College of Engineering and Computer Science
UNIVERSITY OF CENTRAL FLORIDA

Robotic Solar Farm Grass Cutting System

Final Report

Blue Team:

Natalie Cline - ME

Nicolas Delligatti - ME

Zackery Krupa - ME

Bien Nguyen - ME

Advisor:

Dr. Felix Soto Toro

Felix@ucf.edu

Sponsor:

Duke Energy and Orlando Utilities Commission

April 13, 2020

Executive Summary

The introduction of an autonomous grass cutting system would contribute enormously to the efficiency and performance of solar farms. The system designed by the e-GOAT Blue Team would not only reduce ground maintenance costs by eliminating man power needed to operate a grass trimmer, but also the risk of damage to solar panels. Given the natural geometry and mounting of solar panels, it is difficult for a human operated machine to traverse beneath the panels. The e-GOAT rover is capable of reaching these areas, while providing significant clearance below the panels. Considering the purpose of the rover and the environment in which it will operate, design precautions have been taken to incorporate components sturdy enough to tackle tough terrain and weather. Various components are 3D printed in order to provide a solid, waterproof structure. These components also allow for significant design flexibility. Heavy duty wheels are mounted on the rover to drive the rover forward as well as support the base plate. Sufficient torque and RPM of motors is displayed by the movement of the rover and grass trimming. The overall design of the rover incorporates considerations for optimizing trimming radius, ensuring user-friendly operation, and limiting required maintenance. Future revisions of the project could improve performance through enlarging the rover base to include multiple trimmer heads, eliminating the environmental impact by converting to a solar operated rover, and configuring the rover such that it is capable of trimming grass within the supporting I-Beam.

Table of Contents

List of Figures

List of Tables

Revision History

Version	Date	Name	Reason for Changes
1.0	April 13, 2020	e-GOAT Blue Team	Initial Document.

Glossary

Term	Abbreviation
Electronic Guided Omni-Applicable Trimmer	e-GOAT
Robot Operating System	ROS
Photovoltaic	PV
Revolutions per Minute	RPM
Electrical and Computer Engineering	ECE
Mechanical and Aerospace Engineering	MAE
Miles per Hour	MPH
Dual in-line Package	DIP
Printed Circuit Board	PCB
University of Central Florida	UCF
University of South Florida	USF
Planetary Gear Motor	PGM
Orlando Utilities company	OUC
Application Programming Interface	API
Direct Current	DC
Alternating Current	AC
Polylactic Acid	PLA

1. Introduction

1.1 History Behind the Project

This team is part of the second phase of the e-GOAT project. The current team has access to last year's rover and documents to approve upon. This project is a competition between UCF and USF students to see who can come up with the best design and presentation of an autonomous grass cutting system.. The project is sponsored by OUC and Duke Energy.

1.2 Problem to be Addressed

Grass growing underneath the PV panels in a solar farm can be thick and difficult to reach with a conventional mower or weed wacker. These companies that own and operate the solar farms must pay a groundskeeping crew to maintain the grass growing around the panels. Steps must be taken to keep the grass from growing too tall and blocking the panels from the sun. It is also possible that the grass blocks the electrical components of the structures needed by electricians for maintenance.

1.3 Justification of the Project

Solar energy is a very useful renewable resource the world can use for clean energy. With companies having to pay groundskeeping crews, operating costs are raised and the possibility of polluting the air arises if the crew uses an internal combustion engine to cut the grass. An autonomous electric battery powered string trimmer rover would be able to safely and cost effectively maintain the grass around the solar farm, in turn, lowering the operating cost of the solar farm. To provide the customer with a rover that will cause no damage to the PV panels, humans, or environment, the sponsors have provided the team with a set of requirements. These requirements can be found in Section 5: System Requirements and Design Constraints. To ensure the rover meets all the requirements the team will test each rover for each requirement shown in Appendix A.

1.4 Summary

Section 2 of this report outlines the long term objectives of this project and the scope of what the team will accomplish this semester. Following Section 2 is an assessment of existing technologies and standards with detailed information about commercially made autonomous grass trimmers. In Section 4, the possible world impact of this technology is discussed. Section 5 reports the system requirements and design restraints set by the sponsor. System concepts that the team ultimately designed for this project is reported in Section 6. Section 7 includes the analysis the team has performed for this report such as stress simulations on SolidWorks. Following Section 7 is the final design and engineering specifications. This section details the final design chosen by the team, showing the size dimensions and system parameters of each sub system. The evaluation plans for the project are outlined in Section 9 and Appendix B. These sections show how the team will test the rover and each sub system to ensure it meets the sponsor's needs and requirements. Section 10 discusses the team's accomplishments and issues the team had during the course of this project. Conclusions of this report and project, as well as recommendations for next year's team, are in section 11. The final sections of this report are the References and the Appendices which have a variety of additional tables and documents for this report.

2. Project Objectives & Scope

2.1 Long Term Objectives

The long term objective for this specific project is to cut costs regarding solar farm lawn maintenance. These solar farm sites required lawn maintenance to keep the site operational. The majority of the maintenance area is located under the solar panel and is not easily accessible. The concept of an autonomous lawn mower is the most cutting-edge technology in the lawn care industry. Autonomous lawn mowers will eliminate human operation and any possible injuries, which in turn will greatly cut costs. A small, stand-alone mower will mobilize easily into tight locations that are not accessible to a human being. Utilizing a solar powered autonomous mower will greatly increase the effectiveness and also add to the renewable energy sector.

2.2 Planned Semester Objectives

The planned semester objectives for the team are to complete the assembling process and to finish any electronic prototyping and testing. Prior to deeming this project complete, every component must be fully tested and operational to the specification. During this semester the team will carry-out these procedures to ensure the final outcome is successful.

2.3 Statement of Scope

Components testing includes but is not limited to, trimmer motors and height adjustment mechanism, drive motors, LiDar detection sensor, and perimeter wire sensor. The trimmer motors need to be able to operate constantly for a period of at least 15 minutes, since that will be our time frame to complete the test course. The team's objective was to test the rover and all its components at a minimum of 20 minutes intervals to adequately fulfill the required run time. The height adjustment mechanism is fully mechanical so testing for proper fitment was carried out by the team and confirmed it's operation. The team tested the drive motors at two different stages. During the first stage, the motors were tested individually. Once confirmation of proper operation is achieved, the team then moves to the second stage. During the second stage, the drive motors were tested with the rover fully assembled. This is a critical testing point since all operations, such as forward and backward motion along with turning, of the drive motors must be met. The Lidar and perimeter wire sensors were also tested in two stages, prior to and after assembly. These sensors must detect objects and perimeter wire within proper specifications.

3. Assessment of Relevant Existing Technologies and Standards

3.1 Existing Technologies

3.1.1 Electric Motors

A study of electric motors was performed early in the year since the motor component of the rover is critical to both locomotion and trimming abilities. Direct Current (DC) motors were chosen over Alternating Current (AC) motors because of their high starting torque, but both motor types were studied.

DC motors are categorized as brushed or brushless. The three main components of these motors include: commutator ring, armature, and magnets. Brushed motors utilize metal brushes to transfer current between a power source and the commutator ring. The commutator ring passes current to the armature, the main spinning coils on the motor shaft. The electromagnetic coils connect to the power source in series and/or in parallel in order to yield a high starting torque and maintain a constant speed. Brushless motors operate in a similar manner, however, they consist of a commutator ring and a stator containing the coils. Ultimately, brushless motors have a longer life and high efficiency, but do not compare to brushed motors in starting torque.

AC motors alternate between positive to negative flow and negative to positive flow. They are easily controlled and do not require a lot of power. Induction motors use fluctuating power levels to create a magnetic field. Current within this field creates the necessary force to cause rotation. Synchronous motors are reliable in delivering speed.

They use a rotating magnetic field to induce current on a rotor. This allows for controllability of the rotor by adjusting power input [2] [10].

3.1.2 Drivetrain Design

To make the rover as maneuverable as possible, the rover was designed to be a zero turn rover. This means it has a turning radius of zero inches. The rover would have two independent driving wheels in the back and two caster wheels up front. The two caster wheels are bolted directly to the base plate. A study of existing motor mounts was performed in order to assess what products conventional rovers use to secure driving motors. A motor mount of the appropriate height and diameter could not be procured. As a result, a 3D printed motor mount was designed to hold the drive motor in place, withstand the torque of the motor, and support the weight of the rover.

3.1.3 Structural Design

To design a rover with the structural capabilities required by uneven terrain, considerations for a lightweight yet sturdy material were made. A metal plate was chosen to serve as the rover foundation given the structure it would provide to supported components. Aluminum proved to be an acceptable weight at a thickness of ⅛ inch. This structural design decision proved sufficient on the physical rover as the base plate resisted warping due to other components and the overall rover weight does not impede transportation.

3.1.4 Power Supply

Ovonic 11.1V LiPo batteries serve as the power supply for the rover. These batteries are spread throughout the interior of the rover in order to power motors and various electrical components. Since there is heat produced by the batteries during use, separation allows for proper heat dissipation. This separation also contributes to the overall weight distribution of the rover. It is necessary for the rover to maintain a consistent center of gravity as it traverses uneven terrain.

3.1.5 Existing Products

At the start of this project research was conducted on three different pre-existing robotic lawn mowers made by three different companies that are popular in the lawn care industry. The three mowers were the Worx Landroid M 20V Cordless Robotic Lawn Mower [8], the Husqvarna Automower 430XH [11], and the Honda Miimo HRM310 [3][5]. The three mowers can be seen below in Figure 3.1.5-1 while a summary of the features can be seen in Table 3.1.5-1.

Figure 3.1.5-1: Worx Landroid, Husqvarna Automower, and Honda Miimo

These three robotic lawnmowers offer similar performance while containing their own unique features.

The first aspect of these mowers that was studied were the number of wheels on the mower, this includes drive wheels and guide wheels. All three robots utilize two plastic drive wheels. However, the Landroid had only one guide wheel in the front while the Honda Miimo and the Husqvarna used two guide wheels in the front. It was found that all of the guide wheels on these mowers are made out of plastic, have no tread, and are relatively small in size. It was thought by the team that wheels of this material, tread, and size could cause a rover to struggle traversing a large piece of land with thick, bumpy, and possibly wet grass like that of a large solar farm in Florida.

The grass cutter mechanics were the second area of comparison for the three mowers. The three mowers all contained a single disk, triple blades, and height adjustable cutting systems. The cutting disk of the Honda Miimo and Husqvarna is centered under the rovers while the disk of the Landroid is offset from the center and tangent to the side of the mower in order to precisely cut at the edge of an area. Blades cut very efficiently but cannot be used for the competition, so string based trimmers must be used.

The last area of comparison is batteries and battery life. All three mowers utilized Lithium-Ion batteries, but with different voltages. With a 20V battery the Worx Landroid charges in 90 min and is capable of cutting up to a ¼ acre. The run time off of the 90 min charge is not specified. The Husqvarna can run for 145 min off of a 50 min charge with the use of an 18V Li-Ion battery. Lastly, the Honda Miimo utilizes a 22.2V Li-Ion battery and can run for a maximum of 30 min off of a 30 min charge. Comparing the run time to charge time ratios of the Husqvarna and the Honda Miimo, 2.9 and 1 respectively, shows that the Husqvarna is more efficient than the Honda. The Husqvarna will run for 2.9 min for every minute it is charged. Though the Husqvarna is clearly the most efficient, all three of these mowers would be able to cut the competition area of 10 ft by 50 ft in 15 min, assuming they can successfully traverse the solar farm.

Table 3.1.5-1: Existing Product Features

	Guide Wheels	Motors	Cutters	Cutting width	Battery	Incline Capability
WORX Landroid	1	Brushless motor	Rotating disc with 3 blades	7”	Li-Ion 20V	35%
Husqvarna Automower	2	30W motor	3 pivoting razor blades	9.45”	Li-Ion 18V	24 degrees
Honda Miimo	2	28.8W work motor	3 razor pivot blades	8.7”	Li-ion 22.2V	25 degrees

3.2 Patent Search

The team wanted to implement a system that allowed the grass cutting height to be adjusted. This would be an improvement upon the previous Blue Team’s rover and give it more range. To get an idea of how this could be done, a patent search was conducted to find how these systems are implemented on robotic lawn mowers. When conducting previous research on existing robotic lawn mowers and their technologies, it was found that higher end models can electronically adjust the height of the cutting mechanism. For the purpose of this project and for an aspect of the rover that is not required, the team felt that an electronically controlled cutting mechanism by means of a servo motor may be risky to attempt to implement. A patent was found for a mechanically adjustable cutting mechanism which can be seen below in Figures 3.2-1 and 3.2-2. Figure 3.2-1 shows the entire system and Figure 3.2-2 shows the inner cylinder [12].

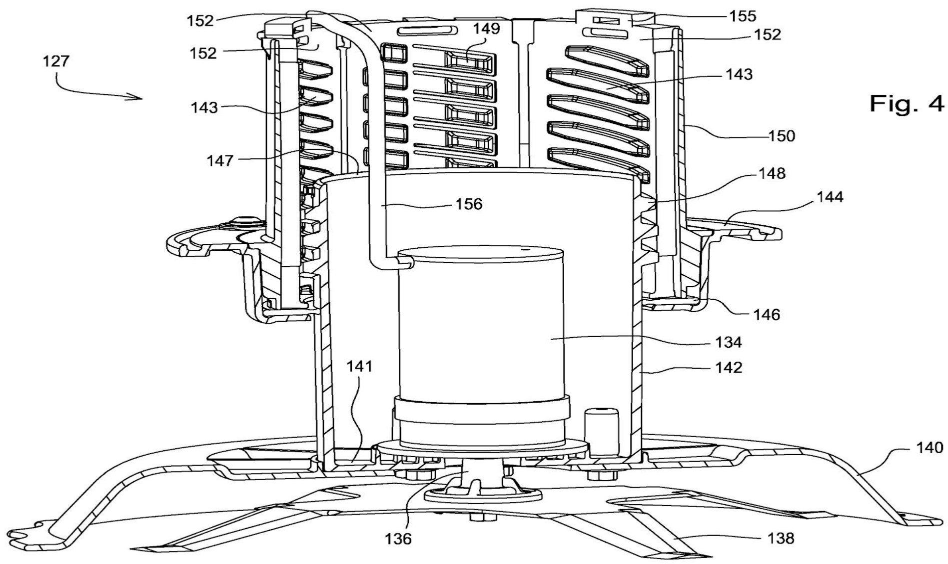

Figure 3.2-1: Cutting Height Adjustment Mechanism Patent

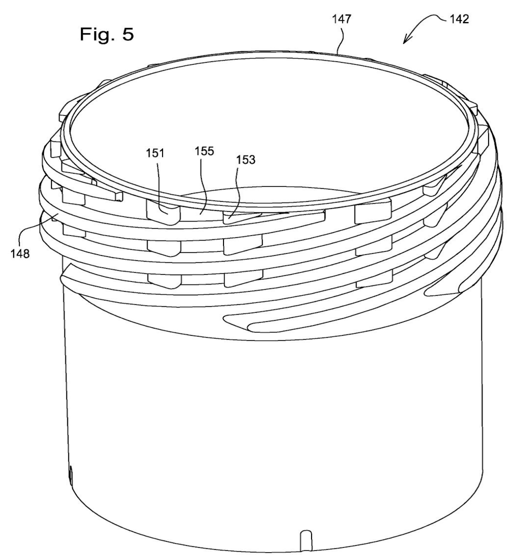

Figure 3.2-2: Inner Cylinder Patent

It can be seen from the figures that the trimmer motor is fixed to the inner cylinder, and trimming blades are fixed to a disk attached to the motor's output shaft. The inner cylinder slides up and down the larger fixed cylinder via threads, and locks into places at different heights by the use of detents.

The team decided to replicate this mechanical system of two concentric cylinders. This simplified version of the mechanism utilizes a rod for locking the inner cylinder in place and guides for a secure fit. Instead of threads, the guides are also used to adjust the height up and down.

4. Professional and Societal Considerations

Duke Energy and OUC use this project to give university students the opportunity to design a system capable of solving the problem that high maintenance costs present to solar farm companies. Not only do students get to challenge themselves with this engineering problem, but the benefits of the end product extend beyond the immediate project scope.

Most importantly, the elimination of manned mowers and the introduction of smaller, more precise mowers contributes to the safe operation and maintenance of the solar panels. The significantly smaller rovers have the ability to navigate around solar panels without risk of damaging either party. Contrary to the current process, rovers would be located far from the actual solar panel during their operation. Damage on the panels that could cause a decrease in productivity and possible injury to panel maintenance personnel would be nonexistent. Robots in general are able to operate in conditions that are not safe for humans. In environments such as Florida summers, a rover would operate with no risk to itself, saving a human from needing to work in the harsh conditions.

Not only does Duke and OUC reduce the cost of their solar farm maintenance, but companies worldwide could adapt a similar system to reap the same benefits. Cost savings stem from both the decrease in maintenance and the decrease in physical damage to solar panels. Companies are then able to put the money saved towards investing in the solar power itself. The cost of solar power on a large scale is less than that of panels installed on homes at $1 per Watt per solar installation [14], and are capable of supplying 1.5kW power per day [1].

The introduction of maintenance rovers is only the first step in optimizing solar farms and promoting environmental consciousness. With each leap in technology, more ways are found to save and reallocate resources to increase yield. As solar power becomes more affordable, more companies will be open to the idea. This is seen by the growing prevalence of solar panels in the United States. Between 2017 and 2018, there was an increase of 102 GW, with predictions to double by 2022 [4]. The same reasoning goes for expanding the use of rovers to commercial yard work. Although commercial autonomous rovers exist, the expense is too much for many. Further developments in this field would aid in driving down cost, making this technology more accessible to a larger group of homeowners. Ultimately, creating an autonomous grass cutting system positively impacts the direct customer, and expands to affect a much larger audience.

5. System Requirements and Design Constraints

5.1 Design Constraints

The e-Goat must be a rover based robot that can cut grass under the PV panels. The overall size of the rover must not exceed 24"W x 24"L x 20"H because the rover will be cutting underneath the PV panels. The cutting mechanism must be a string based trimmer powered by an off the shelf battery and have a cutting height between 3 to 6 inches. The rover must have an autonomous feature to navigate around the support structures of the PV panels by itself. Due to the uneven ground under the panels the rover must be able to safely navigate terrain with a height difference of 3" over a 2' span. The rover must have a manual and remote kill switch stopping all locomotion and the cutting mechanisms from a distance up to 50'. The rover must be able to cut 500 square feet of grass in 15 minutes and cost less than $1500.

5.2 Engineering Requirements

5.2.1 Customer Needs/Key Functions

The rover must display two main functions: locomotive motion across the ground and grass cutting capabilities. Additional requirements include trimming the grass within a set competition area, completing the area at a sufficient rate, and yielding a grass height within a specific range. The need for safe and user-friendly operation is also a focus.

To accomplish these things, careful consideration was put into component choices. Motor choice played a critical role in achieving an acceptable grass cutting rate and rover speed. The chosen width of the trimmer head also plays a role in overall grass cutting time. Lastly, various sensors used for obstacle and perimeter wire detection ensure the safety of surrounding objects and people. A host of 11.1V LiPo batteries are used to operate the aforementioned equipment to meet the off-the-shelf battery requirement.

5.2.2 Competitor Benchmarks

Features of current autonomous lawn mowers on the market can be adapted for this project. Charge and run time of these products far outweigh those of the project as a result of the power supplies incorporated on the machines. In a full scale production of this project, considerations to achieve this level of performance would be made. Dimensions of the system compare closely with those of existing products. The maximum e-GOAT dimensions fall in the middle of the studied mowers. The total height of the rover strays the furthest away from benchmarked products because of the project's nature. The large distance between the ground and the bottom of the solar panels allows a design to build up rather than out. In a standard household yard, the benefits of building up prove insignificant. Due to area requirement of the project, commercial products also far exceed the lawn size capabilities. At this stage of the project, it is not necessary for an area of greater than 500 ft^2 to be cut. A cutting system utilizing metal blades is also prohibited by the project requirements, hence the use of a commercial string trimmer on the rover. One feature installed on this year's rover that was inspired by existing products is an adjustable trimmer height mechanism. This feature has been adapted to fit the project's grass height requirement of three to six inches. Lastly, the project budget falls on the lower end of commercial automower cost. Ranging from $1,000-$3,500 between the three automowers of interest, a $1,500 e-GOAT budget has proved sufficient to accomplish the task. A comparison of the current products studied and their specifications are expanded upon in Section 3.1.5 and listed in Table 3.1.5-1.

These rovers may someday operate as a fleet in order to achieve optimal performance and cost savings. Rather than using commercial batteries equipped with separate battery chargers, these fleet rovers would return to a charging station upon reaching low battery levels in order to eliminate the need to manually replace batteries. In a large scale production, assigning each rover to its own plot of ground would aid in a smooth, interference-free operation. The machines would maintain the ability to avoid obstacles and to cease motion upon command as a safety precaution. The flexibility provided by adjustable trimmer height mechanisms would also make the rover attractive to a variety of industries. For solar power companies with extremely large solar farms in particular, the extra maintenance cost of spraying beneath panels to prevent grass and weed growth would be eliminated. These rovers would provide a fully autonomous, cost efficient, and ultimately cost saving system for companies looking to reduce unnecessary expenditures.

5.2.3 Critical Performance Parameters

There are a few parameters essential to successful performance of the rover. Among these are cutting rate, battery power, navigation, mobility, and dimensions. The rover speed required to complete the set 500 ft area within the 15 minute time limit is 0.41 mph, as seen by a simple speed calculation. The criticality of operation speed is reflected by the rover's ability to steadily cover a set area, rather than missing spots of grass when operating at a higher speed. Batteries capable of providing power to the rover for at least the 15 min competition time is also critical. The motors and electrical components must be fully functional for the entire competition time, while the location beacon must be provided with a much longer battery life. Batteries with less than the required life will prevent the rover from presenting its full mowing capabilities. Given that only half of last year's e-GOAT competitors were able to compete due to faulty navigation, finalizing this system is essential. Not only must it be an autonomous machine, but it also must have obstacle detection capabilities. The solar panel supports must not be damaged during the mowing process. Less than optimal environmental conditions were also prepared for in choosing components for rover mobility. Considering the naturally rainy climate in Florida, traction lug wheels with a large diameter were chosen to combat muddy ground conditions. The choice to incorporate four wheels onto the rover was also made after observing the more unstable three wheel design of the previous year. Lastly, a major contribution to points allotted to the team's rover is falling within specified dimensions. Working with the entire 24" x 24" limit allowed the team to maximize trimming width and overall rover stability. Most importantly, falling under the 20 inch height limit prevents the risk of damage caused by contact between the rover and the solar panels.

5.3 Regulatory Standards and Codes

In September 2019, the American National Standards Institute (ANSI) and Outdoor Power Equipment Institute (OPEI) published a new standard for robotic lawn mowers [9]. The standard is "ANSI/OPEI 60335-2-107-2020 (Standard) for Outdoor Power Equipment — Household and similar electrical appliances — Safety — Part 2-107: Particular requirements for robotic battery-powered electrical lawnmowers (national adoption with modifications of IEC 60335-2-107)." It includes specifications and their requirements for the design and construction of robotic lawn mowers. The standards do not include environmental aspects, except for noise. The document does not apply the risk of internal combustion engines, hybrid and fuel cell powered machines and associated charging systems. This document also covers significant hazards presented by battery powered robotic lawn mowers when they are used for their intended purpose and under conditions of misuse which was deemed reasonably foreseeable [6]. This document can be purchased for $180 from the ANSI webstore in order to access the complete list of standards. The team did not feel it was necessary to purchase this document for the purpose of this project, since Duke and OUC already set requirements of their own. However, the only detailed piece of information provided is that the machine's battery must not exceed 75 V d.c. EMC.

6. System Concept Development

6.1 Concept Generation

The concept generation process began with simple sketches, analysis of previous projects, and studies of existing technology. Researching existing products and their specifications aided the team in having a solid foundation to begin the design process. Once an initial model was created, parts were researched and ordered. With each choice for a component of the design, three concepts were formed and compared against at least three criteria. Ultimately, one concept for each component was chosen, procured, tested, and installed on the rover body.

6.2 Design and Parts Selection

6.2.1 Design

The design of the rover was visualized through the CAD software SolidWorks. The three concepts compared early in the design process are shown in Figure 6.2.1-1. The winning design was then modified throughout the remainder of the year. Modifications in the design stemmed from a variety of reasons including component test failures, inability to procure components, lack of proper manufacturing equipment, and others. The progression of the chosen design can also be seen below in Figure 6.2.1-2. Although the models vary, each was designed to provide adequate volume for components, ensure optimal task performance, and fall within dimension specification limits.

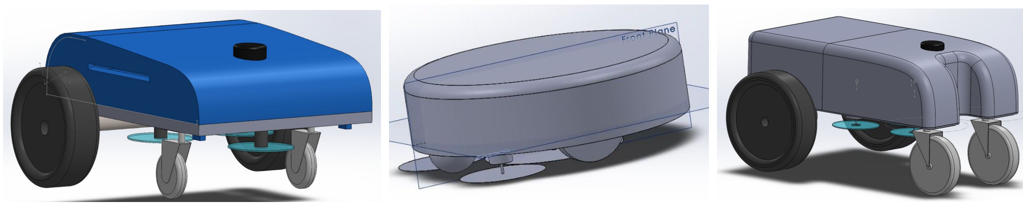

Figure 6.2.1-1: Initial Concept Comparison

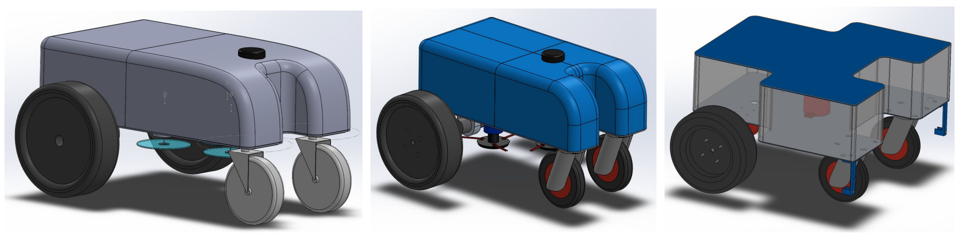

Figure 6.2.1-2: Overall Rover Concept Development

6.2.2 Locomotion Subsystem

The drive motor was chosen with considerations for power, cost, and size. The motor needs to have enough torque to initiate and maintain movement of a 30lb rover up slightly inclined terrain. The team used Robot Shop's Drive Motor Sizing Tool and hand calculations described in Section 7: Design Analysis for determining the required torque.

The drive and caster wheels were chosen in conjunction in order to account for the rover sitting level. Durability and cost were also contributing factors when choosing the parts. Final selection of the wheels and reasoning for the selection is outlined in Section 8: Final Design.

The team designed the layout of the rover's base plate with the size limitations of 24"x24"x20" in mind, as well as the trimmer wire width allowed by the design. The initial plate used approximate component dimensions to estimate overall plate size and component placement. The design was updated as cover design changed and components were finalized. Two of the initial concept changes can be seen in Figure 6.2.2-1. The procurable motor mount options, Figure 6.2.2-2, did not adequately support the motors. As a result, a design was created to give the rover custom motor mounts. The dimensions of these mounts needed to be adjusted and the mounts needed to be remanufactured in order to accommodate the rover.

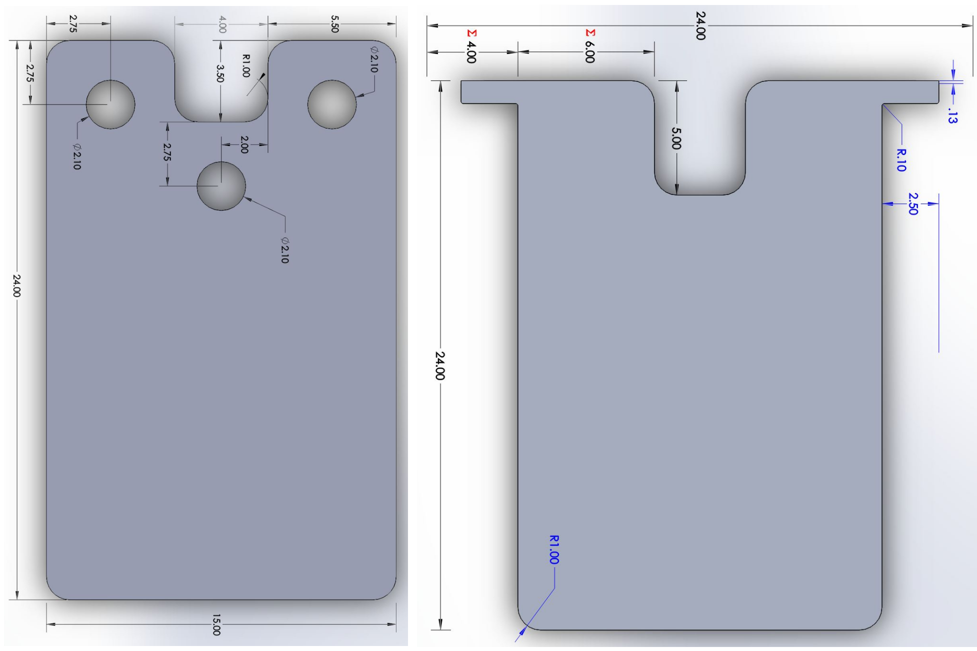

Figure 6.2.2-1: Initial Base Plate Dimensions

Figure 6.2.2-2: Initial Motor Mounts

6.2.3 Trimmer Subsystem

The trimmer system was designed to incorporate a commercial trimmer head with a motor of appropriate RPM ratings. Commercial weed wacker products incorporate trimmers ranging from Dewalt's DCST990 with 6600 RPM, to Echo's 28.1 cc SRM-280T with 10700 RPM [7]. Various motors were evaluated for speed, size, and cost. The chosen motors, however, proved not to be suitable after testing. This roadblock, as well as steps taken to resolve it, is outlined in Section 9.1.3.

Two variations of the height adjustment mechanism were evaluated based on accessibility, assembly, and function. With a project specification of grass height between 3 and 6 inches, each mechanism was designed with the full span of heights in mind. They were also designed to minimize manufacturing cost through utilizing on campus 3D printing machines. Both of these mechanism concepts are shown below in Figure 6.2.3-1.

Figure 6.2.3-1: Initial Adjustable Height Mechanism Designs

7. Design Analysis

7.1 Critical Analysis

The base plate and each 3D printed component was simulated in SolidWorks for stress on the part. Two simulations were run on the motor mount. One simulation tested for the torque of the motor to ensure the bolt holes would not fail due to the thin Polylactic Acid, PLA, material of the motor mount. To find the amount of force each bolt hole would have to hold, the max output torque of the motor was divided by the distance from the center of the output shaft to the center of the bolt holes. A force of that magnitude was then oriented to create a moment around the output shaft of the motor. The second was to simulate the weight of the rover causing a moment about the wheel. The base plate was simulated to have a 30lb force on the top surface to see where the most stress would be and where the plate would deflect the most. These simulations are below in Figure 7.1-1.

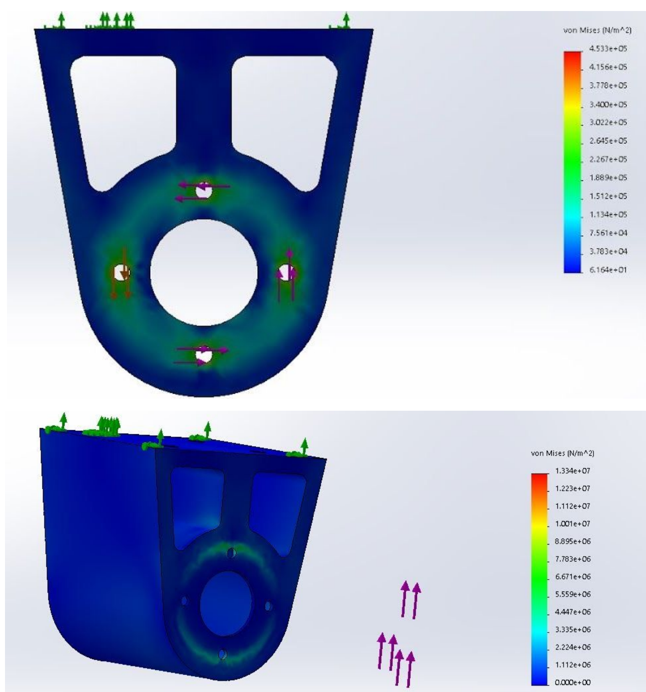

Figure 7.1-1: Simulations of Motor Mount

The adjustable height mechanism was simulated to have the weight of the trimmer head hanging from the component and a torque was placed on the inner cylinder to simulate the torque of the motor while running. Analysis of the results and a visual of the simulation can be found in Section 9.2.

Both the motor mount and the adjustable height cylinders were printed a couple times to perform fit tests. These prototypes aided the team in learning the inconsistencies of the 3D printer used to manufacture the parts. As a result, adjustments were made to the design and to the dimensions if the part could not be sanded to the correct configuration. After a couple increments of prototyping, final versions of each part were printed and installed on the rover.

7.2 Calculation Results

7.2.1 Discussion of Results

Various calculations were used to evaluate required speed of the rover and trimmers, as well as the torque of the drive wheel motors. The videos of the previous rover showed the team that the trimmer heads were not capable of rotating at a high enough speed to cut the grass. To fix this issue, this year's team purchased an off the shelf string trimmer, and incorporated its motor and battery onto the rover. For the rover to complete the cutting area in the designated time the rover would have to travel at a certain minimum speed, as seen by Equation 1 and Equation 2 below. If the rover was able to navigate in a straight line throughout the area without doubling over, the rover would have to travel the least distance allowing it to travel at a slower speed. Without perfect navigation techniques the rover needs to have an increased speed to make up for any area cut twice. The rover travels at approximately 1.2 mph with the current motors.

These motors were chosen after using the Robot Shop Drive Motor Sizing Tool to calculate the required motor torque. The equations incorporated into this tool are shown in section 7.2.2 below. The cutting diameter of 11 inches means the rover will have to make 11 perfect passes, requiring the rover to travel 550 feet in the 15 minutes. For the rover to complete the 550 feet in 15 minutes, the rover only needs to travel at a speed of .416mph. At a speed of 1.2mph the rover could travel 1584 feet in the given 15 minutes, allowing the rover an ample amount of time to make up for the imperfect navigation techniques.

7.2.2 Formulas and Equations

$$V_{MIN,ft/min} = \frac{DISTANCE_{LINEAR}}{TIME_{LIMIT}} \quad (1)$$

$$V_{MIN,mph} = V_{MIN,ft/min} * \frac{60\ min}{1\ hr} * \frac{1\ mile}{5280\ ft} \quad (2)$$

$$V_{MOTOR,m/s} = RPM_{MOTOR\ OUTPUT} * \frac{2\pi\ rad}{1\ rev} * \frac{1\ min}{60\ s} * R_{WHEEL,m} \quad (3)$$

$$V_{MOTOR,mph} = V_{MOTOR,m/s} * \frac{1\ mile}{1609.34\ m} * \frac{3600\ s}{1\ hr} \quad (4)$$

$$T_{oz-in} = \left(\frac{100}{3}\right) * \frac{(a+g*sin(\theta))*M*R}{N} \quad (5)$$

8. Final Design and Engineering Specifications

8.1 Overall Design

The overall dimensions of the rover cannot exceed 24”x 24”x 20” to ensure the proper clearance under the PV panels. The rover is a simple design consisting of a base plate and four wheels to maneuver the trimmer head around the area. There is one trimmer in the middle of the rover to allow the largest cutting radius and better cutting quality. The holes in the base plate were made using a water jet for precision cutting measurements. The navigation is controlled by a PlayStation controller and an operator following along behind the rover. With integration of a camera and LiDar sensor, the rover could exhibit autonomous capabilities.

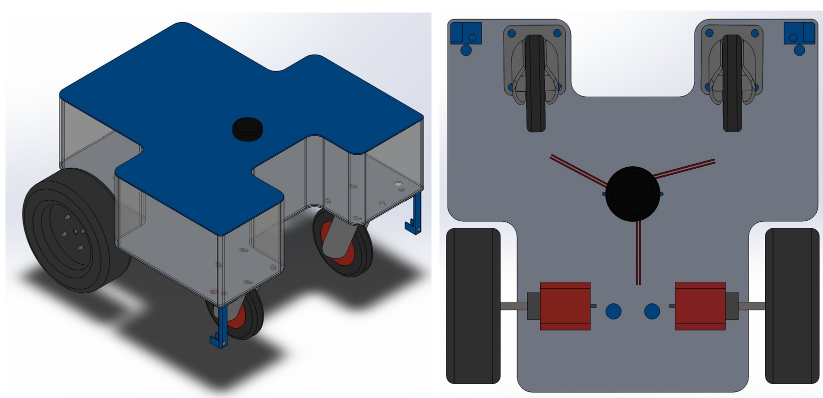

Figure 8.1-1: Final Overall Design

8.2 Locomotion Design

The base plate is a 24” x 24” square with a 4.5”x 11” cutout on each side of the rear. These cutouts are for the 10” drive wheels to fit inside the maximum dimensions. There is also an 8” cutout on the front of the plate, allowing the rover to move around the I-Beam supports of the panels.The drive wheels have an agressive V-tread design to give the rover the traction it needs to drive through the sand under the PV panels. The caster wheels need a 9.5” diameter circle of clearance to ensure full rotation. The two caster wheels are bolted to the front of the rover, 5.6” from the edge of the base plate. Placement of the caster wheels stemmed from the need to clear the perimeter wire sensor mounts and allow for a maximum trimmer diameter. The height of the caster wheel is 7.48” to level the base plate of the rover. From the top of the drive motor mount to the center of the motor shaft hole, is a 2.48” distance. The motor mount is a 3D printed PLA block with cutouts to create a truss. The truss structure makes it strong enough to hold the motor horizontally and proves to be extremely light weight. The cover is a 23.75”L x 16”W x 6.875”H plastic box that will cover all the electronics. The drive motor is a Lynxmotion PGM45-26 12V motor with a max speed of 105 rpm, 7137 g*cm torque output at max efficiency, and a 26.9:1 gear ratio.

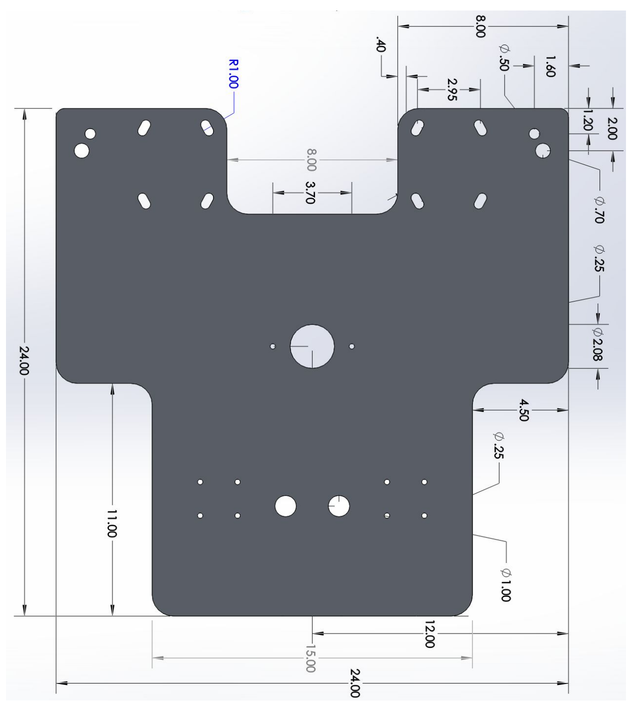

Figure 8.2-1: Final Base Plate Dimensions

Figure 8.2-2: Final Locomotive Components

8.3 Trimmer Subsystem Design

A final cutting height adjustment mechanism was designed in SolidWorks and 3D printed in the UCF Innovation Lab. This mechanism would allow the rover to cut the grass at 3 in, 4 in, 5 in and 6 in and can be seen below in Figure 8.3-1.

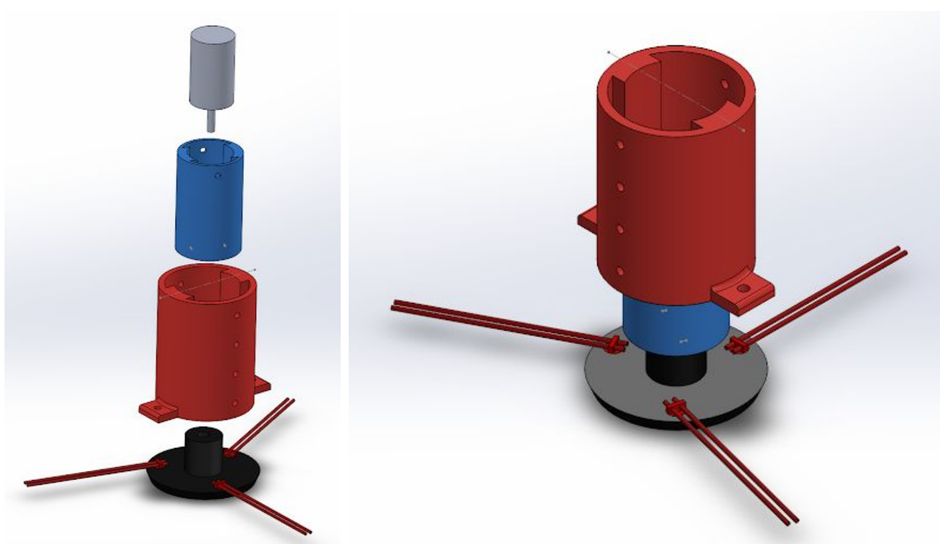

Figure 8.3-1: Final Cutting Height Adjustment Mechanism

The trimmer motor for this system failed at the end of testing so the final design will not include this mechanism.

The final trimming system that is going to be implemented on the rover is a disassembled Ryobi ONE+ 18-Volt Lithium-Ion Cordless Battery Electric String Trimmer. Two Ryobi 18 V trimmers were purchased, one is a 1.3 Ah and the other is a 4.0 Ah, however only one of them will be implemented on the rover. The decision as to which trimmer will be implemented of the two will be based on fit and performance. A longer string will give a string trimmer better cut quality. To achieve the largest cutting radius the rover has a single trimmer head in the center of the rover with a cutting radius of 5 in for the 1.3 Ah trimmer and 6.5 in for the 4.0 Ah trimmer.

Figure 8.3-2: Ryobi String Trimmer 1.3 Ah

Figure 8.3-3: Ryobi String Trimmer 4.0 Ah

8.4 Additional Components

Given the large rover size and 30 lb. overall weight, a carrier for the rover was designed and constructed to aid in transport. Fixed with four, freely rotating caster wheels and a pull rope, the carrier gives users the ability to easily transport the rover. The original purpose of the carrier was to transport the rover to the competition site, however, having this resource could aid during any situation. Having a carrier allows the user to easily move the rover without physically running the rover and using battery power. It also limits any accidents that can arise if the team was to carry the rover during transportation.

Figure 8.4-1: Rover Carrier

9. System Evaluation

9.1 Performance Requirements

The robotic rover is to have an off the shelf battery powered trimmer and may be equipped with an off the shelf remote controlled system that is modified to have an autonomous feature. The rover shall not exceed the maximum dimensions of 24”x 24”x 20” and is required to maneuver across the terrain of a solar farm which tends to have thick, dense grass that is hard to cut via conventional mowing techniques. The rover must have turning capabilities, effective enough to avoid obstacles such as the supporting structures of the solar pv panels. The rover is required to safely navigate uneven terrain, or approximately a 3 inch terrain differential over a 2 foot span in any direction, without capsizing and while avoiding a series of obstacles. For safety purposes, there shall be an emergency stop function on the rover capable of being turned off from a minimum of 50 ft away, as well as a physical emergency stop button on the rover body. For a complete requirements list, see Appendix A.

9.1.1 Maneuverability

The team’s rover utilized two, 10 inch diameter driving wheels with an aggressive tread, each paired with their own Lynxmotion PGM45-26 12V driving motors in the rear. Two free-to-rotate wheels were placed in the front. The rover was designed with a wide drive wheel wheelbase of 20.5 inches, which allows the drive wheels to fit right at the maximum allowable width of the rover. The free-to-rotate wheels are 10 inches apart. The drive wheel set is a total of 8.7 lbs and the two caster wheels combined are 11.38 lbs. This combined wheel weight is 20.08 lbs which keeps the rover planted.

After testing this rover in an area of thick and dense grass, the wheels proved to be successful. The aggressive drive wheel tread was able to put the power from the motors successfully to the ground without slipping. The relatively heavy, less aggressive caster wheels rotated freely as expected. The 5.69 lb weight of each of them as well as the rubber tread, prevented them from slipping. The Lynxmotion drive motors with a "no load" speed of 105 rpm and a max efficiency speed of 90 rpm allowed the rover to traverse the grass area at a high speed of around 1.2 mph which was higher than initially estimated. The stall torque of 499.95 oz-in and max efficiency torque of 99.11 oz-in proved to be enough to move the rover. These motors never showed signs that the rover was too heavy. The Lynxmotion motors provided enough speed and torque to move the rover uphill. Overall, the maneuverability of the rover was a success in the sense that it is physically able to avoid objects while being remote controlled.

9.1.2 Navigation and Control

The team's rover utilizes a Raspberry Pi 4 to make the navigation and control decisions. The framework for the software and the API is complete and can be programmed to do whatever the team wants, within reason. The rover has been programmed through the API to be manually controlled through a remote controller. The layout of the rovers internals as well as the remote controller and relay switch remote can be seen below in Figure 9.1.2-1.

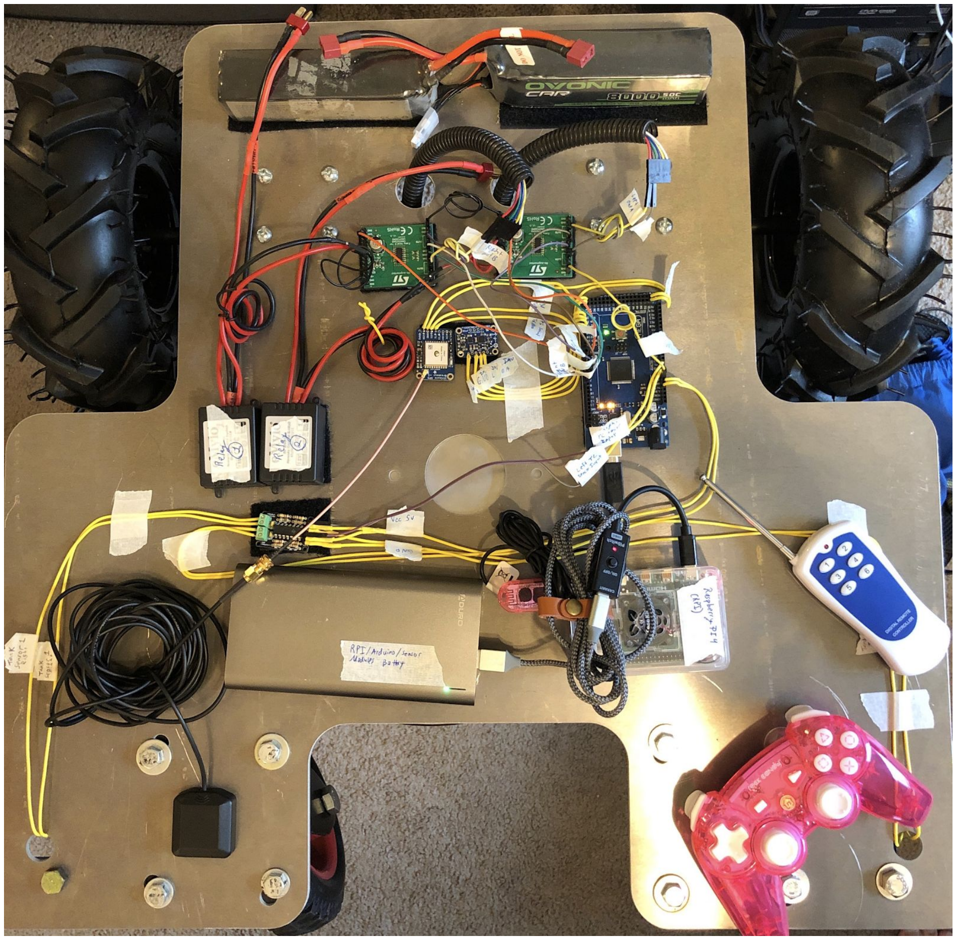

Figure 9.1.2-1: Navigation and Controls

The pink controller is used to control the motors and direction of the rover, while the blue and white remote is used to control the relay switches and shut off the rover. The blue and white remote serves as the emergency remote stop, testing confirmed the remote stop worked from 50 ft away. A physical emergency stop button has also been implemented onto the rover. Pressing this button ceases operation of the computer controlling the wheels.

The rover consists of a GPS antenna and GPS module that can be seen below in Figures 9.1.2-2 and 9.1.2-3. This GPS system serves as the location beacon for the rover. The GPS is used to approximately locate where the rover is in a set environment. Since

Figure 9.1.2-2: GPS Antenna

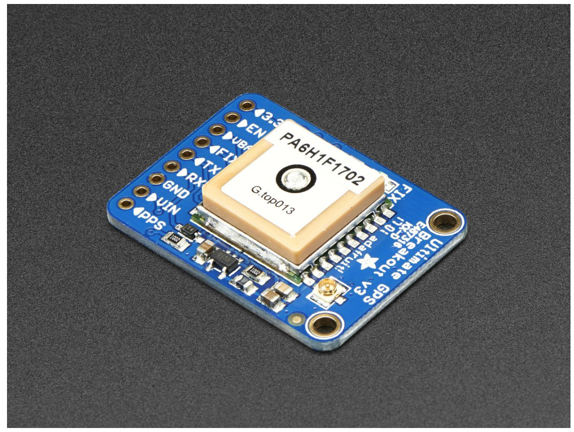

Figure 9.1.2-3: GPS Module

standard GPS is accurate to 10 meters, it is not practical to determine the rover's true position, but more so a "soft boundary" to get an approximation of the rover's location. Greater accuracy and precision is needed for the rover to be a data point to make action decisions on.

In order to detect objects, the Intel RealSense Depth Camera D435 was purchased, and a LiDar camera was used off of last year's rover. The team was able to get the LiDar to detect objects and send a signal to the motors and stop them if an object came too close. The LiDar is very accurate and fast when detecting objects. The Intel

Figure 9.1.2-4: LiDar Camera

RealSense Depth Camera is able to detect many objects and send a signal to the motors to stop them. The camera differs from the LiDar because it can tell what the object is. The camera is able to recognize many things and tell you what that object is, thanks to the TensorFlow API and COCO dataset. This dataset of 300 thousand of the 90 most commonly found objects is what aided in the detection of specific objects like a person, phone, laptop, dog, chair, couch, and many more. Due to the circumstances and time, neither the LiDar or Intel RealSense Camera will make it onto the rover.

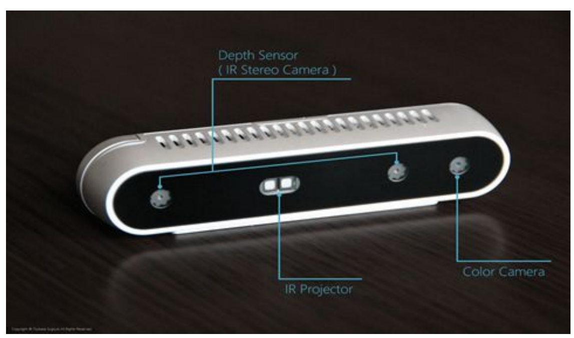

Figure 9.1.2-5: Intel RealSense Depth Camera D435

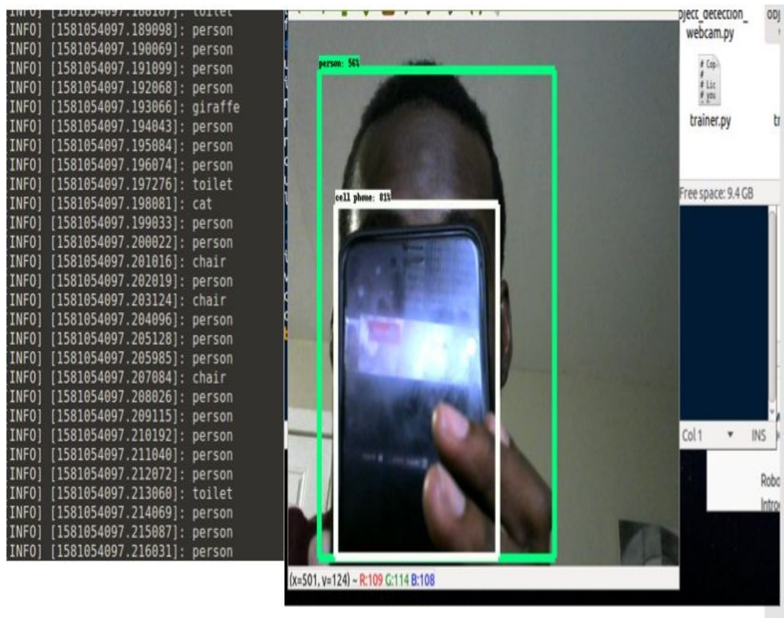

Figure 9.1.2-6: Intel RealSense Person and Phone Detection

The rover is currently equipped with sensors that can detect the boundary wire. In the ideal scenario where the rover traverses the land autonomously, the boundary wire would be layed out, forming an outline around the desired cutting area, and the rover would cut freely and detect the boundary wire. The boundary wire would be used to prevent the rover from escaping the desired area. In the rover's current state, the boundary wire sensors do not quite serve a purpose since the rover is strictly remote controlled, however, they do work.

9.1.3 Trimming System

The team originally purchased separate trimmer motors and an off the shelf trimmer head was fitted onto the output shaft of the trimmer motor. These motors were inexpensive and the team tested 3 of them. A cutting height adjustment mechanism was designed around these trimmer motors. This mechanism allowed the rover to cover 4 different cutting heights, the heights being 3 in, 4 in, 5 in, and 6 in. This height adjustment mechanism worked well with the trimmer motor. After multiple motor tests, the motor with the attached trimmer head could cut the grass, but the motor failed after approximately 3 minutes. This operation time is well under the minimum requirement of 15 minutes. The original trimming system can be seen below in Figures 9.1.3-1, 9.1.3-2, and 9.1.3-3.

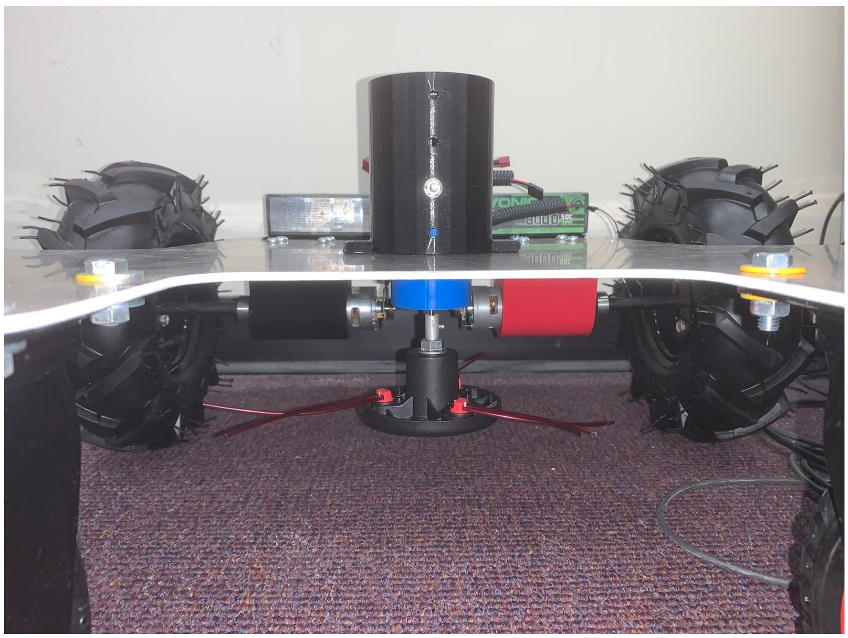

Figure 9.1.3-1: Front View of Adjustable Cutting Height Mechanism

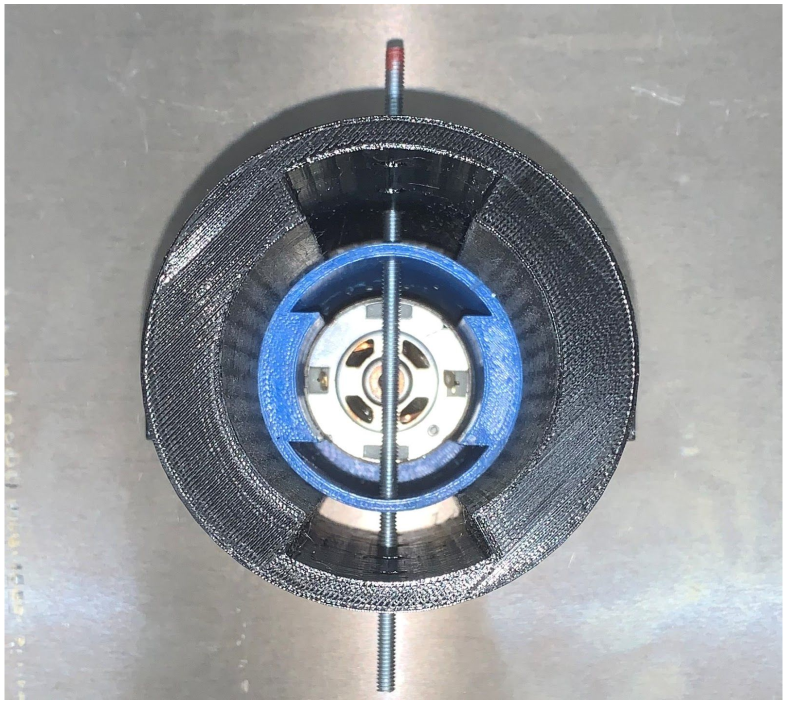

Figure 9.1.3-2: Top View of Cutting Height Adjustment Mechanism

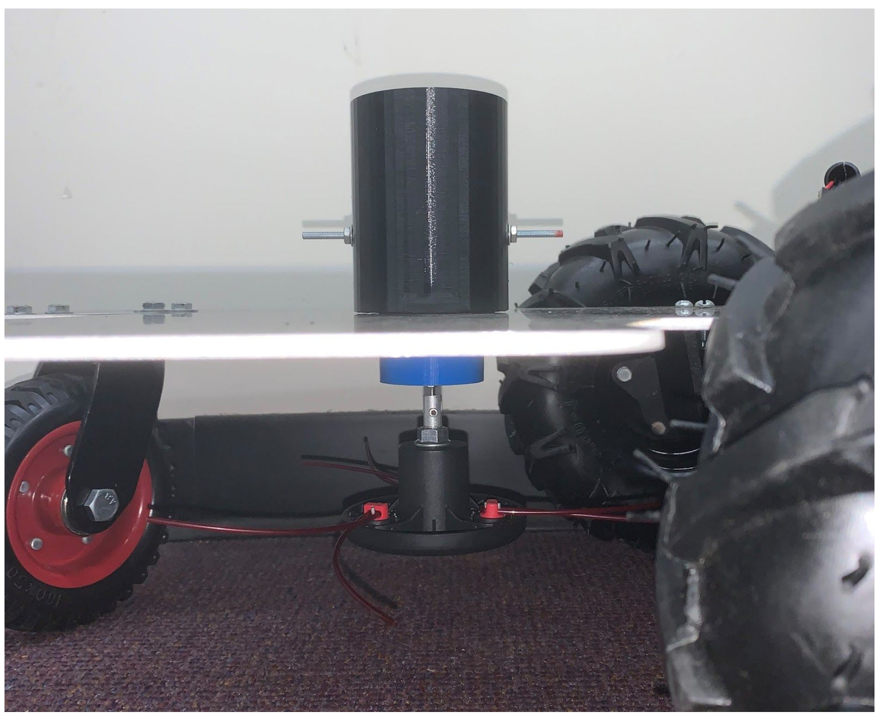

Figure 9.1.3-3: Side View of Height Adjustment Mechanism

Due to the multiple trimmer motor failures, two Ryobi 18 V trimmers were purchased. The team hopes to get the trimmers disassembled and implement one of them onto the rover before the competition date, however, given the circumstances and time, the team feels they will not make it to the rover. These Ryobi Trimmers can be seen in Section 8.3 Trimmer Subsystem Design.

9.1.4 Safety

The rover can be remotely shut off from at least 50 ft away with a remote, and directly on the rover with a physical button shown in Figure 9.1.4-1. The hole for the trimmer is in the center of the rover, this prevents any cutting wire from sticking out of any point on the rover.

Figure 9.1.4-1: Remote and Physical Emergency Stops

9.2 Failure Modes

9.2.1 Cutting Height Adjustment Mechanism

Since the cutting height adjustment mechanism is ideally supposed to be implemented on the rover, simulations were run on the 3D printed mechanism in SolidWorks. The stress numbers may not be the most accurate due to complications in SolidWorks, and the input force and torque values are exaggerated to get a better idea of failure. The simulation does show where the mechanism would experience the most stress and where it would start to fail. As expected, the mechanism experienced a lot of stress in the flanges that attach the outer cylinder to the rover. The corners of these flanges served as stress concentration points. The mechanism also experienced stress as the hole location at which the height locking rod was set. A screen shot of the simulation can be seen below in Figure 9.2.1-1.

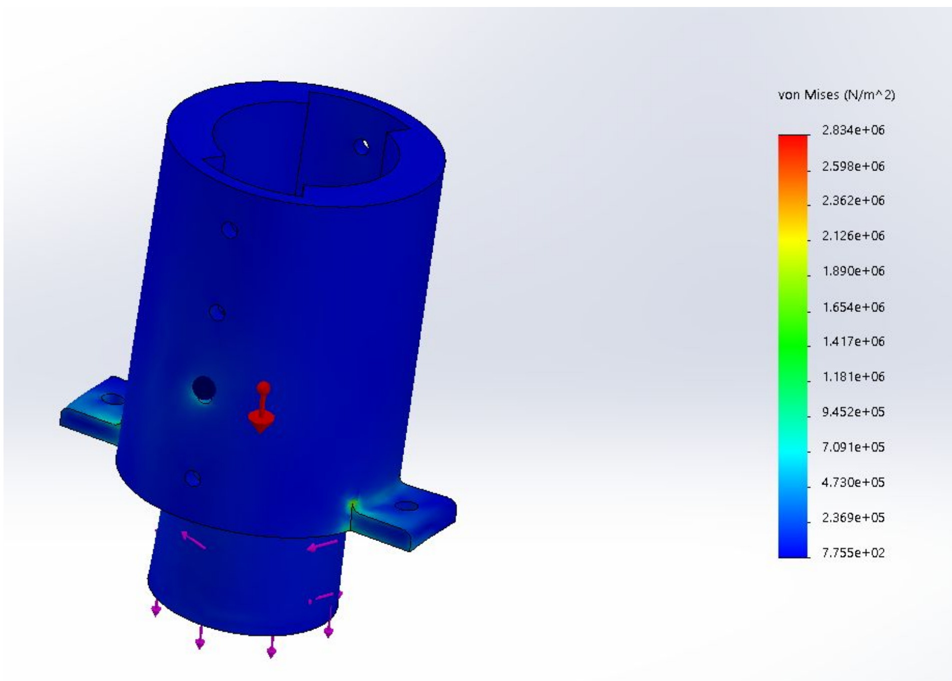

Figure 9.2.1-1: Cutting Height Adjustment Mechanism Simulation

10. Significant Accomplishments and Open Issues

10.1 Evaluation Results

The results of evaluating each component are as follows. Each subsystem was tested in regards to the respective project requirements. The team expects the new Ryobi string trimmer to work perfectly due to the fact the rover would be using the battery and motor that were designed to be used in conjunction with each other. The rover's drive motors were tested without the autonomous feature of the rover by controlling the rover with a PlayStation remote for input controls. The drive motors proved to be a good choice by the team as they had ample torque to drive the rover over uneven ground and could spin fast enough for the rover to complete the cutting area in the given amount of time. The motor mounts for the drive motors did not show any signs of failure just as the SolidWorks simulations predicted. The aluminium base plate held up strong with the weight of most of the electrical components on it while driving through the grass. The team believes the rover would have been a successful rover if all the subsystems were incorporated together.

10.2 Open Issues

There are quite a few open issues with the rover. The first being the trimmer head. The team ordered three Jiaruixin RS550 electric motors to be used for the trimmer heads, all three motors started to smoke and melted the plastic fan inside the motor within 3 minutes of running. To fix this issue the team decided to order an off the shelf Ryobi string trimmer from The Home Depot, but the string trimmer will not be delivered to the team in time to be implemented on the rover. With more time and with the reopening of machining resources, a new trimmer height adjustment mechanism would be printed for the Ryobi motor. The second open issue is that the rover is still not completely autonomous. The team had full intentions of using cameras and LiDar to give the rover an autonomous feature but due to the stay at home order for COVID-19, the teammates working on that aspect of the project and with the necessary components could not meet up in person to work together and incorporate this feature. The last open issue is the cover for the rover. The team wanted to 3D print a cover for the rover as shown in Figure 10.2-1, using the innovation lab at UCF. With the school closing after spring break the team did not have access to a 3D printer to print the cover. The team ordered a plastic tote from The Home Depot, but similar to the Ryobi trimmer it will not get to the team before the project deadline. The entire rover never got to be tested as a complete rover with all its functions running as one. Without the team being able to test the autonomous feature of the rover, the team will not know if the design for the subsystem will function properly or would need a redesign before the competition.

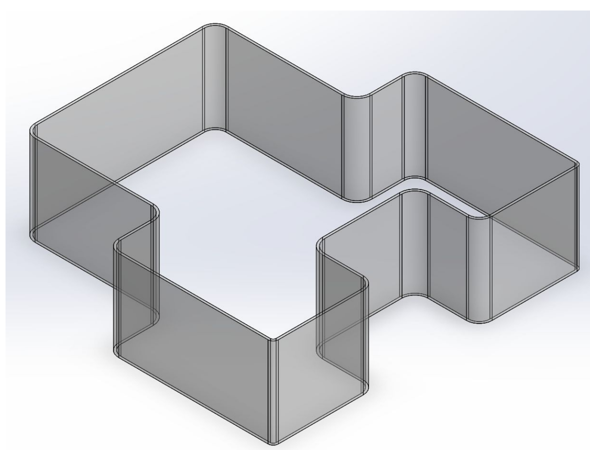

Figure 10.2-1: Planned Rover Cover

10.3 Recommendations for Design Changes

Some recommendations for a design change would be the layout of the base plate. If the trimmer heads were in the very front of the rover they would be given more room for a longer string on the trimmer head which would allow the rover to cut more grass with every pass in the cut area. With this change, steps would also need to be taken to ensure the safety of surrounding objects if the string extended beyond the edge of the plate. The motor simulations on the motor mounts show they are over designed with too much material. If the motor mounts were redesigned to be thinner they would take up less room on the rover body allowing more space for the other components. Although 3D printing allows enormous design flexibility, it may not be the most practical choice for manufacturing the cover. Given the rover's size and the amount of material that would be needed, other options to provide protection for the internal electrical components could be considered. Using plexiglass or sealed wood, for example, could give the design the same amount of waterproof ability and structure, while requiring limited resources.

11. Conclusions and Recommendations

The 2019-2020 e-GOAT Blue Team presents a solution to the design problem extended by Duke Energy and OUC for the creation of an autonomous grass cutting system. Starting with preparatory work completed in the first half of the year to gain knowledge about the problem, the team progressed to an analysis of customer requirements and priorities. Conceptual design generation was then performed to compare and choose the best components and overall design. Finally, rover construction was completed to incorporate procured components. Ultimately, a 24” x 24” x 14” rover equipped with four heavy-duty wheels, powerful DC motors, numerous custom components, and electronics enabling controllable movement was constructed. The rover can easily maneuver around an area at a moderate speed, perfect for trimming grass without damaging surrounding objects upon impact. Features include a GPS system with location tracking, remote and physical kill switch capabilities, and remote control operation. Further capabilities such as autonomous motion and longer duration grass trimming can be accomplished by incorporating the procured object detecting camera, LiDar sensor, and Ryobi trimmer. Most importantly, taking design precautions with safety in mind has yielded a rover that is harmless to surrounding objects and humans. In addition, given an allotted amount of $1,500, the team finished part procurement almost $300 under budget.

The majority of rover subsystems proved successful in performing their specified tasks, however, some components should be avoided in future projects. Heavy duty wheels, like the ones installed on the rover, are essential to movement. LiDar sensors and object detection cameras used in harmony prove promising with incredible accuracy after testing. Custom design of components using 3D printing or other manufacturing techniques allow for extra experience that cannot be gained by ordering parts. Without prior expertise, it is strongly recommended to incorporate commercial trimmers onto the rover. Additional customizations can then be added to the commercial trimmer to give the rover design a unique feature. It is not recommended to purchase separate trimming motors and attaching an off the shelf trimmer head. Early integration of electrical and mechanical components is also recommended in order to account for any situations that would cut testing time short.

Combining the experience gained through extensive work performed in the past year, the team has used the autonomous rover project to experience a true design process. Integrating the skill sets of students from a variety of backgrounds, the team's e-GOAT rover exhibits exceptional locomotive abilities and controllability. It also incorporates numerous innovative component and system designs with unique, cost-efficient manufacturing. Like all designs, improvements can be made to make this rover more beneficial to Duke Energy and OUC. As this project continues to challenge students, the team hopes that each year's design will build upon the next with each team incorporating new and innovative features onto the rover.

References

[1] Aggarwal, Vikram, 2019, “What is the power output of a solar panel?” From, https://news.energysage.com/what-is-the-power-output-of-a-solar-panel/.

[2] Edison Tech Center, 2014, “The Electric Motor.” From, https://edisontechcenter.org/electricmotors.html#sync.

[3] Explore Miimo. From, https://powerequipment.honda.com/lawn-mowers/miimo/explore-miimo#anchor5

[4] Feldman, David and Margolis, Robert, 2019, “Q4 2018/Q1 2019 Solar Industry Update.” From, https://www.nrel.gov/docs/fy19osti/73992.pdf.

[5] Honda Robotic Lawn mower HRM 310/520 Owner’s Manual. From, http://cdn.powerequipment.honda.com/pe/pdf/manuals/00X31VP76000.pdf

[6] Household And Similar Electrical Appliances - Safety - Part 2-107: Particular Requirements For Robotic Battery Powered Electrical Lawnmowers, https://webstore.ansi.org/standards/opei/ansiopei603351072020

[7] Koehler, Kenny, 2016, "Best Battery Powered String Trimmer Roundup." From https://www.protoolreviews.com/tools/outdoor-equipment/best-battery-powered-string-trimmer-shootout/21505/.

[8] Landroid M 20V Cordless Robotic Lawn Mower. From, https://www.worx.com/landroid-m-20v-cordless-robotic-lawn-mower-wr140.html

[9] LM Staff, February 4, 2020, “ANSI/OPEI standards for robotic mowers” From, https://www.landscapemanagement.net/ansi-opei-standards-for-robotic-mowers-published/

[10] Motion Control Online Marketing Team, 2016, “Types of Electric Motors.” From, https://www.motioncontrolonline.org/blog-article.cfm/Types-of-Electric-Motors/3.

[11] Robotic Lawn Mowers Husqvarna Automower 430XH. From, https://www.husqvarna.com/us/products/robotic-lawn-mowers/automower-430xh/967852905/

[12] Robotic mower height of cut adjustment assembly, Inventors: Thomas M. Messina, Paul M. Elhardt, John D. Mouser. Current Assignee: Deere and Co. https://patents.google.com/patent/US8234848B2/en

[13] RobotShopMascot, 2013, "Drive Motor Sizing Tool." From, https://www.robotshop.com/community/blog/show/drive-motor-sizing-tool.

[14] Vickery, Nate, 2017, “Initial Steps for Building a Solar Farm.” From https://energycentral.com/c/gn/initial-steps-building-solar-farm.

[15] Eleftheria, Mitka, 2017, “Applying STAMP to safety standards of mowing robots.” From https://subs.emis.de/LNI/Proceedings/Proceedings232/619.pdf

Appendix A: Customer Requirements

Appendix A-1: Requirements Table

Requirement	**Target**		**Validation and Verification (Test)**
	Target Value	**Range**	
F.I.1 (Cutting Rate)	500 sq ft/12 min	500 sq ft/ 15 min	Time to cut the 500 sq ft boundary needs to be recorded.**
F.I.2 (Cutting Height)	Adjustable between 3”-6”	Any height between 3”-6”	Grass needs to be measured at random locations within the boundary.**
F.II.1 (Stability)	3” over 2’	N/A	The rover has been tested over uneven terrain with at least a 3” differential over 2’.
F.II.2 (Turn Radius)	0 Degrees	0 Degrees - 90 Degrees	The rover alternates power and rotational direction between wheels in order to accomplish a close to zero turn radius.
F.III.1 (Obstacle avoidance)	0 hits	1 hit	Obstacles need to be placed around the rover to test its avoidance capabilities.**
F.III.2 (Autonomous)	Completely	Remote controlled with an autonomous feature	The rover is remote controlled, but needs to be programmed to use camera and sensors to avoid obstacles with an autonomous feature.**

F.IV.1 (Time of Operation)	Day and Night	Night	Rover performs during the day time with remote control.**
F.V.1 (Durability)	Waterproof and Non Corrosive	Waterproof	The cover is of plastic material in order to waterproof the rover body.
F.VI.1 (Time to Charge)	Two Cycles	One Cycle	The batteries will supply sufficient charge to complete at least one 500 square foot area.
C.I.1 (Manual Kill Switch)	2’	1’-2’	Manual kill switch incorporated onto rover.
C.I.2 (Remote Kill Switch)	100’	≥ 50’	A remote kill switch ceases movement at a 50’ distance.
C.I.3 (Location Beacon)	30min	15min-45min	A location beacon is integrated into the GPS system of the rover, with location capabilities.
C.II.1 (Base Structure)	23”x16”	24”x24”	Base structure is 24”x24” in area which is within the maximum.
C.II.2 (Cover Structure)	23”x16”x7”	24”x24”x20”	Cover is within the dimensions of the base and measures below the maximum at 6.875” high.
C.II.3 (Rover Height)	15”	≤ 20"	The total height of the rover is less than 20” at approximately 14.48”.

C.II.4 (Access panel)	2 piece	3 piece	The cover design changed to not feature a panel.
C.III.1 (String trimmer)	5”	24”	The string trimmer has a cutting diameter of 11”.
C.IIV.1 (Wheel Motor)	1 HP	.5HP - 2 HP	The wheel motor drives the rover at about 1.2 mph.
C.IV.2 (Trimmer Motor)	20,000 rpm	15,000-30,000rpm	The initial trimmer motor cut grass consistently and with ease. The Ryobi trimmer is expected to as well.
C.V.1 (Power Supply)	12V Battery	N/A	Each battery’s voltage was tested and recorded.
C.VI.1 (Driving Wheels)	10.5”	N/A	The drive wheels have a diameter of 10.5” to traverse uneven terrain.
C.VI.2 (Caster Wheels)	6.25”	N/A	The caster wheels have a diameter of 6.25”, which is sufficient.
C.VII.1 (Cooling Feature)	2 Cover Vents	One to Four Cover Vents	Internal components did not overheat during subsystem tests.
C.VIII.1 (Sensors)	Lidar Sensor	N/A	A lidar sensor was successfully tested for obstacle detection apart from the rover.

**Test not fully complete due to inability to incorporate necessary components before campus closure/stay-at home order

Appendix B: System Evaluation Plan

The rover is expected to complete cutting the area in less than 15 minutes therefore all components on the rover should be able to run for a minimum of 15 minutes without a failure. To ensure this, all components will be tested for a minimum of 20 minutes. Each component will be tested independently before assembly of the subsystem and entire rover.

Appendix B-1: System Evaluation Tests

Component	Test
Drive motor	Run for 20 minutes with battery that will be used on the rover and inspected
Drive motor with wheel attachment	The drive motor and wheel will be run for 20 minutes and inspected.
Drive motor and wheels attached to the base plate	With all the wheels attached to the base plate, the rover will run for 20 minutes in a grass area then inspected after.
The rover with all the navigation and obstacle avoidance components	The rover will be placed in a marked area by a boundary wire with obstacles for the rover to avoid using its LiDar system.
String trimmer	The string trimmer will run for 20 minutes then inspected after.
The rover with all subsystems	Tested for 20 minutes.

Appendix B-2: System Evaluation Test Equipments

Component	Test Equipment
Drive motor (independent)	Battery, wires, and alligator clips
Drive motor with wheel attachment	Battery, wires, and alligator clips
Drive motor and wheels attached to the base plate	Batteries, breadboards, electronic controller components
The rover with all the navigation and obstacle avoidance components	Batteries, breadboards, electronic controller components, remote control, grass area
String trimmer (independent)	Battery, wires, and alligator clips, workbench with vise
String trimmer with height adjustment mechanism	Battery, wires, and alligator clips, work bench, vise grips, voltage regulator
The rover with all subsystems	Batteries, breadboards, electronic controller components, remote control, grass area

Appendix C: User Manual

1. Operation

This rover is controlled by a PlayStation controller to navigate the rover around the cutting area. When the rover is turned on, the trimmer will turn on and start cutting. Use the controller to steer the rover around the area which needs to be cut. If the rover is equipped with an autonomous feature, before any usage of the rover, a boundary wire will need to be placed around the perimeter of the cutting area. Incase of loss of power, the rover is equipped with a location beacon with its own power source that will send out its location for personnel to retrieve the rover and bring it back to the charging station. Batteries can be recharged using a compatible LiPo battery charger.

2. Safety

If there is power to the rover, do not stick hands or feet underneath the rover. If the rover needs to be stopped in an emergency there is a button on the outside of the cover which when pressed will stop all power to the trimmer and driving motors. The rover also has a remote shut off switch that will cut power to the trimmer and drive motors from a distance of up to 50 feet along. Store the rover in a dry place, such as a household garage. Keep out of children's reach.

3. Troubleshoot

    a. If the rover will not turn on

       - Check wires for connection

    b. If the rover drives past the boundary wire

       -Boundary wire is too far from the sensor.

    c. If the rover bumps into obstacles

-Check wires for connection on camera and LiDar

d. If the trimmer does not turn on

-Check wires for connection on trimmer

-Inspect trimmer motor for failures

Appendix D: Cost Analysis and Manufacturability Analysis

Parts of this rover could be mass produced with the use of 3D printers and an industrial waterjet. If the sheet metal and 3D printing material was bought in bulk, the price to manufacture the rover would decrease. Some parts such as the motors, cameras, and other electronics would have to be bought from another manufacturer. Appendix D-1: Critical Parts and Cost shows the critical parts required to manufacture this rover along with its corresponding cost. Cost of make items have been estimated since 3D printing was available to the team at no cost. The total at the bottom of the table shows the total cost to manufacture this rover without the factor of man hours to assemble the rover. To continue manufacturing the rover, each one would have to be sold at a higher cost to make a profit. Inconsistencies between this cost analysis and the expense report can be attributed to the absence of non-critical components, components procured at no cost to the team, and estimations for make item costs.

Appendix D-1: Critical Parts and Costs

Part	Cost
Base plate	$50
Motor mounts	$14.98
Cover	$7.98
Height adjusting mechanism	$13.10
Batteries	$100
Camera	$179
LiDar	$300
Wheels	$135
Drive motors	$140

Trimmer	$70
Perimeter wire kit	$10
GPS	$55
Computer boards	$144
Push button switch	$6.99
Total	$1,226.05

Appendix E: Expense Report

All shipping costs are included in the unit price unless shipping is specifically noted below the part. Green highlighted items are money back due to returns or discounts.

Appendix E-1: Expense Report

Item	Quantity	Unit Price	Subtotal
Caster Wheel	1	$15.86	$15.86
Drive Wheels	1	$107.52	$107.52
Driving Motors	2	$84.325	$168.65
Trimming Motors	2	$13.58	$27.16
Trimmer Head	1	$17.69	$17.69
Base Plate	1	$49.99	$49.99
(Credit for Base Plate Return)	1	$44.20	+$44.20
Boundary Wire	1	$18.95	$18.95
GPS Module	1	$39.95	$39.95
SMA to uFL/u.FL/IPX/IPEX RF Adapter Cable	1	$3.95	$3.95
GPS Antenna	1	$14.95	$14.95
IMU Sensor	1	$14.95	$14.95
Shipping on Adafruit Items listed above	1	$7.82	$7.82
Perimeter Wire Kit	1	$9.95	$9.95
Odroid XU4	1	$77.85	$77.85
Bearing Pillow	1	$15.95	$15.95

AmazonBasics 4-Port USB to USB 2.0 Ultra-Mini Hub Adapter	1	$6.99	$6.99
Intel RealSense Depth Camera D435	1	$175.99	$175.99
eMylo DC 12V 6X 1 Channel Wireless Relay RF Relay	1	$28.69	$28.69
Ovonic 11.1V 8000mAh 3S 50C Lipo Battery	1	$87.99	$87.99
B3 RC LiPo 2S-3S Battery Balancer Charger 7.4-11.1V	2	$10.99	$21.98
5pcs Male T-Plug	2	$9.98	$19.96
Lipo Bag	1	$7.77	$7.77
Velcro	1	$8.99	$8.99
Amazon discount	1	$0.60	$0.60
Buck converters (5pcs)	1	$26.59	$26.59
Wire loom	1	$11.99	$11.99
Wire	1	$15.99	$15.99
Connectors	1	$11.99	$11.99
Connectors(robust)	1	$10.99	$10.99
Wire(robust)	1	$16.89	$16.89
Amazon discount	1	$0.13	+$0.13
ONE+ 18-Volt Lithium-Ion Cordless String Trimmer/Edger - 4.0 Ah Battery and Charger Included	1	$119.00	$119.00

ONE+ 18-Volt Lithium-Ion Electric Cordless String Trimmer and Edger - 1.3 Ah Battery and Charger Included	1	$69.97	$69.97
Sterilite 32 Qt Latching Storage Box	1	$7.98	$7.98
Express Delivery	1	$8.99	$8.99
Aluminum Baseplate (current)	1	$0.00	$0.00
Total			**$1205.00**

Appendix F: List of Manuals and Other Documents

Appendix F-1: Additional Supporting Documents

Supporting Document	Accessible By
Technical Memorandum: Electric Motors	https://drive.google.com/open?id=1NKJyLgV6SjzzTAe8CCWEkJe0QHJQEDhX
Technical Memorandum: Structural Design and Power Supply	https://drive.google.com/open?id=1gyUfPjclZdWMKHdu08mRhXRXrgI97Tl3bgbA3kyFAYs
Technical Memorandum: Existing Robotic Grass Cutting Products	https://drive.google.com/open?id=1N7vc1vBw30Sb_1m9a2OaAJpQ8ehkPewZ
Technical Memorandum: Drivetrain	https://drive.google.com/open?id=1PRXV9hhr8vzg-JwpQ-JX7I_tQu6gF6Xo
Engineering Design Specification	https://drive.google.com/open?id=1Tb0e39B1vmaSsH2fRysVz2aOL61PzAzj8TDjDP8A5HE
Concept Design Report	https://drive.google.com/open?id=1z7hemlkmLGXNlNb57xdRfTfK4C-x4Q2bDuqXS56pi4k
Statement of Work	https://drive.google.com/open?id=1ZH6Q53J00Zkj1vnZqIsu4UIdEdVSJSREjXrtt5N_khs
Critical Design Evaluation	https://drive.google.com/open?id=1Q_PHZJt7ZhEWt84w7vPAbuzh7pFLEfVbzn1072CCHv4
Autonomous Lawn Mower Safety Code	https://drive.google.com/file/d/1rh-aX6emMbmj-QSHGYHg3z_7TPKLLmEi/view?usp=sharing

Appendix G: Design Competencies

Appendix G-1: ME Design Competence Evaluation

MECHANICAL ENGINEERING DESIGN COMPETENCE EVALUATION

Rate this *design project* in illustrating effective integration of mechanical engineering topics:

Project Title: _E-GOAT____

Please rate the relative importance of the given topic in this design project

ME Design Areas	Critical/Main contributor	Strong contributor	Necessary but not a primary contributor	Necessary but only a minor contributor	Only a passing reference	Not Included in this Design Project
Thermal-Fluid Energy Systems						x
Machines & Mechanical Systems			x			
Controls & Mechatronics		x				
Materials Selection					x	
Modeling & Measurement Systems		x				
Manufacturing			x			

Appendix G-2: Topic Competence Criticality Matrix

Topic	Criticality to Project	Section	Comments
Thermal-Fluid Energy Systems	Not Included in this Design Project	N/A	Considerations for heat dissipation were discussed for space available for electronic components.
Machines & Mechanical Systems	Necessary but not a primary contributor	3.1.1, 6.2.3, 8.2-8.3,9.1.3	Choice of motors, and design of trimmer/locomotion subsystems.
Controls & Mechatronics	Strong contributor	9.1.2	Controllability of the rover is essential to successful operation and completion of project requirements.

Materials Selection	Only a passing reference	3.1.3, 7.1	Brief studies conducted for selecting a base plate and for choosing 3D printing for components.
Modeling & Measurement Systems	Strong Contributor	6.1-6.2, 7.1, 8.1	Heavy use of modeling software for system visualization and analysis.
Manufacturing	Necessary but not a primary contributor	7.1, 8.1, 8.2	A good number of components were designed and manufactured by the team rather than purchased.