# WrightBot

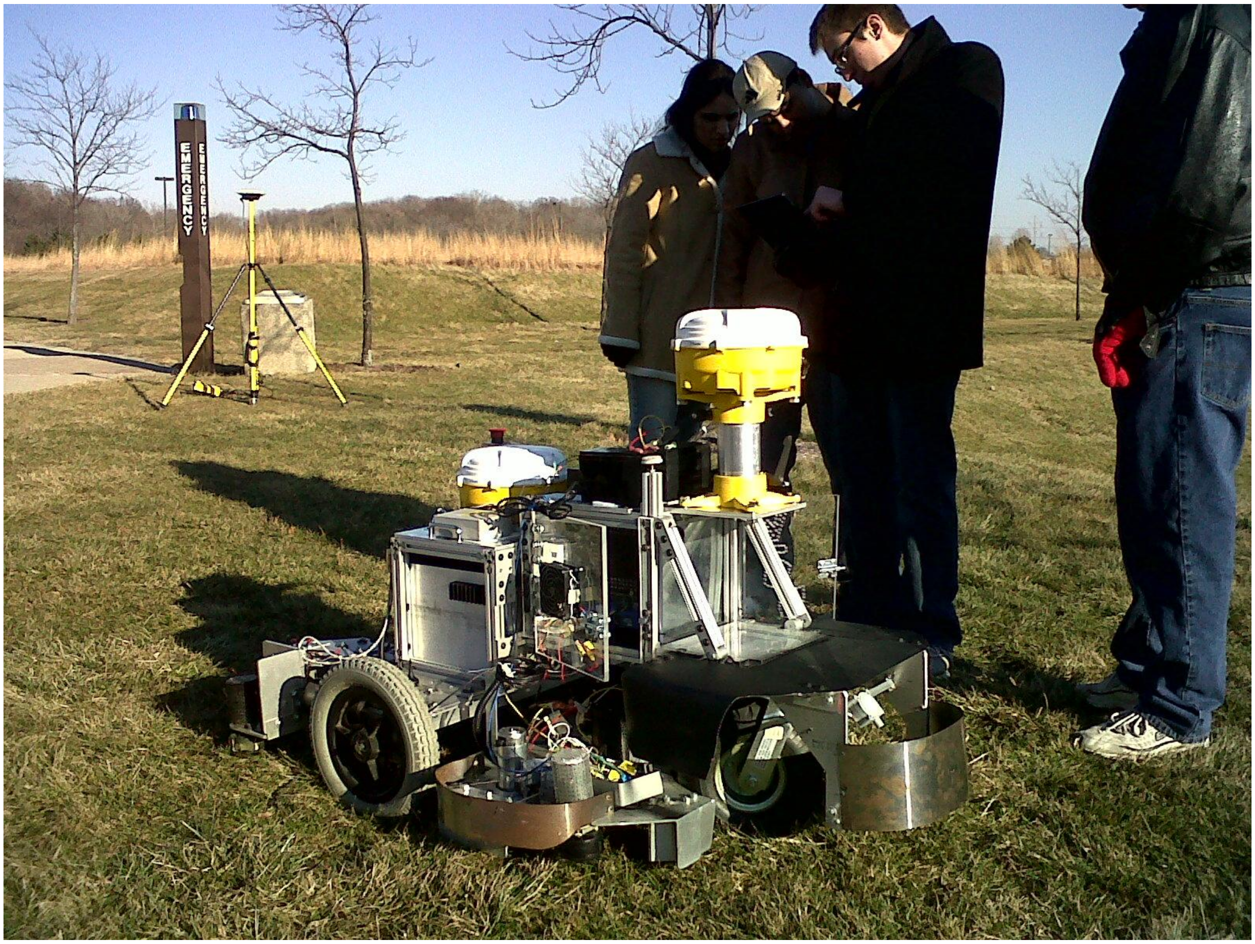
College of Engineering
and Computer
Science

## Intelligent Robotic Lawnmower Design Team

Technical Design Report

7th Annual ION Robotic Lawnmower Competition
June 3rd – June 5th, 2010
Dayton, OH, USA

# Wright State University



# Technical Design Report

Submitted for the Institute of Navigation's Robotic Lawn Mower Competition
June 3rd through June 5th
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# The WrightBot Engineering Design Team

The design team for the WrightBot autonomous lawnmower is composed of undergraduate students from electrical, computer, and mechanical engineering disciplines. After learning from past design successes and failures, Wright State University is proud to enter the competition for the 5th year, with a more robust and intelligent robotic lawnmower design.

## Design Team Members

**Electrical Engineering Team:**
Satbir Dhillon, team lead GPS implementation
Navjot Brar, robust power buss development
Randy Depoy, laser control and data filtering, and reliable wiring
Robert Nicolato, force-bumper calibration and microcontroller fusion
Joseph Esperanza, microcontroller fusion and sensor wiring
Brian Roadruck, reliable wiring

**Computer Engineering Team:**
Rick Fredley, path-planning algorithm development and testing
Terry Kipling, fusing camera and laser data
Kristin Street, GUI development
Jennafer Sparks, GUI development

**Mechanical Engineering Team:**
Kyle Todd, laser gimbal design
Carl Kocon, testing station design and obstacle construction
Justin Ferrell, robust force-sensing bumper design

**Faculty Advisors:**
Dr. Kuldip Rattan, Professor of Electrical Engineering
Dr. John Gallager, Associate Professor of Computer Engineering
Dr. Scott Thomas, Associate Professor of Mechanical Engineering

**Sponsor Recognition:**
Trimble Navigation, Ltd. provided WrightBot with several GPS systems.

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# Abstract

This paper presents the design and implementation of an intelligent robotic lawnmower. The objective is to build a lawnmower with the ability to autonomously mow grass in a specified area, while avoiding both static and dynamic obstacles. Sensor design includes: a differential global positioning system, a laser range finder, force-sensing bumpers, and an electro-optic camera. The sensor design is coordinated precisely with the computer program. A sophisticated navigational algorithm along with a robust mechanical design yields an efficient robotic lawnmower. The implemented robotic lawnmower design efficiently mows an irregular shaped lawn, while avoiding static and dynamic objects within the prescribed amount of time.

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# Introduction

The design and implementation of an intelligent robotic lawnmower requires several engineering strategies that must fuse the functionality necessary for an autonomous robot. For the design of the WrightBot three engineering disciplines joined forces to design and implement an intelligent robotic lawnmower. The engineering teams consisted of one mechanical team, two electrical engineering teams, and a single computer engineering team. Each of the three disciplines developed a unique design strategy for the overall design. Each unique strategy was based around the 7th Annual ION Robotic Lawnmower Competition's criteria and challenges. After analyzing the successes and failures of previous autonomous lawnmower designs, each team contributed ideas to the redesign and modification of the WrightBot.

The three design areas are mechanical, electrical, and computer. Each design strategy is highlighted in its individual section, with each design strategy related back to the overall design specifications. Consistency between the design specifications and each team's approach is essential for the implementation of the intelligent robotic lawnmower. The design strategies of the mechanical, electrical, and computer engineering teams yield an efficient, robust, and reliable lawnmower capable of mowing an irregularly shaped field while avoiding static and dynamic obstacles, within the time allowed for the competition.

The analysis of the final product's specifications is crucial for the "live and learn" aspect of engineering. Testing the WrightBot repeatedly over the past couple of months uncovered several design flaws and improvements needed for future designs. Analyzing the project budget uncovered useful information for future autonomous lawnmower design teams. This includes analyzing actual hardware and material costs along with man-hours dedicated to specific design areas. All of this helps future teams design and implement a more robust, reliable, intelligent, autonomous lawnmower.

# Competition Overview

For the past 7 years, the Institute of Navigation, along with its partners, host an autonomous lawnmower design and mowing competition, in which top universities from all over the United States and Canada come to compete. The competition presents unique challenges for each university's design team. This year the competition requires the autonomous lawnmower to efficiently mow an irregularly shaped field, while avoiding both static and dynamic obstacles and finishing within a designated time limit of 20 minutes. There are two static obstacles: a fence and a flower bed. The dynamic obstacle is a remote controlled dog. The field is a 15 meter by 10 meter area of grass, with differently weighted areas. The field is broken into three areas: Zone 1 will contain the flower bed and the dog, and carries a weight of 30 percent of the total score. Zone 2 is bordered on two sides by the fence, and carries a weight of 40 percent of the total score. Zone 3 consists of the area bordering the static obstacles, and carries a weight of 30 percent of the total score. In addition to the complexity already presented to the design teams, one side of Zone 1 will be slanted with an unknown slope. The 7th Annual ION Robotic Lawnmower Competition poses a multitude of design considerations for each design team [1].

# Design Specifications

The design of the intelligent robotic lawnmower must account for the challenges presented by the competition. For the mechanical design the main specification is a rigid and stable frame that protects the valuable electronics, and maximizes the cutting area of the mower. The electrical design specification includes accurate control of the motors that drive the lawnmower, as well as precisely determining the lawnmower's position in the competition field at all times. Knowing the range of the lawnmower from static and dynamic obstacles in the field is crucial for competition. The dynamic obstacle exits the field after a specified period of time, but the static obstacles remain in the field with the surrounding grass consisting of a valuable portion of the total score. Therefore, it is crucial to include an electrical sensor that mimics the sense of touch. The electrical specifications generate a sensor system that the computer system needs to be able to process. Therefore, the initial computer engineering design is to determine the necessary on-board computer specifications. The remaining computer specification is an efficient path-planning algorithm that can interpret all of the sensory data and make intelligent decisions; all the while remaining efficient with a logical flow. The initial prototype design is based on these specifications.

# Mechanical Design

The Wright State University autonomous lawn mower utilizes a tri-wheel design for increased accuracy and ability to make the sharp turns necessary to navigate and mow a field of grass. The rear drive motors are independently controlled which allows them to both drive and steer the mower. The front wheel is a caster wheel allowed 360 degrees of rotation. All three wheels utilize pneumatic tires and these tires serve as the only shock absorption and damping system on the mower chassis. A solid model overview of the entire mower assembly is shown in figure 2.

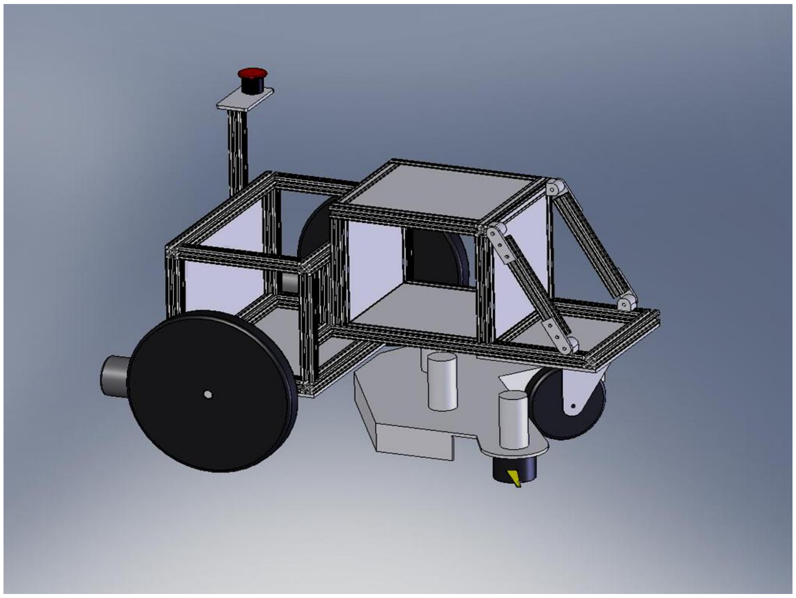

Figure 2: Solid Works Drawing of the Lawnmower Mechanical Design [8].

The chassis is constructed of aluminum 1”x1” extrusion from 8020.net. Refer to Table 1 for the final physical specifications. This material was chosen because it is light weight, durable, and easy to assemble. Ease of assembly and changeability is necessary on a vehicle that is under development and constantly being improved with innovative solutions to be more accurate and more reliable. The chassis is designed with two compartments for batteries and electronics to be isolated from the outside environment.

**Table 1: Final Lawnmower Dimensions**

| Component | Dimensions | Note |
|---|---|---|
| Mower body assembly | Length: 127 cm Width: 94 cm Height: 94 cm (with front GPS unit) | *These dimensions describe the extents of the mower, including protrusions from the bumpers and string trimmer assemblies.* |
| Front caster wheel | Diameter: 25 cm | |
| Rear drive wheels | Diameter: 34 cm<br>Quantity: 2 | |
| Track width | 84 cm | *Represents the distance along the mower's width between the ends of the rear drive wheels.* |
| Wheel base | 74 cm | *Represents the distance along the mower's length between the bottom of the front wheel and the bottom of the rear wheel.* |

The mower deck is constructed from ¼" aluminum plate and solid mounted to the underside of the autonomous lawn mower chassis. This mowing deck is adjustable for different heights of grass. Five main mowing motors and one trimming motor are attached to the mowing deck, and the main mowing blades have an overlap of ¼" to insure a good quality cut. Figure 3 below is a solid model representation of the mowing deck.

Additionally, to guarantee an efficient and high-quality cut, the lawnmower needs high torque blade motors that do not slow down appreciably when loaded by large clumps of grass. This allows the lawnmower to cut thicker grass and gives the grass a more aesthetically pleasing cut. The blade motors were selected to match the chosen 24 volt power supply and provide the large amount of torque. The blade motors are 0.102 m tall and 0.051 m wide, along with a 0.006 m diameter shaft. To cut grass around the static obstacles, the lawnmower requires a trimming system.

The string trimmer motor design focuses on high torque, speed, and power usage, in order to allow for an aesthetically pleasing cut around static obstacles. The string trimmer motor requires the 24 volt power supply while providing a large amount of torque (stalling of the string motor is approximately 0.212 N-m). Overall the string motors provide clean trimming around static objects and pick up extra grass during mowing.

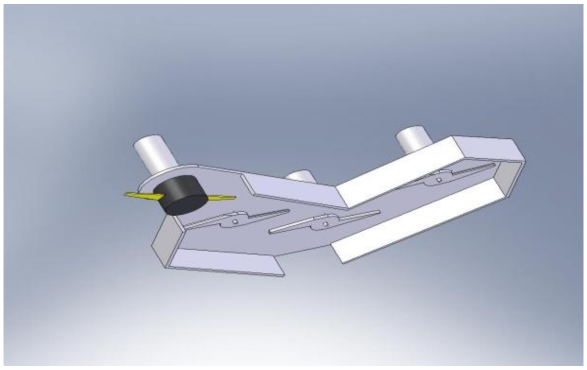

Figure 3: Solid Works Drawing of the Lawnmower Deck [8].

Obstacle detection is undoubtedly one of the most important features of the Wright State University autonomous lawn mower. A laser range finder from the SICK Corporation is used for obstacle detection on the front of the mower, and in past designs this was solid mounted to the mower chassis. This laser range finder utilizes a paper thin beam, and therefore can only detect objects in the path of that beam. The issue this gives is that only obstacles of or at a certain height are able to be detected. To make this obstacle detection system capable of detecting the dog, fence and flower bed, a swivel mount was created this year to allow the laser to pitch up and down, thus allowing the beam to detect obstacles of various heights and at various distances from the mower. A stationary laser only has a two dimensional field of vision for obstacle detection. The overall goal of the gimbal design was to allow the laser range finder to continuously sweep over a range of angles thus providing a three dimensional field of vision for obstacle detection.

The laser gimbal, shown in figure 4, consist of two double sealed ball bearings, brackets with ½” steel shafts, a steel lever arm welded to a steel shaft collar, and a 25lb linear actuator. Several designs were considered and this bearing/shaft design was chosen for its durability, accuracy, and speed. Utilizing the low friction of the ball bearings and placing the shafts at the center of gravity of the laser assembly, very little force needs to be applied to the lever arm to change the angle of the laser relative to the ground. Minimizing the force needed to change the angle was an important design driver to meet the design specification of a 1Hz oscillation through the specified angle range. The linear actuator used has a 10K linear potentiometer integrated inside the device to provide position feedback of the actuator which is a necessary component for accurate autonomous control of the laser gimbal assembly.

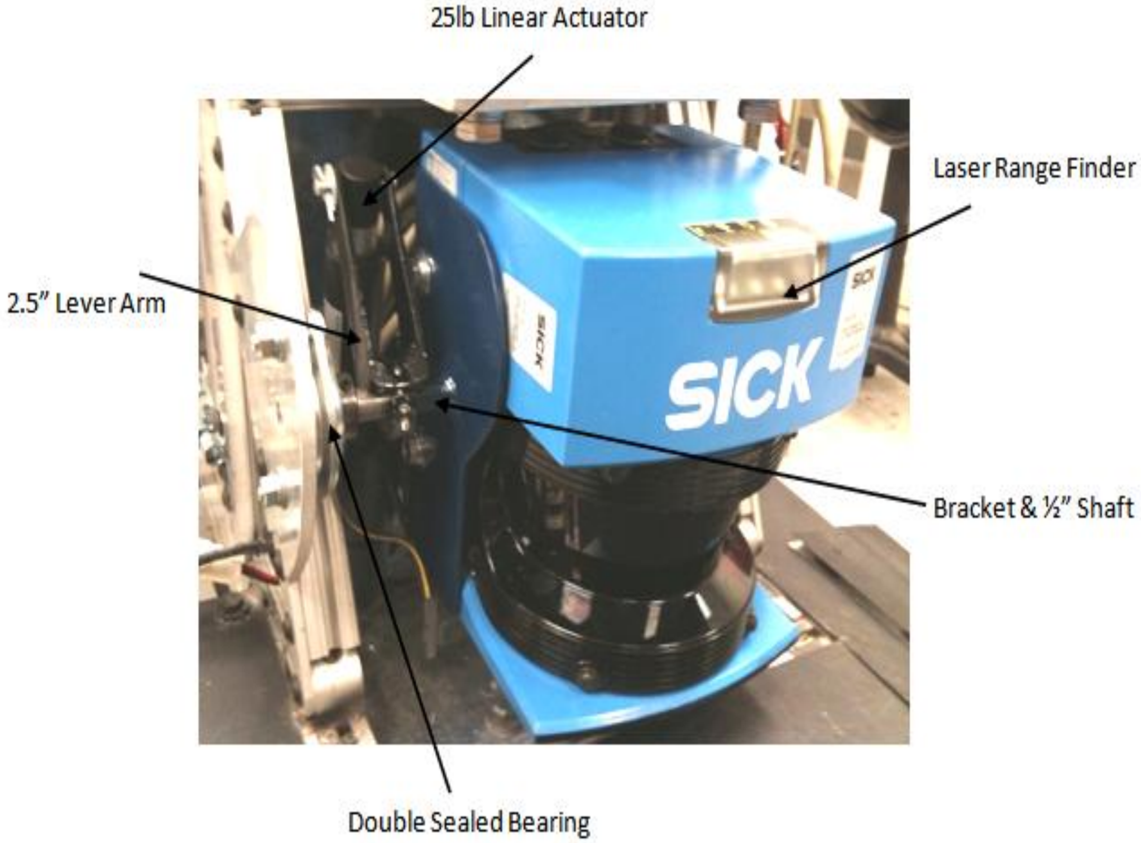

Figure 4: Picture of Gimbal and Laser's Mechanical Design.

# Electrical Design

Figure 5 shows the block diagram of the electrical system. The electrical design is composed of a motor controller, which receives inputs from the computer based on the sensor module's outputs. The sensor module is composed of a differential global positioning system, laser range finder, electro-optic camera, and force-sensing bumpers. The robust power grid provides reliable and safe power to the entire electrical system.

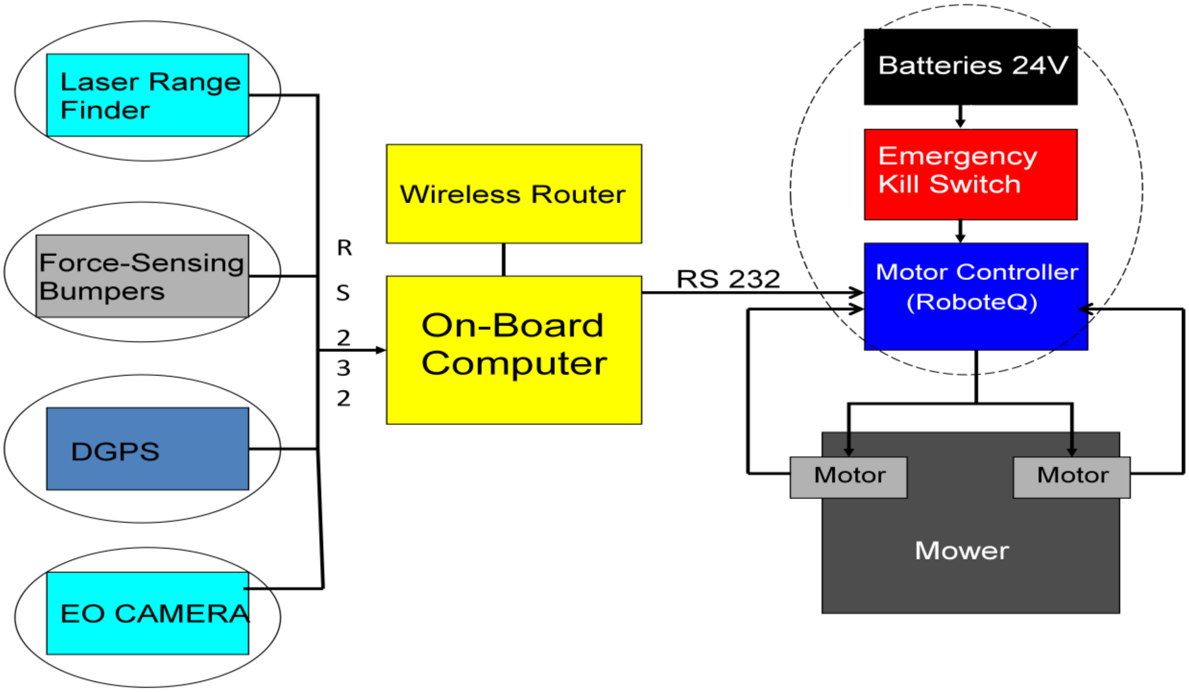

Figure 5: The Block Diagram of Electrical System.

## Motor Controller

To navigate the robotic lawnmower in the field, two DC motors are used. Each DC motor is designed for 24 V power supply and 30 A of constant current. RoboteQ AX2850 motor controller is used to control the two DC motors. Having inbuilt proportional-integral-derivative (PID) controller, the RoboteQ AX2850 can accurately control the speed and direction of the two DC motors. Input from the encoders on the DC motors provides feedback for the PID controller. The motor controller has two separate channels, where each channel handles up to 120 amps providing a safety margin of two. RoboteQ AX2850 can receive inputs from a remote control or the on-board computer [7]. The on-board dual relay switches the control of the lawnmower in between the remote control and on-board computer. Remote control operation is primarily for transporting the lawnmower to the competition field. Once on the competition field, the on-board computer takes over as a primary input to the motor controller. The on-board computer is connected to the motor controller via the RS232 serial port, through which it sends commands to the controller and receives feedback information. Based on this, the on-board computer and motor controller correct the speed and direction of the lawnmower [6]. Accurate control of the motors is useful only if the position in the field is known, which is provided by the differential GPS.

## Differential Global Positioning System

In order to navigate the field during the 7th Annual ION Robotic Lawn Mower competition, the computer needs to know the location of the lawnmower. This is accomplished by using a global positioning system (GPS), which collects four parameters: longitude, latitude, altitude, and time from a minimum of four satellites. However, the data from the satellites still has error associated with it due to distortions caused by the atmosphere, and the fact that satellites may be using more accurate clocks than the GPS. This causes a single GPS setup to have an error of up to 10 meters [2].

Since the field that the lawnmower must efficiently mow is approximately 15 meters by 10 meters, the error associated with normal GPS is unacceptable [1]. The solution is to use a differential global positioning system (DGPS), which has the potential to minimize errors down to the centimeter level. A DGPS consists of a stationary base station GPS and antenna that receives normal coordinate parameters of longitude, latitude, altitude, and time. The four parameters are then sent to the lawnmower's onboard GPS receiver, which performs coordinate correction and removes error. The error can be eliminated because the rover (on-board) GPS and the base (stationary) GPS receive the same atmospheric distortions [2]. The DGPS determines the accurate position of the lawnmower in the field, but it is unable to navigate around the obstacles whose locations are unknown. This design specification is accounted for with the addition of a laser range finder.

## Laser Rangefinder

The lawnmower has a laser range finder mounted to its front that sends out laser pulses, measures the time each pulse takes to reflect back, and through hardware computations determines the distance to an object. The laser range finder mounted on the lawnmower is the SICK LMS 200. The LMS 200 scans continuously by sweeping through a range of 180 degrees (with 1 degree increments). The distance is computed by the hardware in the LMS 200 and outputted as an array of distances corresponding to the angle. The array gives a polar coordinate representation of the objects around the lawnmower [3]. A more meaningful representation of this data is generated by converting to Cartesian coordinates, which coordinates are arbitrarily defined as follows: The y-axis is always in the same direction as the lawnmower's velocity vector, and the x-axis is always orthogonal to the y-axis. In Cartesian coordinates, the data can be filtered with known distance thresholds, such as the distance from the center of the laser to the furthest edge of the mower deck (x-axis). This method of filtering can determine if a collision between the lawnmower's mower deck and an object is eminent. If so, the lawnmower must stop and re-route.

One of the static objects located in the field is the low-profile flower bed. Currently the laser range finder is mounted higher than the flower bed in the z-direction and is unable to detect the flower bed. The innovative solution for this year's mower is to tilt the mounted laser using a linear actuator controlled gimbal. This allows the lawnmower to detect the flower bed edging, and slow down for trimming around the flower bed. For this setup, two major complications arise. First, the grass height is not consistent throughout the field, which may yield false alarms that potentially hinder the lawnmower's performance and detection capabilities. Secondly, once the laser detects a low profile object, how will the lawnmower know if it is actually detecting the flower bed's edging? In order to increase the frequency of positive detection, the lawnmower is given another sensor: the electro-optical (EO) camera.

### EO Camera

The addition of the CMUcam3 EO camera into this year's overall sensor design increases the possibility of detecting the flower bed. The CMUcam3 offers open-source programming, RGB color sensing at 26 frames per second [4]. This is beneficial to the lawnmower's sensor design, since the color of the flower bed edging is given (black). Therefore, when the laser range finder returns a distance within the y-direction threshold, the lawnmower halts forward motion. If black color spectrum is detected by the camera software, then the lawnmower can confidently declare the low-profile object as the flower bed. The next problem faced by the lawnmower after detecting static or dynamic objects, is how to maximize the area of grass cut without colliding with any objects. This is realized by the addition of force-sensing bumpers.

### Force-Sensing Bumpers

The force-sensing bumpers are mounted on two separate places along the lawnmower's mower deck: one on the front and one on the right-side of the mower deck. The force-sensing bumper design is simple, consisting of a string potentiometer attached to a convex sheet of flexible stainless steel shim stock. The Celesco SP1-4 string pot is used to reference any change in the force-sensing bumper's displacement (contact). A known reference voltage is applied to the Celesco SP1-4 (5 volts), and the voltage at the feedback terminal changes linearly with respect to the displacement of the string. The distance can then be determined from the voltage division on the reference pin. Based on the deflection of the convex sheet metal during contact, the force between the bumper and an object can be computed. To guarantee that the lawnmower does not cause any displacement when contacting an object, the computed force is kept constant, which is useful during trimming around static obstacles. The analysis and monitoring of the force-sensing bumpers is performed by a microcontroller.

### Microcontroller Design

The Z8 ENCORE Z8F642 MCU is the microcontroller of choice due to its large supply of memory, clock speed, and I/O pins (Figure 6). Serving as the interface between the force-sensing bumper and the on-board computer, the microcontroller samples the initial voltage on the reference pin of the Celesco SP1-4 string pots. This initial digital representation is then compared to the continuously sampled reference pin. When the two are different, a distance, as well as a corresponding force are computed and sent to the on board computer. The force is proportional to the deflection of the convex sheet metal.

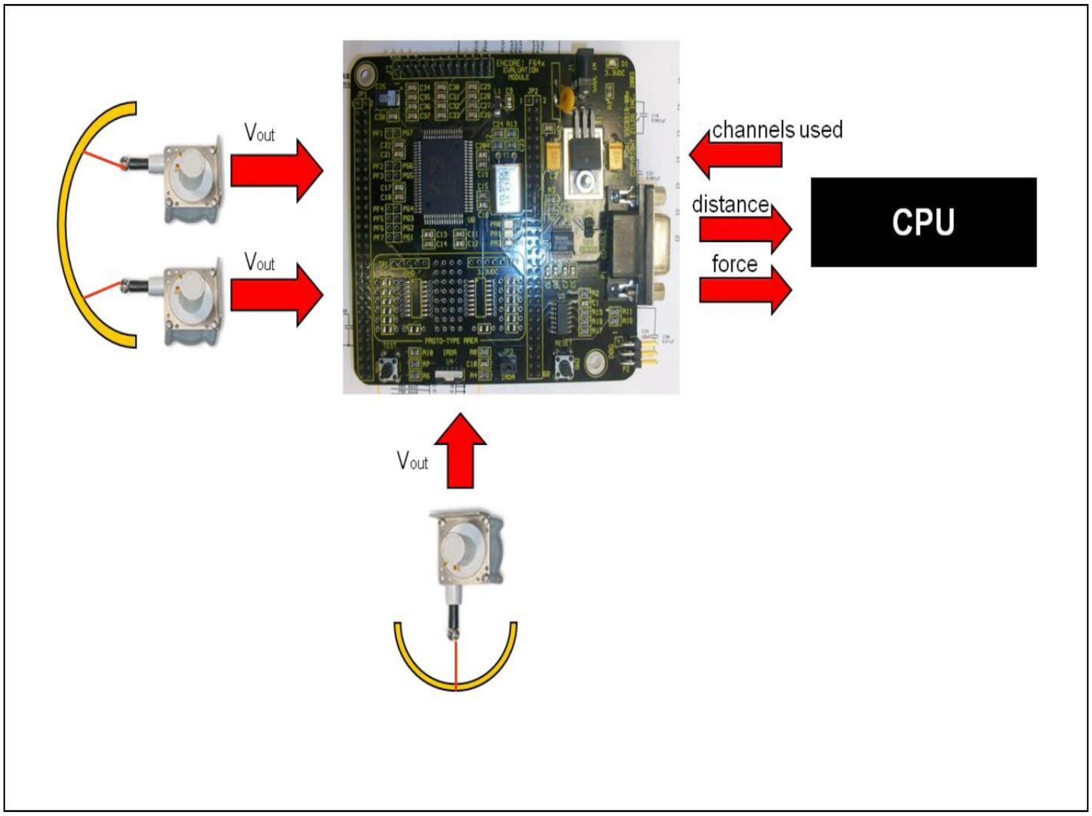

Figure 6: Image of Microcontroller and Force-Sensing Bumper System [6].

## Power Grid and Safety Circuitry

By analyzing the power requirements and ratings of electrical components, a design for the power grid and safety circuit were developed.  The power grid design specifications focused on the battery life, robust operation in harsh environmental conditions, and the safety of the valuable electronic components. In order to guarantee a long-term power source during testing, the design included four 12 volt, 10 amp-hour batteries. 12 volt 10 amp-hour sealed lead acid batteries were selected to provide power due to the battery’s dimensions and amp-hour rating. The battery dimensions are 5.95 inches by 2.56 inches by 4.375 inches (length width height), which is ideal for placement on the frame. The batteries were configured to supply both 12 volts and 24 volts, with a combined 20 amp-hour capacity. This was done by simply wiring two sets of two batteries in parallel, and then wiring each set of two batteries in series. This provides the lawnmower with computer power (12 volts) for nearly two hours, which is essential for longevity during testing. Refer to Table 3 for power and current load data which were collected during testing. The initial boot up time of the lawnmower until the time when the 12 volt supply failed to provide power to components was measured. The 12 volt and 24 volt supply currents were also measured at boot up and steady state, to verify the measurements. The 55 amp-hour loading is purely theoretical; for the drive motors it is assumed that each motor will draw an average of 15 amps for the calculation. Each drive motor is current limited to 25 amps inside the RoboteQ. The blade motors and string trimmer draw approximately 3 amps of current. Therefore, the theoretical current value of 33 amps multiplied by the 24 volt supply yields 796 watts. This theoretical analysis provides a theoretical battery life of approximately 100 minutes for the 55 amp-hour system. However, the 55 amp hour batteries are sufficient for testing, since the drive motors and blade motors are not continuously on.

**Table 3: Final Lawnmower Power Consumption**

| Power source | Components | Power consumption (W) | Operating time (min) |
|---|---|---|---|
| 2 12-V 55-Ah batteries in series | *5 blade motors*<br>*1 string trimmers*<br>*2 drive motors* | 792 | 100 |
| 2 12-V 20-Ah batteries in series | *Laser*<br>*RoboteQ*<br>*Data Switch* | 24 | 600 |
| 12-V 20-Ah battery | *Computer*<br>*GPS/ Radio*<br>*EO Camera*<br>*String Potentiometers*<br>*Microcontroller*<br>*Router* | 112 | 128 |

Based on last year's numerous failures, wiring of the lawnmower was revisited this year. The updated power distribution grid consists of "clean" power and "dirty" power. The "clean" power is the system of 10 amp-hour batteries, which power the sensitive electronics on the lawnmower. The "dirty" power is the system of 55 amp-hour batteries that power the drive motors, blade motors, and string trimmer motor. Isolating "clean" potentials from "dirty" potentials ensures loading from the drive motors and mower blades will not cause varying levels of voltage that could potentially hinder sensitive electronics. The clean power is terminated into two buss lines (12 and 24 volt) with a common chassis ground. The wires then travel from buss to device through a series of wire ducts that protect the wiring from collisions and other potential hazards. The chassis ground provides the electronics with electrostatic shielding, a path for current to travel in case of a short, and removes floating voltages.

Additional safety considerations are implemented through the addition of fuse blocks and circuit relays. For the 12 volt positive potential a spade fuse block provides electronics protection. The implementation of a spade fuse block versus a standard fuse system provides quick fuse replacements and can function as a switch. The safety circuit contains two safety switches in series with the clean 12 volt supply and the control terminals of the high-power solid-state relays. This provides a convenient way of terminating the drive motors and blade motors operation, refer to Table 2. In the application of the kill switches, the computer and other electronics are not terminated, rather they remain on. Additional safety is added by placing a 50 amp circuit breaker in series with the drive motor supply, and adding a toggle switch in series with the blade motor control line. This will minimize the damage caused through accidents during operation. The power grid and safety circuit design effectively makes the lawnmower more reliable and robust.

**Table 2: Final Lawnmower Performance**

| Characteristic | Functionality |
|---|---|
| Maximum speed | 10 km/h |
| Operating speed | 4 km/h |
| Cutting width | 84 cm |
| Hard Kill/ Remote Kill | Stops Drive Motors/Blade Motors<br>Length 1 meters/under 2 seconds |
| Battery Life | 128 minutes |

# Computer System Design

## Hardware

The on-board computer is the brain of the lawnmower, making its utilization pertinent to a successful and collision-free mow. An embedded single-board computer was chosen to implement the design because it is more robust to the harsh lawnmower operating environment. The ADL945PC, manufactured by Advanced Digital Logic, is used based on its hardware specifications. The ADL945PC has a multi-core processor, along with low power consumption. With the addition of the embedded single-board computer, the lawnmower is capable of providing the computational power needed for this project. Multiple cores yield a significant performance advantage since the path-planning algorithm starts a thread for each sensor on the lawnmower [6]. The clock speeds are high enough to sample a sensor during each thread and perform the necessary computations. By using the lawnmower's efficient and powerful hardware, the path-planning algorithm can be implemented.

## Path-Planning Algorithm

The lawnmower's algorithm must develop a meaningful representation of the field to be mowed. The algorithm's code must flow with ease and provide logical methods for debugging. To accommodate this requirement, all of the field knowledge is stored in its own C++ class. Important components of the path planning algorithm include the local coordinates, points, zones, waypoint generation, and a memory grid [6].

### i. Local Coordinates

The path-planning algorithm generates a local coordinate system of the field being mowed. The origin of this coordinate system is one of the corners of the course, the choice is purely arbitrary. Generating a local coordinate system allows for easier navigation through the field, and adds additional meaning to the DGPS data. All of this data is stored in the new course data structure [6].

### ii. Points

Prior to the lawnmower competition, the points that outline the field need to be programmed into the path-planning algorithm. This is done using the teach point graphical user interface (GUI). Each point that is taught corresponds to one of the six vertices of the L-shaped field. The collected points are used to create zones in the field [6].

### iii. Zones

In planning to transverse the field, the mower divides the course into two distinct cutting zones. This creates simple straight-edged boxes, which are easier to mow than irregular-shaped polygons (see figure 6). Each zone covers a known part of the field, arbitrarily chosen around the approximate location of the flower bed. The flower bed is always in Zone 1 per competition rules. Initially the lawnmower mows the perimeter of Zone 1, starting from origin of the field. Completely mowing Zone 2 next is convenient since the lawnmower is entering Zone 2 (see figure 7). After completely mowing Zone 2, the lawnmower re-enters Zone 1. Once in Zone 1, the lawnmower generates waypoints used to efficiently mow the remaining field area [6].

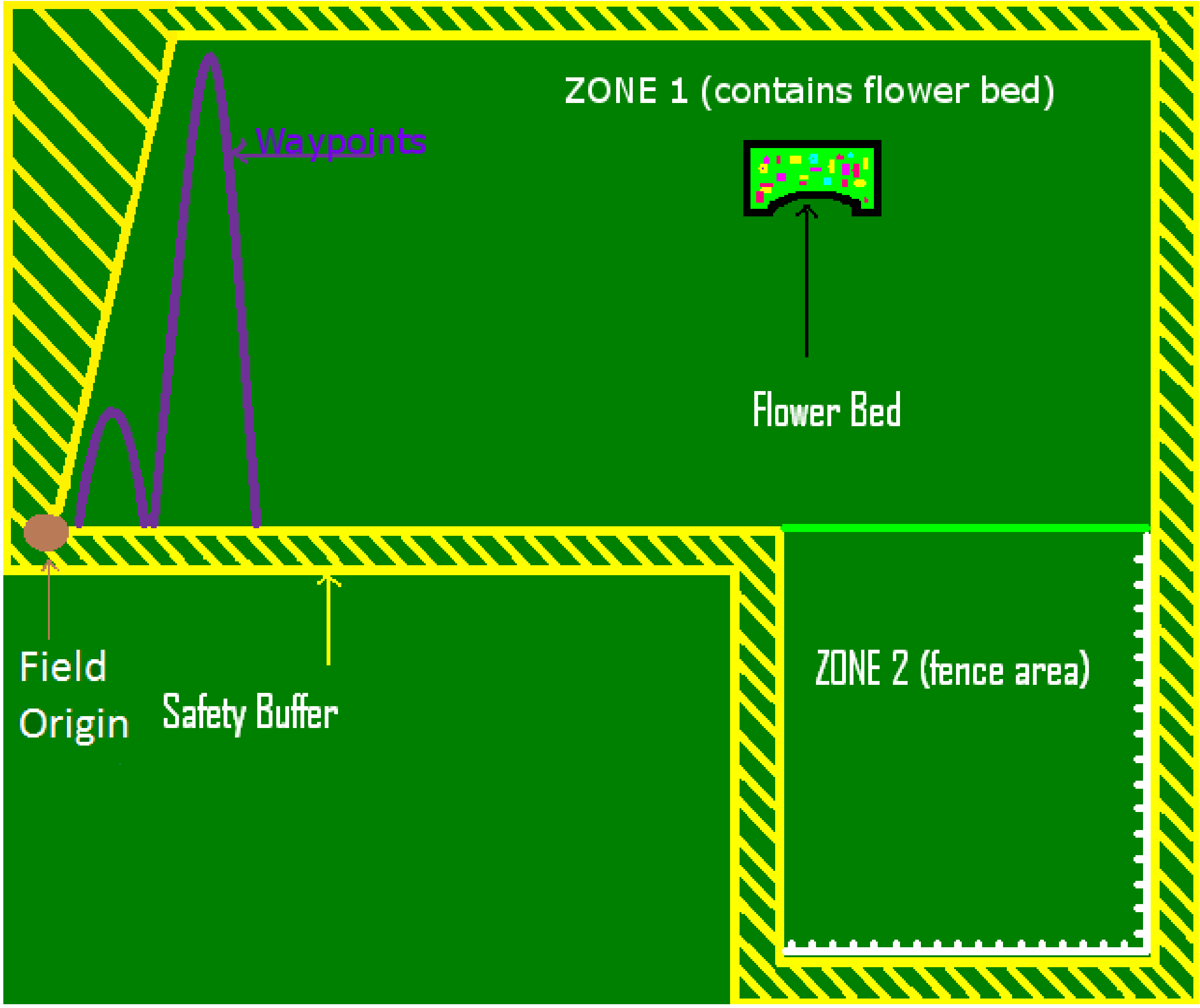

Figure 7: The Zones and Waypoints of the Mowing Field.

### iv. Waypoint Generation

Generating waypoints is beneficial to a clean and efficient mow of the competition field. In order to generate a waypoint for a given zone, the four vertices of the zone must be known, along with the desired distance between lines (sweep). For the lawnmower's application, an arbitrarily chosen distance of 0.4 meters is used for the sweep. Further computations can determine the number of sweeps required for a zone, which generates all the waypoints prior to mowing [6]. The lawnmower proceeds to follow the generated waypoints in zone 1, until the flower bed and the dog are detected. After the laser detects an obstacle the lawnmower stops to verify with the camera. If the camera verifies the flower bed, the lawnmower slowly approaches and mows around the flower bed. If the dog is detected the lawnmower stops and waits for 30 seconds. The lawnmower then proceeds to follow the generated waypoints in Zone 1, completely mowing Zone 1. Waypoints and Zones prove to be an effective method of mowing the field. In order to add more intelligence to the method, a memory grid is incorporated.

### v. Memory Grid

In order to maximize the amount of grass mowed while avoiding impacts with obstacles, an intelligent path-planning memory grid must be used. The memory grid is stored in its own separate data structure. The grid divides the field up into 5 to 10 centimeter cells. The cells allow any point within the field to be queried at any time. The cells offer the lawnmower the knowledge of whether the field has been mowed at that point, or if that point is out of bounds, or if that point is an obstacle. Given approximate specifications of the field and the flower bed, these cells allow for efficient mowing and obstacle avoidance [6]. The memory grid is visually represented with the lawnmower’s visualization tool.

## Visualization Tool

Debugging the flow and maximizing the efficiency of the path-planning program is not an easy task. The visualization tool stores the DGPS data into a data file that can be opened and displayed. Plotting this data with respect to time, maps the path the lawnmower followed. This gives a good approximation of how much area of grass is cut, and highlights the area of grass cut, versus the area of grass uncut. While the visualization tool is collecting DGPS data, a GUI displays the current run-time operations of the lawnmower. The GUI acts as an interface between the lawnmower's eyes and ears, and the user. The GUI displays the lawnmower's velocity and sensor data. Laser data is displayed along with data from the force-sensing bumpers. This provides a bountiful supply of information necessary for debugging and increasing the overall lawnmower efficiency [6].

# Lessons Learned

In order to optimize an engineered prototype, it is essential to learn from any design weaknesses in the initial prototype. Several weaknesses in the current intelligent robotic lawnmower design are: the force-bumper design, the wiring routes for several electrical devices, the GPS navigation tool design, and the “dirty” power supply. Improving each of these aspects of the current design would offer a more reliable and cheaper product to potential buyers.

The force-sensing bumpers are subject to deformation given an unexpected impact with an obstacle. The convex sheet metal is malleable to a certain extent, from which it can retain its initial state. Given a sizeable collision the convex sheet tends to deform past a favorable point and remain deformed after the obstacle has passed. If this occurs, the lawnmower will be unable to trim around any remaining static obstacles. Potential damage to static obstacles could result should the lawnmower lose its sense of touch. Potential solutions include redesigning the actual string potentiometer and convex sheet metal system, with a more rigid, yet sensitive spring padded bumper that will always retain its shape after contact with an obstacle. Another solution could be adding code that backs the lawnmower away given a convex sheet metal excursion greater than a measured threshold.

Although the intelligent robotic lawnmower’s power grid is robust and well suited for the harsh environmental conditions of mowing, several improvements need to be made to guarantee additional safety and reliability. Since the design teams are senior undergraduate students, life is busy, applying for jobs and studying for exams, the hustle and bustle leads to poor wiring and makeshift solder connections (as opposed to running a new wire). By eliminating this problem the robotic lawnmower will be a more reliable product for potential customers and more reliable during the lawnmower competition.

The design weakness with the GPS navigation tool exists in the cost. Each Trimble GPS and antenna costs nearly 15,000 dollars, making this intelligent robotic lawnmower design less desirable to any potential buyers, refer to Tables 4 and 5 in Appendix I. Since the dual-differential GPS is used on the lawnmower to draw a position vector the cost is even more inflated. A simple solution to this is implementing an Inertial-Measurement Unit (IMU), or a digital compass; effectively reducing the cost from almost 45,000 to a several thousand dollars.

The method used for powering the dirty power consists of two 55 amp-hour 12 volt deep cycle batteries in series. An improvement could be made in space and power by acquiring a single 24 volt deep cycle battery with a sufficient amp-hour rating. This will allot more area to improve the protection of the power grid from environmental conditions.

Every design has weaknesses, in order to improve upon an existing design the weaknesses must be recognized and improved, solidifying the reliability and appeal of the final product.

# Conclusion

The design and implementation of an intelligent robotic lawnmower to compete in the 7th annual ION Robotic Lawn Mower competition is presented in this paper. The mechanical design safely houses the electronics and optimizes the cutting area of the deck. Using the fields of control systems, navigation, robotics, power electronics, and computer systems, the electrical design enhances the lawnmower's sensing capabilities. The path-planning algorithm fuses the mechanical and electrical design. The design and implementation of the on-board sensors detects and avoids static and dynamic obstacles. The sensor design integrated with the path-planning algorithm and robust mechanical design makes the robotic lawnmower intelligent and capable of autonomously mowing the competition's irregular-shaped field.

# References

[1] “ION Robotic Lawnmower Competition.” Institute of Navigation. Accessed 21 Mar 2010. <http://www.ion.org/satdiv/alc/>.

[2] Trimble Navigation Ltd., “All About GPS,” 20 Mar. 2010 Internet: <http://www.trimble.com/gps/>.

[3] Sick AG., “Technical Description for LMS 200/211/221/291 Laser Measurement Systems,” 22 Mar. 2010. Internet: <http://www.mysick.com/saqqara/pdf.aspx?id=im0012759>.

[4] “CMUcam3: Open Source Programmable Embedded Color Vision Platform” 22 Mar. 2010 Internet: <http://www.cmucam.org/>.

[5] “Compact String Pot” 22 Mar. 2010 Internet: <http://www.celesco.com/_datasheets/sp1.pdf>.

[6] George Mike, Joseph Mertz, Jonathan Sargent, Yang Xu, Ben McDonie, and Matt Garing. “Design of an Intelligent Autonomous Lawnmower” Wright State University, 2009. IEEE Region II Student Paper.

[7] RoboteQ Inc., “User’s Manual for RoboteQ AX2550/2850 Dual Channel High Power Digital Motor Controller,” 12 Jan. 2007. Internet: < http://www.roboteq.com/brushed-dc-motor-controllers/ax2550-ax2850-dual-120a-brushed-dc-motor-controller.html>.

[8] Darding Kurt, Veronica Rathbun, and Kimberly Reichelderfer. “Automow – Robotic Lawnmower.” Wright State University, 2008. Capstone Design Report.

[9] “ADL945PC” 22 Mar. 2010 Internet: <http://www.adl-usa.com/products/cpu/datapage.php?pid=ADL945PC>.

# Appendix I

## Budget

### Table 4: Inherited from Previous Design Teams

| Lawnmower Materials | Cost ($) | Quantity | Total ($) |
|---|---|---|---|
| Drive Motors | 339.00 | 2 | 678.00 |
| Rear Drive wheels | 73.00 | 2 | 146.00 |
| Wheel Hubs | 40.00 | 2 | 80.00 |
| Front Caster Wheel | 57.33 | 1 | 57.33 |
| Blade Motors | 150.00 | 5 | 750.00 |
| Blade Motor Mounts | 15.00 | 5 | 75.00 |
| Blades | 50.00 | 5 | 250.00 |
| Blade Motor Couplings | 25.00 | 5 | 125.00 |
| String Trimmer Motors | 50.00 | 2 | 100.00 |
| Sheet Aluminum | 265.00 | 3 | 795.00 |
| Shim Stock | 50.00 | 2 | 100.00 |
| T-Slotted Frame Parts | 1,000.00 | 1 | 1,000.00 |
| Bolts and Accessories | 200.00 | 1 | 200.00 |
| 55-Ah 12-V Batteries | 60.00 | 2 | 120.00 |
| 7-Ah 12-V Batteries | 15.00 | 3 | 45.00 |
| Wires and Accessories | 50.00 | 1 | 50.00 |
| Encoders | 50.00 | 2 | 100.00 |
| Robotek DC Motor Controller | 500.00 | 1 | 500.00 |
| USB and Serial Box | 150.00 | 1 | 150.00 |
| String Potentiometers | 100.00 | 3 | 300.00 |
| Ultrasonic Sensors | 20.00 | 6 | 120.00 |
| Relays | 70.00 | 3 | 210.00 |
| Remote Kill Switch | 15.00 | 1 | 15.00 |
| Data Switch | 36.00 | 1 | 36.00 |
| Router | 250.00 | 1 | 250.00 |
| GPS Unit | 15,000.00 | 2 | 30,000.00 |
| Computer Hardware | 3,000.00 | 1 | 3,000.00 |
| **Total Cost of Materials** | | | **$ 38,752.33** |

### Table 5: Parts Budget from Current Year

| Lawnmower Materials | Cost($) | Quantity | Total ($) |
|---|---|---|---|
| 55-Ah 12-V Batteries | 60.00 | 2 | 120.00 |
| 10-Ah 12-V Batteries | 32.50 | 4 | 130.00 |
| Wire Duct/Miscellaneous | 45.00 | 1 | 45.00 |
| Fuse Block/Fuses | 30.00 | 1 | 30.00 |
| Linear Actuator/Mount | 280.00 | 1 | 280.00 |
| CMUcam03 | 253.34 | 1 | 253.34 |
| Encoders | 60.00 | 4 | 240.00 |
| Drive Motors | 339.00 | 2 | 678.00 |
| **Total Cost of Materials** | | | **1776.34** |

### Labor

### Table 6: The hourly description is based on time spent working on project while enrolled in a two-quarter design capstone class.

| Team Member | Labor Description | hours |
|---|---|---|
| Satbir Dhillon | team lead in charge of reliable wiring and GPS implementation | 300 |
| Navjot Brar | reliable wiring and robust power buss development | 200 |
| Randy Depoy | laser control and data filtering, and reliable wiring | 300 |
| Robert Nicolato | force-bumper calibration and microcontroller fusion | 200 |
| Joseph Esparanza | microcontroller fusion and sensor wiring | 100 |
| Rick Fredley | path-planning algorithm development and testing | 250 |
| Terry Kipling | fusing camera and laser data | 75 |
| Jennafer Sparks | GUI development | 50 |
| Kristin Street | GUI development | 50 |
| Kyle Todd | laser gimbal design | 200 |
| Carl Kocon | station design and obstacle construction | 125 |
| Justin Ferrell | robust force-sensing bumper design | 125 |