2010

Deep Green

University of New Haven Robotics Club Autonomous Lawnmower

ION Robotic Lawn Mower Competition 2010

Contents

Abstract

The ION Robotic Lawnmower competition is an annual competition sponsored by the ION Satellite Division and administered by the Dayton Section of the ION. The purpose of the competition is for universities and colleges to design a robot that will rapidly and accurately mow a field of grass autonomously.

The University of New Haven Robotics Club has constructed a lawnmower for the purpose of autonomously mowing a plot of grass as per the regulations of the ION Robotic Lawnmower Competition. This robot was designed around the competition's various criteria, including safety, durability, accuracy, and speed. This lawnmower was also built with the consideration of efficient, green energy and therefore uses a fuel cell rather than an internal combustion engine or other pollutant-producing energy source.

The autonomous lawnmower uses a network of sensors and microcontrollers to mow the patch of lawn. It is the belief of the UNH Robotics Club that the concepts presented by this lawnmower, namely autonomy, distributed computing, sensor networks, and alternative energy, are the direction of future engineering growth.

Introduction

Although the word “robot” has been around for almost 100 years, the field of robotics has only recently begun to expand in a significant way. The goal of most robotics programs is to extend the usefulness of computers in the performance of routine tasks from the domain of computer software into the physical world. Lawn mowing is a prime example of a simple task that could be automated to the benefit of humanity.

The University of New Haven Robotics Club was established in 2006 with the mission of furthering the member’s engineering experiences using real-world problems with a high level of student innovation and responsibility. After competing at a Penn State Abington robotics competition, the club became a regular competitor at the Trinity College Fire Fighting Home Robot Contest. In 2008, design began for the ION Robotic Lawn Mower Competition.

Deep Green, the University of New Haven Robotics Club’s autonomous lawnmower, is the University’s latest step toward the goal of beneficial autonomous robots. In order to realize the design, a number of design choices were made. The physical design of the robot was custom-designed and built by UNH Mechanical Engineering students. The electrical design, including wiring, PCB, and power regulation, was also originally designed, as was the logical design of the system, by UNH Electrical Engineering and Computer Engineering students. Each component of the design will be discussed in the relevant section later in this document.

The UNH Robotics Club feels that Deep Green has been an essential part of our engineering education, both because of the specific engineering challenges and because of the required logistics. We also feel that completing this robot is an essential step toward gaining the expertise necessary to assist as a part of the growing robotics industry.

Team

Advisor

The University of New Haven Robotics Club is advised by Dr. Bijan Karimi, the graduate coordinator for the Computer Engineering Program.

Current Team

- David Pasko, the club's President, is a senior Computer Engineering and Electrical Engineering double major with a minor in mathematics. David coordinated the electrical hardware design of the robot, including laying out the schematics of the printed circuit boards (PCBs) needed.
- David Jervis is a senior Computer Engineering and Electrical Engineering double major. David assisted with the electrical hardware design, as well as the software design.
- Colton Murphy is a senior Computer Engineering major with a minor in Computer Science and a minor in mathematics. Colton coordinated the software design of the project, including the control and navigation algorithms.
- Chris Ballachino is a senior Computer Engineering major with a minor in Computer Science and a minor in English. Chris assisted with software development, as well as the electrical hardware design.

Due to the small size of this year's club, each member contributed significantly to all aspects of the project, although the specific concentrations are given above.

Former Members

Several former members of the UNH Robotics Club also contributed greatly to the project.

- Michael Folcik, the club's founder and former President, began the preparation for the competition, including finding the fuel cell, designing the preliminary circuit, obtaining preliminary funding, and supervising all aspects of the system until his graduation in 2008.
- Michael Monico supervised all Mechanical Engineering aspects of the design, including the fabrication of the robot and mounting of the hydrogen tanks until his graduation in 2008.
- Brian Francisco assisted in all Mechanical Engineering aspects of the design. He also conducted the majority of the relevant research into fuel cell technology. He has since graduated.
- Tom Ruggeri assisted in all Mechanical Engineering aspects of the design.
- Michael Ingmanson assisted in all Mechanical Engineering aspects of the design.

Additional Assistance

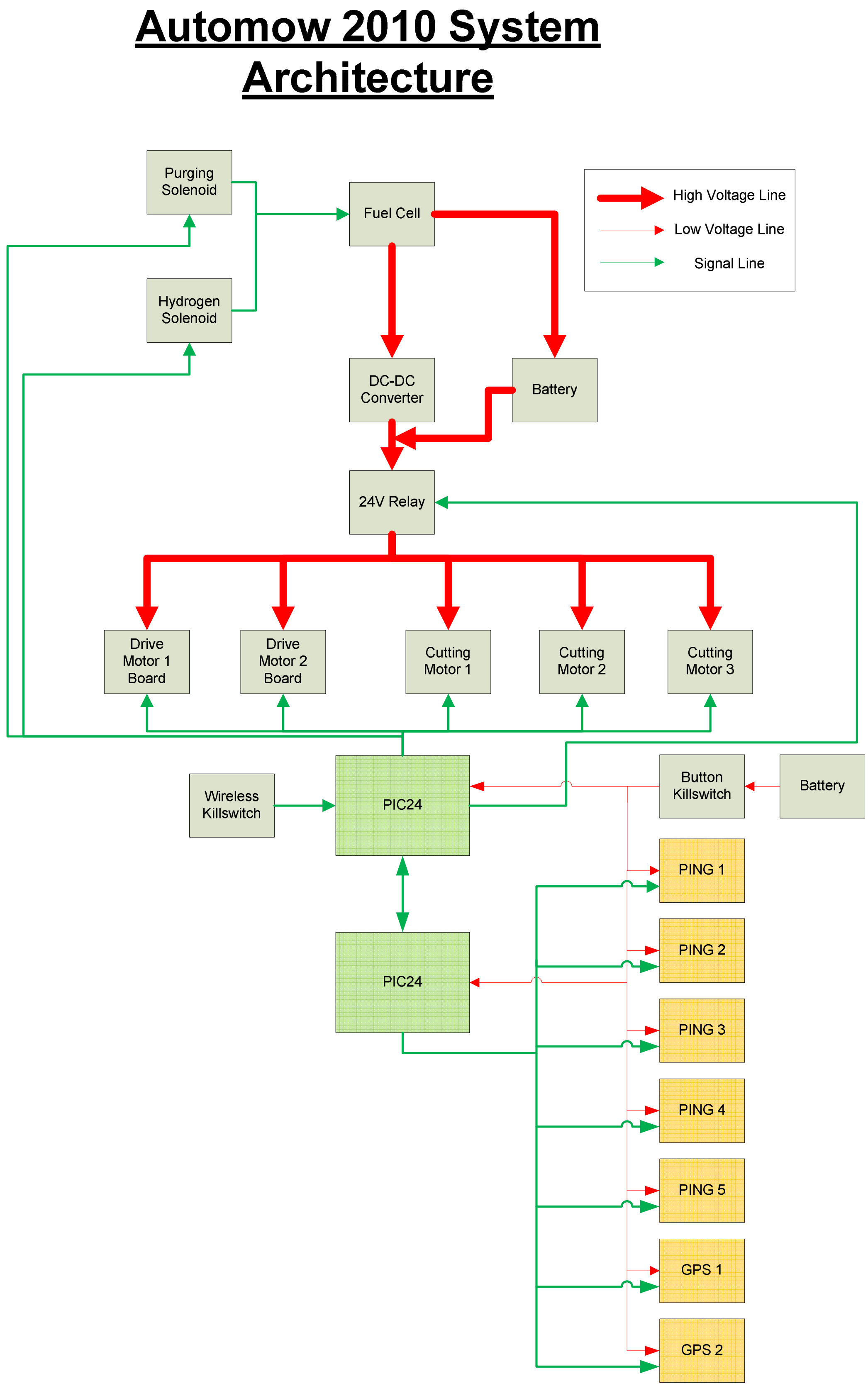
- Dr. Christopher Martinez, the undergraduate coordinator for the Computer Engineering Program, assisted with an advanced knowledge of electrical and electronic system design.
- Nikhil Thiruvengadam, a graduate student in the Computer Engineering program, offered advice on algorithm design.

- Mark Morton, the current UNH Tagliatela College of Engineering lab tech, contributed his knowledge of practical circuit components.
- Paul Bienkowski, the former UNH Tagliatela College of Engineering lab tech, contributed his knowledge of components and circuit design.
- William Flynn Jr. contributed his knowledge of GPS systems.

Sponsors

- Microchip Technology Inc.
- Advanced Circuits
- Bayer Corporation

High-Level System Architecture



Electronic Design

Microcontroller

Deep Green uses two PIC24HJ128GP502 microcontrollers. The PIC line of microcontrollers was chosen due to the club's previous experience with them, as well as the PICs' impressive array of peripherals and Microchip's consistently high quality documentation. The PIC24HJ128GP502 was chosen as a high-level control module due to its large program memory, faster speed, and expanded functionality, which made it appropriate for controlling the lawnmower and peripheral functionality.

Compiler

All of the software for Deep Green was written using the C programming language. The code was compiled using Microchip's C30 compiler. Microchip's compiler was chosen due to its high level of documentation and ease of use. This compiler also integrated well into Microchip's MPLAB IDE.

Networking

The Phillips I^2C (Inter-Integrated Circuit) protocol was chosen to communicate between the different microcontrollers in use. This protocol is a bus communication protocol which uses a single master with multiple slaves to communicate. There are a maximum of 2^7, or 128, nodes in the circuit. This protocol is a convenient protocol due to its speed (400 kHz) and the low overhead associated with the protocol. The PIC microcontrollers used contain a hardware I^2C module, allowing the communication to be handled through interrupts rather than occupying time in the main algorithm.

Two PICs were used rather than one monolithic microcontroller. This provided several advantages. Since the Ping))) sensors each require precise timing, it was easier to divide up the functionality of the system amongst two PICs to avoid accumulating error. In this configuration, one PIC may control the sensors and communication only, while the other may focus on only communication and interpretation, without needing to process any of the raw sensor data.

The PIC24 provided an additional benefit over the lower-numbered PIC models in that each interrupt its own vector, rather than sharing a single vector. This was a help because the code for each interrupt may be shorter, allowing the microcontroller to spend less time in the interrupt subroutine. This allowed for more accurate timing.

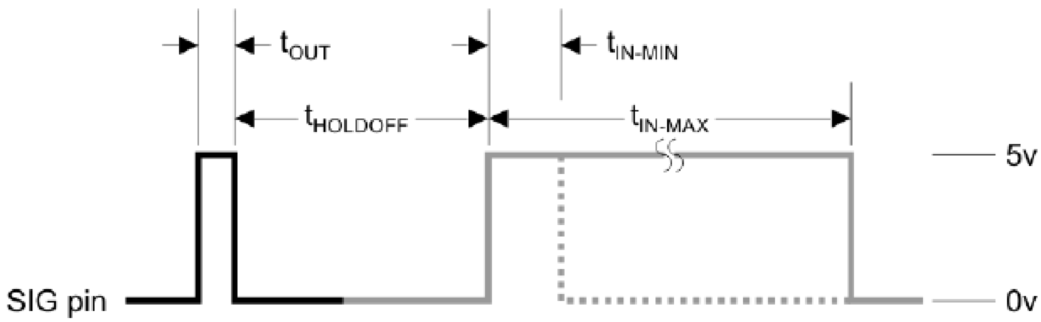
Drive Motor Controller

Each drive motor is controlled by a Simple-H motor controller. These motor controllers are high-quality motor controllers rated for an output current of 20 amps with a PWM maximum frequency of 20 kHz. Since the drive motors are rated for a maximum speed above the maximum 10 km/hr allowed by the ION Robotic Lawn Mower Competition safety guidelines, it was necessary to use PWM to reduce the maximum speed of the lawnmower to an acceptable limit.

Sensors

Ping))) Ultrasonic Sensor

The Ping))) Ultrasonic Distance Sensor is used for object detection. It operates by sending out an ultrasonic (above the range of human hearing) pulse, then measuring how long it takes for that sound to return. It is accurate from 2 cm to 3 m (.78 inches to 9.84 feet), and communicates with a microcontroller via a variable-length pulse, with the length of the pulse proportional to the measured distance, as shown in this timing diagram:



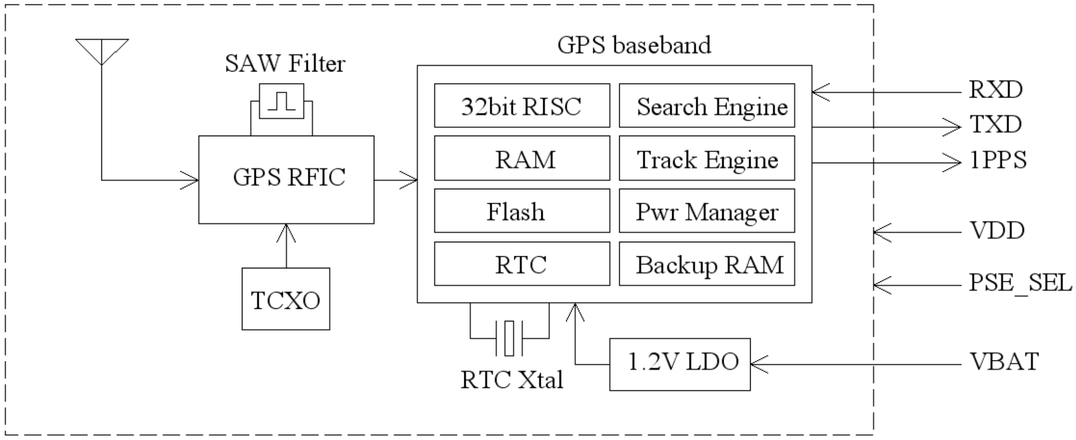
There are some disadvantages to the Ping))) sensor which are inherent to the method of object determination. For instance, the sensor may not be used close to the ground, since sound will reflect off of the ground. The object being measured must also have a certain cross-section to allow for the accurate reflection of the sound, and some reflective surfaces cannot be measured at shallow angles of incidence due to the sound's tendency to bounce away rather than back toward the transducer. All of these disadvantages were considered and found to be inconsequential for this application.

This sensor is used to detect the locations of objects around Deep Green as it mows the lawn.

SUP500F 10Hz GPS Module

The SUP500F GPS Module is an integrated global positioning system (GPS) module that outputs a standard NMEA GPS string containing information about the location of the receiver, such as latitude, longitude, and the current time. This GPS module is controlled through serial communication, and provides 2.5 m positional accuracy at a rate of 10 Hz. The module also provides an integrated antenna. Since 2.5 meters is not very accurate, two of these GPS modules are used, and their results are averaged. This method does not provide protection in the worst case, which is when both GPS modules are off by 2.5 meters in the same direction. However, in most other cases the averaging reduces the error encountered significantly.

A block diagram of the GPS module is included below.



Wi.232 FHSS-250 R Wireless Module

The Wi.232 wireless module is a multipoint to multipoint frequency hopping spread spectrum wireless transceiver module that is accessed through a simple UART communication port. Being frequency hopping spread spectrum, the wireless module is resistant to interference. It will also offer no resistance to other wireless modules in the area, since it is below the noise level. Using frequency hopping spread spectrum also allows for a greater power output, which increases the signal range. The wireless module is used on the lawnmower in two places: a transmitter that acts as the wireless kill switch, and a paired receiver connected to the PIC24.

Electrical Design

Fuel Cell and Hydrogen

Deep Green is powered by a Pearl Hydrogen PhyX 1500 Proton Exchange Membrane (PEM) fuel cell. A fuel cell is an ecologically friendly power source, since it takes oxygen and hydrogen and produces electricity and pure water vapor, rather than producing pollutants. This fuel cell, which outputs 1.5 kilowatts, meets the electrical demands of the two drive motors and three cutting motors.

Since fuel cells are powered by hydrogen, which is considered dangerous due to its flammable nature, special care was taken to assure safety. Rather than storing the hydrogen in its natural gaseous state, the fuel cell uses metal hydride. This means that hydrogen is introduced to an absorbent metal powder which stores the hydrogen in a solid state. In addition, metal hydride may store greater hydrogen densities at a much lower pressure, making metal hydride both a safer and more convenient storage option. The lawnmower uses three 900 liter metal hydride tanks connected in parallel.

The fuel cell takes in a regulated supply of hydrogen and outputs 1.5 kilowatts of power (nominally 57.6 volts at 26 amps). The fuel cell consumes 19 L/min of hydrogen for the rated power, is air-cooled, and gives about 50% fuel efficiency, well above many conventional generation methods. If left operating continuously, the fuel cell can be run off the hydrogen tanks for a minimum of a little less than 2.5 hours before the hydrogen runs out. This value is considered a minimum because the fuel cell will generally not be outputting full power, reducing the amount of hydrogen consumption from its optimal 19 L/min.

A low pressure regulator is necessary between the storage tanks and the fuel cell to drop the pressure down to a level that will not cause damage to the fuel cell, which would be at risk at pressures greater than 10 psi. Also, a directional solenoid valve was installed on the hydrogen inlet of the fuel cell to allow the hydrogen lines to be purged before startup. A second solenoid valve was installed immediately after the regulator to allow the lawnmower system to autonomously start or stop the flow of hydrogen to the fuel cell. This allows the mower to turn its main power source on and off. As a safety precaution, a manual ball valve was installed after the regulator and solenoid as a fail-safe way to control the hydrogen flow and to ensure the fuel cell cannot run while unattended.

DC/DC Converter

The output of the fuel cell is both too powerful and too variable to be used directly in the lawnmower. A Zahn Electronics CH15080F-S DC/DC converter is used to regulate the output down to 24 volts. This DC/DC converter is over 95% efficient and has minimal power loses. It is also able to handle power surges well. In instances where the system requires more power, the converter will output a higher current at 24V. A series of inductors and capacitors clean the normally noisy load response into a clean transient response.

Relay Board

Before being used, the power from the fuel cell is sent through a series of relays. These relays ensure that the lawnmower may be easily and instantly stopped in case of emergency. One relay is connected to Deep Green's emergency stop button, so that a button press will sever power to the system, immediately stopping all of the lawnmower's operations. Another relay is connected to a PIC24, which is connected to the wireless kill switch. Like the physical kill switch, pressing the wireless kill switch button will open a relay and immediately sever power to the circuit.

Kill Switch

The kill switch is a non-momentary, normally closed switch which connects to the electronics battery so that power to the electronic circuit may immediately be cut, halting the hydrogen, the motors, and the microcontroller. To guarantee that the switch operates safely, after the switch is depressed a key must be inserted into the button and turned to open the switch and close the circuit again. This guarantees that the power in the circuit will never be reactivated prematurely or unexpectedly due to switch complications.

Startup Battery

The fuel cell also charges two UBC uninterruptable power supply (UPS) lead-acid batteries. This battery pack is rated at a combined 24 volts at 24 amp-hours. It is charged by the fuel cell while the fuel cell is running. This battery pack is used to protect the fuel cell when the motors are first powered. Since the motors draw a large amount of current at the moment they start up, the sudden draw could damage the fuel cell. However, with the battery pack attached, the fuel cell is protected from excessive draw.

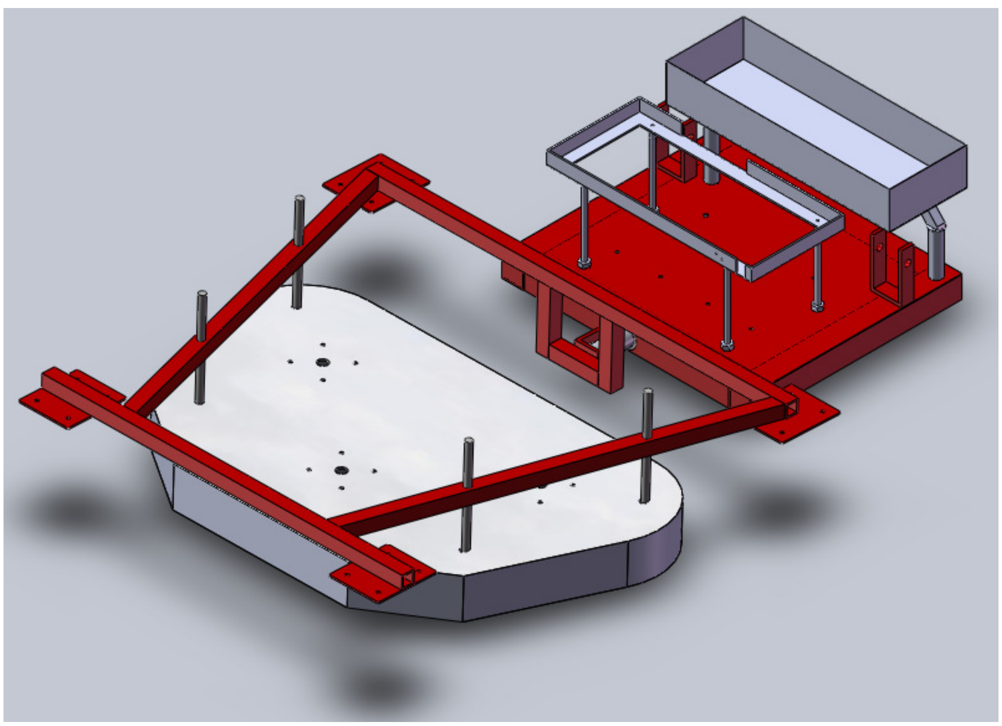
Electronics Battery

The electronics in Deep Green are independently powered by a Tenergy 14.8V rechargeable lithium-ion battery pack, which delivers a continuous 6.5 amp current, and 2200 milliamp-hours. Running the electronics off of an independent power supply assisted greatly in development, since the electronics could be tested using the actual voltage source without powering the fuel cell, which would waste hydrogen unnecessarily. The electronics battery also simplified hardware design, since less voltage regulation had to be done to the fuel cell's high-voltage output.

Mechanical Design

Initial Design Philosophy

After looking at various options early in the design process including ways to cannibalize an existing lawnmower, the team decided it would build this autonomous lawnmower entirely from scratch. This granted the club the freedom to design and construct all aspects of the mower to exact, optimal specification. The basic layout of the mower is split into two sections: the driving section and the mowing section. The driving section contains the main electronic components, navigational sensors, and driving motors. The mowing section consists of the cutting deck and hydrogen tanks mounted on a frame. The driving deck is designated the front of the robot, and the cutting deck follows the driving deck while in motion. This layout is intended to avoid slippage of driving wheels on freshly cut grass, and its modular design allows for easier maintenance of the main components. These two sections are linked via a shaft and pin system. This system allows for two degrees of freedom in the relative motion between the two sections, granting the mower to more easily follow the contours of the land. A rendering of the mechanical components of Deep Green are shown below.



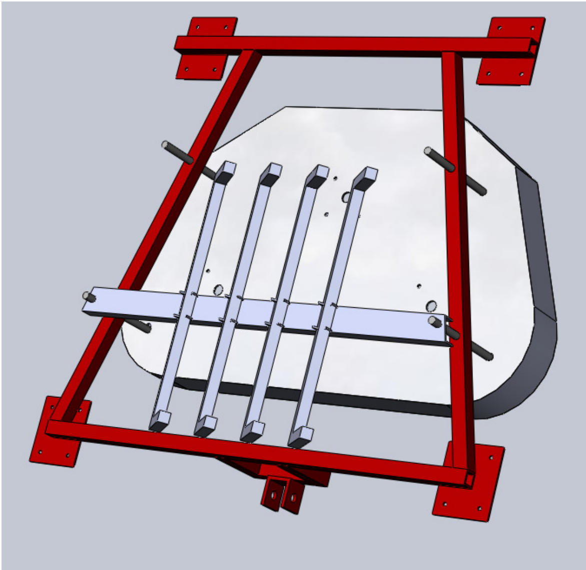
Driving Section

The foundation of the driving section is a rectangular platform made of 1 ¾ inch A513 square steel tubing. A piece of 1/16th inch 1080 sheet metal is welded to the square steel frame to form the working surface. The two driving motors are mounted on this surface using steel brackets. The gear head driving motors are from an electric wheelchair and run the original wheelchair wheels without any additional drive train. These motors were acquired at a very low cost and provide adequate power to propel the lawnmower. Two independent motors were chosen over a rack-and-pinion type steering system for simplicity, the ability to quickly correct for changes in heading, and the ability to perform a zero degree turn.

Also mounted directly on this surface is the UPS battery, the DC-DC converter, and electromagnetic and protective electronic filtering. In order to keep the driving deck as small as possible, additional components were mounted on elevated brackets. These components include the hydrogen fuel cell and its support electronics. The fuel cell bracket is made of steel angle iron, and the fuel cell is held in this bracket with rubber coated steel cable. The electronics box is constructed from 1/16th inch 1024 spring steel, both for its low weight and its electromagnetic shielding. This box is mounted on top of two electrical conduit pipes which provide both stability and a path for wire harnesses to run.

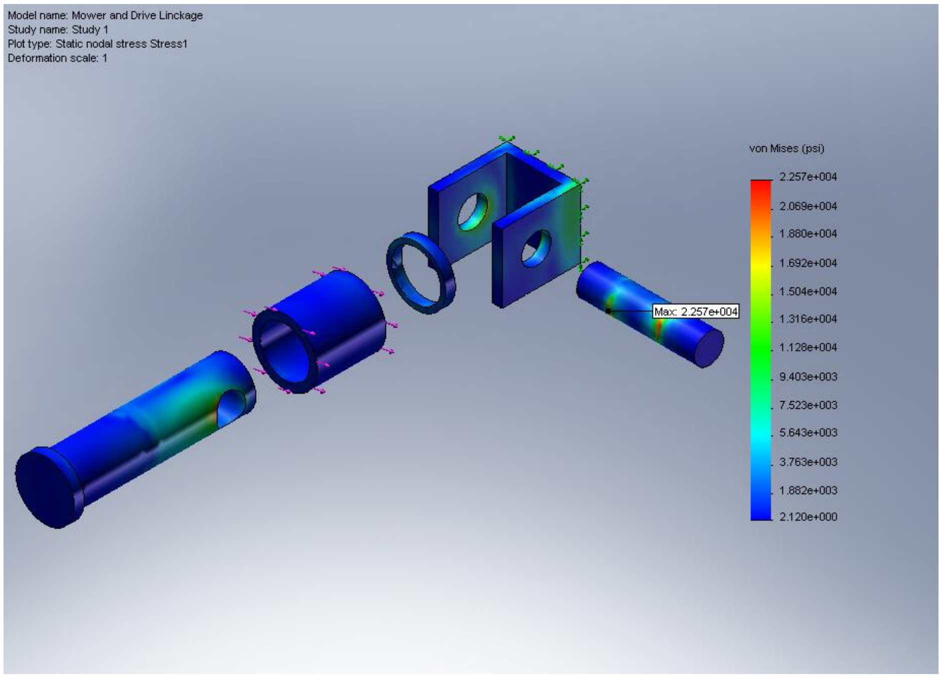
Mowing Section

The mowing section is based off of a trapezoidal frame made of 1 inch 1018 cold drawn steel. Through the frame run four threaded rods which provide mounting points for the hydrogen storage tanks and the cutting deck. The hydrogen storage tanks are mounted side-by-side on a rack made out of aluminum for its weight savings. The cutting deck is hung underneath the frame from the threaded rods, which allows for simple cutting height adjustment. During the design process many different ideas on how to achieve height adjustment were discussed, but the threaded rods proved to be the simplest and easiest to use, taking advantage of the principle that once the user sets the desired cutting height, it will rarely need to be changed. The cutting deck is made of 6061-T6 aluminum to be as light as possible while still providing the integrity to handle forces applied by three individual cutting motors. Each cutting motor is mounted directly on the top surface of the cutting deck, with the shaft running through the deck. During testing, vibrations from these motors proved to be problematic, so sheets of rubber were sandwiched between the motors and the aluminum surface to silence this effect. Each cutting motor drives a finely sharpened 11 inch diameter blade. The arrangement of the cutting blades allows the mower to cut a path 30 inches wide. A rendering of the mowing section is included below.



Linkage

The two sections of the mower are linked by a pin that allows for rotation, as well as upward and downward movement. This combined motion will allow the mower to better follow the contours of the land, and will help maintain maximum traction by ensuring that the drive wheels are always on the ground. The pin connections are made out of 1018 steel, while the main shaft is made from stronger W1 tool steel. A stress analysis was performed on this linkage to ensure that it will not fail during mower operation. This stress test is shown below.



Software Design

Peripheral Microcontroller

The peripheral microcontroller's purpose is to monitor the sensors, which are the five Ping))) sensors and the two GPS modules. This module is a slave on the I^2C bus it shares with the navigational PIC, which means that the master may at any point request the sensor data from the peripheral PIC. To make sure this data is available, the sensor values will be buffered, so that the most current complete values may be read without simultaneous access errors. It was determined that reading the buffered sensor input would not be a significant source of error for the system, since the time between updates is very small.

Navigational Microcontroller

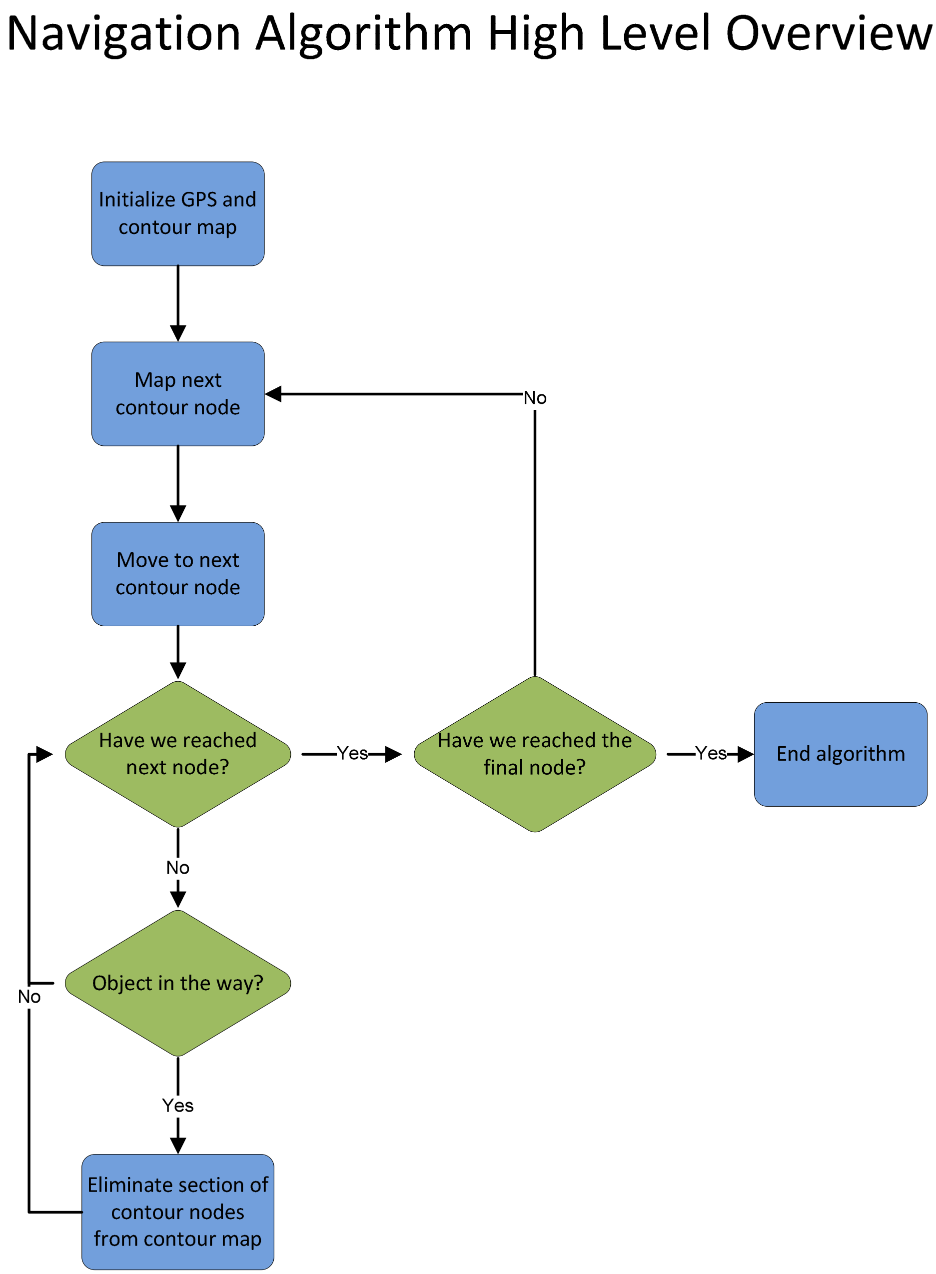
The navigational microcontroller's purpose is to drive navigation, as well as interface with control hardware, including the wireless kill switch and the hydrogen solenoids. It will make navigation decisions based on data it receives from the peripheral microcontroller.

Navigation Algorithm

Deep Green starts in the safety area, as per the competition rules. Before moving, the robot constructs a matrix representing the arena, separating the arena into 150 (15 x 10) blocks, each representing a one meter by one meter square. Each of these squares is identified by an "unmowed" tag. The robot also initializes the GPS modules before moving.

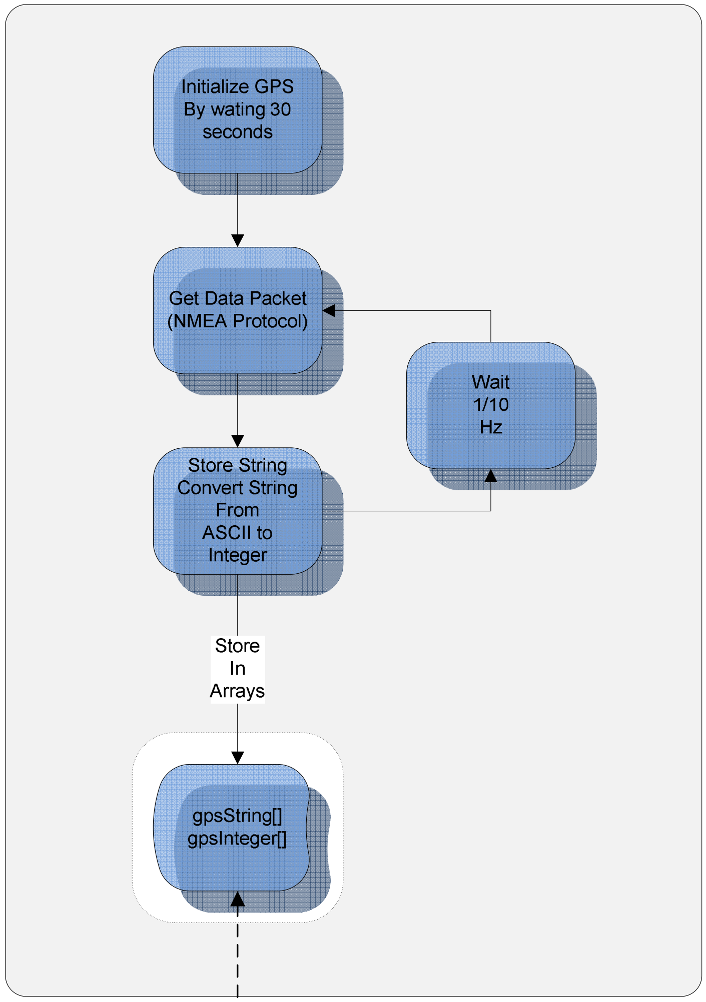
When the initialization phase has completed, the robot begins moving. While moving, the robot is aware of the node that it is in. Given this information, it decides on the next node to mow. To decide, the robot considers all available nodes in proximity to the one it is in, then picks the most optimal one. Once it decides on the next node to travel to, the robot marks the current node as "mowed" and moves. If the robot detects an object using the Ping))) sensors, it marks that node as "unavailable" before calculating where to move to next. If a situation arises where the robot is surrounded by nodes which are all not marked "unmowed," the robot will locate the closest "unmowed" node, then travel to it, avoiding any "unavailable" nodes. When every node is marked as either "mowed" or "unavailable," the robot will power down.

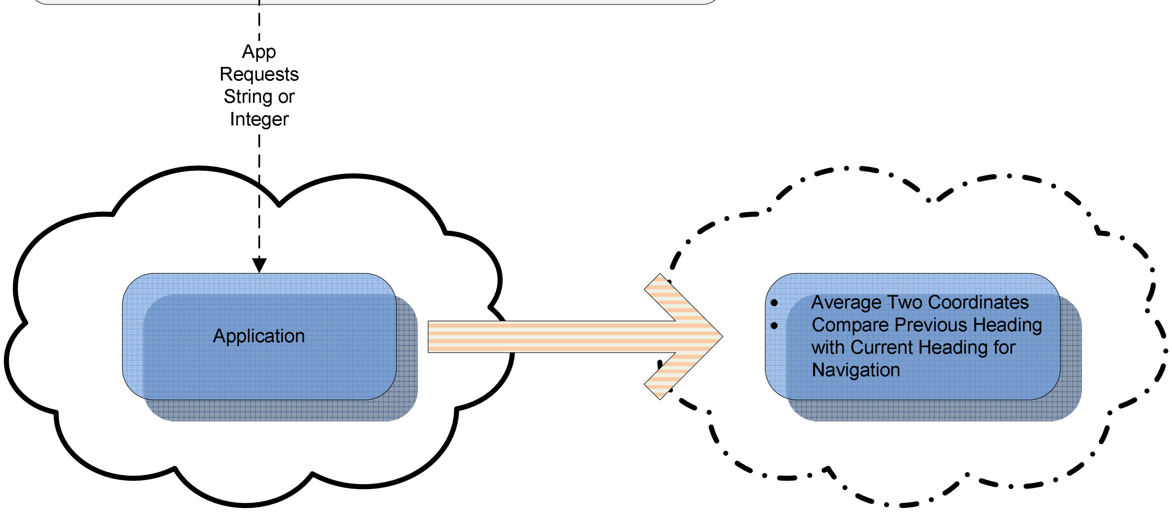
Navigation Flowchart



GPS Flowchart

GPS Driver with Application Implementation





65 Channel SUP500F 10Hz GPS Receiver with Smart Antenna

Additional System Specifications

Maximum Speed

The drive train on the robot was taken from an electric wheelchair, which has the capability of driving at speeds up to 15km/h. Not only is this above the competition's speed limit of 10km/h, it was determined to be unsafe for use in any venue. The speed is regulated using software pulse-width modulation (PWM). This method allows the motors to be reliably operated at safe speeds with no additional hardware and very little software overhead. Consequently, the lawnmower runs at an average velocity of 6.5 km/h. This speed was decided upon by taking into consideration both the electrical demand on the fuel cell from the motors and the allotted time limit for mowing. We found that moving at 6.5 km/h would allow us to mow the field with excess time while not placing too much stress on the fuel cell.

Cutting Width

The lawnmower's cutting width is 30 inches. The cutting deck was designed with this size, larger than the average robotic lawnmower, as a priority. It is the opinion of the UNH Robotics Club that the lawnmower, though designed for competition, should be as practical as possible in a general-use environment. The larger cutting deck, combined with an operational time of over two hours, gives Deep Green the ability to mow very large lawns.

Blade Height

The blades are located one inch above the bottom of the cutting deck. This was a safety consideration; small rocks or sticks which are disturbed up by the blades will be caught by the cutting deck rather than being launched at bystanders, cars, or houses.

Cost

Item	Quantity	Unit Price	Total Price
Raw Material			
Aluminum - plate - 1/4" thick - 48" x 48"	1	$295.11	$295.11
Aluminum - tubing - 1/8" wall - 1" x 1"	2	$25.78	$51.56
Machine steel - rod - 1.5" dia. - 12" long	1	$27.69	$27.69
Steel - 90° angle - 1/8" thick - 1" x 1" - 36" long	1	$11.29	$11.29
Steel - plate - 1/16" thick - 36" x 36"	1	$75.99	$75.99
Steel - plate - 1/4" thick - 1" x 12"	1	$6.30	$6.30
Steel - plate - 1/4" thick - 2" x 12"	1	$10.24	$10.24
Steel - threaded rod - 1/2" dia. - 36"	2	$5.26	$10.52
Steel - tubing - .12" wall - 1" x 1" - 36" long	3	$21.36	$64.08

Steel - tubing - 1/8" wall - 1.75" x 1.75" - 36" long	2	$25.96	$51.92
Components			
Assorted nuts & bolts	1	$30	$30
Assorted piping	1	$336	$336
Cutting Blades	3	$9.49	$28
Casters - 6" wheel - pneumatic	4	$34	$136
Elastic fasteners	2	$3.60	$7
Hydrogen hose - steel braded	1	$100	$100
Hydrogen quick disconnects	5	$41.20	$206
Hydrogen regulator	1	$150	$150
Hydrogen tank	3	$800	$2,400
Tank Manifold	1	$405	$405
Shaft couplers	3	$51.33	$154
Electronics			
Printed Circuit Boards	3	$50	$150
Battery - 24 volt	2	$80	$160
DC-DC Converter	1	$2,400	$2,400
Fuel Cell	1	$7,000	$7,000
Miscellaneous Electrical Components	1	$300	$300
Kill switch	1	$30	$30
Cutting Motors	3	$137.94	$414
Drive Motors	2	$50	$100
Motor Controllers	2	$80	$160
Pressure Sensor	1	$40	$40
Ultrasonic Distance Sensors	5	$25	$125
Signal wiring - 100' - 22 gauge	1	$10	$10
Wiring - 100' - 10 gauge	1	$70	$70
PIC24HJ128GP502	2	$3	$6
Wi.232 Transceiver	2	$25.76	$51.52
			Total Cost
			$15,573.70

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