

# Yardbot: Design and Implementation of a Robotic Lawnmower

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## ABSTRACT

This paper presents the design and implementation of a robotic lawnmower, Yardbot. The objective is to build a lawnmower with the ability to mow grass in a specified area autonomously in less than twenty minutes, while avoiding collisions with obstacles located within that area. The obstacles to be taken into consideration are: a flower bed, fenced area, and a moving obstacle that will engage the lawnmower for thirty seconds and then move off of the field. The main tasks to be achieved are to create a frame, select the proper wheel motors and powering system, integrate off the shelf sensors, implement control algorithms for the motors, and design a functional and efficient navigational algorithm, which is able to process data from a differential GPS, a digital IMU, ultrasonic sensors, a touch sensor, and a laser range finder. The output of the algorithm controls the speed and direction of the mower through the use of encoders.

## INTRODUCTION

The objective of this paper is to describe the design of the Wright State University Autonomous Lawnmower, built by undergraduate students. The team is comprised of members from the Mechanical and Materials Engineering Department, the Computer Science and Engineering Department, and the Electrical Engineering Department. Each department has their own individual team and tasks. The mechanical engineers focused on the frame and material to mount the electronics, the batteries, the electric motors, the touch sensor and the fiberglass shell. The computer engineers focused on the computer programming and worked with the electrical engineers to integrate all of the electronics into the computer. The electrical engineers focused on providing power for all of the electrical systems and helped the computer engineers to integrate the hardware with the software. When these tasks were combined together the team was able to accomplish the overall objective, which was to build an autonomous lawnmower.

Mowing a field of grass is considered to be tedious chore by many, so there is a demand for methods to eliminate this task. The customary method of dealing with unpleasant tasks is to pay someone else to perform them. There is another option, however, for those who can afford it at this stage in its development, and that option is robotics. Robots are currently being used in industry to perform manual labor tasks but only a few applications are available for use by a home owner [1, 2]. At this point, robots are being introduced for many simple tasks such as vacuuming, which is a task similar to lawn mowing [3]. Like vacuuming, mowing is a simple

and time-consuming task that the average person generally prefers to avoid. The robotics industry has responded to this anticipated demand by creating a simple robotic lawnmower capable of autonomously cutting grass and navigating around obstacles. The mower available is relatively simple. It does not mow with any particular pattern; instead, it uses a copper wire laid around the perimeter of the area where it is allowed to operate. It runs in a straight line until it senses a copper wire or it runs into an obstacle. When either of these events occurs, the robotic mower changes its direction and continues its operation. Obstacle avoidance is done with only a bumper. The mower simply discovers obstacles by bumping into them. The mower has no onboard navigation other than its ability to react to collisions and identify a line it is not allowed to cross. This may work relatively well for small lawns and lawns of simple shape, but it has its shortcomings when the area to be mowed is of complex shape or substantial in size. A more sophisticated design for a robotic lawnmower involves navigation through the use of GPS (Global Positioning System) and an IMU (Inertial Measurement Unit). The IMU and GPS enable the robot to mow in specified patterns. Three sensors, a laser range finder, ultrasonic sensors and a touch sensor, are used to avoid collisions with obstacles. The laser range finder sensor (LRFS) is the main sensor to detect and avoid moving and static obstacles. However, if the obstacle is below the height where the LRFS cannot see the obstacle, the ultrasonic sensors are used to detect this obstacle. Since the ultrasonic sensors are not able to give an accurate distance of the static obstacles such as flower beds and fences, a touch sensor is used to accurately detect these obstacles. The touch sensor is also used to go around a curved path using force control. All sensors send information to a laptop computer that carries out a navigation algorithm allowing it to make decisions and direct the motors accordingly.

## **LAWNMOWER DESIGN**

The lawnmower frame is composed of 80/20 T-slotted aluminum framing [4], which was chosen for ease of fabrication. The outside of the frame is covered with 1/32 inch aluminum plating and a custom fiberglass shield to protect internal components from the weather. Outside the robot, a custom electric mower deck made from 1/4 inch MIC6 aluminum is suspended from the main body. The mower deck is comprised of a three blade system, that has a cutting width of 22.5 inches, and a weed eater for trimming. The mower deck is completely enclosed, with the exception of the weed eater area, to prevent grass clippings from blowing into the electronic compartment of the robot. The mower deck was designed with four motors. Three of the motors operate the mower blades that are encased within the mower deck for safety. The fourth motor controls the weed eater that is mounted on the right side of the mower deck for trimming purposes. There are two separate 24V/8A drive motors to provide mobility to the robot. Two 12V batteries, connected in series, supply 24V electrical power the mower deck and the motor controller, which controls both drive motors. The power supplied to the mower deck and the drive motors can be terminated instantaneously by the use of safety kill switches. The robot has two safety switches: One is a large red circular switch that is located on the top of the robot near the rear, as shown in Figure 1; the other is a remote keychain transmitter similar to those used on remote keyless entry systems for automobiles. The kill switches are integrated into the system in such a way that, if a wire came loose or the switch broke, the system would break in the off position. To prevent the electronic noise produced by the motors from interfering with the operation of electronic devices, three separate 12V batteries are used to power the onboard electronics. Two of the 12V batteries are placed in series to power the laser range finder and the

other 12V battery is used for the remaining electronics. Since the laptop has a strong current pull, the power for the laptop is drawn from one of the 12V batteries that operates the drive motors.

## Frame

In order to minimize cost and weight of the frame, the decision was made to design the frame using T-slotted extruded aluminum purchased from 80-20. While a steel frame may have been stronger, the extruded aluminum is strong enough to handle the needs of the lawnmower. The extruded aluminum also does not require any welding, the pieces are held together with connectors that are designed for the 80-20 material. The goal of the frame is to improve the speed of the mower and the amount of torque required by the drive motors. The resulting design of the frame was geared toward being compact. One way to optimize the frame design was to reduce as much empty space as possible. In order to accomplish this, the battery and electronics compartments were separated, so that each could be sized according to their respective components. In order to increase the amount of usable mounting surface area, a mounting plate made of 1/32" aluminum sheeting was added to the back of the battery compartment. A few of the electrical components need to have some amount of thermal regulation and minimal exposure to dust and dirt. In order to accomplish this, four sides of the electronics compartment are enclosed with 1/32" aluminum sheets. These sheets also provide a mounting surface for the electronic components. One side of the compartment has a 3/8" thick Plexiglas door to allow for quick and easy access to the electrical components. This door has a fan with a filter to push air through the compartment for thermal regulation and limit the amount of dust and dirt entering the compartment. The other side of the compartment is covered with an expanded metal mesh to allow the air pushed by the fan to escape.

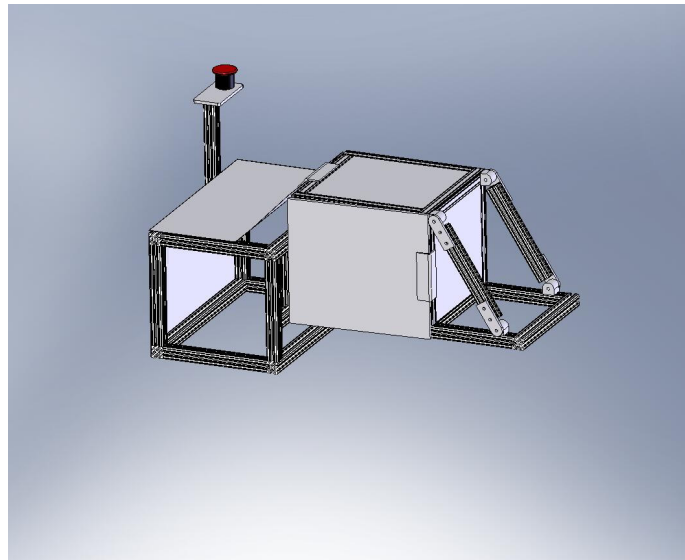


Figure 1. Solid Works Drawing of Lawnmower Frame.

Figure 1 shows a SolidWorks representation of the lawnmower frame with the shelves and doors. The rear section is the battery compartment, the middle section is the electronics compartment, and the laser and GPS receiver are mounted in the front section.

## Mower Deck

After considerable research concerning the possibility of purchasing a pre-manufactured deck and blade system, it was determined that the best choice would be to purchase just the blades and motors from the Robomower distributor and fabricate a custom deck so that a string trimmer could be added to one side [5]. A custom deck was designed in SolidWorks with a 1/4" overlap between the blades. A string trimmer was added to the end of the deck so that the mower can get close to the obstacles without damaging them.

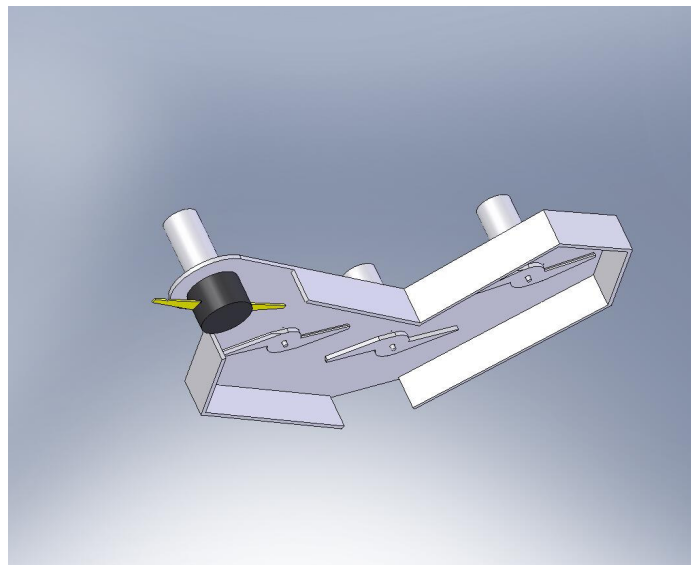


Figure 2. Solidworks Drawing of the Lawnmower Deck.

Figure 2 shows a SolidWorks representation of the deck. In order to reduce the weight of the deck, research was carried out into the possibility of fabricating the deck out of fiberglass. However, due to the complexity of the shape, fiberglass was not an option. It was determined that the next best choice would be 1/4" aluminum. The aluminum is a very durable product that can take a hit from objects protruding from the ground, such as rocks or debris, and not be damaged while also providing a structure that protects users from the blades. The overall cutting width of the mower deck is 22.25 inches through the use of the three blade system shown in Figure 2. Using three blades allows the model to have a large cutting path while still maintaining a torque that the electric motors are capable of outputting.

## Motors and Rear Wheels

The drive motors are an integral part of the lawnmower. Along with pushing the lawnmower, they are also responsible for turning. A motor with a 90-degree gearbox was desired to save space and to allow for mounting the motors external to the main frame. This was done to reduce heat within the frame. As a result, the motors chosen were taken from a wheelchair, which uses

motors with 90-degree gearboxes to allow the operator to control where they are going. The rear wheels that are on the mower are the same wheels that were used on the wheelchair.

### **Caster Wheel**



Figure 3. Front Caster Wheel.

The front wheel on the lawnmower is a caster wheel, shown in Figure 3. A caster wheel is used in the front because casters are designed to swivel and move in the direction the back wheels are driving. The pneumatic swivel wheel has a 6 inch diameter and has a 1 1/2 inch width. The pneumatic wheel helps soften the impact of the lawnmower on the ground. This helps decrease vibrations and movements that could be harmful to the functioning of some of the electrical components.

## **CONTROL SYSTEMS AND SENSORS**

The control system obtains input from the GPS, IMU, ultrasonic sensors, touch sensor, and laser range finder. This input is processed by the navigation algorithm on the laptop computer. The computer then sends commands to the controller to change the individual wheel speeds.

### **Motor Controller**

The motor controller chosen for this design is a RoboteQ AX2550 [6]. This controller was chosen because it has the two independent power stages required to control the independent drive motors, and these power stages can handle the delivery of 80A each for an extended period of time. The motors consume a maximum of 8A each, providing a safety margin of 5 for the motor controller. Requiring the motor controller to run no higher than 20% of its capacity makes the heat sink temperatures easy to manage. The controller also has a built in PID (Proportional-Integral-Derivative) controller and works off the input from the encoders on both motors. This feedback control can be programmed and set up using the Ziegler-Nichols rules for tuning [7]. This makes programming the controller possible without having to model the response of the mower as a system and develop its transfer function. The controller also has two modes of operation built into it: R/C (radio controlled) and RS-232 (PC serial communications). The R/C mode is used in conjunction with a receiver and a controller to allow for a human interface. This interface can be used during testing to move the mower from location to location. RS-232 mode

is used when mowing autonomously, giving control of the motors to the computer. The computer then determines the speed required for each of the motors and sends commands via RS-232 to the motor controller. In addition, the computer has the ability to request information from the controller. This data includes encoder counts (to detect wheel slippage), heat sink temperatures, and analog input state (to monitor the touch sensor). The computer also has the ability to control the state of a digital output on the controller, which is used to turn the mower blades on and off. To switch between the two control modes, an interlocked double pole R/C relay switch has been utilized. When a switch on the R/C transmitter is turned on, it sends out a signal that activates the relay, resetting the controller. The controller reboots into R/C mode by default. This same relay also controls the switch-over of the data input from the R/C module to the RS-232 port. To switch to computer mode, the line is switched to RS-232 and any ten ASCII characters are sent to the controller via the computer.

### **Computer**

The computer that interfaces with the RoboteQ controller is a Dell laptop. It contains one RS-232 port and one parallel port. One RS-232 port is insufficient for the communication needs of the robot, so a USB to RS-232 converter is used to increase the number of ports available from one to eight. The computer runs software written in C++ that sends commands to the RoboteQ controller based on information gathered from several sensors via RS-232 connections. These sensors include a differential GPS, an IMU, a laser range finder, ultrasonic sensors, and a touch sensor. The differential GPS and IMU sensors are used to navigate the field. The laser range finder, ultrasonic sensors, and touch sensor are used for collision avoidance. The laptop can be remotely controlled through remote desktop software. This is accomplished through the use of a Linksys router (Model WRT54GL) that gives control of the laptop to a remote user. With a remote desktop, the user no longer has to stand beside the lawnmower which increases the safety of its operation.

### **Global Positioning System**

GPS is the main instrument of navigation used by the robot. To mow grass in an efficient manner and stay within a set of boundaries, the position of the robot needs to be precise. The average GPS device is accurate to approximately ten meters [8]. This error is unacceptable for use in a robotic mower.

GPS works by using a receiver to listen to satellites, using the time of flight of the signal in calculating the distance between the position of the antenna and the satellites. Given the distance to several satellites, a position is calculated by triangulation. Several non-ideal conditions make the determination of an accurate position a complicated process. The first error is in the timing. The timing between the satellites has to be extremely accurate. Satellites have highly accurate atomic clocks onboard, but the receiver does not have anything approaching that level of sophistication. The error in the receiver clock is minimized by a least squares algorithm that determines the best time fit given the time of flight information of more than three satellites (the minimum number required to triangulate a location). Other errors are due to the atmosphere, satellite position errors, and multipath signal reception. To minimize atmospheric and satellite position errors, there is a satellite-based augmentation system available in the U.S. called WAAS (Wide-Area Augmentation System). It transmits updates and corrections for ionospheric errors

and satellite orbit errors. This improves the known position to around two meters, but that is still not acceptable for the current application.

Another method of improving the accuracy of the measurement is through the use of differential GPS, which works through the interaction between the satellites, a base station and a rover unit, located on the robotic lawnmower. The base station, located at a known position, calculates necessary corrections to be made to the signals received from the satellites and sends these corrections to the rover unit by radio. The rover unit uses the corrections and the signals received to calculate a position that is accurate to within two centimeters, which is accurate enough for this application. However, a latency error is created by the calculation time required to produce the error corrections. The magnitude of the latency error is proportional to the velocity of the rover unit. Since the top speed of the robot is less than ten kilometers per hour, the latency error produced is not significant. The differential GPS used is a Trimble GPS system (Model MS750) designed for heavy construction equipment. The GPS unit sends coordinates in terms of latitude, longitude, and altitude. The default spherical coordinate system used by the GPS receivers is the WGS-84 ellipsoid. The latitude and longitude values in degrees, minutes, and seconds are converted into usable Cartesian plane values, i.e., the UTM (Universal Transverse Mercator) coordinate system. The computer is given the converted values by the GPS receiver in convenient Northing and Easting values which can be used as x and y values of a Cartesian plane. Due to the robustness of the navigation algorithm and the heading calculations, no conversion to a local coordinate system is necessary. All navigation will be performed using only global UTM Northing and Easting values. Using these global coordinates, the robot is able to successfully navigate by turning in the direction of a determined next point in the field and following a line to that point. This process is repeated in order to cover the entire field.

### **Inertial Measurement Unit**

The inertial measurement unit, by Spark Fun Electronics (Model ADXRS150), is used to control turns and determine the heading of the lawnmower [9]. The IMU, as shown in Figure 4, can determine if the lawnmower is changing direction through the use of gyros that give roll, pitch, and yaw rates.



Figure 4. Inertial Measurement Unit (IMU).

The result of integrating the rate of change over a period of time is the change of heading in degrees. When a turn is desired, the computer can decide how much to turn, in degrees, and then monitor the IMU during the turn until that number, in degrees, is met.

### **Navigation Algorithm**

The navigation algorithm can be broken down into two fundamental tasks. “Go straight,” which guides the robot from the start point of a line to the end point while following the resulting line as close as possible. The other task is called “Turn toward point,” where the robot is given another point in the global coordinate system that is desirable to turn toward. “Follow a straight line” is carried out using a proportional control algorithm where the wheel speed of the wheel that is closest to the line is varied, depending on which side of the line it is on. This is determined by taking the angle (alpha) relative to the global x-axis of the line formed between the current position and the starting point of the line. A second angle (beta) is determined relative to the global x-axis using the line formed by the end point of the desired line and the current position of the robot. A difference angle is calculated which is the absolute value of alpha minus beta. The further away from the desired line the robot’s position is, the more the speed of the inside wheel is decreased which will ensure that the robot is continually moving toward the line. As the robot approaches the line, this speed is again increased. In order to control the actual orientation of the robot relative to the desired line, the outside wheel’s speed is determined by using the current robot heading relative to the global x-axis minus the angle formed by the desired line relative to the x-axis. As the robot is heading away from the desired path, this algorithm will reorient the robot towards the line by increasing the outside wheel’s speed. As the robot again approaches the line, the algorithm orients the robot back along the desired path in order to minimize overshooting the line as it attempts to correct itself. Turning toward a point in the global coordinate system is done using the robot’s current heading relative to the global x-axis and an angle relative to the global y-axis formed by the current point and the point that it is desirable to turn towards. The robot then spins in place by equally spinning its two wheels in opposite directions until the robot heading corresponds to the desired heading within a tolerance. The direction of rotation is chosen based on the shortest rotation needed to achieve the new robot heading. This navigation algorithm works very well when applied in an empty field, however, it is necessary to allow for collision detection if an obstacle is present in front of the lawnmower.

### **Collision Avoidance**

To accomplish the identification of obstacles, a series of sensors are used. The robot is equipped with a laser range finder (Sick LMS200), which performs a 180° sweep with laser pulses at every degree, as shown in Figure 5 [10].

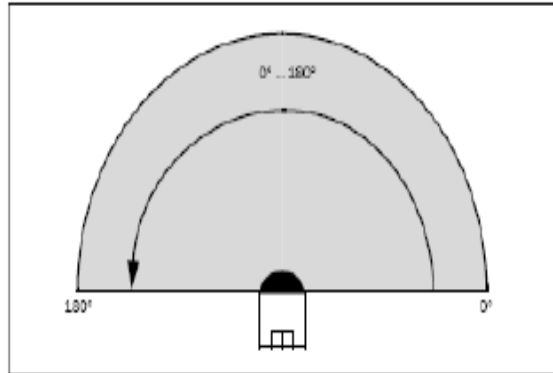


Figure 5. The Scanning Radius of the Sick LMS200 Laser Range Finder.

Through hardware calculation of time of flight of the laser pulse, the range finder returns an array of values to the laptop. This array represents distances to obstructions in polar coordinates. The data is then converted into Cartesian coordinates and used to determine the location of obstacles relative to the field. If an obstacle remains in the way of the robot or appears to be on a collision course as determined using data from multiple scans, the robot slows down as it approaches the obstacle. This is done by reducing the speed once the obstacle enters different thresholds, to an eventual stop prior to reaching the obstacle and waits for the obstacle to move out of the way. In order to detect obstacles that are lower than the laser range finder can see, ultrasonic sensors are mounted on the lawnmower's frame. Ultrasonic sensors operate on the principle of time of flight of a pulse. The transmitter sends out a pulse and the receiver takes in the pulse. The ultrasonic sensors are controlled by a microcontroller that can process the data and track the time between the transmitted and received signals to get the distance to the object. This information is then transmitted to the laptop through RS232. In order to avoid collision with obstacles that are permanent to the area, such as flowerbeds or fences, a touch sensor allows the lawnmower to mow right along side of the obstacle without damaging it. The touch sensor is comprised of a 6-inch-diameter pneumatic wheel that is held horizontally by a bracket which is attached to a linear slide. A linear potentiometer is also attached to the bracket. Springs maintain the wheel in the extended position. When something solid is touched, the wheel is deflected, the springs are compressed, and the resistance of the linear potentiometer is changed. The touch sensor sends an analog dc voltage to the same microcontroller used by the ultrasonic sensors. The microcontroller can then convert the analog signal to a digital value via an A/D converter. The digital signal is then processed and sent to the computer so that the computer can then determine whether the lawnmower needs to move closer or farther away from the obstacle.

## THERMAL MANAGEMENT

As always, thermal management issues may arise when dealing with electronic devices in an enclosed space. The robot has an aluminum box with several heat-producing electronic devices inside, and the robot will be operating outside in a warm environment. To prevent overheating, an on-board fan pulls in cool outside air and exhausts the hot air through the metal mesh wall on the backside of the electronics compartment. The temperature of the heat sinks on the controller and the ambient temperature in the front of the robot are monitored. In the event that the controller is overheating, the computer reduces the speed of the robot by 50%, and, if the temperature continues to rise, the robot stops.

## **SOFTWARE**

Using Ubuntu, a Linux operating system, a C++ program was written that contains multiple threads in order to control the lawnmower. This was accomplished first by initiating a connection to each device through serial communication. The devices interfaced include: a Laser Measurement System (Sick Model LMS 200), a differential GPS (Trimble Model MS750), a motor controller (RoboteQ Model AX2550), ultrasonic sensors (Devantech Model SRF04 by Acroname), a touch sensor and an IMU (Spark Fun Electronics Model ADXRS150). After setting up serial connections with each device separately, they are integrated together, each in its own thread, with a main thread to control the functioning of the lawnmower. Threading was chosen so that the program uses timesharing to manage each thread or lightweight process. This allows the program to operate as though each thread is running simultaneously, although in reality each threads takes turns sharing CPU time. In order for the threads to work properly, it is important that two or more threads are not accessing a shared resource at the same time. A synchronization mechanism is needed to ensure that only one thread uses a resource at one time. Mutex is a synchronization primitive that grants exclusive access to the shared resource to only one thread. If a thread acquires a mutex, the second thread that wants to acquire that mutex is suspended until the first thread releases the mutex. Data can be sent and received over multiple serial ports simultaneously. When data is received, it is stored in a temporary buffer, parsed, and then stored in a global variable. These variables are then accessed by other threads and used to control the lawnmower. There are seven threads used in this program: a laser thread, a GPS thread, an IMU thread, an ultrasonic thread, a touch sensor thread, a controller thread and a main thread. For the laser thread, if an object is in range, the thread analyzes the data and determines if a collision is possible and sends that information on to the main thread. For the GPS thread, the longitude and latitude are received, transformed into local coordinates, and placed in a global variable. The IMU thread is similar to the GPS thread in that the IMU heading is retrieved and stored in a global variable. The ultrasonic thread determines whether or not an obstacle has been detected by the ultrasonic sensors and if so at what distance. For the main thread, there is an algorithm that calculates all the waypoints needed to mow the field and then sets them in an array. Next the mower is instructed to travel to the first point. Based on our current location, as indicated by GPS, the thread adjusts motor speeds based on how far the mower is off course. Once the mower arrives at the next point a turn is executed toward an area of grass that has not been mowed, and then the mower proceeds to the next point, staying on a straight line. This is continued until all the grass has been mowed.

## **COST**

The cost of all the equipment that makes up the lawnmower places the price tag at over \$10,000. The LMS 200 retails for close to \$3,000.00. The GPS system that was donated by Trimble retails for around \$50,000.00. The IMU was purchased for \$400.00. The RoboteQ motor controller costs \$495.00. The material that was required to construct the frame including the wheels and mower deck cost \$2,434.00. The laser range finder, the GPS receivers, the motor controller, and the computer could all be replaced with less expensive equipment in the future. The cost of the laptop could be reduced by replacing it with a field-programmable gate array (FPGA). The laser range finder sends data at higher resolution and at higher speeds than are

necessary for this application and could be scaled down to a more affordable model. The GPS system is one of the best on the market and is one of the largest costs for the production of this prototype lawnmower, especially since two receivers are needed for differential mode. Different systems have been proposed to replace the GPS in the design. One proposed system uses radio navigation with low cost transmitters, which are located around the perimeter of the field to be cut at known locations. However, the GPS system was gratuitously donated to the team and is a very good system to use due to its accuracy. The last of the expensive components is the motor controller. It is capable of delivering five times the current the motors can handle. It could be replaced with a lower cost motor controller that is designed to fit our needs, and the feedback can be controlled with a programmed microcontroller rather than having it built into the motor controller.

## CONCLUSION

Mowing a field of grass is a tedious task that the average person prefers to avoid. There are two options to eliminate this task from a person's schedule. One is to pay someone else to perform it; the other is robotics. There is a simple robotic lawnmower on the market, but it is unable to perform well in fields that are of complex shape or substantial size. The robotic mower proposed in this paper is a more sophisticated approach using GPS navigation and is capable of mowing fields of large size and complexity. It is equipped with a motor controller that drives two motors based on commands sent by the computer. The computer sends the commands to the motor controller based on data received from an array of sensors, including a differential GPS, ultrasonic sensors, an IMU, a touch sensor, and a laser range finder. With all these systems, the robot is an autonomous lawnmower capable of navigating a field, avoiding obstacles, and cutting the grass.

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