also the trimmer arm is designed so that it will be higher than the flower bed this will insure that the trimmer arm will not interfere with the flower bed.

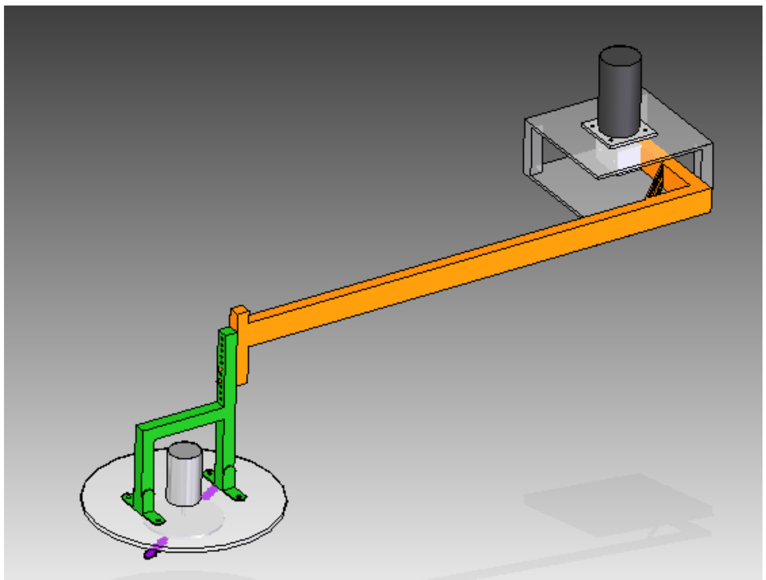


Figure 6: Trimmer Subsystem

7.3 Vibration Isolation Sensor Mount System

The Vibration Isolation Sensor Mount System is designed to filter out unwanted noises produced by vibrations in the autonomous lawnmower and also allow sensors to be mounted in the most effective orientation. The chosen concept for Vibration Isolation Sensor Mount System is broken down into two subsystems a Vibration Isolation Apparatus and a Rotating Sensor Mount system.

Vibration Isolation Sensor Mount Requirements

- Vibration Isolation
- Multiple Orientations (adjustable, but rigid when set)

The vibration isolation apparatus consists of a flat plate mounted to the structure of the autonomous lawnmower. The flat plate will be mounted by the use of a screw and an 80/20 nut. The noises will be filtered out by an o-ring and washer which will be placed in between the flat plate and autonomous lawnmower structure as shown in Figure 7.

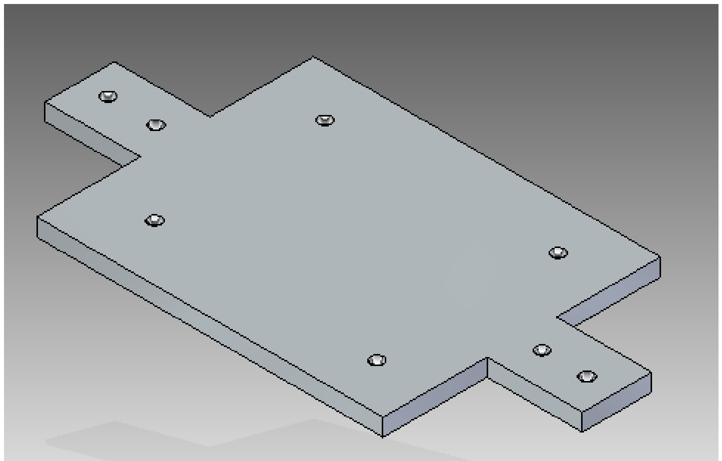


Figure 7: Vibration Isolator

The rotating sensor mount system consists of square piece and a circular piece and a metal ring. The square piece will have a bore that is the diameter of the metal ring cut in the center of it also a threaded hole will need to be cut in the center of the square piece. Two threaded holes will need to be place on opposite sides of the bore. On one side of the square piece threaded holes will need to be placed. On the opposite side two more holes will need to be place on the face that the bore is located. The circular piece will need to have a clearance hole cut into it to match the bolt hole on the square piece. Two threaded holes will need to be placed on opposite sides of the circular piece. Once sensors are chosen a mounting hole pattern can be added to the circular piece so that the sensors can be mounted in the best possible orientation. The metal ring will sit in the bore that is cut into the square piece. A bolt will fix the circular piece to the square piece. The circular piece can then be adjusted so that the desired sensor orientation is achieved. Once the desired sensor orientation is achieved set screws will be used through the bottom of the square piece and top of the circular piece to fix the circular piece to the metal ring. Figure 8 shows a two degree of freedom rotating senor mount. This figure demonstrates how degrees of freedom can be added to the sensor mount by connecting multiple sensor mounts together.

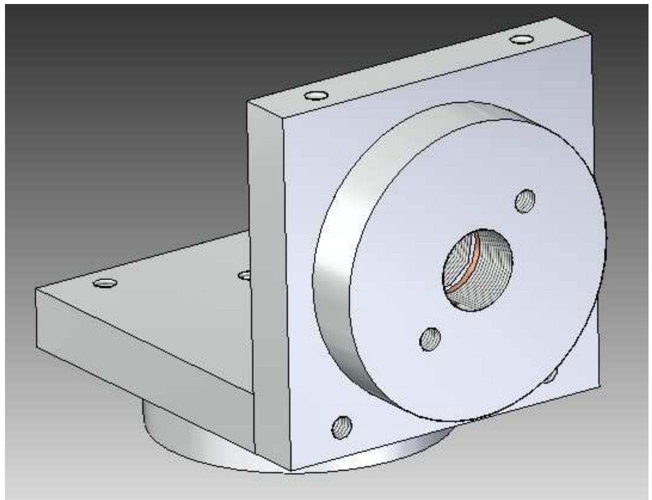


Figure 8: Sensor Mount

The combined concept for the vibration isolation sensor mount system will consist of the rotating sensor mount mounted to the vibration isolation apparatus as shown in Figure 9.   Noises that are produced by the autonomous lawnmower will be filtered out by the vibration isolation sensor mount and the rotating sensor mount will allow the sensor to be mounted in the most effective orientation. The vibration isolation sensor mount will help optimize the performance of the autonomous Lawnmower control system by optimizing the performance of the sensors that measure the data used during the control of the autonomous lawnmower.

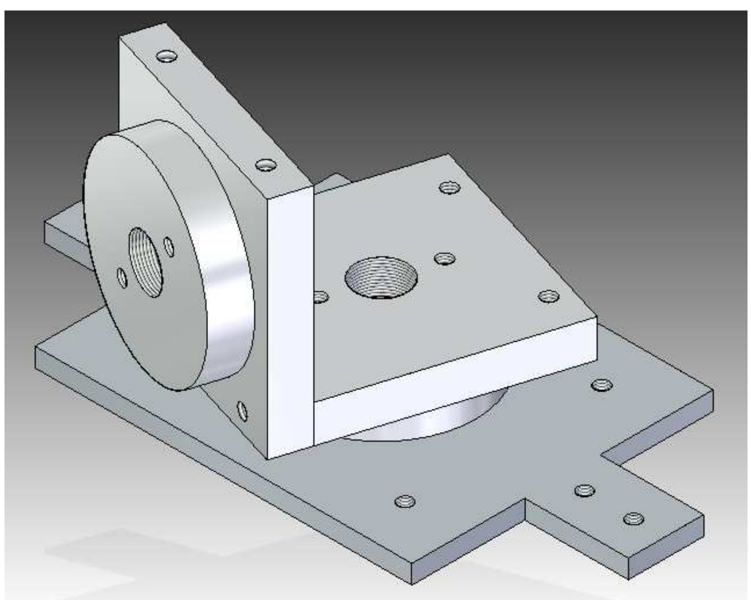


Figure 9: Combination Sensor Mount and Vibration Isolator

7.4 Thermal and Environmental Protection System

The thermal and environmental protection system is a system that is designed to protect the electrical components such as: circuit boards, motors, motor controllers from dust, grass, and water. This system is also designed to help maintain optimal operating temperatures for the electrical components. The thermal and environmental protection system is broken down into two main systems a fan and filter system and an environmental protection system.

Thermal and Environmental Protection System Requirements

- Environmental Protection (Dust, Grass, Water)
- Thermal Management
- Provide Access

Figure 10 shows that the fan and filter system will consist of a filter located on the back of the bottom level of the lawnmower and two fans placed at opposite corners of the front section of the bottom level of the lawnmower. Also filters will be placed in front of the fans so that debris from the cutting blades will not be blown into the lower level of the cutting deck. This system will function by the two fans pulling air through the lower level of the lawnmower. The fan and filter system will help the electrical components of the autonomous lawnmower maintain optimal operating temperatures.

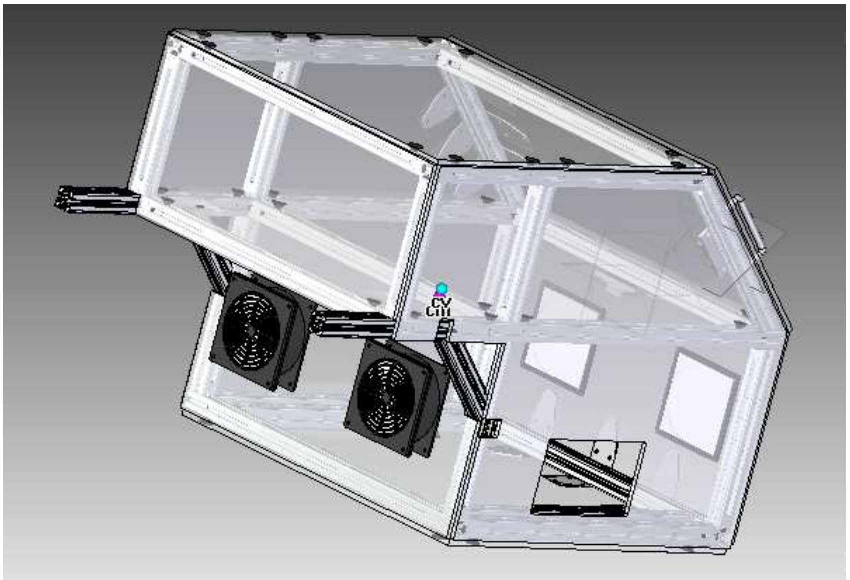


Figure 10: Fan Placement

The environmental protection system will consist of panels that will help protect the electrical components from dust grass and water. These panels will also allow for access to the electrical components of the upper and lower levels. The panels will be mounted with hinges to the frame to allow access to both levels of the mower as shown in Figure 11. Each panel will use a latch system so that it will be secure when closed. Rubber gaskets will be installed to keep out moisture and dust when the panels are close.

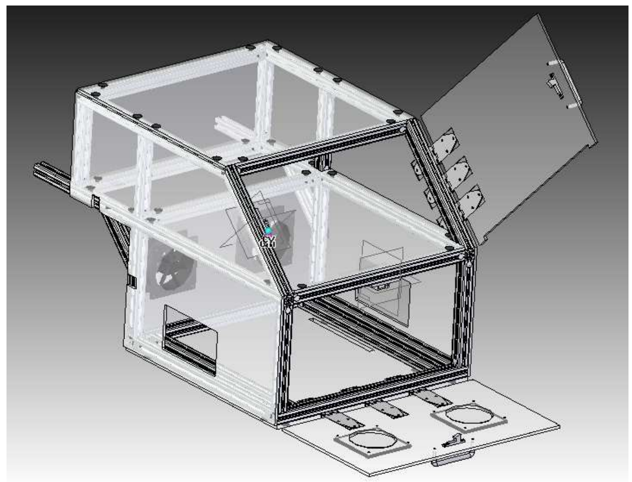


Figure 11: Access Panels Open

7.5 Height Adjustment

After discussion with team leader Zach Lamb and advisor Dr. Beale, it was decided that the task of designing the Mower Deck Height adjustment mechanism will be left to later mechanical design teams. This decision will help team beta maximize the performance of the Trimmer mechanism by allowing more resources to be used in its development.

8.0 Validation of Concepts

In order to build an optimized trimmer attachment for the lawnmower, the concepts had to be confirmed plausible in order to implement them. This could be done by building small models, purchasing several different motors and fans, or by using 3D CAD software to build virtual models. Mechanical Team Alpha tested the trimmer motor head that will be used by Mechanical Team Beta last semester. It would have been more time consuming and expensive for the team to purchase several different mechanisms to possibly be used to rotate the arm about the robot. Due to these reasons, 3D models, Working Model simulations, and MATLAB simulations were used to validate the chosen concepts.

Solid Edge models were generated to confirm the spatial requirements and kinematic movement of the arm about its rotational point and around the mower. Kinematic models were made using Working Model to test different concepts concerning controlling the trimmer arm. For example, springs were considered for use earlier in the design process, but were deemed to be too risky due to a high restoring force produced by the spring when the arm would lose contact with a barrier. 3D CAD models were also generated to help validate the concepts that were generated for the trimmer head.

9.0 Analysis and Calculations

Forces that were going to be exerted on the flower bed needed to be calculated to make sure they would not be high enough to knock over the barrier and damage the field. This was done by taking the torque provided by the DC-motor and dividing it by the length of the arm, shown in Equation (1).

$$F = \tau / L \quad (1)$$

The power usage by the DC-motor also needed to be calculated. This can be done using Equation 2. The torque is multiplied by the motor's rpm and divided by a conversion factor of 5252 to get units in HP.

$$P = \frac{\tau * n}{5252} \quad (2)$$

It was important to calculate the mass flow rate needed to keep the inside of the mower from overheating. Using concepts of internal flow from heat transfer, the mass flow rate needed at a certain temperature difference. This can be done using Equation (3):

$$q = \dot{m} C_p (T_{m_0} - T_{m_i}) \quad (3)$$

This equation will be used twice: once to calculate the mass flow rate for a given temperature difference, and again to find the temperature difference for the given mass flow rate from the fans. The fans are rated by a volumetric flow rate which can be converted into a mass flow rate using the density of air at an average mean temperature denoted as $\overline{T}_m$. Detailed hand calculations are provided in Appendix A and results of the calculations are shown in Section 12.3.

10.0 Failure Modes Analysis

With such a complicated build, it is crucial for the team to recognize possible failures of each subsystem and to devise plans to mitigate the possibility of a subsystem failing during a run or not running at an optimal performance. With several subsystems being designed, this is a vital step to understanding each subsystem in their entirety and how they operate mechanically, kinematically, and thermally.

The most crucial subsystem that was designed by Team Beta was the trimming arm. If the trimming subsystem does not properly perform its given tasks, it will be a complete mission failure for Team Beta, and a partial mission failure for Team Alpha. Obviously, it is one of the more important subsystems of the lawnmower. The two failure modes that can prove fatal to the mission are the trimmer head motor failing and the trimming arm not deploying.

If the trimmer motor head fails, the trimmer subsystem will not be able to cut the grass in Zone 3, which consists of about 30% of the overall possible score. Unfortunately, this problem cannot be fixed once the lawnmower is on the field during a run, so the team will need to be conscious of this possibility when preparing the lawnmower for the competition. The team will need to make sure that the motor is secured to the trimmer head and that there are not any loose electrical connections before the run starts.

If the trimmer arm does not deploy, the results will be the same as above. The team needs to be aware of the spatial requirements for the arm to be able to rotate, and make sure during the fabrication process that the parts are milled, drilled, and assembled properly. Another possible failure mode for arm deployment is the DC motor. It needs to be integrated into the subsystem properly and tested repeatedly to verify that it will operate as expected during the competition.

Two other important, yet not as crucial to mission success, failure modes that need to be considered include failure of the thermal management subsystem and failure of the panel access subsystem. Neither of these scenarios will lead to a mission failure, but they could possibly reduce the efficiency of the lawnmower system and lead to a decrease in its operating lifetime.

11.0 Safety Management

User safety is a top priority for everyone working on this project. Team Alpha has already highlighted safety protocol for everyone working on the lawnmower, so it will not be reviewed. However, Team Alpha did not consider safety precautions for the systems designed by Team Beta. The safety precautions that will be added to the overall list are as follows:

- No one is allowed near blades while the batteries are being adjusted and connected
- Users need to remain clear of the radius of the trimmer arm while maintenance is being performed on the deployment motor.
- Electrical wiring will not provide power to trimmer head motor while maintenance is being performed.
- Hands are to remain clear of the thermal management system.

A first aid kit will be available in case there is an accident. A two man rule can be implemented if the team feels that working on certain parts of the lawnmower appear too hazardous to work on alone.

12.0 Subsystem Design Engineering

12.1 Control Motor Assembly

The control motor assembly is the existing solution for the positioning of the trimmer arm on the 2010 ION Automower. The assembly consists of support structure to attach to the mower, a driver assembly to support the motion of the arm, and a DC-motor to move the trimmer arm. The arm will function by moving out to meet an obstacle when either a fence of flowerbed is connected. This motion will be provided by a DC-motor rated at 7.25 foot-lbf at 10 rpm. The motor has a gear head with a 1 to 353 gear ratio. Because high angular rates were not needed, we were able to use a lower power motor with a high gear ratio for the necessary torque. Figures 12 and 13 give visual representations of what the DC-motor assembly will look like.

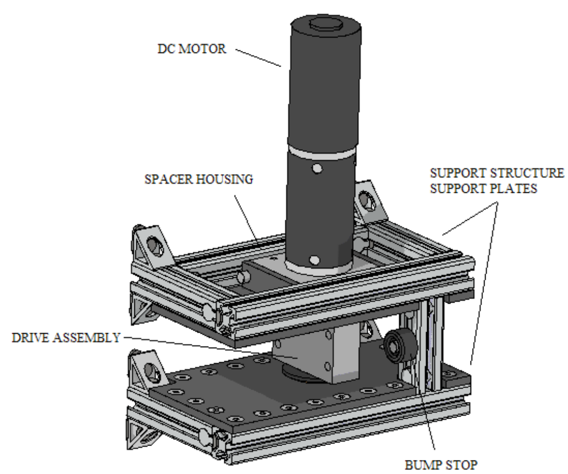


Figure 12: DC Motor Assembly

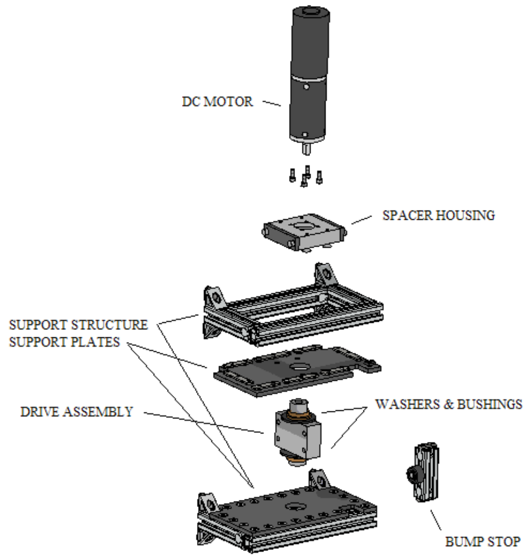


Figure 13: Exploded View of DC Motor Assembly

The inputs for the control and positioning of the trimmer arm will come from the LIDAR and from the trimmer head assembly. The LIDAR will detect when an object that needs to be trimmed is within range and the arm will deploy. Likely, the robot will slow down when it determines it is in a trimming area. The arm will continue to move in an outward sweeping arc until it reaches the bump stop at 90 degrees or until it receives a signal from the trimmer head assembly. The trimmer head which consists of a bump ring surrounding the original bump plate is home to multiple cherry switches which will provide info as to whether the arm has run into the barrier that it is trying to trim. As the robot moves forward, these signals will tell the arm to retract until it is no longer touching the barrier. In this manner, the robot will move forward "tracking" the barrier and avoiding damage to the gear box.

The control assembly attaches rigidly to the mower near the front half of the structure on its right side. A bushing, washer, and drive assembly provide the one degree of freedom rotation desired while not translating any other forces or moments onto the control motor which could reduce its MTBF. A bushing was chosen over a bearing, because of the very low speed and load being applied. For such an application, a bushing provides a cheaper and yet still dependable joint. The bushing also provides vertical support on its lip, but two large washers were added to keep the assembly tight while allowing more clearance for the trimmer arm between the plates.

The spacer housing seals the motor gears and internals from the harsh mowing environment while also providing access to the set screw which couples the DC-motor to the drive assembly. The drive assembly, shown in Figure 14, consists of three separate aluminum pieces with 4 set screws holding it together. The necessity for this design came from the lack of access to a CNC mill, which could be used to produce the part from one solid piece of aluminum. This design consists of plate and bar stock with simple machining procedures to produce the desired assembly.

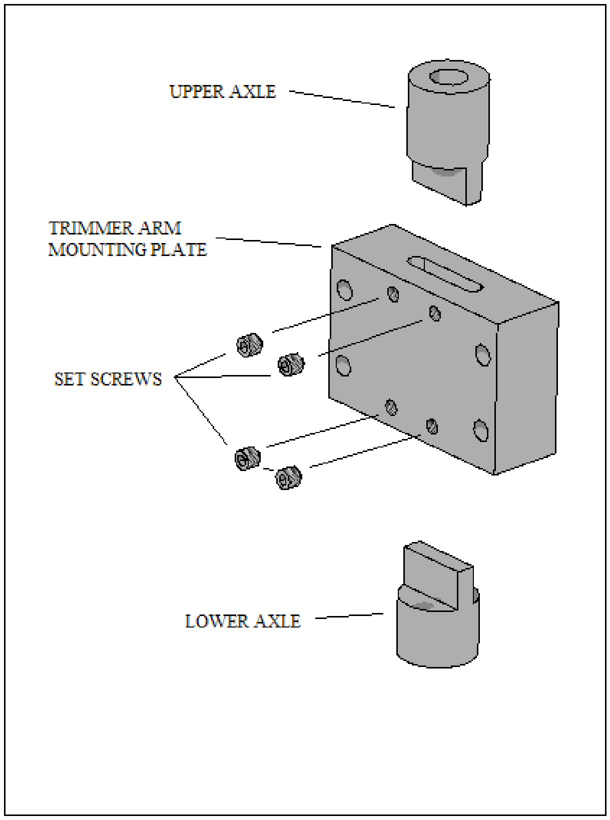


Figure 14: Drive Assembly

After all of the components have been assembled the control motor assembly will provide a rigid single degree of freedom (DOF) joint with minimal transverse loads on the DC-motor being used. It will allow for the trimmer arm to be moved to whatever position is desired, and because the DC-motor has an encoder installed, the control design can progress to incorporate complex control algorithms. The control will simply run a discreet touching-vs.-not-touching algorithm at first, but as the design progresses, this control will become more complex as necessary to increase performance.

12.2 Trimmer Head Assembly

The Trimmer Head Assembly (Figures 15 and 16) was designed to provide the trimming capabilities for the 2010 ION Automower. This design consists of a support structure, a DC motor which will drive the trimmer blades, and a bump sensor which will be used to aid in the detection of obstacles such as a fence or flower bed. The Trimmer Head Assembly will function by moving out to meet an obstacle when either a fence or flowerbed is detected by the bump sensor, then the DC-motor will be activated, and then the Trimmer Head will begin to cut the area that surrounds the obstacle.

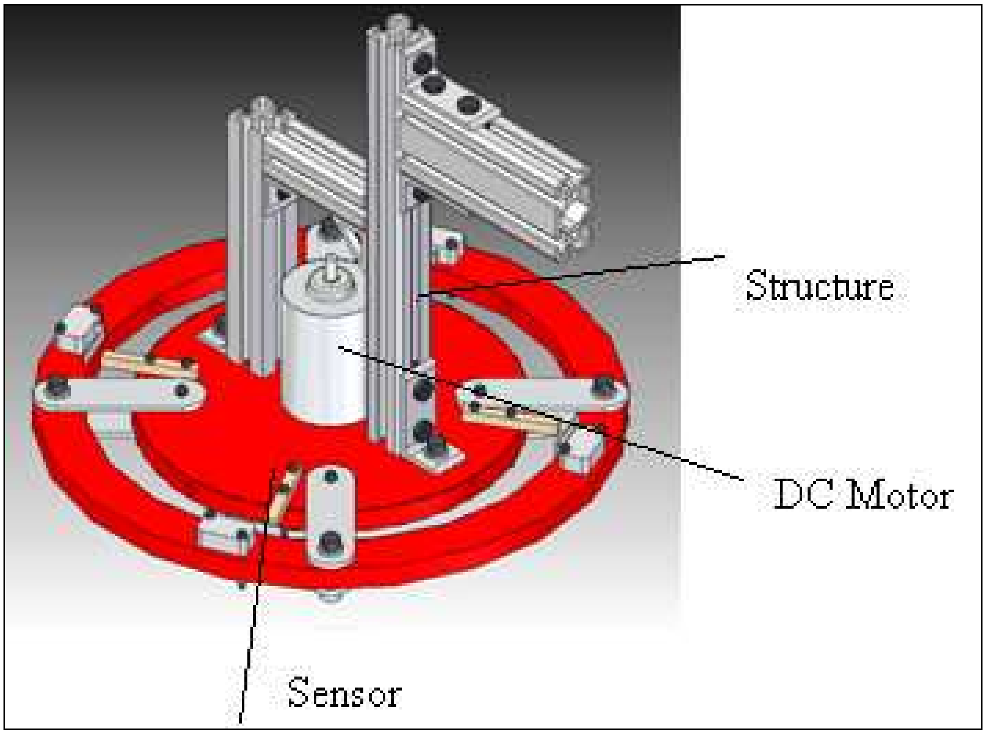


Figure 15: Trimmer Head Assembly

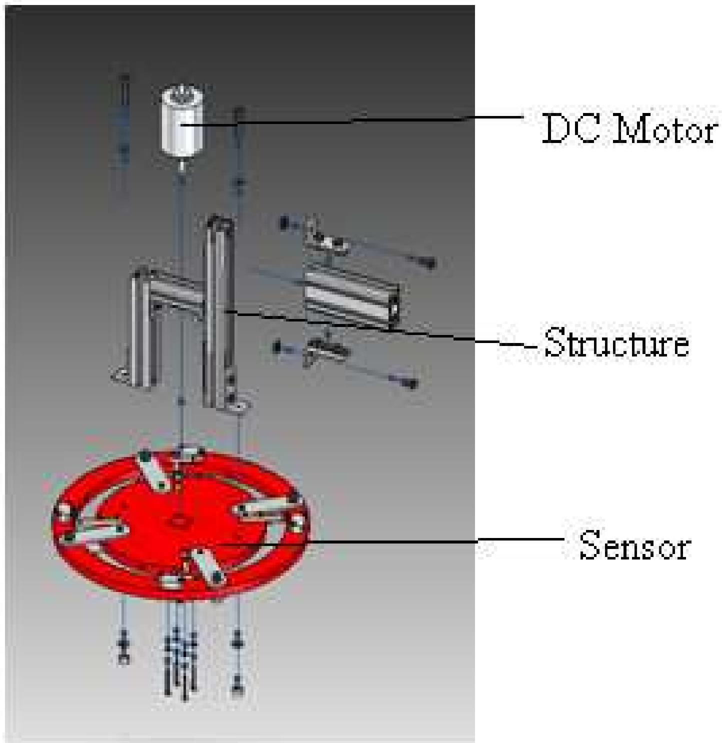


Figure 16: Exploded View of Trimmer Head

The DC motor will be attached to the bump sensor by four 4 40 thread 1 ¼ inch length cap screw purchased from McMaster-Carr. The DC motor will be the same one that was purchased from Neuton Power by Team Alpha. The structure will be attached to the bump sensor by two ¼"-20 thread l" length cap screw purchased from McMaster-Carr.

The Structure will consist of three 1010 profile 80/20 pieces, Trimmer Head Support Member, Trimmer Head Cross Member, and Trimmer Head Height Adjustment Member as shown in Figure 17. Two inside corner gusset brackets will be used to fasten the three 1010 profile 80/20 pieces together. Figure 18 shows two Three Hole Corner Brackets purchased from 80/20 that will be used to fasten the structure to the Bump Sensor.

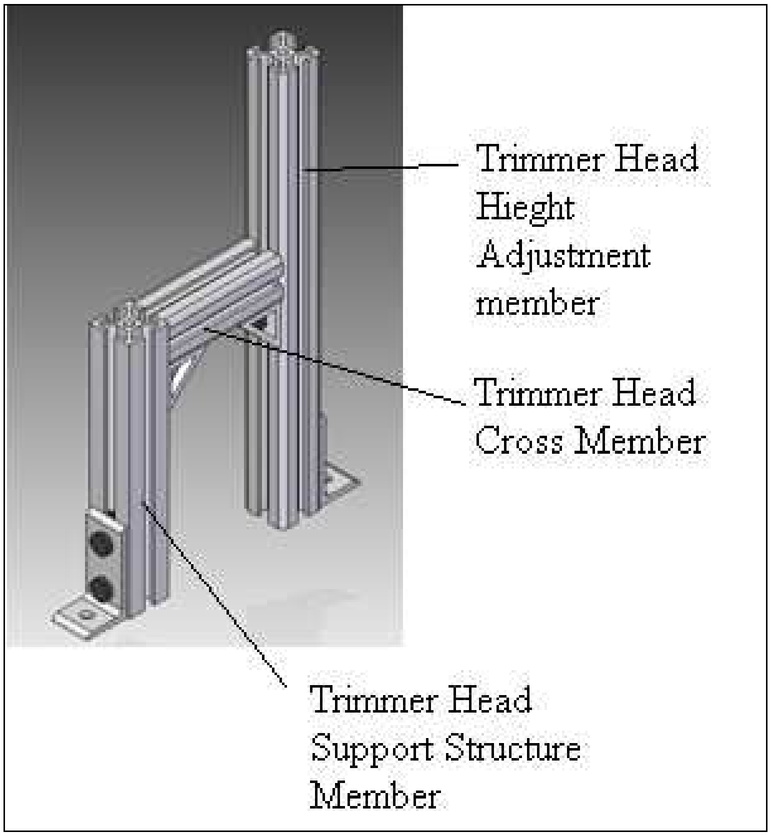


Figure 17: Structure Assembly

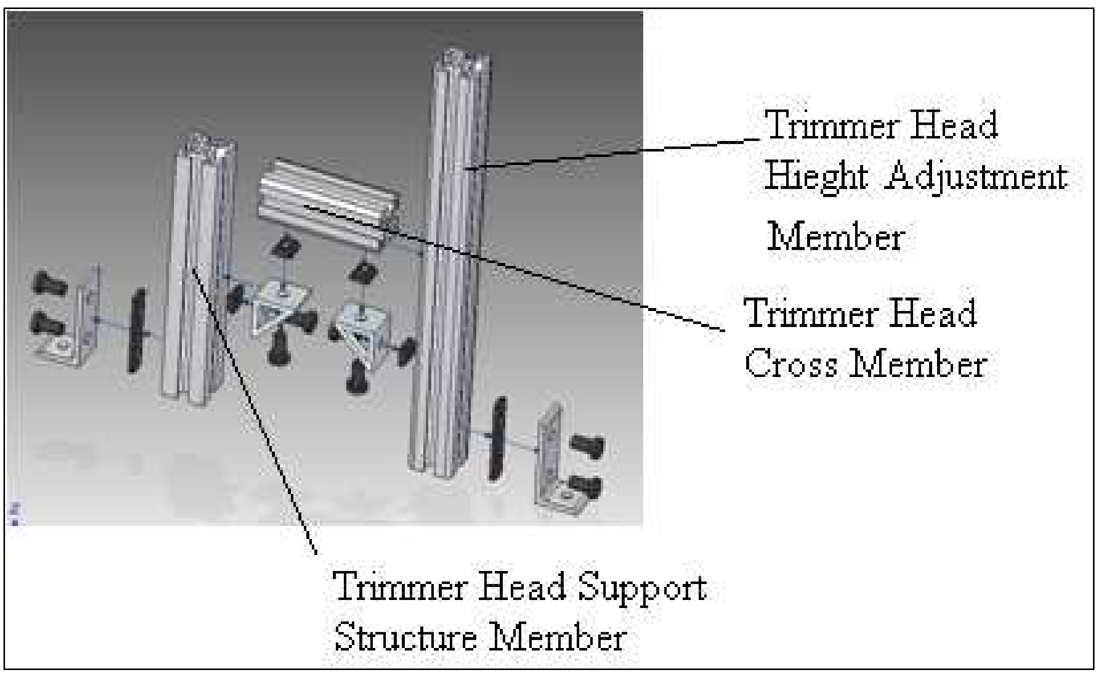


Figure 18: Exploded View of Structure Assembly

The Bump Sensor (Figure 19) will consist of the Trimmer Deck, a Flex Sensor Disk, four lever switches, and four compression springs. The Trimmer Deck and Flex Sensor Disk will be cut out of 12” X 12”X ½” polyethylene sheet which can be purchased from McMaster-Carr. The four lever switches are purchased from Digi-Key. The four compression springs are also purchased from McMaster-Carr.

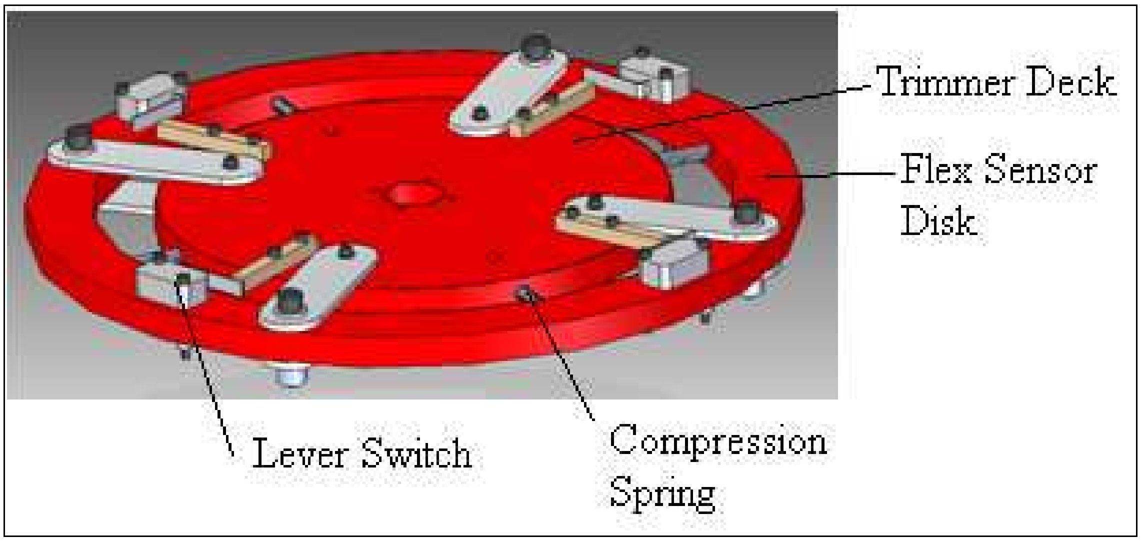


Figure 19: Bump Sensor

The Flex Sensor will detect obstacles by using the lever switches purchased from Digi-Key and four 2 inch length Gray PVC (Type I) 1/4" Square Bar purchased from McMaster-Carr. The Flex Sensor Disk (Figure 20) presses up against an obstacle one of the four lever switches which are attached to the Flex Sensor Disk will be activated by pressing against the gray PVC Bar that is attached to the Trimmer Deck.

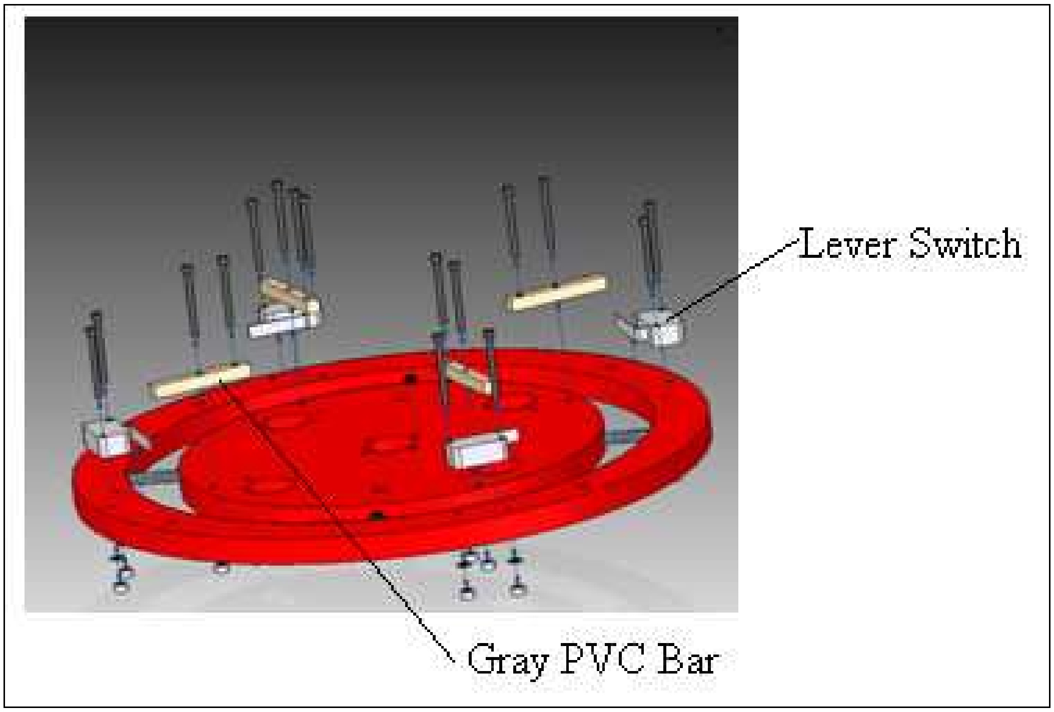


Figure 20: Demonstration of Bump Sensor

The motion of the Bump Sensor will be controlled by using four compression Springs purchased from McMaster-Carr and eight .125" thick brackets. The four compression springs will be used to maintain the flex sensor disk original position after an obstacle is detected. The eight .125" thick brackets will used to limit the amount of travel the flex Sensor Disk can experience in the vertical direction shown in Figure 21. The four 1-inch diameter holes cut into the Flex Sensor Disk will allow it to move in any direction up to a maximum of a quarter inch.

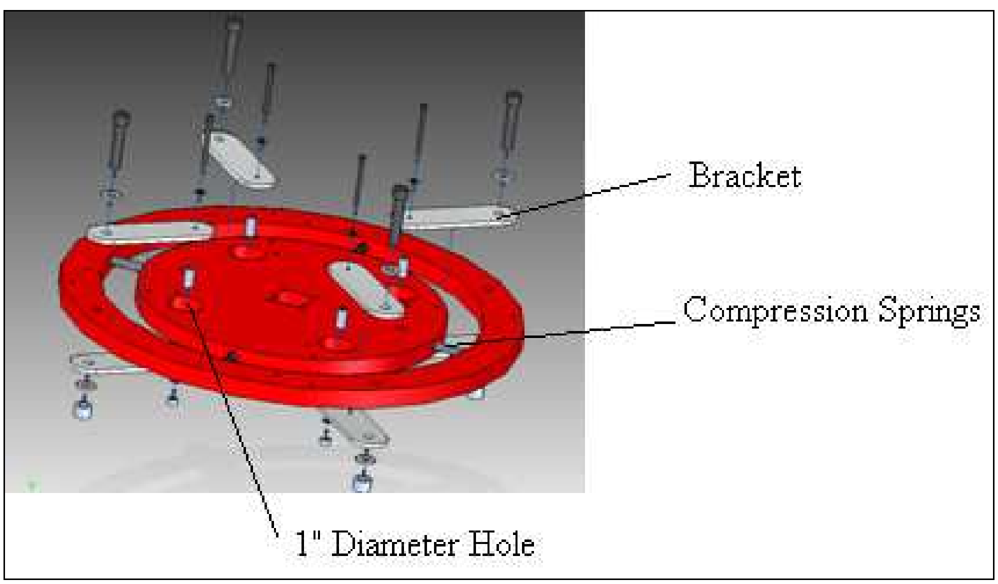


Figure 21: Exploded View of Bump Sensor

12.3 Thermal Management

The thermal management subsystem will consist of two fans placed at the rear of the lawnmower. Air will be flowing out of the lawnmower to reduce the amount of contaminants inside. Filters that are specially made for the fans will be used in conjuncture. The fans were chosen based on volumetric flow rate and power usage. The goal was to maximize the flow rate while keeping the power consumption as low as possible. The fan shown in Figure 22 have a flow rate of ninety cubic feet per minute and only have a power draw of .35 amps each.

Figure 22: Fan Used in Mower

Calculations for the mass flow rate needed to remove the required heat and the mass flow rate are shown in Appendix A. MATLAB was used to determine the mass flow rate needed over a range of temperature differences. It was also used to determine the temperature difference achieved by the fans due to the mass flow through the mower. Figure 23 shows a range of temperature difference and corresponding mass flow rates. The star on the graph represents the temperature difference achieved by the two fans. The volumetric flow rate and air density were used to calculate the mass flow rate provided by the fans. The temperature change could then be calculated using Equation 3 from Section 9.0.

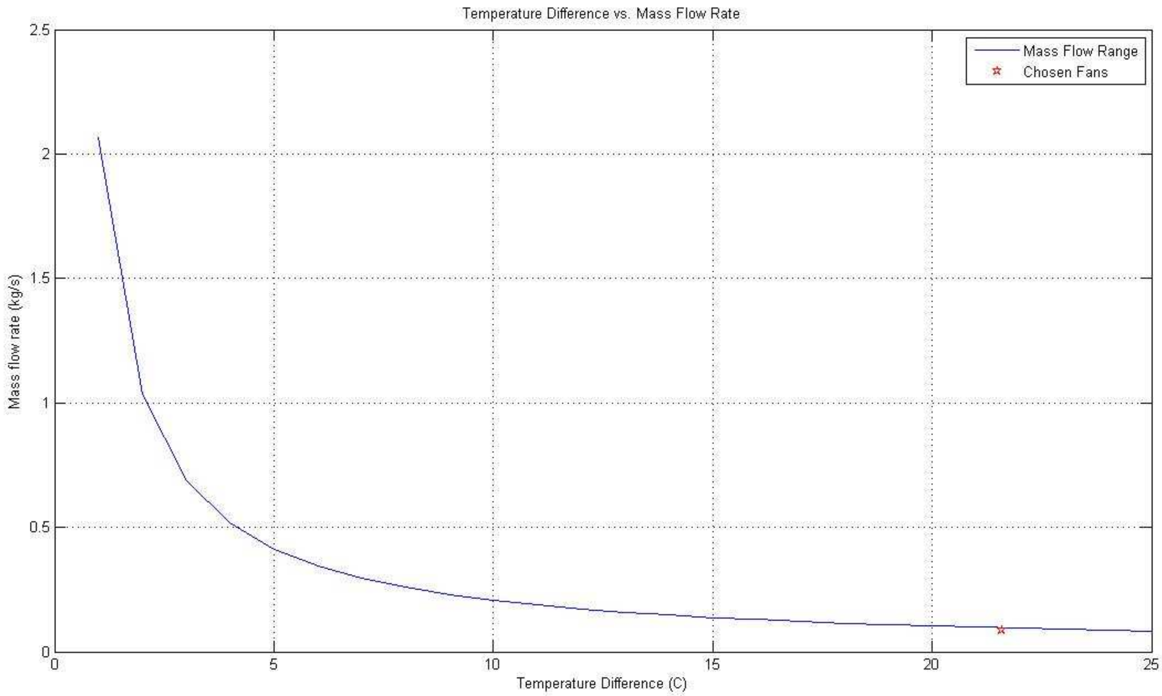


Figure 23: Mass Flow Rate vs. Temperature Difference

12.4 Protection from Environment

Polycarbonate panels have been picked out to provide protection from elements such as rain, dust/dirt, and wind-blown grass. Rubber gaskets will also be used to line the interface between the panels and 80/20 profile.

13.0 Manufacturing Considerations

In order to minimize cost and meet design requirements and specifications certain manufacturing methods will be used in to manufacture the Trimmer, Environmental Protection, and Thermal Protection Subsystems. The Drive assembly and Plates in the motor control assembly will need to be machined also the 1010 profile 80/20 pieces will need some machining work and cut to length. In the Trimmer Head assembly the 1010 profile 80/20 pieces will need to be cut to length also The Trimmer Deck and Flex Sensor Disk will need to be machined. The panels in the environmental protection system will need to be cut down to size using either saws or mills, with holes drilled following the drill patterns on the drafts.

14.0 Product Hierarchy

Detailed below is the product hierarchy for all parts that have been designed for the Trimmer, Environmental Protection and Thermal Protection subsystems. A drawing package also accompanies that shows assembly drawing and detailed dimensions for all individual parts.

MOTOR CONTROL

AUTOMOW2010-5200 – CONTROL ASSY
AUTOMOW2010-5201 – SIDE TRIMMER
AUTOMOW2010-5202 – REAR TRIMMER
AUTOMOW2010-5203 – FRONT TRIMMER
AUTOMOW2010-5205 – BUMBER
AUTOMOW2010-5206– PLATE TOP TRIMMER
AUTOMOW2010-5207 – PLATE BOTTOM TRIMMER
AUTOMOW2010-5208 – PLATE, SPACER
AUTOMOW2010-5209 – PLATE, SPACER COVER
AUTOMOW2010-5210 – DRIVE ASSY
AUTOMOW2010-5211 – BLOCK, MOUNTING, ARM
AUTOMOW2010-5212 – AXLE, UPPER
AUTOMOW2010-5213 – AXLE, LOWER
AUTOMOW2010-5214 – BUSHING

TRIMMER HEAD

TRIMMER HEAD ASSEMBLY

AUTOMOW2010-5100 – TRIMMER HEAD ASSY

STRUCTURE

AUTOMOW2010-5300 – STRUCTRURE ASSY
AUTOMOW2010-5301- TRIMMER HEAD SUPPORT MEMBER
AUTOMOW2010-5302– TRIMMER HEAD CROSS MEMBER
AUTOMOW2010-5303- TRIMMER HEAD HIEGHT ADJUSTMENT MEMBER

SENSOR

AUTOMOW2010-5400- TRIMMER HEAD BUMP SENSOR ASSY
AUTOMOW2010-5401- TRIMMER DECK
AUTOMOW2010-5402- FLEX SENSOR DISK
AUTOMOW2010-5403- GRAY PVC BAR

ENVINRONMENTAL PROTECTION

TOP PANEL

AUTOMOW2010-6301- HINGE MOUNTING BRACKET

AUTOMOW2010-6302 – TOP PANEL

UPPER REAR PANEL

AUTOMOW2010-6500 – UPPER REAR PANEL ASSY

AUTOMOW2010-6301 – PANEL, UPPER REAR

LOWER REAR PANEL

AUTOMOW2010-6600 – LOWER REAR PANEL ASSY

AUTOMOW2010-6301 – PANEL, LOWER REAR

LOWER FRONT PANEL

AUTOMOW2010-6700 – LOWER FRONT PANEL ASSY

AUTOMOW2010-6701 – PANEL, LOWER FRONT

PANELS

AUTOMOW2010-6801 – PANEL, UPPER FRONT

AUTOMOW2010-6802 – PANEL, RIGHT FRONT

AUTOMOW2010-6803 – PANEL, RIGHT REAR

AUTOMOW2010-6804 – PANEL, LEFT

15.0 Cost Breakdown

Supplied in Figure 24 is a pie chart with the cost breakdown of the materials needed for Team Beta to build the subsystems that were designed. As expected, raw materials make up a sizable portion of the cost, sharing space with paneling and components such as the geared DC-motor, fans, etc.

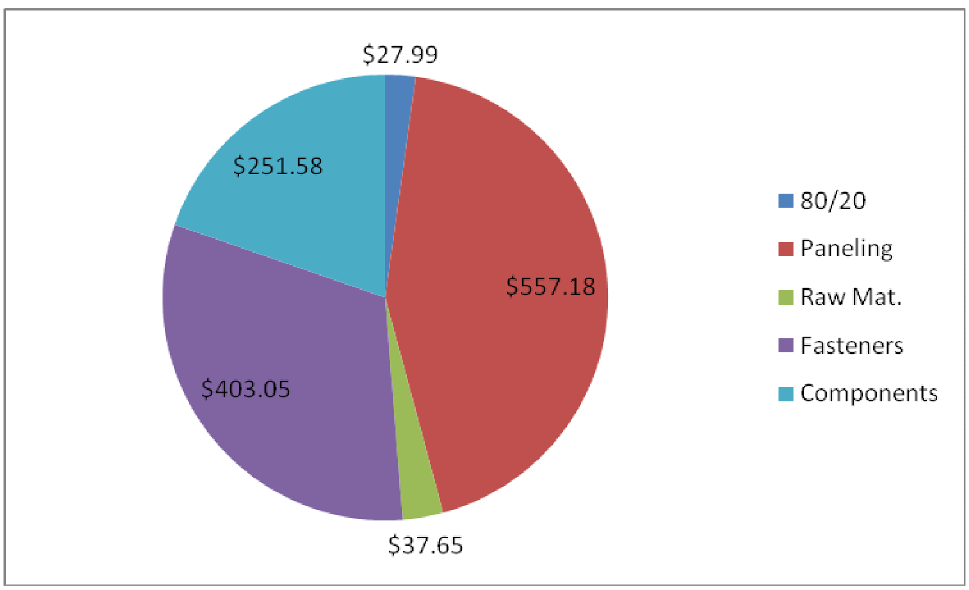


Figure 24: Cost Breakdown

16.0 Conclusion

The goal of this design report is to give a detailed view of what was designed for the lawnmower throughout the semester. Several concepts were generated, but only one for each subsystem was chosen; and the team believes each design will be able to complete the mission objectives effectively. In the coming semester, the team will put into action the proposed manufacturing methods and the verification plan described. Modifications will also be made depending on the rule changes in the upcoming Automow competition.

Appendix A: Calculations

A.1 Motor Calculations

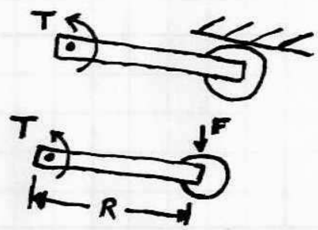
Force on Flowerbed Barrier

$F = \tau / R$

$\tau = 7.25$ ft-lbf
$R = 30$ in.

$\Rightarrow F = \boxed{2.9 \text{ lbf}}$

(output force at rated Torque)



Maximum Allowable Force on Arm

$\tau_{max} = 3\,\tau_{rated} = 3(7.25 \text{ ft-lbf}) = 21.75 \text{ ft-lbf}$

$\Rightarrow F_{max} = \tau_{max} / R$, $R = 30$ in

$\Rightarrow F_{max} = \boxed{8.7 \text{ lbf}}$ (gearbox can only survive momentary peaks at this level)

Control Motor Power Usage (at rated output)

$P = \frac{T \cdot n}{5252}$; $T = 7.25$ lbf-ft , $n = 10$ rpm

$\Rightarrow P = \frac{(7.25)(10)}{5252} = .0138 \text{ hp} = \boxed{10.3 \text{ watts}}$

A.2 Thermal Analysis Calculations

To determine the amount of heat generated:

$q = P = \frac{I}{t} V$ where $I = 64$ amp-hr

$t = .75$ hr

$V = 24$ V

$q = \left(\frac{64}{.75}\right)(24)$

$q = 2080 \text{ W}$

To determine the temperature difference achieved

$q = \dot{m} C_p \Delta T$ | $q = 2080$ W, $\dot{m} = \frac{90 ft^3}{min}(2)(\rho)$ $\dot{V} = \frac{90 ft^3}{min} = .04247 \, m^3/s$

$\dot{m} = .04247 \frac{m^3}{s}(2)(1.127 \frac{kg}{m^3})$

$\dot{m} = .0957 \, kg/s$

$2080 \text{ W} = (.0957 \frac{kg}{s})(1007 \frac{J}{kg \cdot K}) \Delta T$

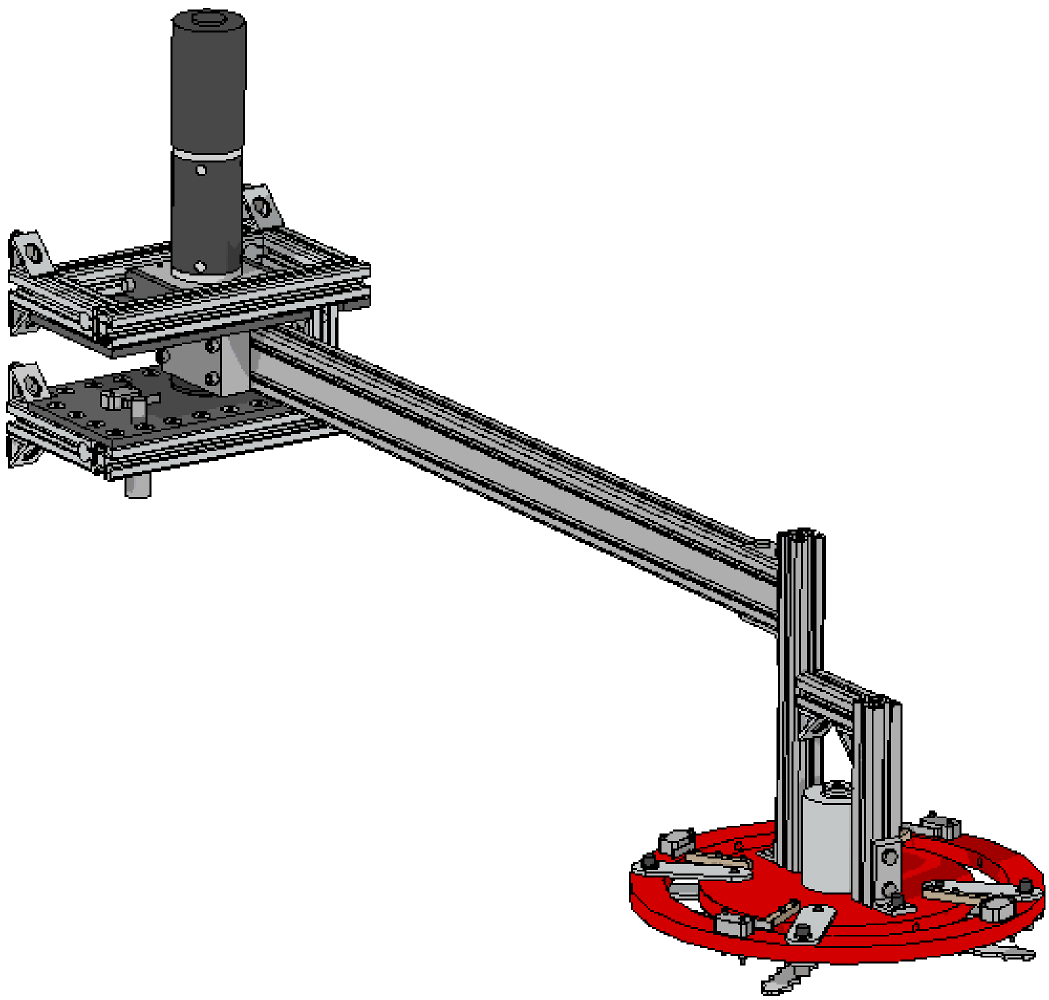
$\Delta T = 21.5°C$

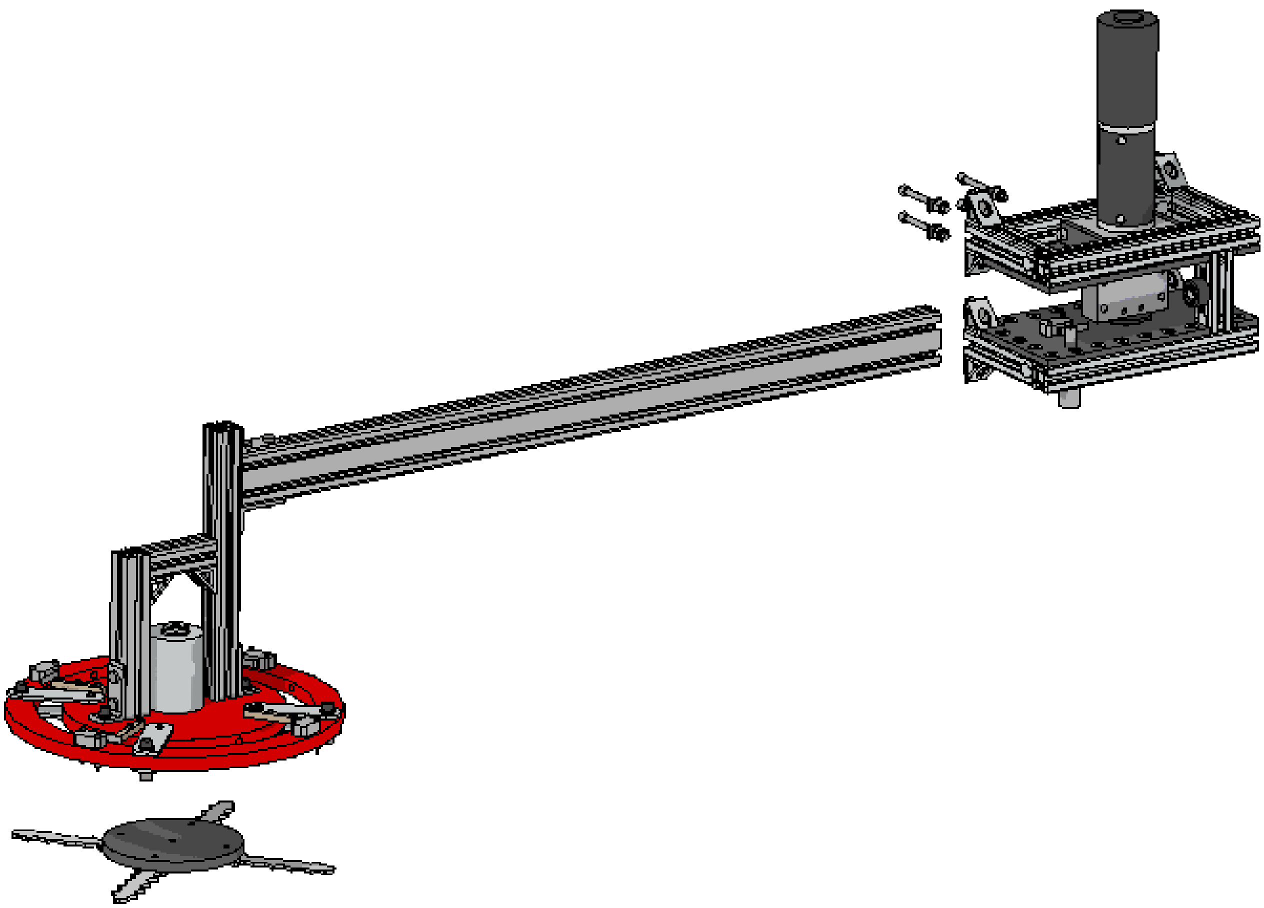
$\Delta T = 36° F$

Properties of air (ρ, C_p) are taken at a mean average temperature $\bar{T}_m$ of $36°C = 309 K$

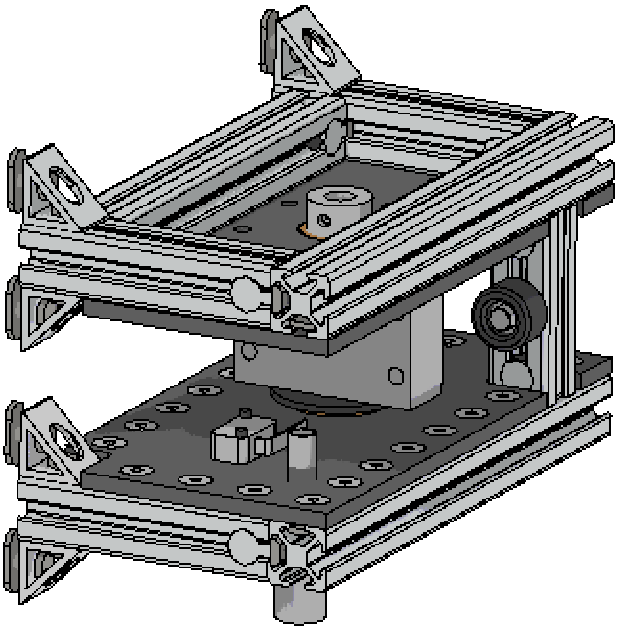
Appendix B: Additional Subsystem Pictures

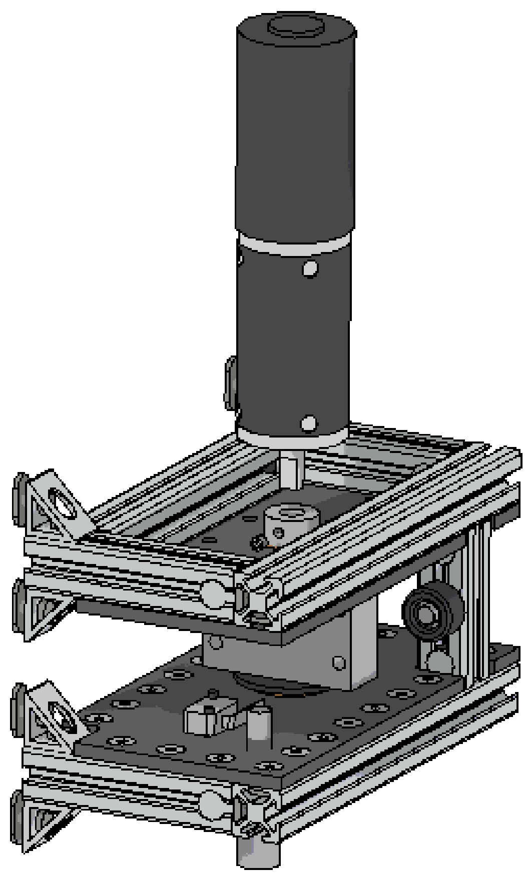
B.1 Trimmer Arm Subsystem



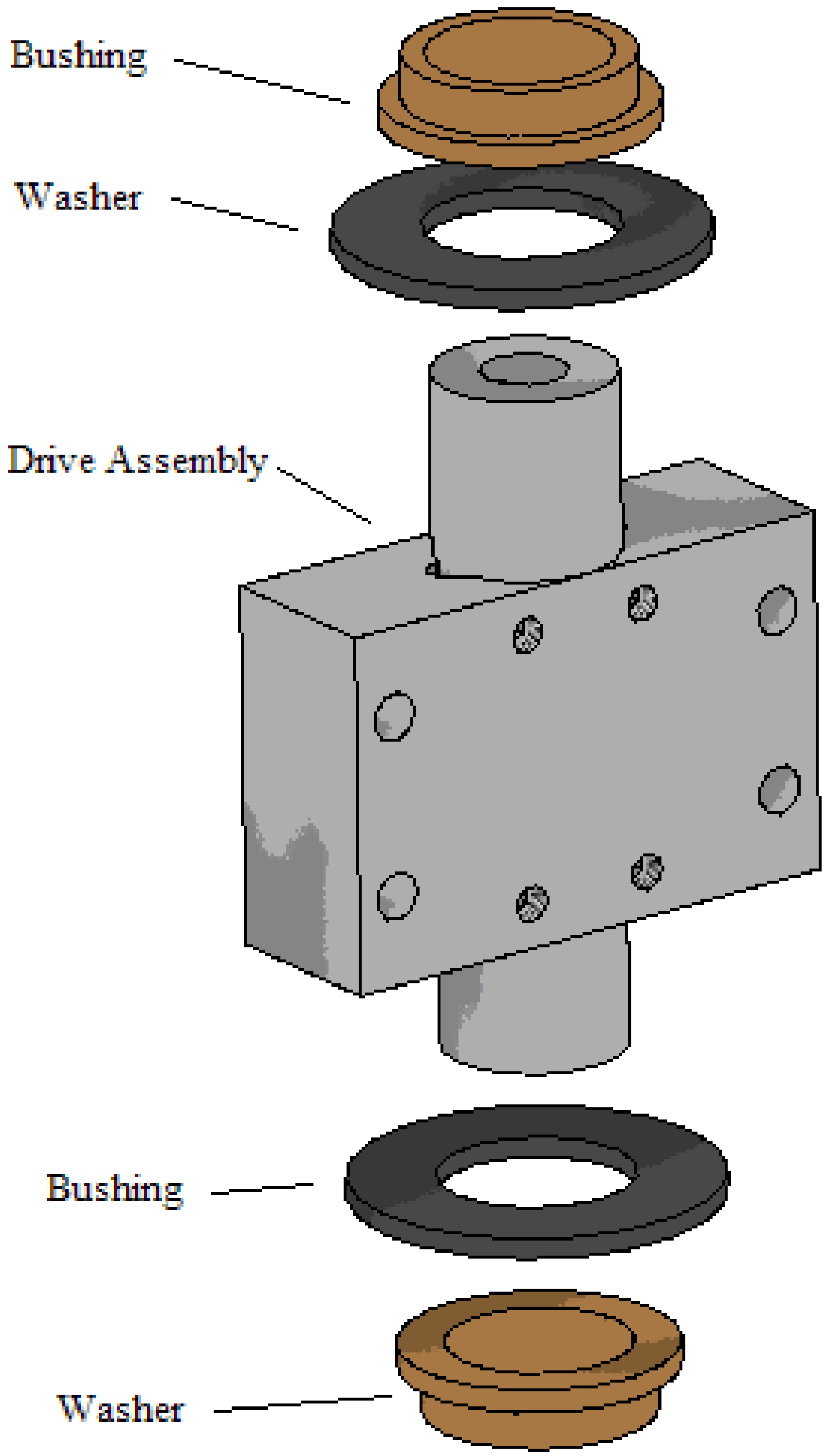


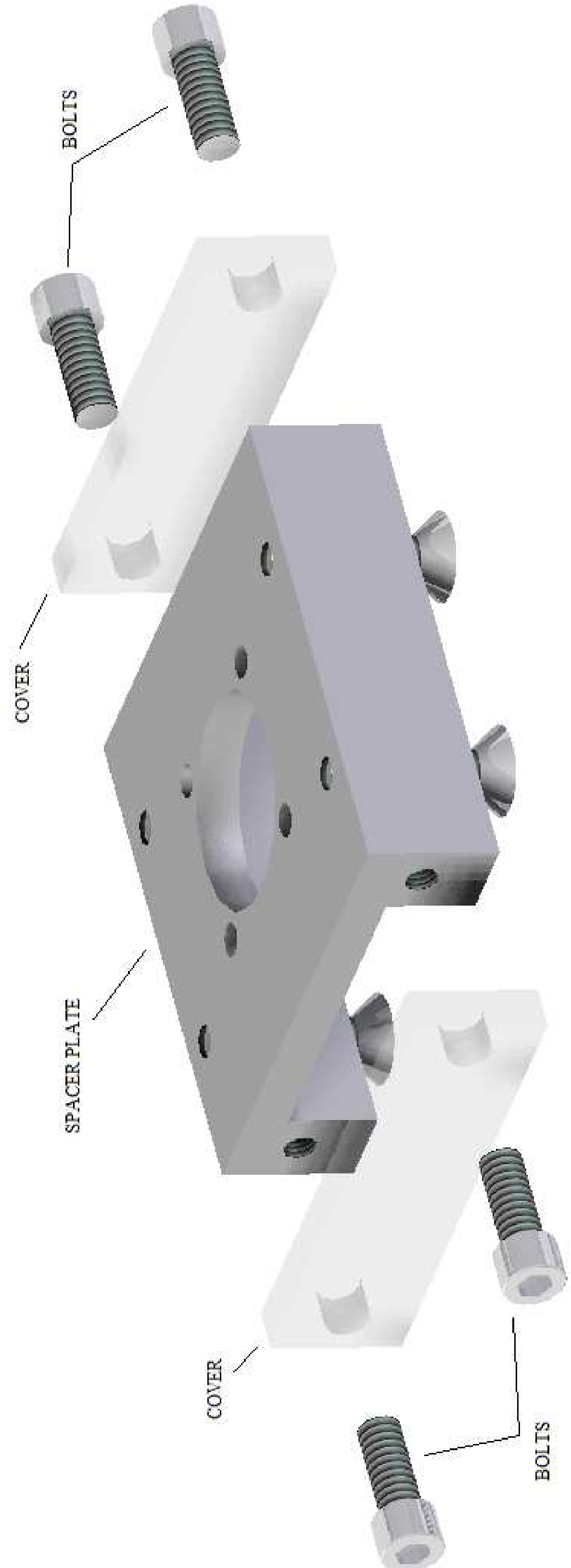
B.2 DC-Motor Housing



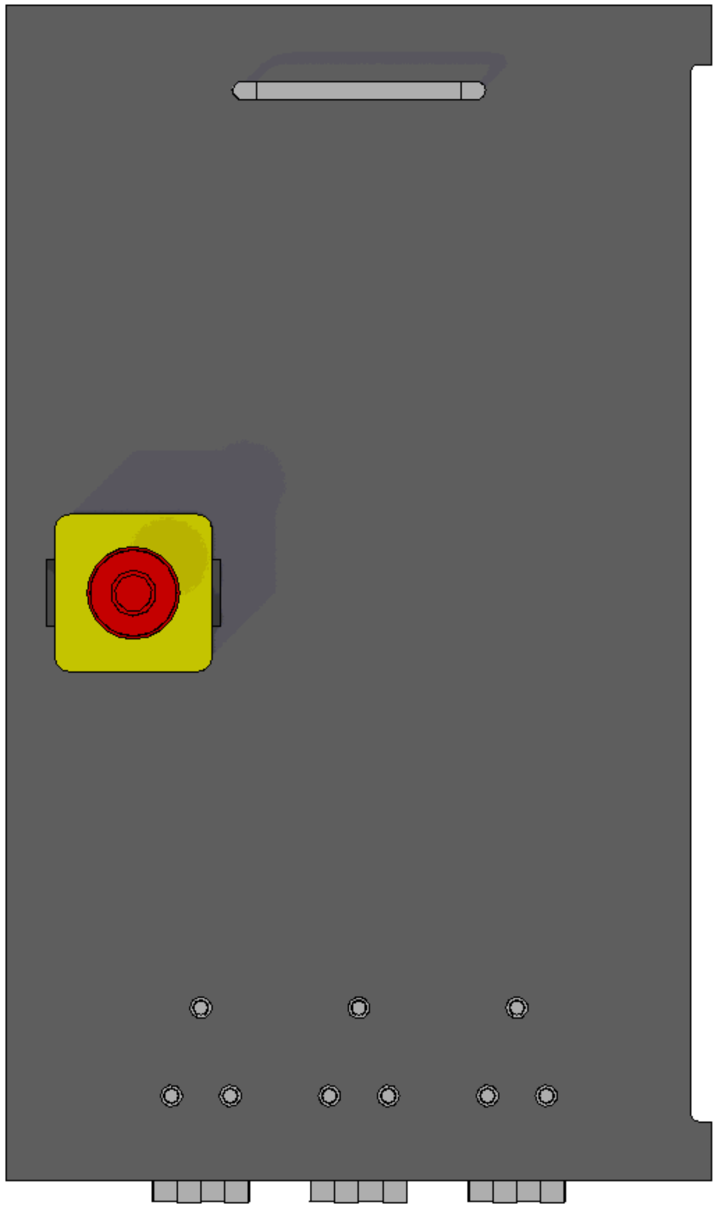


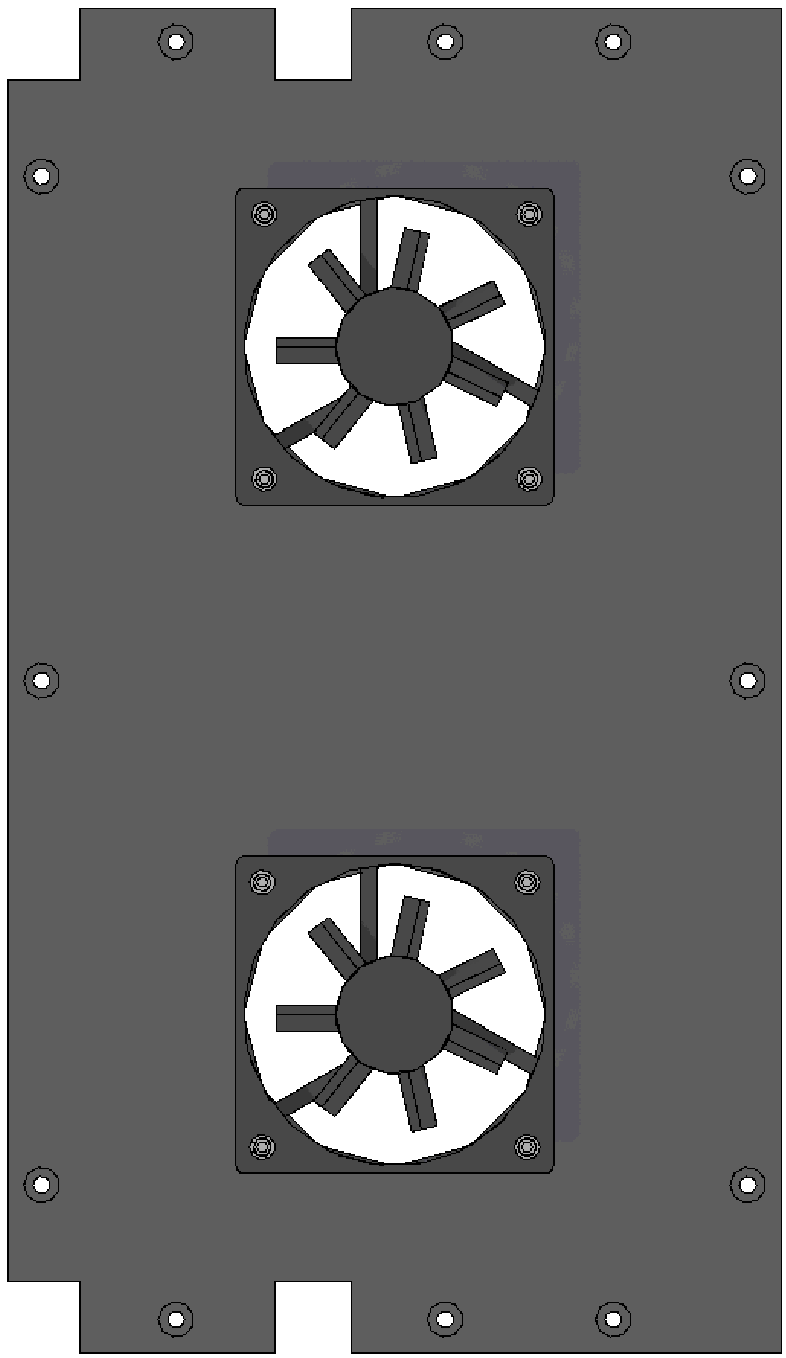
B.3 Drive Assembly




BOLTS
COVER
SPACER PLATE
COVER
BOLTS

B.4 Paneling and Fans





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B.5 Final Robot

Appendix C Economic Analysis

Item #	DRAWING NUMBER	DESCRIPTION	PART NUMBER	MATERIAL INFO	MATERIAL NOTES	VENDOR	QTY	Price	Total
1	Automow 2010-5201	Bar, Side Trimmer	1010	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 4.25''	80/20	4	$0.23/in	$3.91
2	Automow 2010-5202	Bar, Rear Trimmer	1010	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 7''	80/20	2	$0.23/in	$3.22
3	Automow 2010-5203	Bar, Front Trimmer	1010	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 9''	80/20	2	$0.23/in	$4.14
4	Automow 2010-5204	Bar, Bumper	1010	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 2.97''	80/20	1	$0.23/in	$0.68
5	Automow 2010-5301	Trimmer Head Support Member	1010 7042, 7004	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 6.00"	80/20	1	$0.23/in	$1.38
6	Automow 2010-5302	Trimmer Head Cross Member	1010 7042, 7005	1''x1'' Extruded 6061-T5 AL Profile	Cut to length 2.875"	80/20	1	$0.23/in	$0.66
7	-	Trimmer Arm	1020	1''x2'' Extruded 6061-T5 AL Profile	Cut to lenth 30''	80/20	1	$0.39/in	$11.70
8	Automow 2010-5303	Trimmer Head Height Adjustment Member	1010 7042, 7006	1''x1'' Extruded 6061-T5 AL Profile	CUT TO LENGTH 10.00"	80/20	1	$0.23/in	$2.30
9	-	2 Hole Inside Corner Gusset	4132	-	-	80/20	10	$3.95	$39.50
10	-	Triple Economy T-Nut	3287	-	-	80/20	8	$0.79	$6.32
11	-	Double Economy T-Nut	3280	-	-	80/20	9	$0.69	$6.21
12	-	T-Nut	3204	-	-	80/20	3	$0.79	$2.37
13		T-Nut, Drop-In	3376	-	-	80/20	60	$1.70	$102.00

14	-	Double Anchor Fastener	3090	-	-	80/20	10	$5.25	$52.50
15	-	Rubber Bumper	2850	-	-	80/20	1	$2.65	$2.65
16	-	1/4-20 BHSCS Econ T-Nut	3393	-	-	80/20	2	$0.40	$0.80
17	-	Catcher Mount Plate	2123	-	-	80/20	2	$4.60	$9.20
18	-	Keeper, 10 lbs	2125	-	-	80/20	2	$6.25	$12.50
19	-	WSHR, 1.000	96765A210	Stainless Steel w/ Black Oxide Finish	$8.38 per pack of 5	McMaster-Carr	2	$8.38	$8.38
20	-	SCR, SET .250-20 X .250L	92311A533	18-8 Stainless Steel	$4.50 per pack of 100	McMaster-Carr	1	$4.50	$4.50
21	-	SCR, FLAT HD. .250-20 X 1.000L	92210A542	18-8 Stainless Steel/Hex Socket	$10.23 per pack of 50	McMaster-Carr	4	$10.23	$10.23
22	-	SCT, FLAT HD. .250-20 X .500L	92210A537	18-8 Stainless Steel/Hex Socket	$7.17 per pack of 50	McMaster-Carr	48	$7.17	$7.17
23	-	SCHS, .250-20 X .625L	92196A539	18-8 Stainless Steel/Hex Socket	$7.59 per pack of 50	McMaster-Carr	4	$7.59	$7.59
24	-	SCHS, .250-20 X .250L	92210A537	18-8 Stainless Steel/Hex Socket	$7.17 per pack of 50	McMaster-Carr	60	$7.17	$14.34
25	-	WSHR, .250	92141A029	18-8 Stainless Steel	$3.06 per pack of 100	McMaster-Carr	1	$3.06	$3.06
26	-	SHCS, M5 X 0.8MM X 12L	9129A125	-	$7.88 per pack of 100	McMaster-Carr	4	$7.88	$7.88
27	-	WSHR, .164	92141A009	18-8 Stainless Steel	$1.82 per pack of 100	McMaster-Carr	32	$1.82	$1.82
28	-	SHCS, .164-32 X .750L	92196A197	18-8 Stainless Steel/Hex Socket	$6.30 per pack of 100	McMaster-Carr	32	$6.30	$6.30
29	-	SCR, BTN .138-32 X .375L	92949A146	18-8 Stainless Steel/Hex Socket	$4.79 per pack of 100	McMaster-Carr	4	$4.79	$4.79
30	-	Nut, Flange .164-32	93776A381	18-8 Stainless Steel	$5.95 per pack of 50	McMaster-Carr	28	$5.95	$5.95

31	-	1/4"-20 Thread 1" Length cap screw	90128A247	-	$6.13 per Pack of 25	Mcmaster-Carr	1	$6.13	$6.13
32	-	1/4" washer	90940A013	-	$11.50 per Pack of 25	Mcmaster-Carr	1	$11.50	$11.50
33	-	Hex Locknut 1/4"-20	91831A029	-	$5.27 per Pack of 50	Mcmaster-Carr	1	$5.27	$5.27
34	-	4-40 Thread 1-1/4" Length cap screw	90128A119	-	$5.47 per Pack of 10	Mcmaster-Carr	1	$5.47	$5.47
35	-	4-40 washer	90945A716	-	$9.26 per Pack of 250	Mcmaster-Carr	1	$9.26	$9.26
36	-	1/2" Spacer	92415A545	Round Spacer 1/4" OD, 1/2" Length, #6 Screw Size	$1.29 each	Mcmaster-Carr	4	$1.29	$5.16
37	-	1/4" washer	91090A105	1/4" Screw Size	$3.95 per Pack of 100	Mcmaster-Carr	1	$3.95	$3.95
38	-	1 1/4 in 1/4 20 cap screw	90128A247	-	$6.13 per Pack of 25	Mcmaster-Carr	1	$6.13	$6.13
39	-	1/4 20 Nylon-Insert Hex Locknuts	91831A029	-	$5.27 per Pack of 50	Mcmaster-Carr	1	$5.27	$5.27
40	-	1/8 inch washer	90945A716	-	$9.26 per Pack of 250	Mcmaster-Carr	1	$9.26	$9.26
41	-	Nylon-Insert Hex Locknut 4 40	90631A005	-	$2.36 per Pack of 100	Mcmaster-Carr	1	$2.36	$2.36
42	-	1 1/4 inch 4 40 hex bolt	90128A119	-	$5.47 per Pack of 10	Mcmaster-Carr	2	$5.47	$10.94
43	-	Steel Compression Spring	9657K78	4.98 lbs Load	$6.29 per Pack of 12	Mcmaster-Carr	1	$6.29	$6.29
44	Automow 2010-5206	Plate, Top Trimmer	-	-	-	-	-	-	-
45	Automow 2010-5207	Plate, Bottom Trimmer	-	-	-	-	-	-	-
46	Automow	Plate, Spacer	-	-	-	-	-	-	-

	2010-5208								
47	Automow 2010-5209	Cover, Spacer Plate	-	-	-	-	-	-	-
48	Automow 2010-5210	Drive Assembly	9062K211	6061 Aluminum- 1" OD X 12 "L	1" OD x 12"L	McMaster-Carr	1	$12.52	$12.52
49			8975K314	6061 Aluminum- 1.25" X 3" X 12"L	1.25" X 3" X 12"	McMaster-Carr	1	$22.33	$22.33
50	Automow 2010-5214	Bushing, Modified	2938T25	SAE 863 Bronze		McMaster-Carr	2	$1.40	$2.80
51	-	Hinge	1528A250	-	-	McMaster-Carr	6	$15.14	$90.84
52	-	Handle, 4 X 1.313 X .313 OD	1568A12	-	-	McMaster-Carr	3	$3.49	$10.47
53	-	Gasket	1067A3	Rubber Gasket (50 ft)	$1.13/ ft	McMaster-Carr	50	$1.13	$56.50
54		Gasket	93295K31	Foam Rubber Cord	.375 OD X 20 ft	McMaster-Carr	1	$3.88	$3.88
55	Automow 2010-6501	Panel, Upper Rear	8707K132	Abrasion Resistant Polycarbonate 24'' X 12'' X 0.25""	20'' X 12'' X 0.25''	McMaster-Carr	1	$37.03	$37.03
56	Automow 2010-6601	Panel, Lower Rear	8707K132	Abrasion Resistant Polycarbonate 24'' X 12'' X 0.25""	20'' X 11.5'' X 0.25''	McMaster-Carr	1	$37.03	$37.03
57	Automow 2010-6701	Panel, Lower Front	8707K132	Abrasion Resistant Polycarbonate 24'' X 12'' X 0.25""	20'' X 11.5'' X 0.25''	McMaster-Carr	1	$37.03	$37.03
58	Automow 2010-6801	Panel, Upper Front	8707K132	Abrasion Resistant Polycarbonate 24'' X 12'' X 0.25""	20'' X 9.29'' X 0.25''	McMaster-Carr	1	$37.03	$37.03
59	Automow 2010-6802	Panel, Right Front	8707K131	Abrasion Resistant Polycarbonate 12'' X 12'' X 0.25''	9.29'' X 7'' X 0.25''	McMaster-Carr	1	$21.30	$21.30
60	Automow 2010-6803	Panel, Right Rear	8707K134	Abrasion Resistant Polycarbonate 24'' X 24'' X 0.25''	20'' X 19.79'' X 0.25''	McMaster-Carr	1	$64.42	$64.42

61	Automow 2010-6804	Panel, Left	8707K135	Abrasion Resistant Polycarbonate 48'' X 24'' X 0.25''	28'' X 19.79'' X 0.25	McMaster-Carr	1	$112.05	$112.05
62	Automow 2010-5401	Trimmer Deck	84765K115	Polyethylene Sheet 1/2" Thick, 12" X 12" Sheet Size	Used For Trimmer Deck, Flex Sensor	Mcmaster-Carr	1	$24.80	$24.80
63	Automow 2010-5402	Flex Sensor	84765K115	Polyethylene Sheet 1/2" Thick, 12" X 12" Sheet Size	Used For Trimmer Deck, Flex Sensor	Mcmaster-Carr	1	$24.80	$24.80
64	Automow 2010-5403	1/4" PVC Lever	8660K29	Gray PVC (Type I) Square Bar 1/4" Square	Sold in Lengths of 5 ft at $0.86 per Ft	Mcmaster-Carr	1	$4.30	$4.30
65	Automow 2010-5404	Trimmer Bracket	88685K13	1100 Aluminum .125" Thick, 12" X 12"	-	Mcmaster-Carr	1	$13.91	$13.91
66	-	120 mm Aluminum Mesh Fan Filter	80328	-	-	Xoxide	4	$4.99	$19.96
67	-	120 mm Cooler Master R4 Series	90377	-	-	Xoxide	2	$9.99	$19.98
68	-	12VDC to 24VDC Spring Return Solenoid	G16036	-	-	Electronic Goldmine	1	$0.99	$0.99
69	-	Gear Motor with Encoder	TD-045-010	-	-	SuperDroid Robots	1	$139.97	$139.97
70	-	Grass Gator Blades	6610	-	-	Grass Gator	1	$6.99	$6.99
71		SWITCH LEVER DPDT	CH506-ND	-	-	Digi-Key	4	$11.37	$45.48
72	-	Nueton Trimmer Motor	-	-	-	Neuton	1	-	-
73	-	Emergency Stop	U80226U	-	-	-	1	-	-
								Total	$1,277.45

Appendix D: Manufacturers’ Specifications Sheets

Data Sheet for Gear Motor Assembly

直流馬達 (DC Carbon-brush motors)

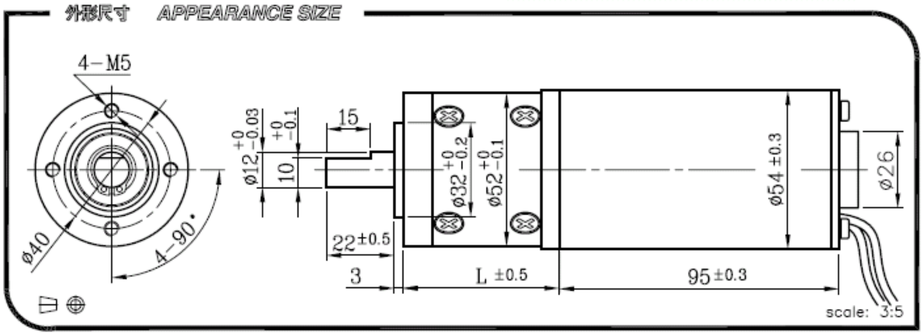
IG-52 GEARHEAD SERIES

IG-52GM

03&04 TYPE

REDUCTION RATIO	L	REDUCTION RATIO	L
1/3~1/4	53.0	1/150~1/936	99.5
1/12~1/26	68.5		
1/43~1/113	84.0		

外形尺寸 APPEARANCE SIZE



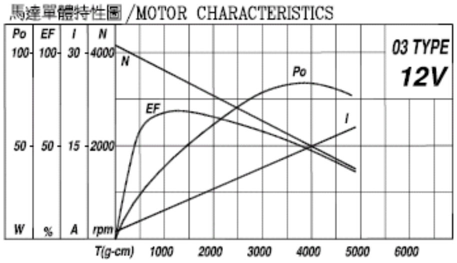
GEARED MOTOR TORQUE/SPEED

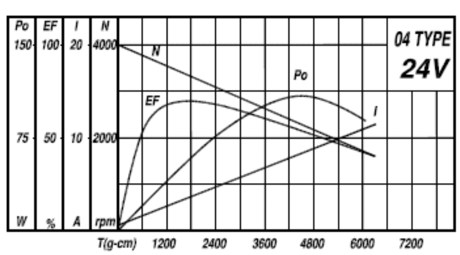
	減速比 Reduction ratio	1/3	1/4	1/12	1/15	1/19	1/26	1/43	1/53	1/66	1/81	1/100	1/113	1/150	1/230	1/285	1/353	1/488	1/546	1/676	1/936
12V	定格扭力(Kg−cm) Rated torque	2.5	3.1	7.7	9.5	11.8	16	23	28	35	44	54	60	67	100	100	100	100	100	100	100
	定格回轉數(rpm) Rated speed	1030	835	295	238	192	139	84	68	55	44	36	32	24	15.5	12.8	10.4	7.6	6.7	5.6	4.0
24V	定格扭力(Kg−cm) Rated torque	3.6	4.5	11	13.5	17	23	33	41	51	62	78	88	97	100	100	100	100	100	100	100
	定格回轉數(rpm) Rated speed	1000	815	285	230	185	136	82	67	54	44	35	31	23.5	15.6	12.9	10.5	7.7	6.8	5.7	4.1

馬達單體型式 /MOTOR DATTA

定格電壓 Rated volt (V)	定格扭力 Rated torque (g−cm)	定格回轉數 Rated speed (rpm)	定格電流 Rated current (mA)	無負荷回轉數 No load speed (rpm)	無負荷電流 No load current (mA)	定格出力 Rated output (W)	重量 Weight (g)
12	900	3620	≤ 4100	4000	≤ 1200	33.5	920
24	1300	3550	≤ 2850	4000	≤ 700	48.6	920

馬達單體特性圖 /MOTOR CHARACTERISTICS





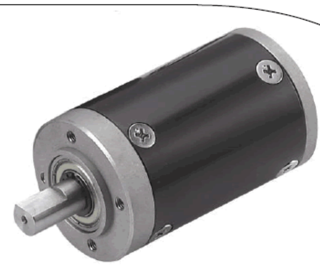
Data Sheet for Gear Box

行星齒輪 (*Planetary gear*)

IG-52
GEARHEAD
SERIES

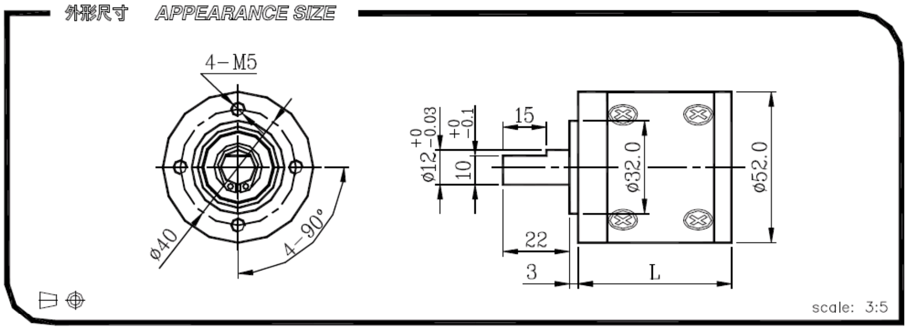
IG-52

● 滾珠軸承型式
Gearbox with ball bearings



★使用相對溼度：20%~85%RH
Operating relative humidity

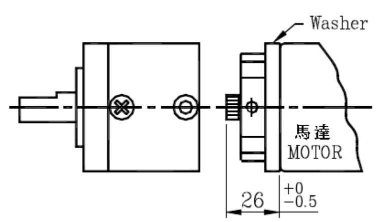
★使用溫度範圍：-10℃~+60℃
Operating temperature range



馬達齒輪型式
PINION SPECIFICATIONS

模數 Module	1.0		
齒數 No. of teeth	8	12	16
壓力角 Pressure angle	20°		
孔徑 Hole diameter	Ø3.98	Ø5.98	
減速比 Reduction ratio	1/21, 1/26, 1/126 1/156, 1/488, 1/546 1/676, 1/756, 1/936	1/4, 1/15 1/53, 1/66 1/81, 1/230 1/285, 1/353	1/3 1/12 1/43

馬達裝卸方法
MOTOR INSTALLATION



標準減速比型式
GEARBOXES SPECIFICATIONS

減速比 Reduction ratio	精確減速比 Exact reduction ratio	定格容許扭力 Rated tolerance torque	最大瞬間容許扭力 Max momentary Tolerance torque	效率 Efficiency	軸之徑向公差 Radial play Of shaft	軸之軸向公差 Thrusts play of shaft	L
1/3, 1/4	3 1/2 , 4 1/3	15kgf – cm Max	45 kgf - cm	80%	≦ 0.05mm	≦ 0.3mm	53.0
1/12, 1/15	12 1/4 , 15 1/6	50kgf – cm Max	150 kgf - cm	70%	↑	↑	68.5
1/21, 1/26	21 , 26	50kgf – cm Max	150 kgf - cm	70%	↑	↑	68.5
1/43, 1/53, 1/66	42 7/8 , 53 1/12 , 65 13/18	100kgf – cm Max	300 kgf - cm	60%	↑	↑	84.0
1/81, 1/100	81 10/27 , 100 2/7	100kgf – cm Max	300 kgf - cm	60%	↑	↑	84.0
1/126, 1/156	126 , 156	100kgf – cm Max	300 kgf - cm	60%	↑	↑	84.0
1/230, 1/285	230 1/36 , 284 43/54	100kgf – cm Max	300 kgf - cm	50%	↑	↑	99.5
1/353, 1/488	352 49/81 , 488 2/9	100kgf – cm Max	300 kgf - cm	50%	↑	↑	99.5
1/546, 1/676	546 , 676	100kgf – cm Max	300 kgf - cm	50%	↑	↑	99.5
1/756, 1/936	756 , 936	100kgf – cm Max	300 kgf - cm	50%	↑	↑	99.5

The specifications sheet for the Digikey limit switch is attached at the end of Appendix D. It could not be integrated into the document effectively due to formatting issues, so it was printed separately.

Appendix E: Thermal Analysis MATLAB Code

```
clear all
clc
close all

Q = 2080; %Watts
rho = 1.127; %kg/m^3
Cp = 1.007*1000; %J/(kg*K)
del_T = 1:25; %change in temp range (C)
flow = 180; %the volume flow rate by fans (ft^3/min)
m_d = Q./(Cp*del_T); %range of mass flow for temp range

%4.719e-4 (conversion factor from ft^3/min to m^3/s)

flow = 4.719e-4*flow; %m^3/s (air moved by fan)
m_flow = flow*rho; %mass flow of air moved by fan (kg/s)
temp = Q/(m_flow*Cp);
plot(del_T,m_d)
hold on
plot(temp,flow,'rp')
grid on
xlabel('Temperature Difference (C)')
ylabel('Mass flow rate (kg/s)')
title('Temperature Difference vs. Mass Flow Rate')
legend('Mass Flow Range','Chosen Fans',1)
```