

Autonomous Wright State Mower Mows Outstandingly and Wonderfully

(A.W.S.U.M.M.O.W.)

Project Report

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1. Abstract:

The objective of this project is the successful implementation of an autonomous lawnmower which is capable of cutting a specified area while avoiding obstacles. The system implements a force-sensing bumper, a laser-range finder, and a differential GPS. Furthermore, it employs robust mapping and navigation algorithms along with a stable and well-tested mechanical system to produce an adaptable and reliable mower. This project builds upon the experience of previous years and implements several crucial innovations in the control and bumper system. This implementation will allow the autonomous lawn mower to succeed in this year's ION Robotic Lawn Mower Competition.

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2 Introduction

Wright State University has participated in the ION Robotic Lawnmower Competition for several years. This project provides an excellent chance to exercise student's current knowledge base, interact with other teams in an interdisciplinary manner, and develop a practical extension of the team's engineering skills. Moreover, as a multi-year project, the venture gives the team experience with the advantages and disadvantages of such a design and development process which is common in industry.

2.1 Team Overview

The ION Robotic Lawnmower Competition provides an opportunity for interdisciplinary teams to come together and design a functional autonomous lawnmower system. This year's design for Wright State's dynamic competition entry, although building on the development of previous years, required the utilization of a broad range of skills and knowledge bases; the team included members with signal processing, control systems, computer engineering, and mechanical engineering experience.

2.2 Inherited Design Overview

The previous lawnmower design utilized a chassis and frame constructed from 1"x1" aluminum extrusions and ¼" aluminum plating. The mower utilized a three wheeled design, with two wheels under the control of independent motors while the third wheel was a caster wheel that provided support for the mower. The chassis was designed for three containers to hold computing systems, battery systems, and the SICK LMS-200 Laser-range-Finder. Two Trimble OEM4 family GPS receivers were placed on top of these containers, as were additional battery systems. A deck containing five motors and a string trimmer were placed on the deck to provide a sufficient cutting pattern, both on the field and near static objects. A linear actuator allowed the laser-range-finder to sweep through a number of angles for object detection [1].

A force sensing bumper, consisting of three strips of neoprene rubber, on a sheet of 1/8" sheet

metal, and four Selesco SP1-4 string potentiometers provided object detection when close to static objects. An AX2550 RoboteQ motor controller conferred accurate motor control for the two NPC-B82 motors which controlled the orientation and speed of the mower via its rear wheels. The power system consisted of “clean” power, for powering and controlling the electrical components, and “dirty” power, for powering the motors. This separation of power systems helped ensure that the noise from the motors did not negatively impact the performance of the electrical equipment [1].

The mower was controlled by an ADL945PC board which provided processing and memory sufficient for this project. The board communicated to the peripherals via an RS-232 serial cable, which was connected to the board by a USB to Serial hub, allowing for multiple peripheral cables to communicate with the board. The code used in the mower used a simple path planning algorithm: a set of points were stored in memory representing the boundary points of the course, then a set of waypoints were generated that allowed the mower to follow a specific path with a high degree of accuracy. If a dynamic obstacle came in front of the mower, then the mower would stay stationary until the obstacle left the field [1].

2.3 Design Revisions

Based on Wright State’s performance at last year’s competition, this year’s team selected several items to change.

- The previous bumper system was replaced in favor of a more robust design that would avoid the cases of false detection that occurred during last year’s competition. The new design utilizes more string potentiometers, each located at the center of a single lobe of 3/16” neoprene rubber to provide more accurate data on the static obstacles while an outer layer of 1/4” neoprene rubber reduces the effect of dead spots between individual string potentiometer lobes.

- The laser range-finder is implemented to map the field during the competition to acquire accurate data on the location of static obstacles. With the development of a stable mapping algorithm, the path-planning algorithm has additional means to avoid static obstacles while simultaneously mowing close to them.
- The underlying code suffered from several years of uneven development. Thus, much of the source code for the mower was rewritten in a consistent format. Furthermore, errors caused by improperly maintained code were also fixed.

Other aspects of the previous project, like the chassis, GPS receivers, computer hardware, and deck were retained. Based on the performance of the mower during the previous competition, these features performed within expected parameters and could be kept without much concern. By improving on the previous design and utilizing previously successful components, the team hoped to overcome the problems of previous years while also taking advantage of the well-tested and developed aspects of other years' efforts.

3 Mechanical Implementation

3.1 Overall Design

The Wright State University autonomous lawnmower requires basic mechanical components to operate as a functional lawnmower. Every mower needs to start with the frame, on which everything is built. Careful consideration had to be taken to select the materials for construction based primarily on standing up to the conditions of mowing a field and being robust, and secondly efficiency. Once the frame is in place, a mower needs a deck. The layout of the mower deck maximizes the time and efficiency when cutting a field of grass. To autonomously move the mower, a drive system was placed to accurately maneuver and navigate the field. With no human interaction, a system of sensors is needed to guide the lawnmower in a field.

Obstacle detection is the most important feature of the Wright State University autonomous lawnmower. A laser-range-finder from the SICK Company is utilized to detect obstacles in the path of the mower. When stationary, the laser range-finder returns information in a two-dimensional field. An actuator system was added to the laser to vary the pitch of the viewing field. This ability now gives the robot a three-dimensional view, being able to detect short obstacles as it approaches them. The robot then uses a force sensing bumper system to come into close contact with obstacles. This permits a close trim of the grass as the robot is able to maintain a calculated distance as it “hugs” (i.e., maintains close constant contact) the obstacle. Together, these components permit the Wright State University’s autonomous lawnmower to be a functional mower adapted for autonomous use. An overview of the physical specifications of the mower is provided in Appendix II.

3.2 Chassis

The frame of the chassis is constructed of 1”x 1” extruded aluminum. The material was chosen because of its light weight, durability, and the ease of construction. The chassis consists of two main

compartments to provide separation of the batteries from the electronics. The forward compartment houses the computer and wireless router. Both sides of the compartment have a 3/8" thick Plexiglass doors to provide quick and easy access. The rear compartment contains the batteries for the motors, where all sides are enclosed in 3/16" aluminum. Optimizing the available space, the aluminum sides of the rear compartment are used to mount the RoboteQ controller, the micro controller, and parts of the power distribution system. The separate compartments also isolate the electronics and batteries from the outside environment keeping grass and dust out.

The frame rests upon a tricycle wheel configuration, as shown in Figure 1. This permits accurate, sharp turns that are necessary to navigate and mow a field. The two rear drive motors are independently controlled by the RoboteQ controller. This allows the motors to drive and steer the mower, also providing the ability of have a zero degree turn radius. The front wheel is mounted on a caster, allowing 360 degrees of rotation as the rear motors steer the mower. The caster is designed to swivel and move in the direction the back wheels are moving.

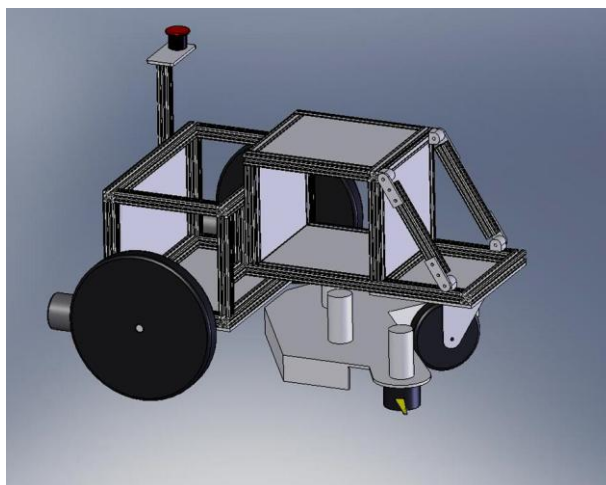


Figure 1: Mower Chassis and Frame Model [1]

3.3 Deck

As compared to the typical household push mower, the Wright State autonomous lawnmower employs a multiple blade design, as shown in Figure 2. The deck has a width of 0.838 meters matching

the width of the wheel base and maximizing the cutting area of the mower [2]. It is constructed out of $\frac{1}{4}$ " aluminum plate and mounted to the underside of the chassis. Six motors are used, five for mowing and one for weed trimming. Each cutting motor is equipped with a single blade. The weed trimming motor uses a conventional string trimmer, like that of the typical weed-eater, providing a clean trim around static objects. The motors are mounted in a staggered pattern on the deck so the blades have a minimum overlap of $\frac{1}{4}$ ", ensuring the cutting efficiency of the mower. The configuration and wiring of the mower deck allows for quick and easy access of the motors for maintenance purposes.



Figure 2: Deck Configuration

3.4 Force-Sensing Bumper

The bumper system of the mower has been designed to eliminate error and to provide a reliable response for static obstacle approach. The goal in mind was to ensure robustness, and allow ease of maintenance by making the bumper modular. The bumper is mounted on the front and wraps around the right side of the mower as demonstrated in Figure 3. The frame is constructed of two parallel $\frac{1}{2}$ " conduit rails curved to fit the shape of the mower. To strengthen the frame, 1-1/2" angle aluminum is attached to the conduit rails using conventional u-bolts made for use with $\frac{1}{2}$ " pipe. The bumper system also consists of seven convex shaped lobes constructed of $\frac{3}{16}$ " neoprene rubber. Within each lobe is a Celesco SP-1 string potentiometer. The string potentiometers are the sensors that will detect the

inward deflection of the rubber as the mower touches static objects. Along the outside of the rubber lobes is a band made of $\frac{1}{4}$ " neoprene rubber and is connected to each individual lobe. This allows for interpolation at points between the lobes and to eliminate the possibility of the bumper not detecting deflection, or encountering dead spots.

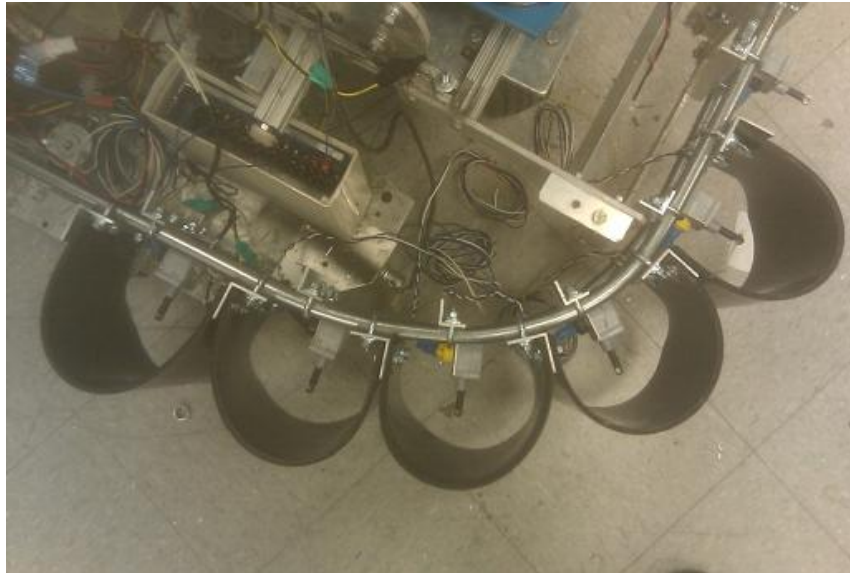


Figure 3: Force Sensing Bumper Frame

3.5 Linear Actuator

The laser-range-finder needs the ability to pivot up and down to detect obstacles of varying heights and distances on the field. To accomplish this there are two double sealed ball bearings, brackets with $\frac{1}{2}$ " steel shafts, a steel lever arm welded to a steel shaft collar, and a 25 pound linear actuator [1]. This configuration easily allows the change in pitch of the laser range-finder to a desired angle. The linear actuator has a 10 k Ω linear potentiometer within the device to provide feedback information for its position giving accurate control of the laser range-finder. A diagram of the linear actuator and its set up is in Figure 4.



Figure 4: Linear Actuator and Laser Range-Finder [1]

4 Electrical Implementation

4.1 Overview

An autonomous lawnmower requires the basic electromechanical components of an ordinary, manually-operated lawnmower, such as a drive system and a mower deck. For a manually-operated system, these components are controlled by a human interface; for an autonomous system, however, these components must be controlled by a computer. It is important that an accurate control system be implemented so that the computer has precise control of the system's actuators.

Sensors are the key components of autonomous systems; they replace the eyes and ears of human operators. The following sensory information has been identified as important for this autonomous system: location, obstacle detection, and force-detection. A differential GPS has been included in the design to provide location information. A laser-range-finder is used to acquire range data for obstacle detection. Force-detection is implemented with a neoprene bumper and a series of string potentiometers. A micro-controller and power system provide necessary support for the components. The block diagram in Figure 5 gives an overview of the sensing system.

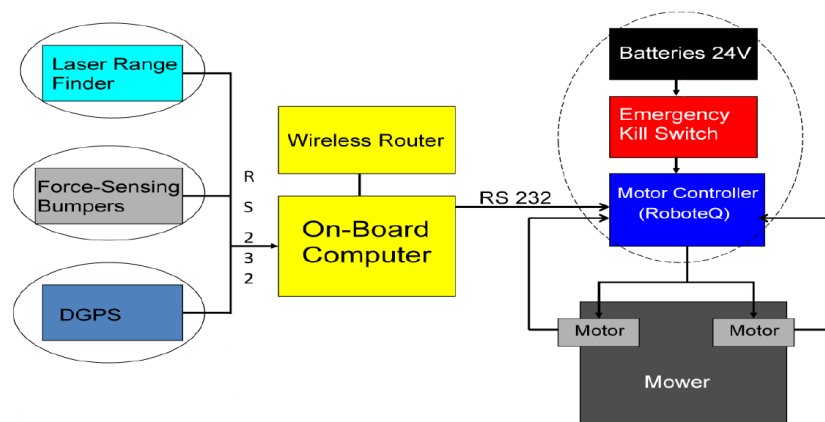


Figure 5: Block Diagram of the Electrical System [1]

4.2 Drive System

An autonomous lawnmower must be mobile and implement a control system for accurate maneuverability. The drive system of this robot consists of two NPC-B82 motors attached to each of the rear wheels. The drive motors are built for continuous 24V, 30A operation [3]. The motor controller chosen for this system is a RoboteQ AX2550. This controller is capable of independently controlling the two drive motors and the on/off state of the blade motors. The RoboteQ achieves accurate control of the drive motors with a built-in PID (Proportional-Integral-Derivative) controller. Encoders are built into each of the drive wheels and provide position and velocity feedback to the controller. Built-in compatibility with both RS-232 serial input and R/C radio input makes the RoboteQ a convenient controller choice. The RS-232 interface allows the controller to be connected to the computer for autonomous control. The R/C radio allows human-control of the robot for transportation and testing. An interlocked double-pole R/C relay switch has been implemented to toggle between the two control modes [4].

4.3 Differential GPS

The ability to determine relative position is a necessary feature of an autonomous lawnmower because the system must be capable of staying within the bounds of a specified area and must also be able to differentiate between areas where it has and has not been. The location technology that has been selected for this system is GPS. The principle behind GPS is trilateration based upon timing of satellite signals. Because of signal distortion and inaccuracies in receiver clocks, the accuracy of a single GPS unit is approximately 10 meters [4]. Due to the relative dimensions of the lawnmower to the positioning accuracy, a single GPS unit is insufficient. The system implements a differential GPS (DGPS) to attain greater accuracy. A DGPS system consists of two GPS units; one stationary unit and one unit attached to the mobile system. The position of the stationary unit is averaged over a period of several

minutes to achieve a very accurate position. At any time, the difference between the immediate GPS position of the stationary unit and the averaged position of the stationary unit is used to correct the immediate GPS position of the mobile unit. With DGPS, the position of the autonomous lawnmower can be determined with an accuracy of 2 cm [4]. A third GPS receiver is attached to the lawnmower to provide heading information. One receiver is attached to the center of the robot and the other is attached to the front; the heading is calculated by comparing the immediate positions of the two mobile units. The particular DGPS that has been implemented on the lawnmower is a Trimble MS980. The DGPS relays positioning information to the computer over an RS-232 serial connection.

4.4 SICK LMS-200 Laser range-finder

To be completely autonomous, a lawnmower must be able to detect obstacles in its path and effectively navigate around them. The SICK LMS-200 laser-range-finder is mounted to the front of the lawnmower and is attached to an actuator. The LMS-200, as configured for this implementation, generates a continuously updated planar depth-field over a 180 degree arc and with a resolution of 0.5 degrees. The maximum range of the laser is approximately 8 meters when used outdoors. The laser communicates with the computer over an RS-232 serial connection and updates depth-field data at approximately 2.5 Hz. The actuator allows the laser to be rotated up to 20 degrees below horizontal. By rotating the laser and coordinating the depth-data with the immediate angle, a three-dimensional depth-field is created. Because the laser updates depth-field data at a relatively low frequency, the robot must be stationary to create an accurate three-dimensional depth-field. The capability of detecting dynamic obstacles and accurately characterizing static obstacles has been successfully demonstrated with the LMS-200.

4.5 Force-Sensing Bumper

An autonomous lawnmower needs to be capable of accurately trimming around low-lying

obstacles. The laser-range-finder is not practical for this purpose because it takes a significant amount of processing time to differentiate between the ground and an obstacle. The solution for this design is a force-sensing bumper. The mechanical aspects of the bumper have already been described. To detect forces, 7 Celesco SP1-4 string potentiometers are mounted such that a displacement of the rubber lobes causes a corresponding displacement of the potentiometer strings. The outputs of the string potentiometers are read by the ADC converter of the micro-controller. A secondary function of the force-sensing bumper is to detect obstacles in the immediate forward-path of the robot. If the laser were to miss something or inaccurately portray something in a three-dimensional scan, the bumper would serve as a last-resort detection mechanism.

4.6 Microcontroller

In order to generate accurate three-dimensional depth-fields using the laser-range-finder, it is critical that precise control of the actuator is achieved. Control of the laser actuator is enabled by a Z8 Encore! Micro-Controller and a National Semiconductor LMD 18201T H-bridge. The Z8 Encore! has, among other features, 64K of memory, an 18.4 MHz clock, 12 ADC channels, PWM capability, and a built-in RS-232 serial interface. One ADC channel of the micro-controller is connected to the potentiometer feedback that is built into to the actuator actuator. The computer sends the desired angle of the actuator to the micro-controller over an RS-232 serial connection. The micro-controller converts the angle into a corresponding potentiometer voltage and determines the direction that the actuator should move by relating it to the immediate potentiometer voltage. The H-bridge allows the 12 V actuator power source to be controlled by logic-level micro-controller signals; both direction and speed of the actuator can be controlled with just two micro-controller output pins. The micro-controller continuously compares the actual and desired position of the actuator to determine when the laser reaches the appropriate angle. This control mechanism gives accuracy of approximately 0.5 degrees.

The displacements of the string potentiometers on the force-sensing bumper must be converted to digital values that can be read and interpreted by the main computer. The Z8 Encore! Micro-controller enables ADC conversion of the voltages from the 7 bumper string potentiometers. Data from the force-sensing bumper is continuously sent to the computer over an RS-232 serial connection at a rate of approximately 350 Hz.

4.7 Power System

The electrical and electromechanical components on the robot have varying voltage and current requirements; a robust and well-devised power system is therefore a necessary element of the design. The system is powered from two separate supplies: a “clean supply” and a “dirty supply”. The clean supply consists of a 20 A-hr, 12 V, sealed, lead-acid battery and a 38 A-hr, 12 V, sealed, lead-acid battery. The two “clean” batteries are connected in serial to provide a 24 V supply and the 38 A-hr battery is also used independently as a 12 V source. The “clean” power is used for electronic components. The dirty supply consists of two 55 A-hr 12 V batteries which are used to power the drive motors and blade motors. Separation of these two power sources ensures that electronic components are not affected by noise from the motors. A color-coded wiring scheme is implemented for consistency and clarity: red wires carry 24V, yellow wires carry 12V, blue wires carry 5V, and black wires are connected to ground. The chassis of the lawnmower serves as a common ground for all components. An emergency stop switch and emergency stop remote are implemented to allow operators to immediately disconnect power from the drive motors and blade motors. When fully charged, the power system provides approximately one hour of operation time.

5 Software Implementation

5.1 Computer Hardware

5.1.1 Onboard Computer

The onboard computer is a device that runs the software implementation. An embedded single board computer is used, providing the advantage of having all components, including the power supply, make a minimal physical footprint. With all the components of a computer in such a small area, active and passive cooling are employed to ensure strong airflow and efficient operating temperatures. This particular computer, an Advanced Digital Logic ADL945PC, has a 2.16 GHz dual core processor and 2 GB of memory [6]. The purpose of the computer is to provide the computational power necessary to run a multithreaded program. The onboard computer is a small black box with dimensions of 5" x 5" x 4". One face of the box provides access to the I/O and networking ports. In the center of that same side the access door is located is an exhaust fan for the computers enclosure. To allow the onboard computer to network with remote devices a wireless router is connected via Ethernet cable.

5.1.2 Wireless Router

The wireless router is a communications device that forwards data packets across computer networks. The router creates a wireless network that serves as an access point to the operating system running on the onboard computer. The router is a consumer grade Linksys WRT54GL enhanced by custom firmware to allow for stronger control. A pair of antennae are attached to the router, one mounted on each side of the mower to increase the coverage of the wireless network. The wireless router is a 6" x 7" x 1.5" black and blue box. The rear panel provides Ethernet jacks, one of which is utilized for networking the onboard computer. The onboard computer is also augmented by a serial hub connected to one of its USB port.

5.1.3 Serial to USB Hub

A Serial to USB hub is a device that increases the number of possible serial connections since the onboard computer has a limited number of RS-232 ports. The hub multiplies the number of serial ports from 1 to 8 which is more than enough to satisfy the requirement of five with room for future expansion. The serial hub is a black box measuring 2" x 6" x 2" located atop the mower in a central easy access location to all the sensor output cables. Together these hardware components provide the computational power and tools necessary to run the software design as detailed in section 5.2.

5.2 Software Design

5.2.1 Overview

The software design choice was to create a multithreaded application using C++ and the object oriented programming paradigm. At the root of the application is a Control Listener class which handles all communication between the mower and graphical user interface by spawning a TCP server. The Control Listener also creates the mower object which is an instance of the Master class. The Master class is the hub of all decision making for the mower. The Master thread spawns two instances of a GPS class and one instance each of a Laser, Motor, and Microcontroller class. The sensor threads simply gather data and update the corresponding variables in their respective data structure. Using data gathered from the GPS, Laser, and Microcontroller objects, the Master thread is able to make decisions and send commands to the motor to accomplish the tasks at hand. The Master thread contains modules designed with data coupling and informational cohesion to address the various areas of the course described in section 5.2.2. All of the above classes implement a Thread class using POSIX threads and provide functionality for data logging in addition to the base features of Pthreads. The GPS, Laser, Motor, and Microcontroller also employ functionality from a Serial class providing a way to set up serial communications and the sending and receiving of data across the port. The multithreaded program is

able to constantly read each of the sensor threads and make decisions in a timely manner.

5.2.2 Path Planning Algorithm

Path planning is a procedure in which points relative to a mowing area are gathered and then used to generate a route for completing the course. The path planning process involves the following steps: calibration, teach points, perimeter, fence, flowerbed, and field completion.

5.2.2.1 Calibration

Calibration is the creation of a local coordinate system using a pair of UTM world coordinates. By converting coordinates into a local system, the orientation of the x and y axes so that they line up with the boundaries of the field.

To create the local coordinate system the mower is parked at a location and take a reading of that position's UTM coordinates which serves as the origin. A second point is then gathered which acts as a vector giving the direction of the y-axis. In order to convert these points into the local coordinate system, a translation of the inverse magnitude of the origin is applied to both calibration points. Taking these shifted points, the heading is calculated from the origin to the second point. The difference between the calculated heading and that of true north (90 degrees) is then found. The difference between these headings is the rotation that needs to be applied to UTM coordinates so that the local system axis can be defined by the user during calibration. After applying the rotation another translation is performed by adding 1000 to the coordinates of all positions to guarantee that all coordinates will remain in the first quadrant. Once a local coordinate system has been established points can now be taught to the mower.

5.2.2.2 Teach Points

Teach points are vertexes along the boundary of the field passed to the mower in the local coordinate system. The teach points are used by the mower as references when creating waypoints

that will guide it through the course. Points are taught to the mower by parking it at one of the vertices and using the 'Create Course' functionality of the graphical user interface that is running on a remote computer. At each vertex the position data for that point is saved for future usage. A total of six points are gathered which wholly define the boundaries of the field. Once all points have been taught the data is sent to the mower where its Course class calculates and assigns waypoints to each section of the course based on the teaching points. The first section of the course to be mowed is the perimeter.

5.2.2.3 Perimeter

The perimeter step guides the mower around the outside edge of the course. This step cuts along the course border while knowing that its path is free of obstruction from the flower bed. Mowing this area is a simple starting point and reduces the amount of unmowed grass immediately. The mower is sent three waypoints to visit during the perimeter step, each of the three initial teach points moved in by a scaling factor that accounts for the width of the cutting deck and the mounting location of the GPS units. Once the mower reaches the third waypoint it is next to zone 2 which contains the fence.

5.2.2.4 Fence

The fence step is used to mow the entirety of zone 2 while minding the position of the fence. To begin the mower cuts the edge of the zone without the fence until it detects the fence within a particular threshold in front. The mower is then turned so that it will run parallel to the bottom section of the fence. Once turned the mower follows the fence until it detects the next section of fence ahead of it. Another turn is performed to make the mower parallel to the remaining section of fence which it follows until reaching the end. With the edges of zone 2 now complete the mower takes another pass at the interior of zone 2 to ensure it has been completely mowed. The mower then reenters zone 1 where it finishes mowing the perimeter by traveling back to its starting point. With the completion of zone 2 the remaining field to be cut is of a much simpler shape and the detection of the flowerbed can

now begin.

5.2.2.5 Flowerbed

The *flowerbed* function first detects the position of the flowerbed and then proceeds to mow it once the position and shape have been determined. To begin, the perimeter of the uncut area of zone 1 will be mowed as a way of gathering information regarding the position and shape of the flowerbed. To get this information the mower will stop at the midpoint of each side to be mowed and turn towards the center of the course where it will perform a laser scan of 180 degrees. This action is performed for all four sides of the mowing area and once complete the data is fed into the mapping algorithm described in section 5.2.3, where a determination is made as to the position and shape of the flowerbed. Using the data returned by the mapping algorithm, a decision is made on where best to initiate contact with the flowerbed. The mower then visits this location and mows the flowerbed using feedback data from the bumper system.

5.2.2.6 Field Completion

Field completion is the following of waypoints which are generated based on the remaining unmowed area. To keep track of what has been mowed, a box using the coordinates from the unmowed area prior to the flowerbed mowing is used as a starting point. Based on the position of the flower bed a section can be removed from the unmowed area. The remaining unmowed area can be defined by four boxes. Using the vertices defining each of those boxes waypoints are generated to mow the interior of those boxes. Once each box is mowed the course is then considered complete.

5.2.3 Mapping Algorithm

The primary intent of the mapping algorithm is to locate the static objects after scanning the field. Since the objects of interest can be considered as planar objects which lie approximately normal to the ground plane (the inclination of the ground plane is limited to no more than 5°, as per the

competition rules). This year's team elected to use feature extraction techniques to locate the objects, specifically the 3-Dimensional Hough Transform (3DHT) [7][8]. The 3DHT is a method for detecting planes in a 3-dimensional space, and is a generalization of the original Hough Transform [8]. As outlined in [8], the 3DHT takes a set of points and generates a set of curves for each of those points using equation (1) and the Cartesian coordinates of the point (p_x, p_y, p_z) and the spherical coordinates for the plane normal (ρ, θ, ϕ) [8]:

$$p_x \cos(\theta) \sin(\phi) + p_y \sin(\theta) \sin(\phi) + p_z \cos(\phi) = \rho \quad (1)$$

The point of intersection of the curves (generated from (p_x, p_y, p_z)) (ρ, θ, ϕ) provides the plane normal that best fits the point cloud. Since the above equation is not discrete, a discrete object called an accumulator is utilized to find the best fitting plane. The accumulator is a 3D discretization of ρ, θ , and ϕ in the Hough Space. A tolerance ϵ is used to judge whether or not the point (ρ, θ, ϕ) is a likely match for (p_x, p_y, p_z) . If it is, then the cell corresponding to (ρ, θ, ϕ) is incremented, or voted for. The cell with the highest number of votes is then the "best fit" for that point set. Because of the problems of discretization, a windowing method is normally utilized to select the maximal value of the accumulator, and this project uses a cubic window. The basic algorithm is simple and easy to implement, but computationally expensive, so a variety of computation mitigation strategies have been developed. This year's team selected the probabilistic Hough Transform (PHT) to reduce computational burdens, processing only a set number of points in each partition [8]. A block diagram outlining the mapping algorithm is provided in Figure 6.

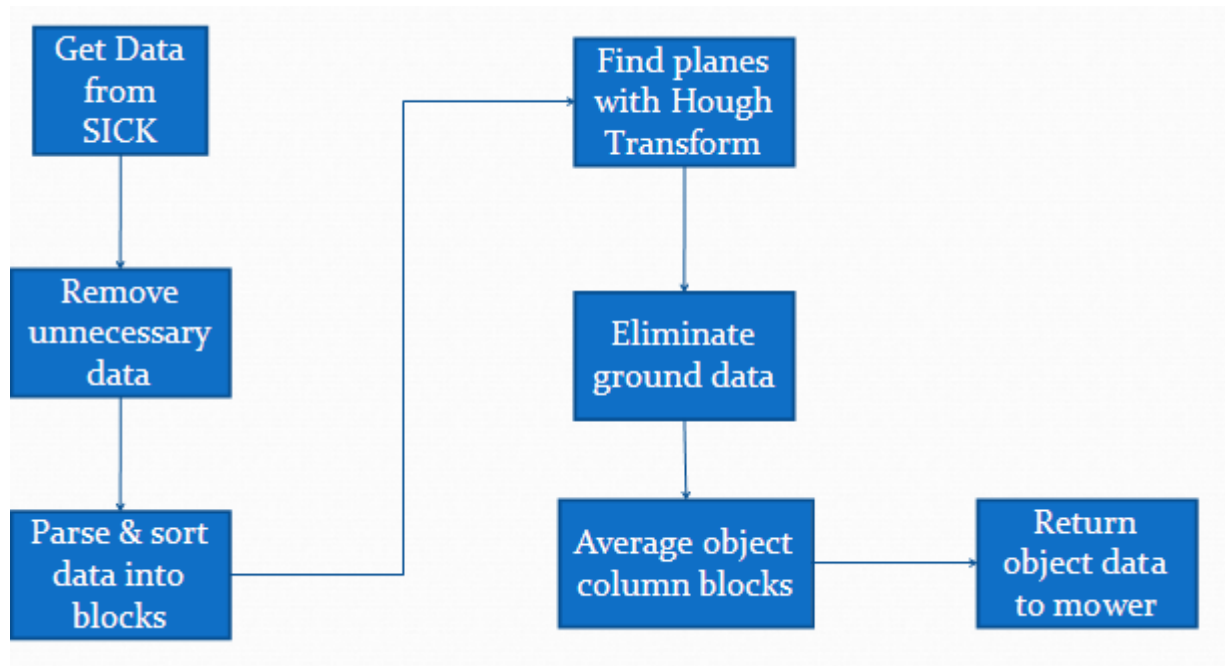


Figure 6: Block Diagram of the Mapping Algorithm

Since the SICK LMS-200 Laser-range-Finder is moved in a fixed manner by a linear actuator (as outlined elsewhere in this paper), this year's team decided to utilize this information to map the field during the competition. The laser scans from 0° to -20° in 1° increments with respect to the horizon and 0° to 180° in either 1° or 0.5° increments a single plane at a time. The SICK LMS-200 stores data in two byte unsigned integers representing the range to an object at a given angle in either centimeters or millimeters. The SICK LMS-200 has been set to process data in millimeters and to scan in 0.5° increments. After scanning from 0° to -20° with respect to the horizontal, the laser-range-finder has 21×361 two byte unsigned integers representing the range to objects. Once this data has been acquired, the main thread summons the mapping algorithm.

The mapping algorithm takes the 21×361 array of two byte unsigned integers, as well as the mower's current location in local x and y coordinates and heading. The mower takes the array of two byte unsigned integers and interprets this data in terms of local three-dimensional Cartesian coordinates, measured in meters.

Because the linear actuator moves the laser range-finder as low as 20° below the horizontal, the laser returns some reflections from the mower itself instead of the field. Moreover, the SICK LMS-200 laser range-finder was designed primarily for indoor use and thus has a limited range outdoors [5]. If the laser range-finder doesn't detect any objects within a few meters it returns data that states the object is nearly 80 meters away. Thus, the data must be processed to remove both of these types of data that should not be processed. This removes a noticeable number of points in the point cloud.

Next, the point cloud must be parsed into sub-sections for individual processing. As the 3DHT is utilized for locating planes in three-dimensions, the point cloud can then be used to generate simplices (in this case, planes) that can be used to judge the point cloud as either likely an object or the ground. As the point cloud exists as an unorganized set of points, the mapping algorithm finds the maximal and minimal dimensions in the x, y, and z direction. Since the boxes that the points are being placed in measure 20x20x20 centimeters, the difference between the maximal and minimal measurements in the x, y, and z direction are rounded up to the nearest 20 centimeters. Once the number of partitions of the space is determined, the points are individually sorted into the corresponding box.

The accuracy of the 3DHT is proportional to the number of points being used in the voting scheme [8]. Hence, the mapping algorithm then examines the total number of points in each box. The partitioned data is then examined and if the number of points is too few, the mapping algorithm elects not to keep that box for later processing. If the number of points meets the minimum specification, then the partition is kept for processing.

Because the remaining data has sufficient points to justify analysis, the 3DHT is then carried out on each data partition. For each point up to the maximal number of points, ρ , θ , and ϕ is tested and voted on. Once the accumulator has been tested for the set number of points, the maximal value is searched for with the cubic window that is 3x3x3 cells wide. The highest value of the window is then

selected, and the corresponding ρ , θ , and ϕ values are used to generate a normal to the plane that best fits the data of that partition, and the vector is fixed at the center of each partition.

Once all the partitions have been processed, each vector is analyzed. If its angle with respect to the z axis is between $\pi/18$ or $17\pi/18$, then the plane corresponds to a ground plane. Otherwise it is an object plane. Three points on the object plane are selected and these points are projected to the xy plane. By doing this, the mapping algorithm has generated a set of points for each object plane in the local xy coordinates that are outlined earlier in the Path-Planning Section. These points are returned to the main thread as object points to be avoided.

5.3 Graphical User Interface

The graphical user interface provides ways to teach points as mentioned in section 5.2.2.2 and gather data from the mower after a run has been completed as well as real time information while mowing. The real time component visualization window is made up of two panes. The left pane provides an overhead view of the course area and the perimeter points as taught when visiting the course for the first time. As the mower moves through the course, its path is presented on the screen with the width of the cutting deck overlaid as it moves through the course. The right pane contains information pertaining to the various sensor threads. It provides the current location in local coordinates, the current heading, speed of each wheel, and distance and direction to the nearest obstacle.

6 Conclusion

The objective of this project is the successful implementation of an autonomous lawnmower which is capable of cutting a specified area while avoiding obstacles. The system utilizes a chassis made from aluminum extrusions and plating that houses the electrical and mechanical components. The design utilizes a laser range-finder, a force-sensing bumper, and a differential GPS system to detect obstacles and locate the mower on the field. The mower also dynamically maps the field to locate static obstacles using the 3DHT. Finally, the mower design utilizes computer, electrical, and mechanical engineering skills and thus is an important demonstration of the engineering method and interdisciplinary capabilities. The mower design is satisfactory and the mower adequately cuts the assigned area within the allotted time.

6.1 Lessons Learned

Despite the excellent design, this year's project had several problems, both in the design plan and resource management section. Since the chassis was inherited and several mower components underwent modification, the team had difficulty placing the newly designed components on the frame. Better attention during the design stages to the physical dimension of the new components would have done much to reduce the effort required to place the new components on the frame, and further design modifications should include examining the possibility of expanding the current frame or constructing a newer one. During the testing phase, the H-bridge used with the linear actuator suffered a number of failures. With better communication and closer inspection of the frame, the source of these problems could have been identified more clearly and accurately. Finally, as an interdisciplinary project, resource management was key and not always properly handled. A clear hierarchy within the group, with a clear delineation of responsibilities would have prevented duplication of effort and wasted time. However, as an educational project, these failures provide invaluable experience that will doubtless be utilized in

future employment.

6.2 New Design Overview

This year's entry for the 2011 ION Robotic Lawnmower competition is built upon a solid foundation. The design provides a platform which is robust and stable. Rather than simply placing potentiometers on the frame, an entirely new system was built on the mower, allowing for a much stronger and uniform design. Furthermore, the lower placement of the bumper than the previous design improves the bumpers detection capabilities significantly. The material used to construct the bumper has also been more carefully selected, overcoming the deficiencies of the previous bumper design [1].

The SICK LMS-200 laser-range-finder can now be manipulated by a linear actuator to sweep through an entire range of angles, allowing for depth data and field mapping. The implementation of a mapping algorithm also provides the path planning algorithm with additional data for obstacle avoidance. This is a significant step forward from previous designs which can allow the path planning algorithm to more precisely choose where to come close to static obstacles and thus avoid damaging such obstacles. The 3DHT is also a simple and elegant means of detecting objects and can be easily adapted for many different circumstances.

The overhauling of the source code is another milestone in the project. By standardizing the source code the problems of multi-year changes and incomplete documentation has been solved. As other teams continue to build and improve the design, successful discipline and documentation can keep the code stable and prevent further inherited design flaws. Overall, this design builds on a reliable plan while correcting several weaknesses, and thus this design shall meet the specifications of the Eighth Annual ION Robotic Lawnmower competition.

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Appendix I: Itemized Component Cost [1]

Component	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
Sheet Aluminum	265.00	3	795.00
Shim Stock	50.00	2	100.00
T-Slotted Frame Parts	1000.00	1	1000.00
Bolts and Accessories	200.00	1	200.00
Wires and Accessories	50.00	1	50.00
Encoders	50.00	2	100.00
RoboteQ DC Motor Controller	500.00	1	500.00
USB and Serial Box	150.00	1	150.00
Relays	70.00	3	210.00
Remote Kill Switch	15.00	1	15.00
Data Switch	60.00	1	60.00
Router	250.00	1	250.00
GPS Units	15,000.00	2	30,000.00
Computer Hardware	3,000.00	1	3,000.00
55 A-h 12-V Batteries	60.00	2	120.00
10 A-h 12-V Batteries	32.50	2	65.00
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	254.00	1	254.00
Encoders	60.00	4	240.00
Drive Motors	339.00	2	678.00
Conduit	3.00	1	3.00
Neoprene Rubber	160.00	1	160.00
H-Bridge	11.00	1	11.00
String Potentiometers	125.00	8	1,000.00
Total Cost			41,113.00

Appendix II: Physical Specifications

Final Mower Dimensions [1]

Component	Dimensions	Notes
Mower Assembly Body	Length: 127 cm Width: 94 cm Height: 94 cm	Includes all protrusions in each dimension
Front Caster Wheel	Diameter: 25 cm	
Rear Drive Wheels	Diameter: 34 cm	
Track Width	84 cm	The distance along the mower's width between the ends of the rear drive wheels
Wheel Base	74 cm	The distance along the mower's length between the bottom of the front wheel and the bottom of the rear wheel

Final Mower Performance [1]

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 1 meter in under 2 seconds
Battery Life	128 minutes

Appendix III: Mower Power Consumption [1]

Power Source	Components	Power Consumption (W)	Operating Time (min)
2 12-V 55 A-h Batteries	5 blade motors 1 string trimmer 2 drive motors	792	100
12-V 38 A-h and 12-V 20 A-h batteries in series	Laser RoboteQ Data Switch	24	128
12-V 38 A-h and 12-V 20 A-h batteries in parallel	Computer Router Microcontroller Bumper H-Bridge Linear Actuator	112	128