



# Green Reaper II

8<sup>th</sup> Annual ION Autonomous Lawnmower Competition Report

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## Abstract

Green Reaper II is an undergraduate student-designed autonomous lawnmower intended to mow a field of grass while avoiding obstacles without any external user input. This is accomplished through the integration of global positioning system (GPS) and various sensor technologies all controlled by microcontrollers. The design has been implemented in order to participate in the 8<sup>th</sup> Annual ION Autonomous Lawnmower competition. The design was created by an interdisciplinary team of undergraduate students from the Electrical and Mechanical Engineering programs at the University of North Florida. Green Reaper II is powered using direct current (DC) wheelchair motors adapted to operate with all terrain vehicle (ATV) tires, and controlled using a motor controller that can be interfaced with either through remote control or autonomously using microcontrollers. The mower operates and turns much like a standard zero-turn radius commercial lawnmower using differential steering. Navigation is implemented using a differential GPS (DGPS) system that is augmented with dead-reckoning navigation using a combination of a digital compass and dual digital encoders on the drive wheels. Obstacle avoidance for the Green Reaper II is based off of the signal of multiple ultrasonic sonar sensors. The mowing platform consists of a nineteen inch electric lawnmower motor and blade.

## Introduction

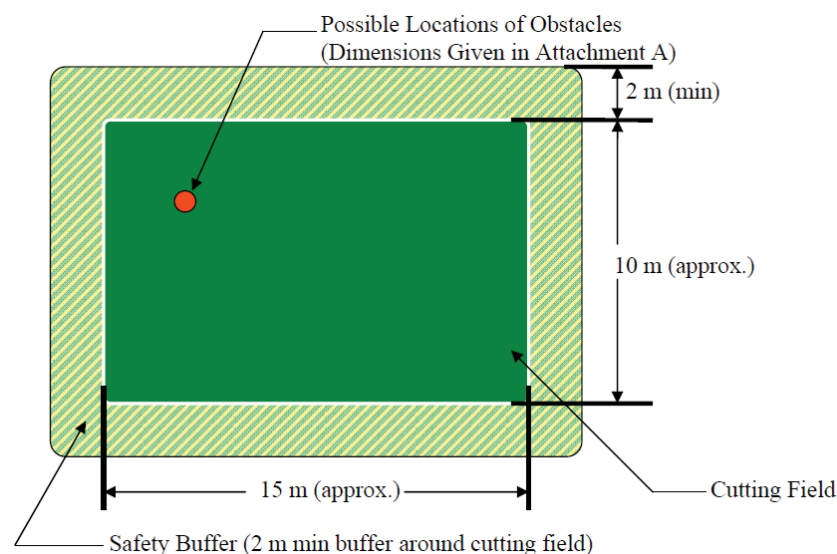
The Green Reaper II is the second iteration of UNF's autonomous lawnmower program. The design has been implemented in order to address many of the shortcomings present in Green Reaper I, last year's autonomous lawnmower. In order to develop a more sturdy design for the autonomous lawnmower, an undergraduate mechanical engineering student was charged with developing the mechanical design aspects of the project, including frame and weatherproof cover design, wheel selection and encoder integration. Six undergraduate electrical engineering students worked to implement all of the navigational and control aspects of the design, including power subsystems, microcontroller implementation, DGPS navigation, dead reckoning navigation and obstacle avoidance.

Outdoor autonomous navigation requires the integration of several subsystems in order to successfully navigate an area. Because the system is running outdoors in an unknown environment, no assumptions regarding the availability of reference points or objects can be made. Because of this, navigational aids such DGPS, digital compasses and digital encoders need to be integrated in order to provide positional feedback to the autonomous vehicle.

Green Reaper II is an autonomous lawnmower that uses a combination of sensors and navigational aids to navigate a playing field through the integration of a GPS and dead reckoning approach. It was decided that while GPS provides an excellent means for determining the outer perimeter of the playing field, internal navigation could be more reliably accomplished using dead reckoning.

## Competition Description

The 8th Annual Robotic Lawnmower Competition is sponsored by The Institute of Navigation, The Satellite Division and Air Force Research Laboratory, The Sensors Directorate and John Deere. The competition requires university teams to autonomously mow a field of grass in order to demonstrate the art of autonomous navigation. There are two competition options from which to choose. The first option as shown in Figure 1 is the static competition that involves cutting a rectangular field with one static object randomly placed somewhere on the field.

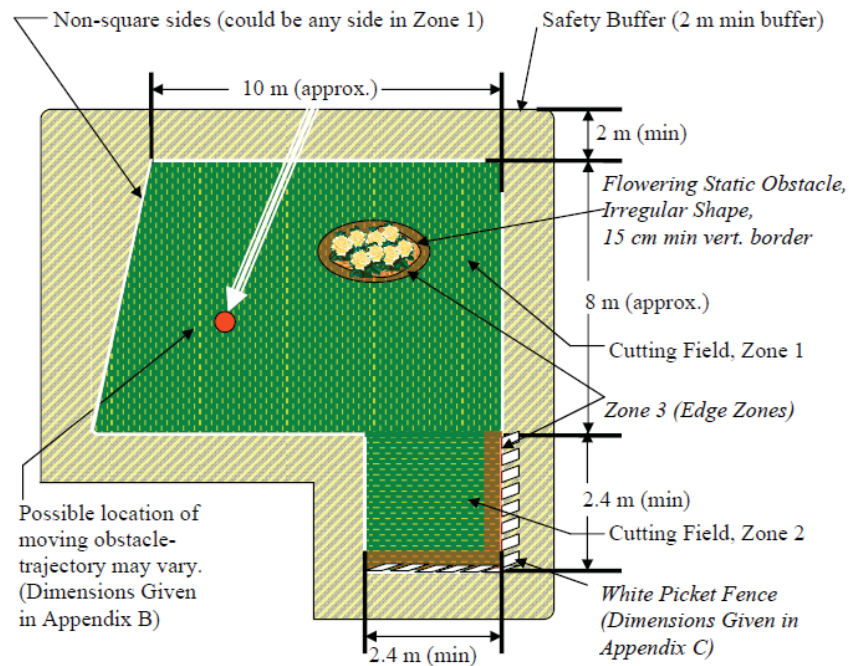


**Figure 1:** Static Competition Field [13]

Figure 2 shows the second option, the advanced or dynamic competition, consisting of an irregularly-shaped field with a fixed boundary, such as a fence. This field also contains a fixed obstacle as well as a dynamic obstacle that must be avoided during the competition. The competition requirements are as follows [13]:

- Lawnmowers shall be autonomous and unmanned.
- The speed of the lawnmower cannot exceed 10 km/hr.
- Lawnmowers must be equipped with both manual and wireless remote emergency stop capability. The wireless emergency stop must be effective over the entire length of the field plus 15 meters in all directions. The lawnmower must cease operation within 3 seconds and come to a stop within 2 meters after the emergency stop is initiated.

- The lawnmower may not exceed 2 meters in any dimension.
- The lawnmower movement shall be accomplished with direct contact with the ground.  
The mower shall be provided power by combustible fuel and/or batteries.
- There is a maximum of 20 minutes to cut the field.
- The lawnmower should be designed to operate in any weather condition.



**Figure 2:** Dynamic Competition Field [13]

## Green Reaper II Team

Team Green Reaper is composed of an interdisciplinary undergraduate group of engineering students who have dedicated the past twelve months on improving the University of North Florida's autonomous lawn mower project. The team aims to build on the successes of previous teams as well as making new innovations in student led design in the areas of: custom mechanical design and fabrication, GPS algorithms and electronic circuit integration. The team members are as follows:

Ernie Bautista, <i>BS</i> : Electrical Engineering: Software and MCU Controls	May 2011
Bill Carlson, <i>BS</i> : Electrical Engineering: Hardware Integration and PCB Design	Dec. 2011 <small>ANTCP</small>
Joshua Davis <i>BS</i> : Electrical Engineering: Differential GPS Hardware Integration	May 2011
Joe Lisiecki, <i>BS</i> : Mechanical Engineering: Mechanical Design and Fabrication	May 2011
Francis Obiozor, <i>BS</i> : Electrical Engineering: Differential GPS Software	Dec. 2011 <small>ANTCP</small>
Hershel Parmar, <i>BS</i> : Electrical Engineering: System Integration and Software	Dec. 2011 <small>ANTCP</small>
Nathan Schmidt, <i>BS</i> : Electrical Engineering: Hardware Integration	May 2011

In order to function and communicate between team members from mixed backgrounds, a hierarchical structure was developed in order to facilitate communication between team members. Figure 3 shows the hierarchical team structure developed by the Green Reaper II team.

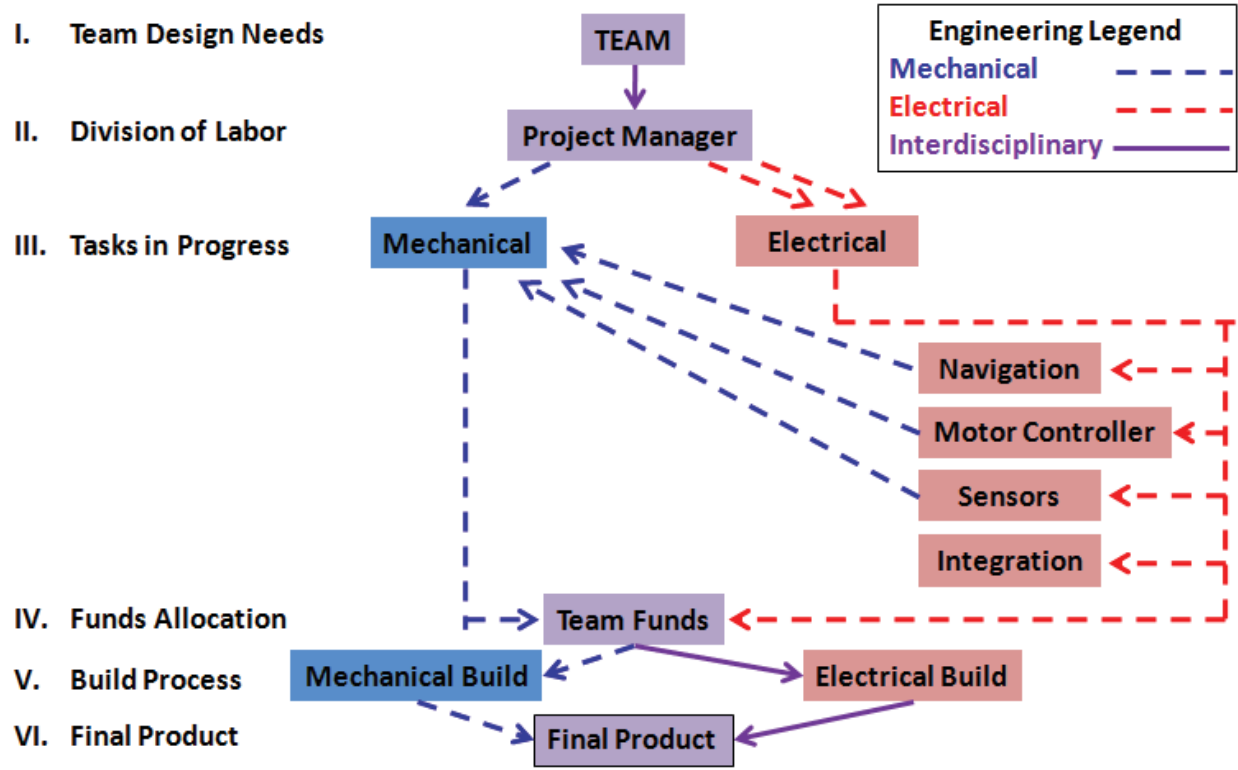


Figure 3: Hierarchical Team Communication and Interaction Structure

## Green Reaper II Description

The Green Reaper II is built on a carbon steel frame that is a 96.5 cm long and 51 cm wide. Weather protection is provided by a modified steel wheel barrow that is 98 cm long and 52 cm wide. The overall dimensions of the mower are 98 cm x 52 cm x 71 cm. Autonomous navigation is implemented through the integration of multiple subsystems. The motion control subsystem consists of two Sunrise wheelchair motors and gearboxes, each operating at 24 VDC. These are controlled using a Roboteq HDC2450 motor controller that allows for either manual radio control (RC) operation or microcontroller-based autonomous operation of the lawnmower. The rear-mounted motors are connected to all-terrain vehicle (ATV) wheels through a custom adapter. The front of the frame houses a pair of casters in order to allow for implementation of a zero-turn radius. This motion control subsystem is powered by a pair of 12 V, 18 amp-hour gel-based batteries wired in series. The mowing subsystem consists of a Black and Decker cordless electric lawnmower motor, 19 inch blade and shroud. This system is powered by a second set of batteries consisting of two 12 V, 17 amp-hour lead acid batteries connected in series. The navigation and control subsystem consists of two Freescale HSC12C128 microcontrollers. This subsystem is powered by a 12 V lead-acid battery, this voltage is stepped down to 5 V through the use of a voltage regulation PCBs. The navigation and obstacle avoidance subsystem consists of a Trimble DGPS system, a pair of US Digital incremental encoders mounted on the drive wheels and an array of Maxbotix Ultrasonic Range Finders. The digital encoders are interfaced through the HDC2450 motor controller in order to provide the necessary feedback for straight line navigation. A tachometer is used in conjunction with the microcontrollers to calculate the linear distance travelled by the mower. Directional turns are implemented through the use of a Sparo digital compass. Together, the encoders and digital compass are used to determine a displacement vector in order for the mower to navigate between DGPS waypoints.

**Bill of Materials****Table 1. Project Cost**

	Part#	Quantity	Value	Cost
Digital Compass	SP3004D	1	\$700.00	\$00.00
Differential GPS	SPS-852	1	\$15,000.00	\$00.00
Actuator	N/A	1	\$75.00	\$00.00
Wheels	N/A	2	\$150.00	\$00.00
Wheelchair Motors	013551	2	\$600.00	\$00.00
12V Batteries		2	\$140.00	\$00.00
Wire	N/A	50ft	\$60.65	\$60.65
Fuses	N/A	5	\$79.59	\$79.59
Solid State Relay	Crydom D06D80	3	\$330.00	\$330.00
Switches	N/A	4	\$23.81	\$23.81
Relays/Solenoids	N/A	10	\$400.97	\$400.97
Manual E-stop	N/A	1	\$73.31	\$73.31
Wireless E-stop	Logisys 12V 15AMP	2	\$33.00	\$33.00
CircuitComponents	N/A	N/A	\$22.83	\$22.83
Batteries	Energizer 12pk	2	\$25.64	\$25.64
Building Materials	N/A	N/A	\$275.13	\$275.13
Connectors	N/A	N/A	\$113.16	\$113.16
8" Pneumatic Swivel Castor	Harbor Freight 42485	2	\$25.98	\$25.98
Enclosures	N/A	N/A	\$65.88	\$65.88
Tires	145/70-6	4	\$121.98	\$121.98
Ultrasonic	Maxbotix XL-Maxsonar WR1	5	\$342.14	\$342.14
Encoders	US Digital H-4	3	\$56.84	\$56.84
Battery Chargers	Schumacher SC-600A	4	\$275.13	\$275.13
Tachometer	N/A	1	\$50.00	\$50.00
Microcontrollers	Freescale MC9S12C128	4	\$429.07	\$429.07
Tools	N/A	N/A	\$30.98	\$30.98
Remote Control	Futaba Attack T2DR	1	\$54.98	\$54.98
Motor Controller	Roboteq HDC 2450	1	\$597.50	\$597.50
Trash Can	Brute 2632	1	\$32.08	\$32.08
Laptop Hardrive	ST940814AS	1	\$53.48	\$53.48
<b>Total</b>			<b>\$20,239.13</b>	<b>\$3574.13</b>

## Green Reaper II Sponsors

In order to develop an autonomous lawnmower that included features such as DGPS, it was essential for the team to find sponsors willing to donate both funding and equipment. Figure 4 shows the sponsors who supported this effort.



Figure 4: Green Reaper II Sponsors

## Competitive Analysis

Autonomous lawnmowers have been becoming more and more popular since the mid 1990's, however, few if any of these products meet the requirements set forth in the ION Autonomous Lawnmower competition rules. Several commercial products were investigated in order to form a basic comparison to the development of Green Reaper II.

Figure 5 shows the Automower 230ACX which is one of Green Reaper II's closest commercial comparisons, as it cuts the grass in a random fashion, using three cutting blades and a perimeter wire. The price of this robot is \$2,699.95. This robotic lawnmower can only mow inside an area that is demarcated using a perimeter wire.



**Figure 5: Automower 230ACX [14]**

The Robomow RL850 is another close competitor, using the same navigation style as the Automower. The Robomow, as shown in Figure 6, also uses a three blade cutting system. The price of the Robomow is \$2085.95.



**Figure 6: Robomow RL850 [15]**

The LB1200 Spyder, shown in Figure 7, is an example of a lower-end model of an autonomous lawnmower that is commercially available. This mower does not have a perimeter wire and uses only one blade for cutting. This lawnmower retails for \$1,199.



**Figure 6: LB1200 Spyder [16]**

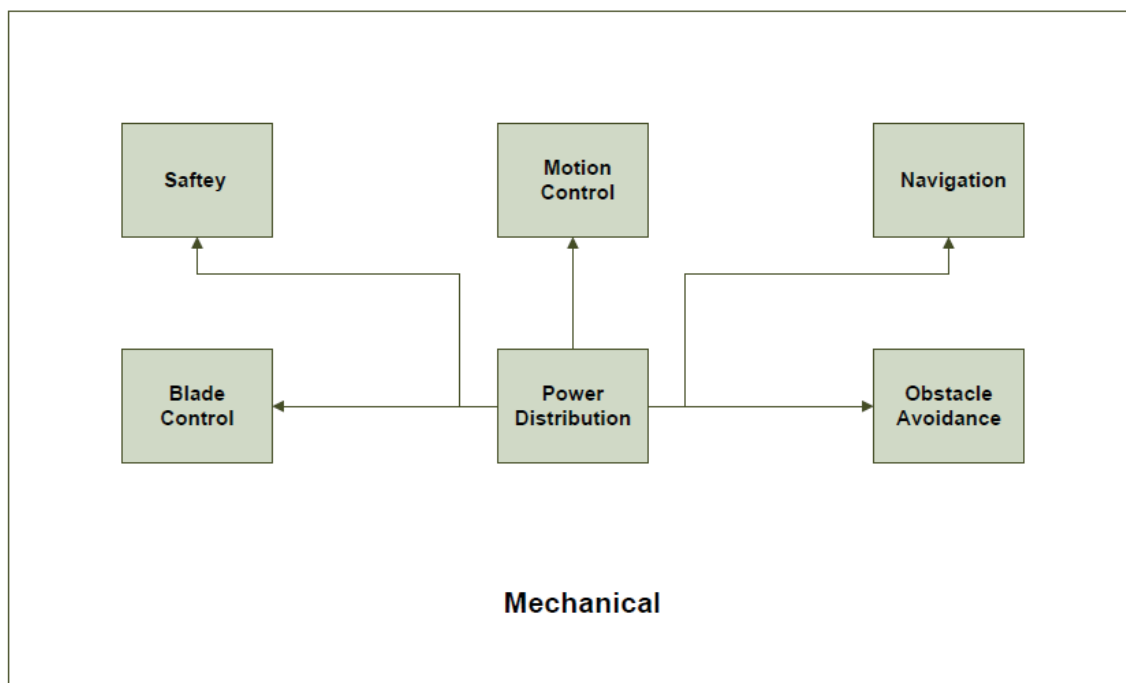
Overall none of these autonomous lawnmowers share enough similarities with the Green Reaper II to truly be compared. These robots are less expensive than the Green Reaper II, but are not capable of meeting the requirements of the competition.

## Design

As the Green Reaper II team consists of both a mechanical and electrical design, the design process was separated into two major components – electrical and mechanical. The electrical design was focused on motor control, navigation and object detection, while the mechanical design was focused on the materials needed to construct a custom frame and housing that would be the basis for a robust and functional lawn mower. The design was approached in an interdisciplinary manner in which both the electrical and mechanical students worked together to design and build the mower.

### *Overall System Design*

The overall system design, integrating the mechanical and electrical subsystems for Green Reaper II is shown in Figure 8.



**Figure 8:** Green Reaper II Subsystem Integration

The overall system consists of a mechanical subsystem, consisting of the frame design, weather enclosure, digital encoder mounts, mower blade and shroud and wheel mounts. The mechanical subsystem was designed using multiple software suites in order to develop a sound frame design, determine suitable material selection and determine the environmental impact of the design.

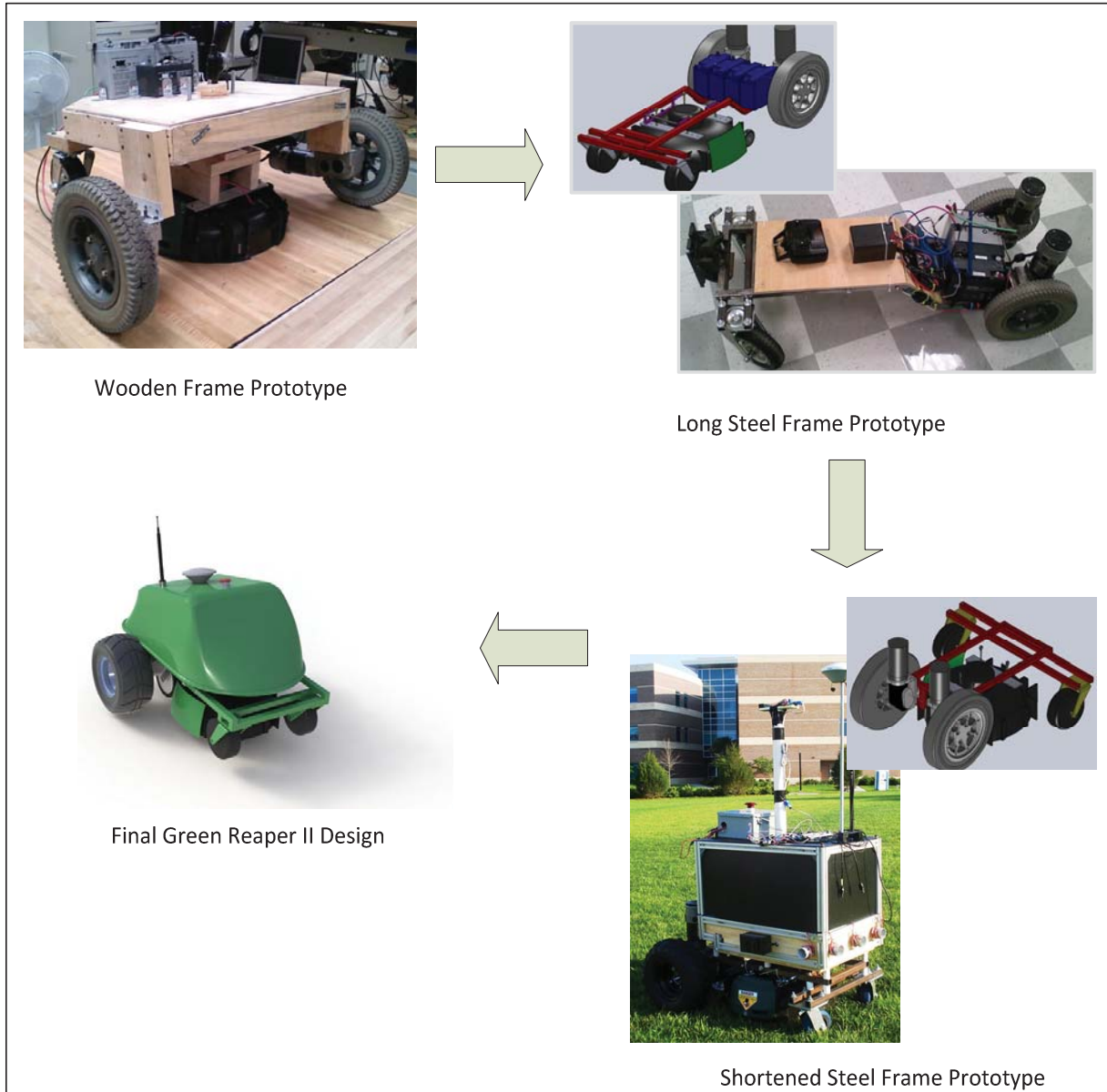
### *Mechanical Subsystem*

The mechanical subsystem was designed by a mechanical engineering student. The design involved the development of several prototypes.

### *Frame Design*

The final frame design for Green Reaper II was the result of several different prototypes that were designed and constructed. Figure 9 shows the evolution of the Green Reaper II frame design process.

The final frame is a weldment design for strength and low cost. Welding was performed with a MIG style welder and drilled into with fasteners for mounting. Earlier in the design process, the motors were mounted vertically on the frame to allow for a better ground clearance and to create more space saving design. However, it was determined that the loss of fluid through an accessory port detracted from the advantage of the vertical mounting scheme, so in the final Green Reaper II design, the motors are mounted horizontally. The blade is mounted on the frame through a set of hinged brackets which act as a height adjustment feature of the mower. The hinged brackets are attached to its rotating fulcrum in between a set of binding nuts. The binding nuts proved too weak to withstand the torque exerted on the brackets under the weight of the cutting blade.



**Figure 9:** Green Reaper II Frame Design Evolution

### *Weather Enclosure*

In order to allow for operation in inclement weather conditions, a waterproof weather enclosure was required for Green Reaper II. To save both time and due to budgetary concerns, a metal wheel barrow was purchased and modified to create a weatherproof covering. This is mounted to the frame using piano hinges to allow for easy access to the electronic subsystems.

### *Digital Encoders*

A pair of digital encoders are mounted directly onto the drive wheels using a custom frame. These encoders allow the lawnmower to drive in a straight line, while simultaneously measuring the distance traveled by the mower during the dead reckoning navigation algorithm. Figure 10 shows the encoder mounted on the drive wheel.



**Figure 10:** Drive Wheel Encoder

### *Space Saving Level Design*

A level design was made to provide the mower with ample storage room for the necessary components. The leveling stages were of three levels composed of three  $\frac{3}{4}$ " plywood section about 24" by 14". The sections were placed on  $\frac{1}{2}$ " threaded rods which pierced the sections at four corners and two sides through  $\frac{1}{2}$ " holes. A clearance for the height of a compartment existing between two of the sections was held by the use of  $\frac{1}{2}$ " PVC sections cut to length to match the desired compartment height. The ends of each rod were secured by a nut at the top plywood section and the bottom of the frame where the whole assembly was attached. This space-saving level design will be modified to a two-level design in the final frame and covering system.

### *Wheel Offsets*

Wheel offsets were assembled out of both commercially available and manufactured parts. The commercial parts were included to satisfy the geometry of a 3 inch wheel offset. The offset would have been much more expensive if a more traditional wheel offset was made out of a solid block of aluminum as many are. Each assembly consisted of two manufactured round aluminum plates of ½” thickness and four hexagonal ½” threaded steel spacers. The spacers were placed in between the two plates to create the suitable offset and bolted into place at through holes in the plates. The plates were manufactured using hole saws, drills and angular and radial measurements for accurate hole placement. The spacers allowed for a lighter and cheaper design. The spacers had a dual purpose: to widen the track of the mower (to increase maneuverability) and to adapt the four lug hub bolt pattern to the three lug wheel bolt pattern of the rugged aftermarket tires. Figure 11 shows a solid works visual of the wheel offset.



**Figure 11: Wheel Offset Design**

### *GPS Antenna and Compass Booms*

The GPS antenna and digital compass both are quite susceptible to Electro-Magnetic Interference (EMI). The mounting of the two sensitive components on the top of a boom avoids any interference from the high EMF source below, namely, the drive motors. In the future shielding can be made to protect the delicate EMI susceptible components from harm without the use of booms. Figure 12 shows the GPS and compass booms. In the final design, these will be lowered into a more low-profile design.



**Figure 12: GPS and Compass Mounting on Short Frame Prototype**

### *Mechanical Design Validation*

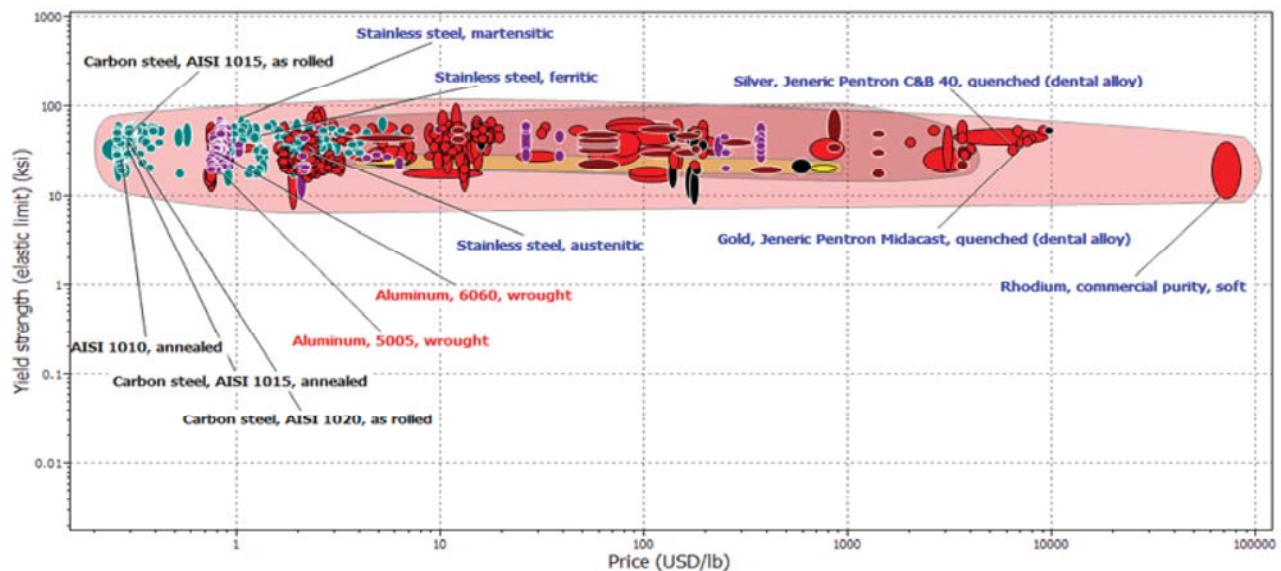
Calculations for validation purposes were used to show that the frame, which was constructed out of carbon steel, was adequate for use in the application. Equation 1 gives the formula used to calculate deflection which was used to relate the Elastic modulus to the load on the frame. The moment arm of the frame for deflection was deemed to be 24 inches or roughly half of the frame length wise. The maximum deflection and stress will occur at that mid-point length wise since it produces the maximum moment arm. The load was rated at 50 lbs, so as to produce an elastic modulus of  $61 \frac{kpsi}{in^2}$  necessary for a  $\frac{3}{8}$ " deflection with an available  $32.2 \frac{Mpsi}{in^2}$  available modulus in carbon steel. The modulus has a large 500 times safety factor. The strength was determined using Equation 2 and 3, and was found to have a large safety factor of 154 times since the calculated necessity was of 343 *psi* and the available strength of material was 53.7 *ksi*.

$$\delta_{\max} = \frac{Pl^3}{3EI} \quad (1)$$

$$M_{\max} = M\left(\frac{L}{2}\right) = -\frac{pL^2}{8} \quad (2)$$

$$\sigma_{\max} = \left| M_{\max} \right| \frac{c}{I} = \left| \frac{pL^2}{8Z} \right| \quad (3)$$

Materials selection methods were used to show the validity of a decision based on mechanical engineering experience. The decision to choose carbon steel was on the basis of low price. The materials selection graph seen below in Figure 13 shows that among other materials, plain carbon steel is one of the cheapest materials with sufficient strength. This step was performed for validation purposes more and not necessarily to devise creative material selections, since carbon steel was also the most readily available material.



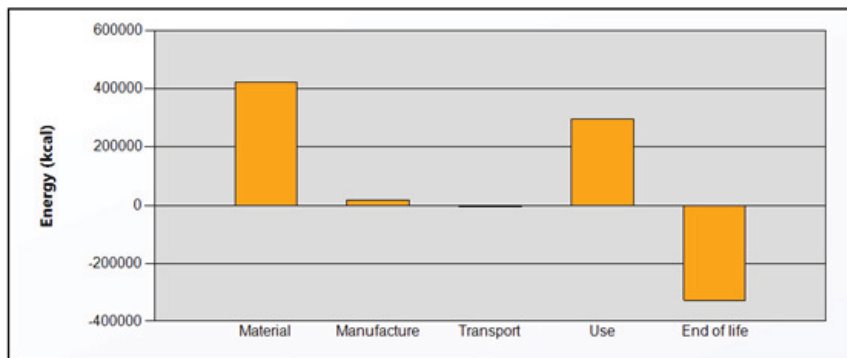
**Figure 13:** Frame Material Selection

### *Design Environmental Impact*

The materials used on the project also included amounts of aluminum in the construction of the mower. The combination of frame steel, aluminum, and an estimate amount of steel peripherals was included in an audit of the estimated environmental impact of the design as seen in Figure 14. This audit suggests impact based on estimates from the prototypical design and not

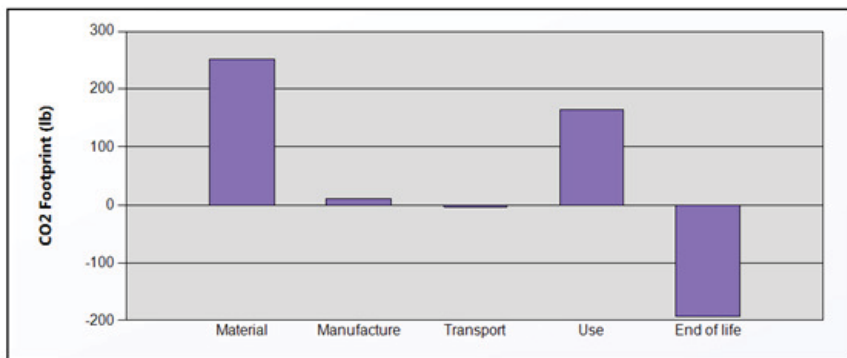
necessarily the impact of a mass producible design. The environmental impact audit shows that the majority of the impact to the environment is the production of the material, which is done in ore refineries and foundries. Also of note, the end of life column shows that upon recycling the damage to the environment has an environmentally advantageous offset associated with recycling. This effect is due to the fact that recycling omits the necessity for ore to be refined for new future material usage. However, the project's environmental impact is not directly affected by recycling, but helps offset indirectly the total material refining CO<sub>2</sub> and Embodied energy production on a macro level.

**Energy and CO2 Footprint Summary:**



**Breakdown by component**

Component	Energy (kcal)	%
Steel Bar	1.2e+05	28.5
Aluminum Plate	4.5e+04	10.6
Aluminum Extrusion	2.2e+05	52.9
Wood	8.2e+03	1.9
Steel Fasteners	8.8e+03	2.1
Steel Rod, and Components	1.7e+04	4.1
<b>Total</b>	<b>4.2e+05</b>	<b>100</b>



**Breakdown by component**

Component	CO2 Footprint (lb)	%
Steel Bar	87	34.4
Aluminum Plate	24	9.5
Aluminum Extrusion	1.2e+02	47.4
Wood	4.5	1.8
Steel Fasteners	5.1	2.0
Steel Rod, and Components	12	4.9
<b>Total</b>	<b>2.5e+02</b>	<b>100</b>

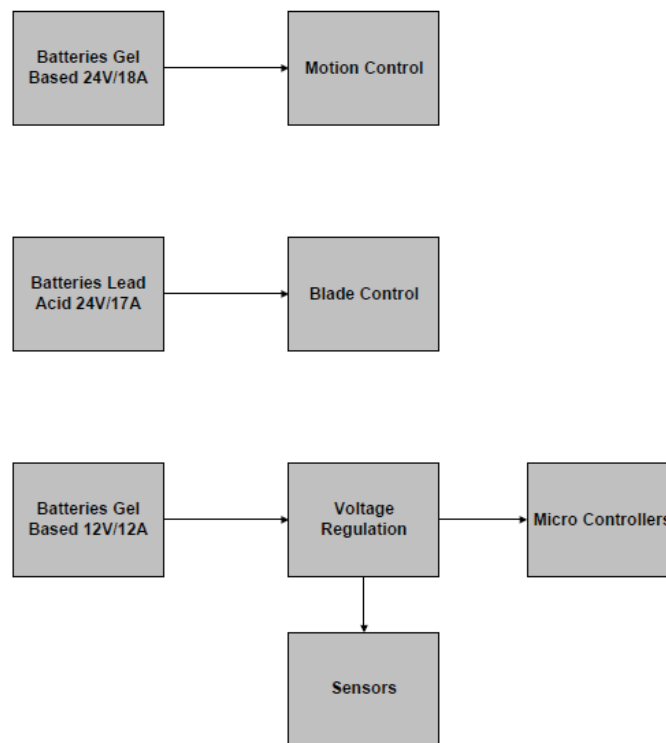
**Figure 14:** Estimated Environmental Impact of Green Reaper II

## *Electrical Subsystem*

The electrical design consists of six different subsystems, power, motion control, navigation, obstacle avoidance, mowing and safety.

## *Power Subsystem*

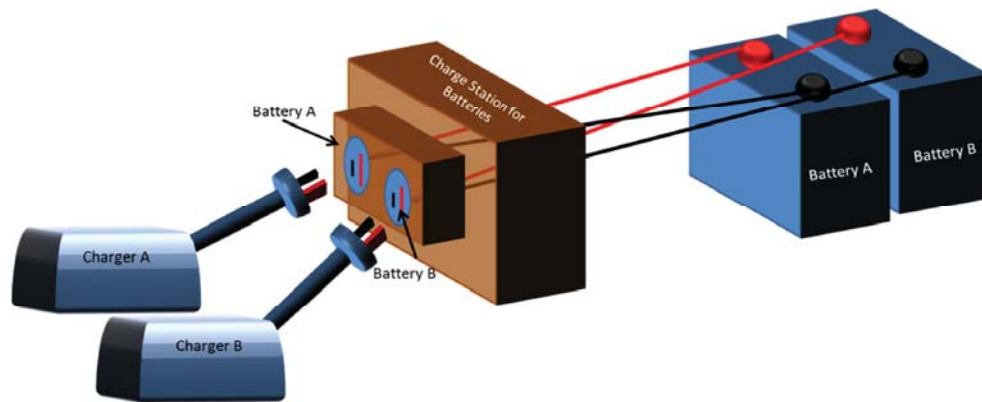
The power subsystem provides electrical power to the remaining five electrical subsystems. Each of these subsystems has different power requirements. Figure 15 shows a schematic view of the overall power distribution scheme for Green Reaper II.



**Figure 15:** Power Distribution Subsystem

The motion control subsystem is powered gel-based wheelchair batteries. The batteries are rated at 12 VDC with 18 amp hours and are wired in series to produce 24 VDC. The blade control subsystem is also powered by a set of lead acid based 12 VDC, 17 amp hour batteries connected in series to produce 24 VDC. A custom voltage regulation circuit is powered by separate gel-based 12 VDC, 12 amp hour batteries to provide power to the microcontroller and sensor systems.

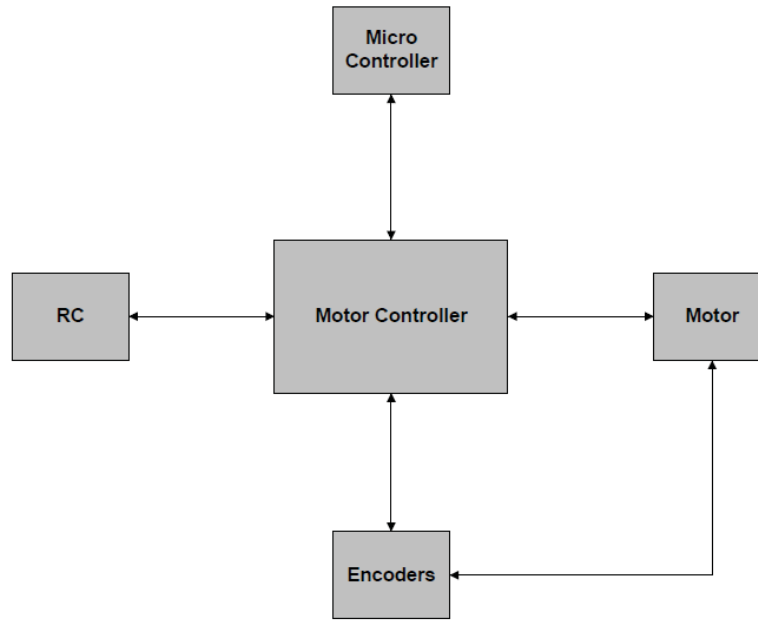
The batteries are charged through custom built charging dock, which is displayed in Figure 16. The battery charging dock was designed by modifying some commonly found items. These items consisted of a 12VDC battery charger, outdoor electrical outlets, and extension cords. Each battery was connected to an outdoor electrical outlet. These outlets were then mounted on the outside of the frame. The male sides of the extension cords were spliced in order to replace the stock clamps of the battery chargers. This made for very easy and efficient charging of the batteries. There are a total of four modified battery chargers and four charging stations. This allows for all the batteries to be charged simultaneously.



**Figure 16:** Battery Charging Dock System

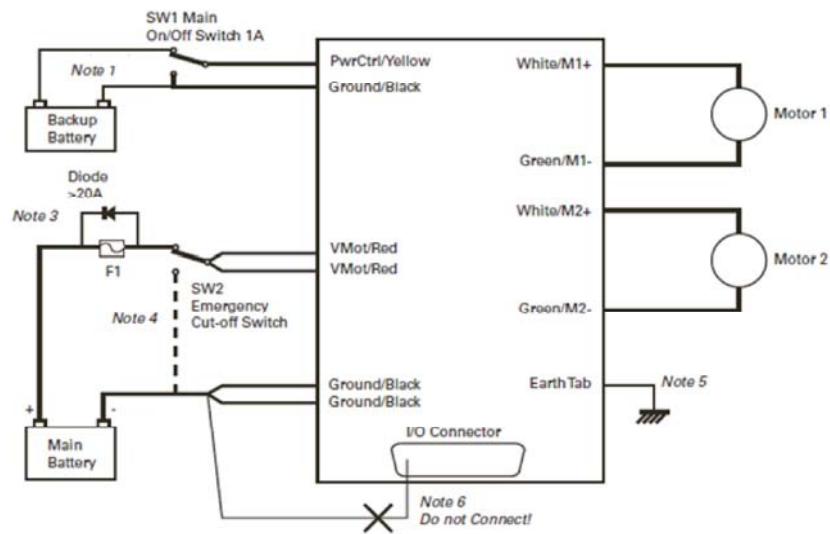
### *Motion Control Subsystem*

The motion control subsystem is a differential drive system composed of the Roboteq HDC 2450 motor controller, 2 Sunrise wheel chair motors, US Digital encoders and a Freescale HCS12C128 microcontroller. The mower switches to manual mode in which control is assumed using a Futaba radio controller. Figure 17 shows a block diagram of the motion control subsystem.



**Figure 17:** Motion Control Subsystem Block Diagram

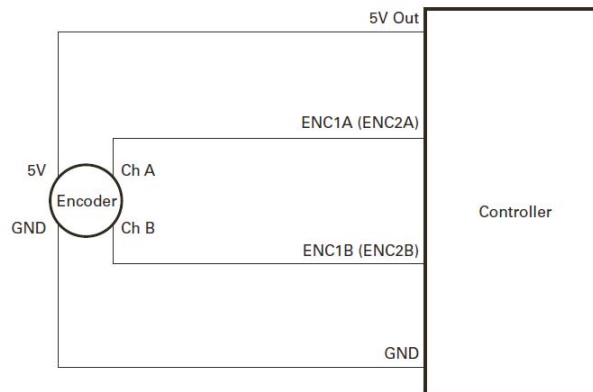
The Sunrise Medical wheelchair motors are 4 brush/24 volt motors that have a peak torque of 796 lb.-in. They can handle loads up to 300 pounds, which is quite sufficient to handle the weight of the mower. The motors have a peak stall current of up to 120 amps. The measured stall current was 109 amps. Figure 18 shows the wiring diagram of the HDC 2450 with wheelchair motors. The HDC 2450 motor controller was chosen as it can handle up to 150 amps of current and it can be programmed to only allow the motors to reach a certain current level while operating.



**Figure 18: Roboteq HDC2450 Wiring Diagram [5]**

The HDC 2450 can receive commands from the HCS12C128 microcontroller via an RS-232 cable. A string can be sent from the MCU to the HDC 2450 and command it to move the motors forward or backwards. The HDC 2450 uses ASCII characters to establish simple communication protocols with the MCU. The runtime commands vary from acceleration/deceleration to change in velocity and change in position.

The system also uses the H5 2-channel quadrature encoders from US Digital. There are two of these encoders that are attached to a freewheel system underneath the mower. The encoders communicate with the HDC 2450 via DB-25, The HDC 2450 handles the analysis of the encoder data and the MCU can request this data to provide the necessary feedback needed to keep the mower straight. Figure 19 shows the connection between a digital encoder and the HDC 2450.



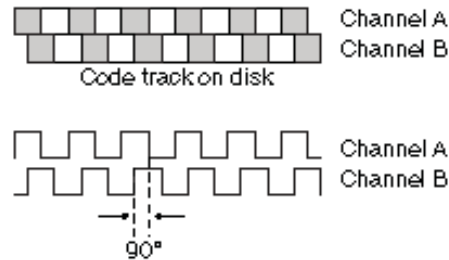
**Figure 19:** Interfacing the HDC2450 Motor Controller and Encoder [5]



**Figure 20:** US Digital H5 Encoder [REF]

The H5, shown in Figure 20, is a ball bearing optical shaft quadrature encoder which has dual channel output. It is set for an operation of 200 cycles per revolution of the encoder. The encoder is mounted to a free wheel which is underneath the frame of the mower. An encoder is located on the left and right side of the mower which will provide the necessary feedback to allow the mower to correct its drive path by ensuring that both drive wheels turn at the same speed while traversing a straight path. The encoder uses two code tracks with sections that are positioned 90 degrees apart. The dual output channels will indicate both the position and direction of rotation. Thus, if channel A leads B, then the wheel is spinning clockwise. If channel B leads A then the opposite occurs and the wheel is spinning counter clockwise. This encoder phase relationship is shown in Figure 21. The HDC 2450 will monitor the channels and be able to track the position

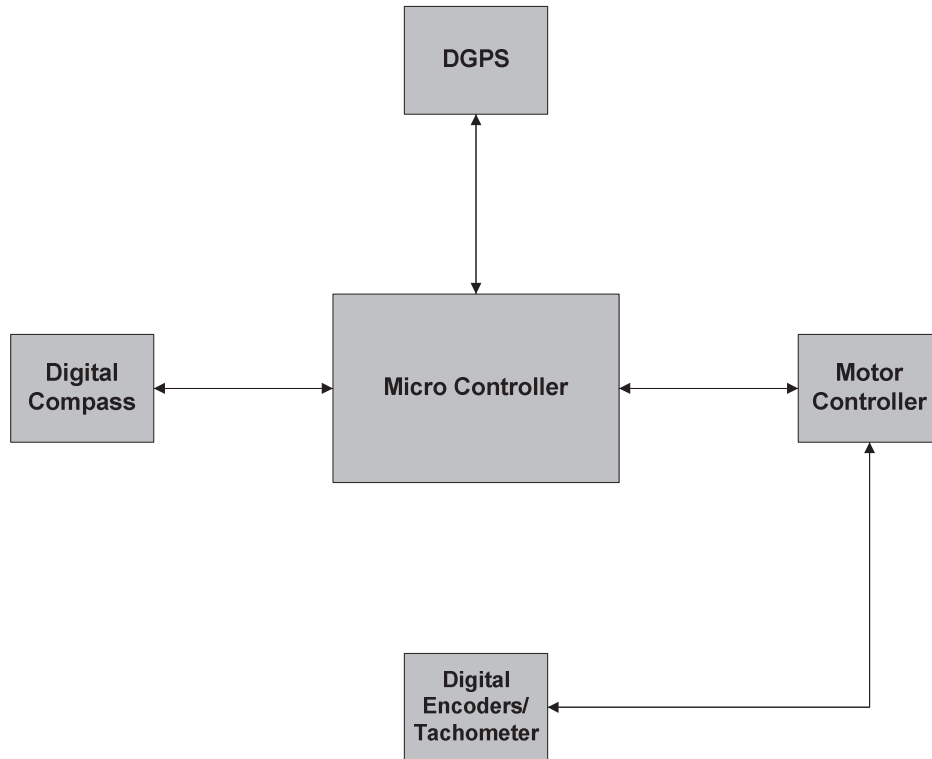
and rotation of the wheel. The HDC 2450's encoder interface can process 250k counts per seconds. As the counts produced on each transition of Channel A and Channel B. Thusly the HDC 2450 can operate with encoders the generate outputs up to 62,500 pulses per second. The MCU can request the encoder data from the HDC 2450 and make any necessary path corrections.



**Figure 21:** Encoder Channel Phase Relationship [14]

### *Navigation Subsystem*

Figure 22 shows a block diagram of the Green Reaper II navigation subsystem. The navigation subsystem consists of three main components in order to provide information about the mowers position and direction. These navigational components are a differential global positioning system (DGPS), a digital compass and a pair of digital encoders that in addition to providing straight path motion to the motion control subsystem also serve as digital tachometers.



**Figure 22:** Navigation Subsystem Block Diagram

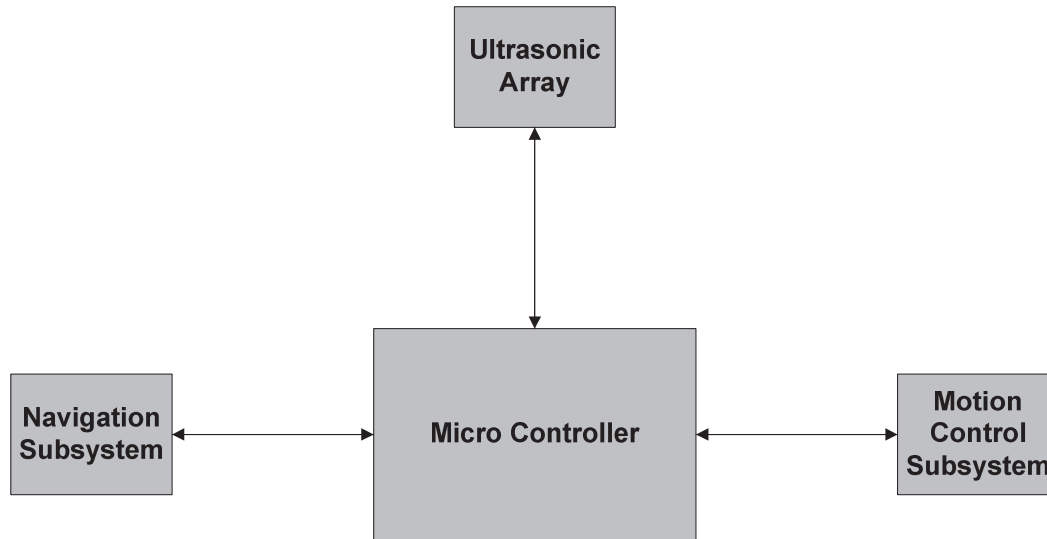
A Freescale HCS12C128 microcontroller coordinates all operation between the components of the navigation subsystem. A set of Trimble GPS SPS-852 GNSS receivers provides the necessary GPS information for the navigation subsystem. A Sparton Digital Compass SP3004D digital compass provides the navigation subsystem with bearing information needed for autonomous navigation. The US Digital H5 encoders from the motion control subsystem function as tachometers for accurate distance readings. Figure 23 shows the components that comprise the navigation subsystem.



**Figure 23:** Navigation Subsystem Components (From left to right, digital compass, DGPS and digital encoder)

### *Obstacle Avoidance Subsystem*

Figure 24 shows the block diagram of the obstacle avoidance subsystem. This subsystem consists of an array of ultrasonic sensors that interface with the Freescale HSC12C128 microcontroller. Based off of the readings from the ultrasonic array, the microcontroller interfaces with both the motion control and navigation subsystems in order to perform obstacle avoidance.



**Figure 24:** Obstacle Avoidance Subsystem

The ultrasonic sensor array consists of 3 Maxbotix XL-Maxsonar WR1 ultrasonic sensors, shown in Figure 25. These sensors are mounted at varying angles around the frame to provide for a wide viewing field for the obstacle avoidance system. These sensors are weather resistant and designed for deployment rugged environments. The WR1 is housed in a sturdy PVC housing which makes it weather resistant and allows to be attached to standard ¾” electrical PVC fittings. The sensors have a range 0-7.65 meters with a 0.01 resolution. The sensors can be powered from a 3.3 to 5 VDC. The sensors can gather range information in three different methods: analog, serial or PWM. All of these methods can be active at the same time. The analog output on pin 3 will produce a voltage proportionality of the distance measured. The sensitivity of this proportion is  $\frac{V_{CC}}{1024 \text{ cm}} \frac{V}{cm}$ . The serial output is formatted for RS-232 communication. The voltage ranges from 0 to  $V_{CC}$ . The serial pin can output the distance in centimeters without any conversion while the analog output must be converted in the code of the HCS12C128. Lastly, the PWM will output a pulse with a scale factor of  $58 \frac{\mu\text{s}}{cm}$ . The mower has five of these sensors mounted to it, there are three on the front and one on each side. All of the sensors cannot be on at the same time as they will interfere with each other and any readings of distance will be incorrect. Holding pin 4 on the sensor low will turn off the sensor; if it is left alone it will be held high and the sensor will operate. Using the HSC128C, the sensors can be multiplexed to cycle on and off so readings can

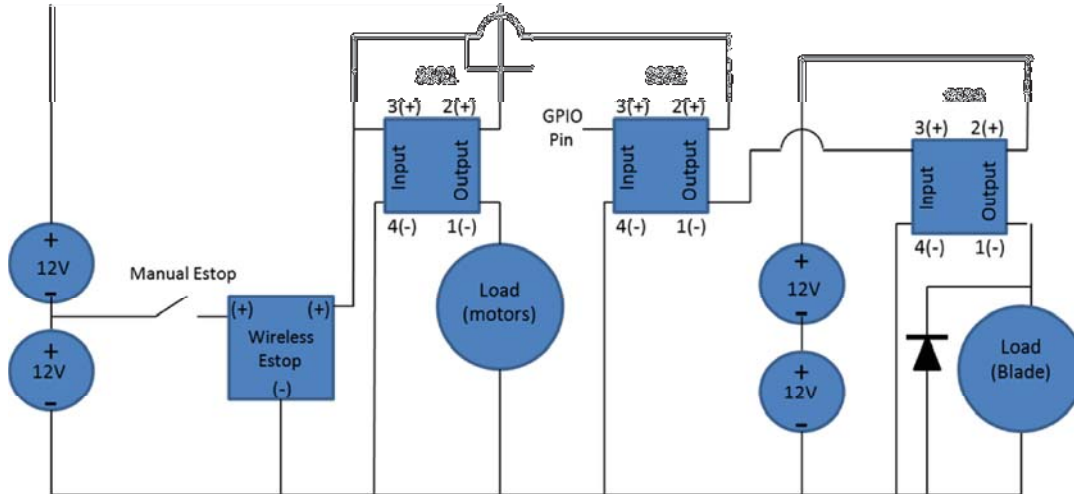
be taken without interference. The sensors are resistant to acoustic and electrical noise and can take stable readings in winds up to 55 mph. Each sensor is wired with ground and 5 volts from a voltage regulation circuit. Pin 4 of each sensor is connected to a GPIO port of the MCU, this control scheme will permit constant scanning of the sensor array. One GPIO will go high and turn on a sensor while the other four are held low. While the sensor is held high, a voltage reading is taken over the A/D port. After this process is finished, the MCU will pull this GPIO low and move to the next sensor and repeat the process. This will be a continuously refreshed process during the mowers operation.



**Figure 25:** Maxbotix XL-Maxsonar WR1 ultrasonic sensor

### *Safety Subsystem*

The safety subsystem is necessary to ensure that the autonomous lawnmower can be safely disabled at anytime. The safety subsystem consists of two parts; a manual emergency stop and a wireless emergency stop. The wireless emergency stop consists of aLogisys 12V 15AMP relay kit remote control. This was combined with the Crydom Solid State Relays (SSR) to develop the wireless emergency stop. The manual emergency stop is a simple switch with a large red top. The manual emergency stop and the wireless emergency stop are in series with the one of the Crydom SSR's. If either the manual or wireless emergency stop is activated, both the drive motors and the blade will be shut off. To reenergize both the manual and the wireless systems must be activated. Figure 26 shows a schematic view of the lawnmowers safety subsystem.



**Figure 26:** Safety Subsystem Schematic Diagram

The robot utilizes solid state relays (SSR) for switching high current loads. The D06D80 by Crydom is the SSR that was chosen for this purpose. It is rated to handle 80 amps continuous on the load side. The minimum turn on current is 1.6mA. These are used by the wireless emergency stop to interrupt the current to both motors. The other use for the solid state relays is in turning the blade on and off with the microcontroller.

### ***Mowing Subsystem***

The mowing subsystem consists of a commercial 19 inch Black and Decker cordless DC electric lawnmower blade and safety shroud. The mowing subsystem is connected through the safety subsystem to the microcontroller. A manual override switch is connected to the mowing subsystem to allow the blade to be turned on and off manually.

## Navigational Approach

Navigation of the Green Reaper II is accomplished through the integration of the power, motion control, navigation and obstacle avoidance subsystems.

Green Reaper II incorporates uses two navigational approaches in order to navigate the field. The first and most basic navigation method is dead reckoning. Dead reckoning is the process determining current position based on a known position and previous movements. To accomplish this, the Green Reaper II uses two digital encoders to measure the distance traveled by each drive wheel. The initial point is the fixed or known position. The Green Reaper II is then programmed to drive a specified distance, make a zero degree turn, and then drive again. A specific route can be preprogrammed in this manner. The advantages to this navigational method are that it is simple to program and to modify. The disadvantages are that error accumulates with distance traveled. The second navigational method the Green Reaper II uses for navigation is waypoint navigation. This method uses a Trimble differential GPS to drive from a current point to a specified point. It was initially thought that the Haversine formula would be needed to calculate the distance and bearing between two points in order to take the curvature of the earth into account.

This method was deemed unnecessary due to the small distances being traveled by the lawnmower. A flat earth approximation model was used in order to simplify the calculations being done by the microcontroller. The way it was done was to first read the data from the DGPS into the microcontroller, parse it into latitude and longitude coordinates which were then converted to decimal. These values are then converted from a string into decimal, and a conversion factor is used to normalize the values of latitude and longitude into the same units.

Once the latitude and longitude are in the same units the flat earth approximation can be used taking advantage of basic trigonometric identities. This results in a calculation for both distance and bearing, shown in Equation 6 and 7 respectively.

$$\text{Distance} = \sqrt{(\text{lat}_1 - \text{lat}_2)^2 + (\text{long}_1 - \text{long}_2)^2} \quad (4)$$

$$\text{Bearing} = \tan^{-1}\left(\frac{\Delta \text{long}}{\Delta \text{lat}}\right) \quad (5)$$

### *GPS Hardware Overview*

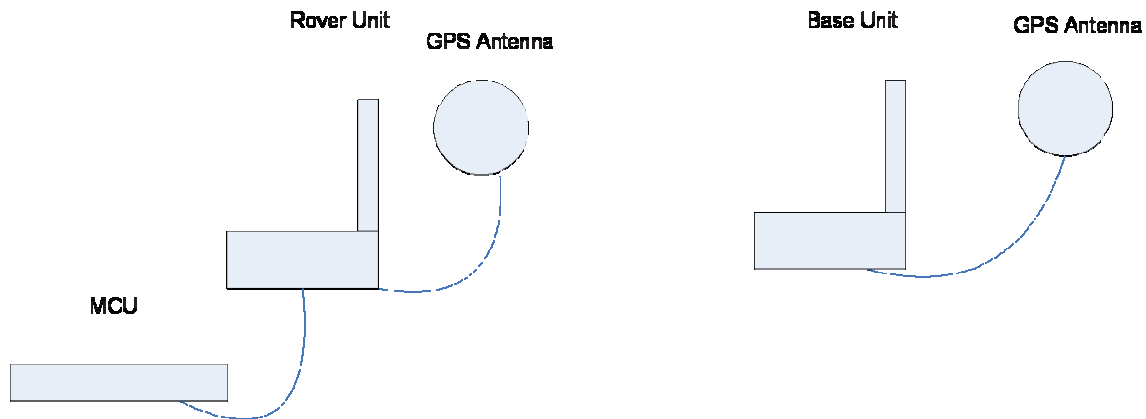
GPS (Global Positioning System) is a worldwide navigational system consisting of 24 satellites. These satellites send out a signal and receivers on the ground receive the signal from multiple satellites. The receiver unit then uses triangulation to determine a position. Green Reaper II uses Differential GPS (DGPS) to navigate. DGPS uses the same principles, but employs at least two receivers to gain a more accurate and precise position. One receiver is set up at a known position. It receives data from the GPS satellites and then determines any error or drift in the information from the satellite as compared to its known position. A second receiver that is at an unknown location receiving satellite data will then receive the correction data from the first receiver thereby increasing the accuracy and precision of the coordinates. A DGPS system with accuracy and precision to within an inch of a designated position, allows an autonomous unit to determine a heading and distance from one point to another. The current latitude and longitude of the vehicle can be recorded and saved as a waypoint. Multiple waypoints can be stored in the microcontroller allowing movement over a predetermined area. Safety boundaries can also be setup to stop the autonomous lawnmower if it moves outside a set area.

Each SPS-852 Trimble units used for Green Reaper II can be configured as a base or a rover unit. To set a unit to “base” one must manually select the mode of operation on the front panel of the Trimble unit. Once the mode of operation has been established, the base station coordinates can be manually set or an option is given to select the current coordinates that the GPS is indicating for its current location.

The SPS-852 unit is very versatile and can be configured using any computer with an Ethernet port. Each unit has an IP address that you can type into the address bar of an internet browser to access and program it. Programmable aspects of the unit include setting up each I/O port for serial communication such as baud rate, flow control, and data management. The output data is also configurable and it can be set to NMEA format or GSOFF format. NMEA format offers a range of options as to what strings of information it can output and multiple selections can be made.

The latitude and longitude of the current position of the rover is then compared with the longitude and latitude of a saved waypoint. The distance in meters is calculated to the waypoint

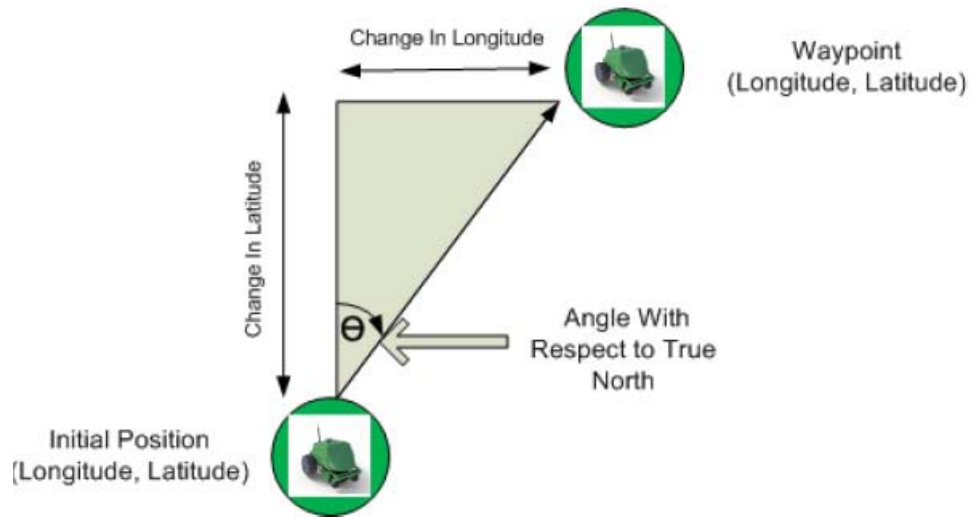
and the heading from true north to the waypoint is determined. This information is updated at 10 Hz and is continuously provided by the unit. The serial data is sent at a baud rate of 115,200 via an RS-232 connection to the microcontroller. Figure 27 shows the DGPS configuration used on Green Reaper II.



**Figure 27:** Green Reaper II DGPS configuration

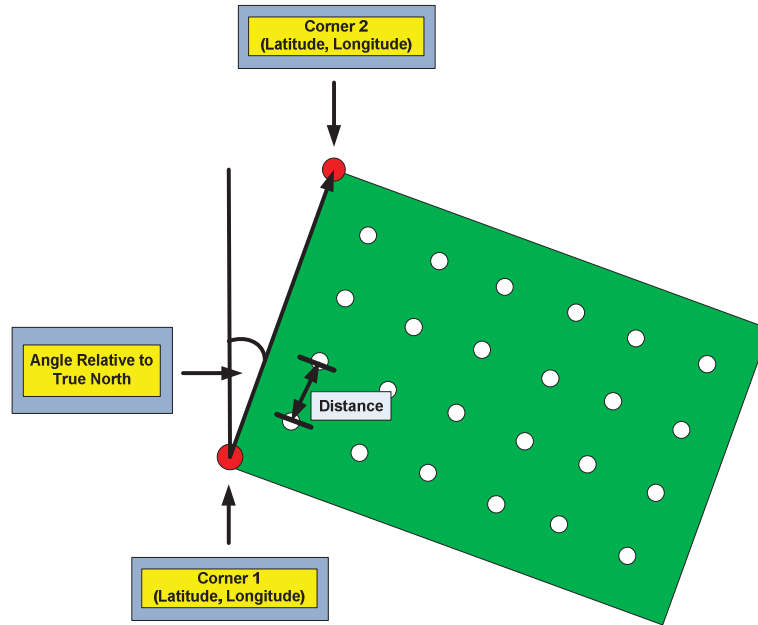
### *GPS Algorithm Overview*

The DGPS allows the lawnmower to navigate from its current position to a series of waypoints on the playing field. To accomplish this, a vector from the current position to the waypoint is generated using basic trigonometry. The microcontroller (MCU) then calculates the angle of the vector with respect to true north. The angle that the MCU generates allows the lawnmower to know the direction of the waypoint relative to its current position. The computed angle combined with the actual direction established by the compass allows the mower to constantly point towards the waypoint. Using similar trigonometric principles, the MCU determines the distance from the lawnmower's current position to the waypoint. The calculated distance tells the mower when it has arrived to the waypoint. Using the distance and bearing calculations, the lawnmower is able to consistently point towards the waypoint and determine when it has reached the destination as shown in Figure 28.



**Figure 28:** GPS Waypoint Calculation

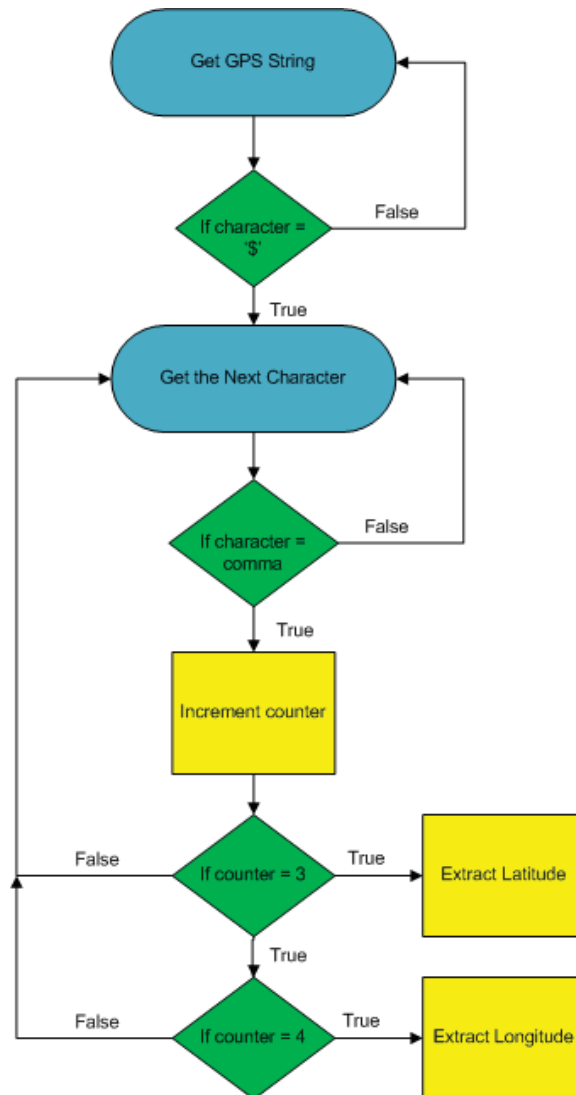
In addition, the team wanted to avoid arriving at the competition and creating each individual waypoint manually. Instead, the team was able to generate waypoints automatically using the MCU. The only data required to create the waypoints is the latitude and longitude coordinates of two corners of the playfield and the distance between each waypoint. With the two corners of the field, the MCU produces a vector between the two points then determine vector's angle with respect to true north using trigonometric properties. This allows the lawnmower to know the orientation of the field. The optimal distance between each point is determined through testing. Once the distance is defined, the MCU will utilize three known variables, which are the initial position, the distance between waypoints and the orientation of the field relative to true north as shown Figure 29. Using these known variables, the waypoints may be generated by using basic trigonometric properties.



**Figure 29:** Data Derivation from Field Orientation with Respect to True North

### *GPS Support Code*

The first step to coding the GPS algorithm is to begin reading in the GPS string. The GPS delivers data packets via RS232 serial communication. The GPS format is read using the NMEA standard. The only information needed is the RMC data string containing the latitude and longitude position of the rover in order for Green Reaper II to navigate. A flow chart of the GPS algorithm is shown in Figure 30.

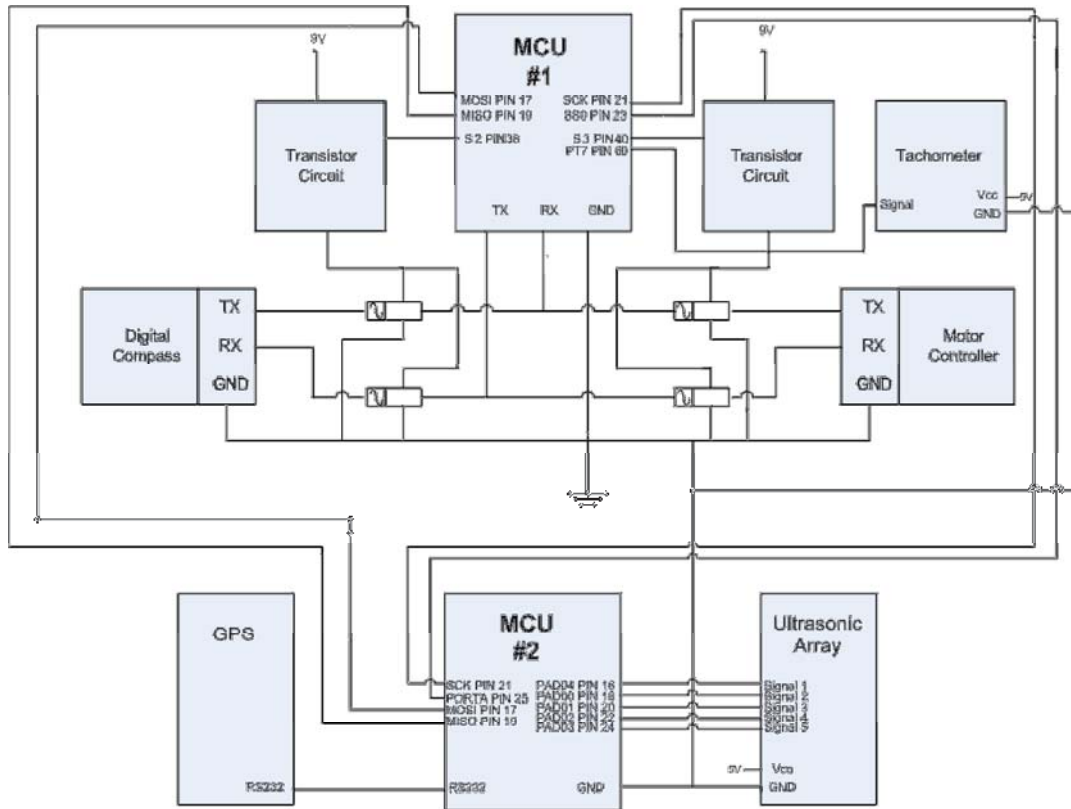


**Figure 30:** GPS Algorithm Flowchart

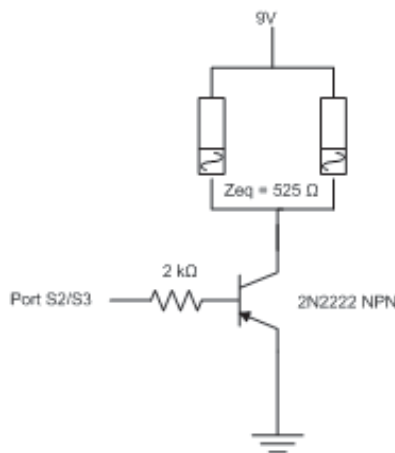
The next phase converts the latitude and longitude positions from degrees, minutes, seconds, etc. to a decimal value. To convert the coordinate to decimal degrees, the minutes and seconds are converted to its equivalent value in degrees then added to the degrees. Knowing that a minute is equal  $1 \text{ degree}/60$  and a second is  $1 \text{ degree}/3600$ , the next divisor being  $60^N$ , the conversion to degrees can be easily computed as shown in Equation 6.

$$DD = \text{degrees} + \frac{\text{minutes}}{60} + \frac{\text{seconds}}{60} \quad (6)$$

Following implementation of the GPS algorithm, a directional bearing is assumed by Green Reaper II using the digital compass of the navigation subsystem. The compass utilizes SCI communication between itself and the HCS12C128 microcontroller. Both the digital compass and Roboteq motor controller are multiplexed using one SCI, RS232 port to the microcontroller. This RS232 standard communicates within  $\pm 12$  volt logic levels. A custom multiplexing circuit and data cables were built for connection purposes. The two custom data cables cross the transmit pin and receive pin between each device while maintaining ground potential. The multiplexing circuit consists of a series of relays, transistors and resistors. This circuit multiplexes these devices by enabling the specific transmit and receive pin of the device of interest. Only the enabled transmit and receive pins of one device will communicate with the microcontroller at one time.. Figure 31 shows a global view of the system, and while Figure 32 shows the schematic of the transistor circuit used for multiplexing.



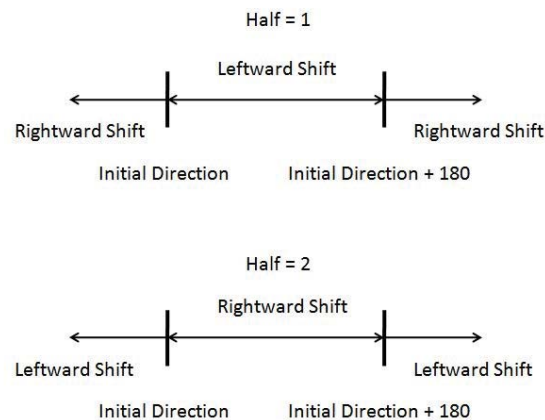
**Figure 31:** MCU and Navigational System Integration



**Figure 32:** Transistor Multiplexing Circuit

The digital compass in conjunction with the pair of digital encoders aids the lawnmower to navigate and remain on a fairly straight path. The algorithm responsible for this behavior is very straightforward. The only evident complication within the algorithm stems from mathematically

retaining all angle values lower than 359.9 degrees. The digital compass only reads values between 0 and 359.9 degrees. So any degree values before zero or beyond 359.9 degree needed to be converted to its equivalent degree value within 360 degrees of rotation. All angles must remain within those boundaries in order for the compass to correctly evaluate each angle. Otherwise, the digital compass will not recognize a particular angle though it may have an equivalent readable angle between 0 and 359.9 degrees. The digital compass keeps the lawnmower navigating straight by storing its initial direction and then continually comparing its new direction to the initially stored direction. This comparison of new bearing versus the bearing of interest produces the needed logic for the motor controller in making the appropriate navigation changes, whether it needs to veer left or right in order to remain straight. The algorithm begins with an understanding of the unit circle except this particular unit circle increases in angle values in the clockwise direction. From the unit circle perspective, this basically causes a flip of the quadrants upon the horizontal axis. This circle is now divided into two halves, top and bottom. These halves are only needed to indicate upon which half of the circle the initial direction was taken. This information helps with the preceding mathematics in order for the following read data angles to remain between 0 and 359.9 degrees. The calculations for each half dictate the angles differently and are shown in Figure 33.



**Figure 33:** Motor Correction Logic for Digital Compass

As shown, depending upon which half of the circle the initial direction fell on will determine which calculations will be performed. For example, if the initial direction happened to be 45 degrees then the circle would now be split between 45 degrees and 225 ( $45 + 180$ ) degrees, these

calculations being in conjunction with the initial direction falling upon the bottom half of the circle. Following the figure, if the new bearing read by the digital compass was now arbitrarily 90 degrees then it would definitely need to shift left since 90 degrees lies on the right side of 45 degrees. And 90 degrees falls between 45 and 225 degrees which constitutes for a leftward shift. The same exact logic is repeated for the other half except 180 is subtracted from the initial direction in order to keep the incoming angle values within boundary. Also, the logic for the left or right shift was reversed due to the orientation of the circle with the angles increasing along the clockwise direction.

### *Navigation around Obstacles*

When the ultrasonic sensor arrays detect an obstacle in the playing field, an obstacle avoidance algorithm is triggered. This algorithm causes Green Reaper II to abandon its standard dead reckoning navigational approach and to reduce the travel distance to avoid the obstacle. The algorithm then marks the area of the field that will be uncut due to the obstacle avoidance in order to return to that area later.

## **Microcontroller System Integration**

The HCS12C128 MCUs have domain over a group of subsystems. MCU 1 handles the motor controller, tachometer, encoders and digital compass while MCU 2 handles the GPS navigations and the ultrasonic sensors. Each MCU will communicate over SPI protocols and each MCU will communicate with the peripherals over SCI protocols. Unique software is flashed to each MCU with the proper algorithms to direct the mower through the field. Figure 34 displays the logic that the mower will follow as it navigates the field.

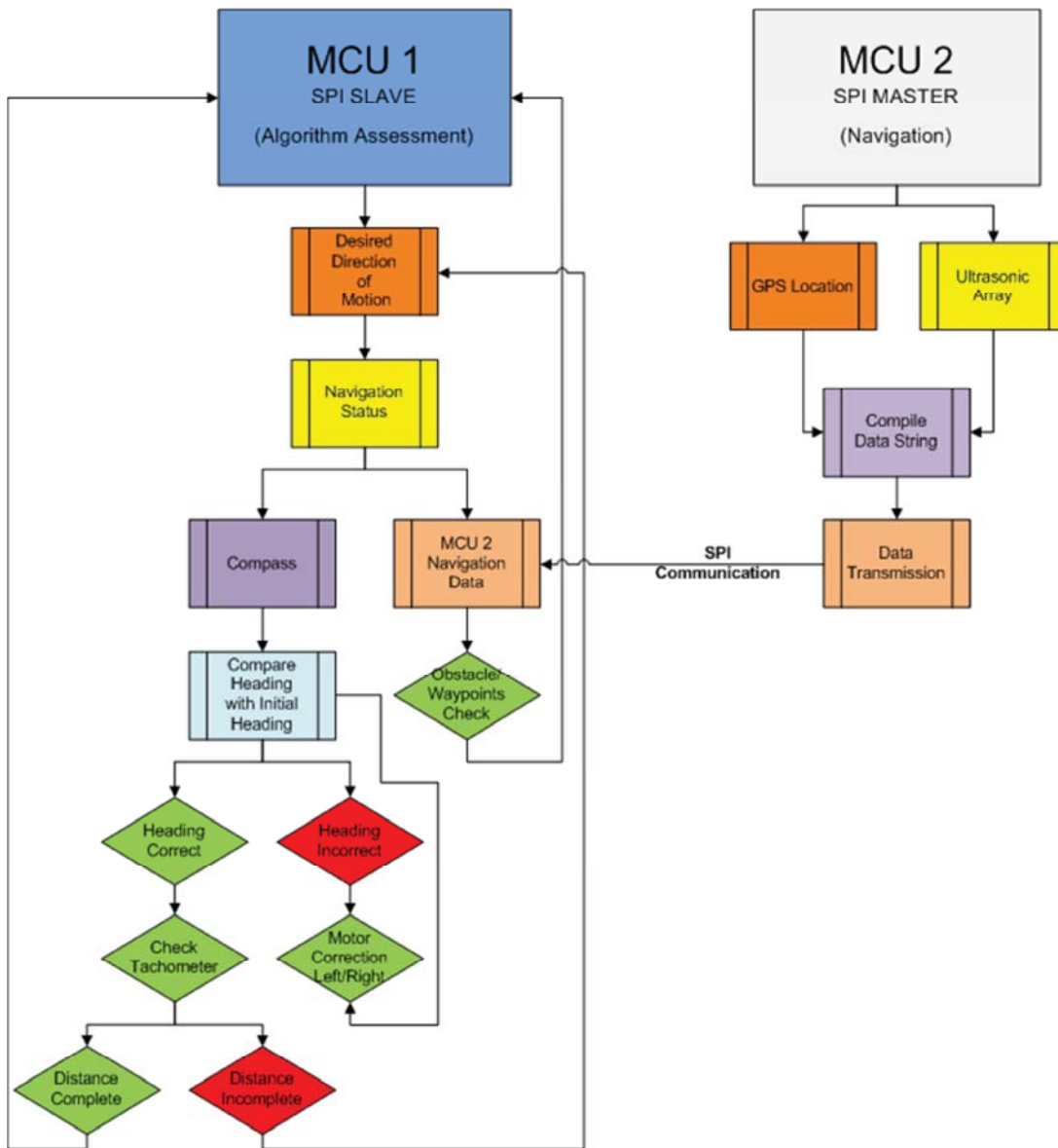


Figure 34: Microcontroller Software Integration Flowchart

## Lessons Learned and Problems Encountered

Over the course of the projects there have been numerous problems but each of these problems provided a learning opportunity. Initially, the issues with computer hardware and software slowed progress down. The decision was made to go with micro controllers, as the team had previous successes with the units and felt confident in using them again. In the future, LabView should be considered as it will provide more processing power and the possibility to integrate more advanced components into the design. Planning and time management became an issue for the team. Even though there was a team hierarchy with a project manager and defined team roles, the burdens of a regular class load and poor time management push the team behind schedule. With hindsight, the team members should hold each other more accountable for their work and production. As far as hardware issues are concerned, there was a problem with only using the digital compass to keep the mower on a straight path. The compass could not keep the mower going in a straight line. It could correct the heading but the mower would be on a parallel path to the original. To overcome this issue, dual encoders were added to the mower. Using the compass in unison with the encoders has produced a straight path with the correct heading.

Some of the lessons learned with this project are as follows:

- There are a multitude of events and problems that occur in field testing that cannot be found in bench testing a system.
- The integration of sub systems into a final product needs to occur in steps and they need to be prioritized.
- The initial concept and design needs to be as simple as possible and then when it is achieved, more can be added to it.
- A system such as Green Reaper II requires more processing power that the team planned for, for future development, the microcontroller system should be replace by a PC-based control system.

## **Future Work**

Looking forward, the project should move from microcontrollers to a netbook or PC-based system. As previously stated, this will add more processing horsepower to the design. Also, introducing a LIDAR laser range finder will allow for more accurate object detection as it has an extremely wide viewing range and it is contained in a single device. It was also discovered that the ultrasonic array is unable to detect the dynamic obstacle due to no sonic reflections from the soft dog.

## Conclusion

The objective of this project was to produce an autonomous lawn mower that could compete in the 8<sup>th</sup> Annual ION Robotic Lawn Mower Competition. Electrically, the fundamental basis of the mower is the use of the encoders and the tachometer. These two components will provide the feedback necessary for the mower to drive straight and allow it to calculate its linear distance travelled. The team is confident with these two components Green Reaper will be able to drive autonomously. With the addition of the other elements: ultrasonic, DGPS and the digital compass, the mower will have all necessary components that competition encourages its participants to investigate and build upon. As far as the mechanical aspects, it was found that the 3-D modeling steps taken functioned as a three pronged advantage. The drawings allowed for ease of construction and machining, for manufactured and assembled parts. The 3-D design helped the team communicate ideas through the use of 3-D renderings. Also, the 3-D renderings made for a great way to communicate with the public on the status of the teams design. This can be considered an advantageous component of the aforementioned marketing objective. The team has gone through two versions of the mower and has learned that designing a complete system is quite challenging. The challenges have manifested as personnel issues as well as technical problems. The team has worked in numerous endeavors: technical research, system design, fund raising, team building and field testing. All of these endeavors will be seen again as the team members go their separate ways into the professional world of engineering but by participating in this event the members have learned lessons in engineering and in how to deal with the stresses and complications of technical projects.

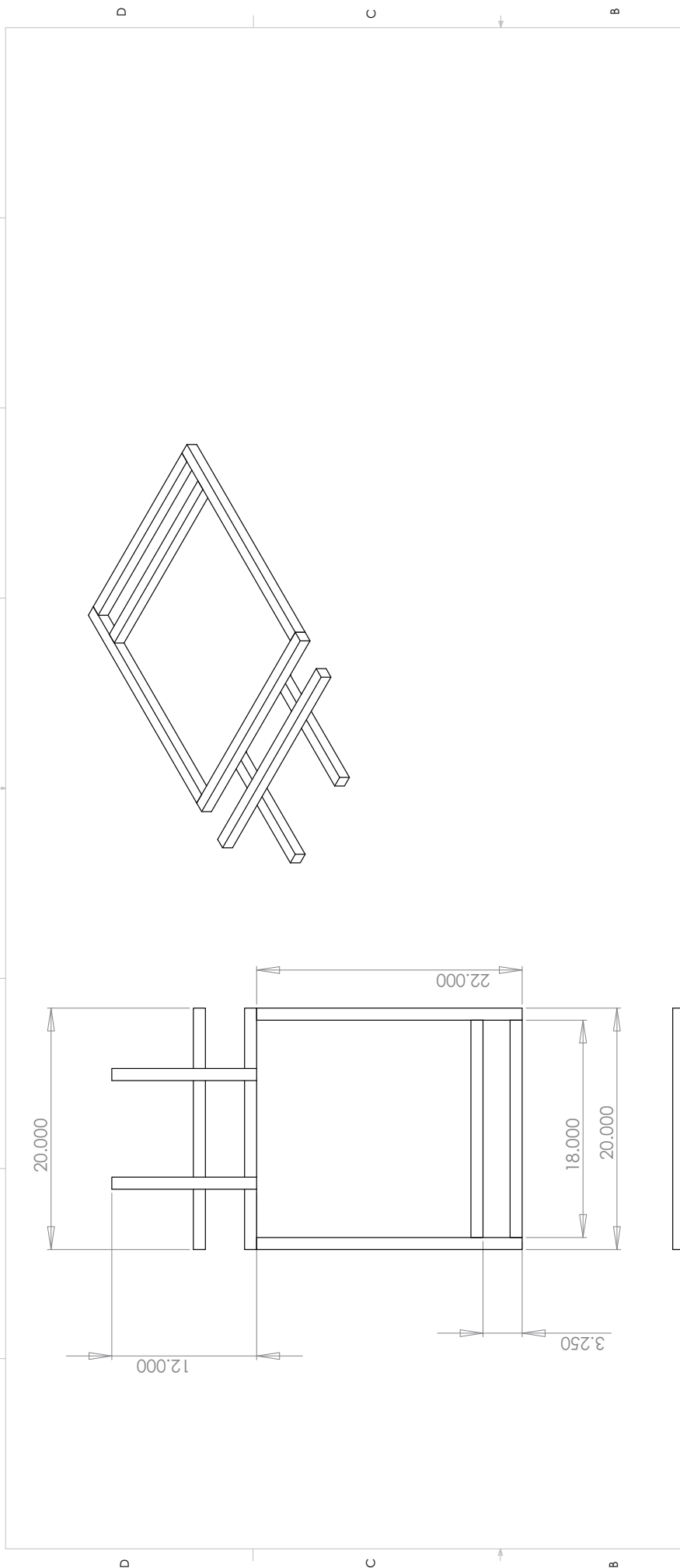
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## **Appendix I – Schematic Diagrams**

The following pages contain the schematic diagrams of the electrical and mechanical components of Green Reaper II.

1 2 3 4 5 6 7 8



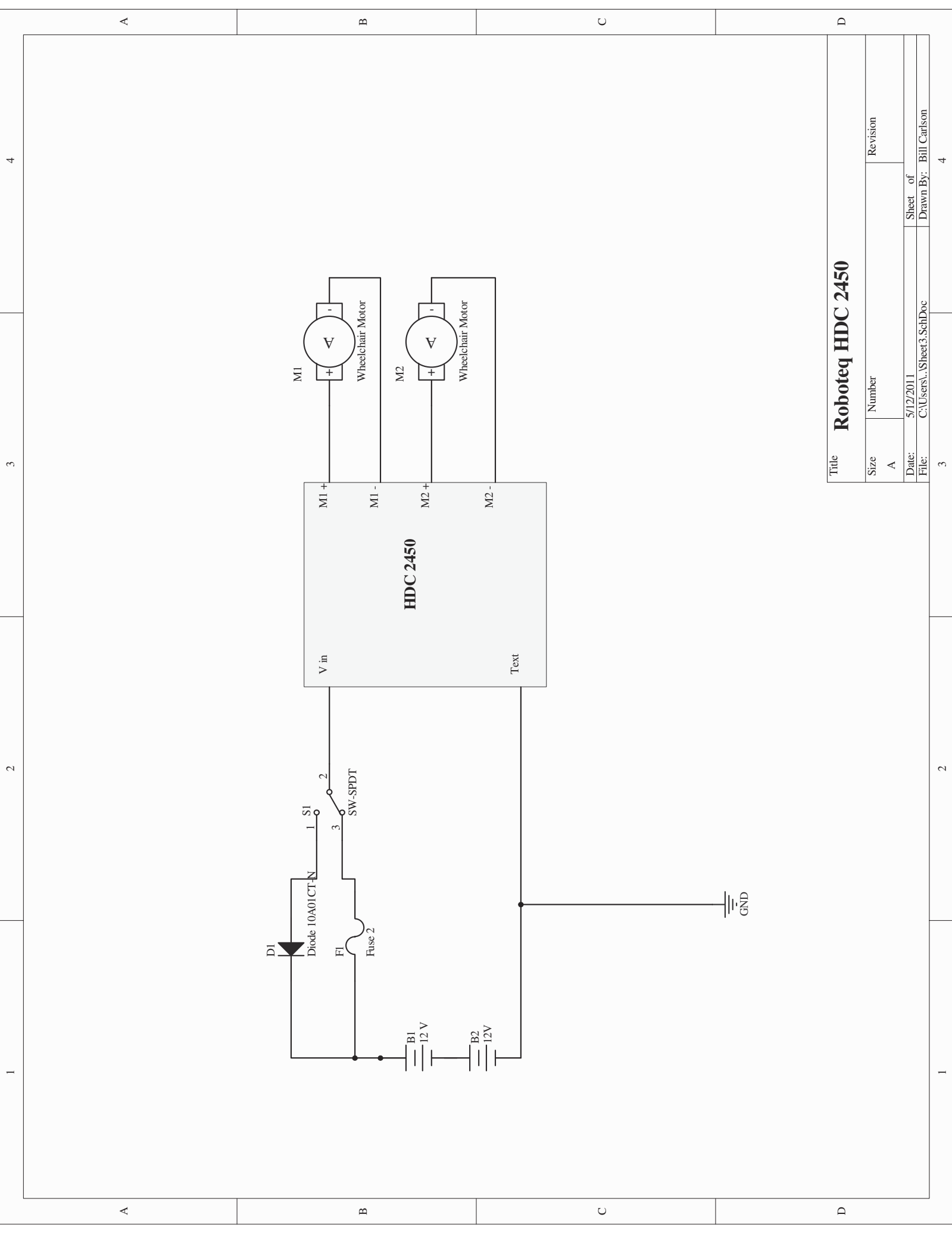
ITEM NO.	PART NUMBER	REV
1	1" X 1" X 20 Square Tube	2
2	1" X 1" X 22 Square Tube	2
3	1" X 1" X 18 Square Tube	2
4	1" X 1" X 12 Square Tube	2

UNLESS OTHERWISE SPECIFIED:  
 DIMENSIONS ARE IN INCHES  
 TOLERANCES:  
 FRACTIONAL: ± .005  
 ANGULAR: MACH ± .05 BEND ± .05  
 DECIMAL: ± .005  
 THREE PLACE DECIMAL ± .001  
 Q. A.  
 INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL  
 FINISH  
 NEXT ASSY USED ON APPLICATION  
 DO NOT SCALE DRAWING

**PROPRIETARY AND CONFIDENTIAL**  
 THE INFORMATION CONTAINED IN THIS DRAWING IS THE PROPERTY OF INSERT COMPANY NAME HERE. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF INSERT COMPANY NAME HERE IS PROHIBITED.

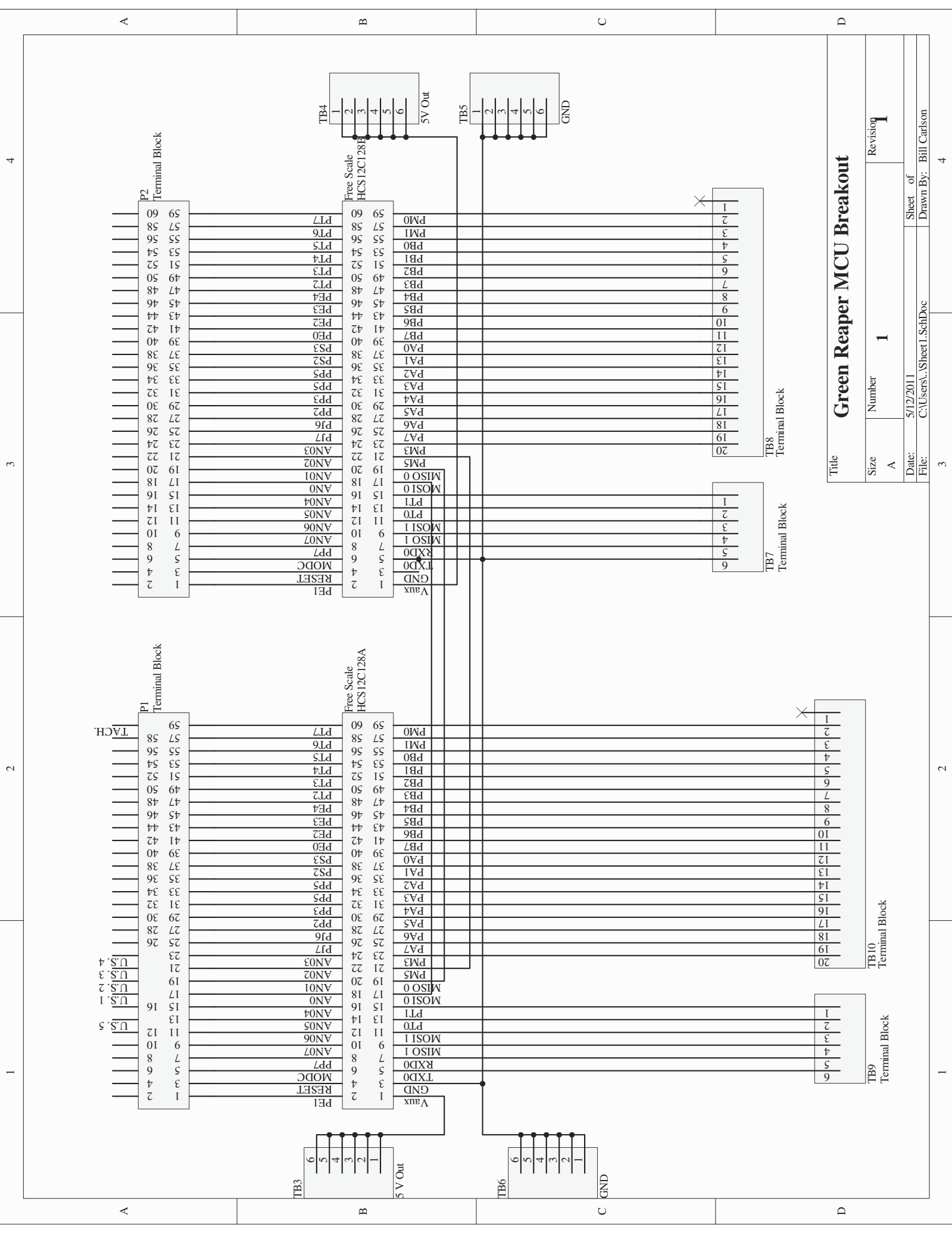
TITLE:  
**FRAME W/ CUT LIST**  
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**B** Frame cut list  
 SCALE: 1:8 WEIGHT: SHEET 1 OF 1

D C B A



**Title**  
**Roboteq HDC 2450**

Size	Number	Revision
A		
Date:	5/12/2011	Sheet of
File:	C:\Users\A. Sheet3.SchDoc	Drawn By: Bill Carlson



Title			Revision		
Green Reaper MCU Breakout			1		
Size	Number	Revision			
A	1				
Date:	5/12/2011	Sheet of			
File:	C:\Users\A.SchDoc	Drawn By: Bill Carlson			

1 2 3 4

A B C D

P1 Terminal Block

59	PT7
58	PT6
55	PT5
53	PT4
54	PT3
52	PT2
49	PT1
47	PT0
48	PT7
46	PT6
45	PT5
43	PT4
44	PT3
42	PT2
41	PT1
40	PT0
39	PT7
38	PT6
37	PT5
36	PT4
35	PT3
34	PT2
33	PT1
32	PT0
31	PT7
30	PT6
29	PT5
28	PT4
27	PT3
26	PT2
25	PT1
23	PT0
21	PT7
19	PT6
17	PT5
16	PT4
15	PT3
13	PT2
11	PT1
9	PT0
7	PT7
5	PT6
3	PT5
2	PT4
1	PT3

P2 Terminal Block

59	PT7
58	PT6
55	PT5
53	PT4
54	PT3
52	PT2
49	PT1
47	PT0
48	PT7
46	PT6
45	PT5
43	PT4
44	PT3
42	PT2
41	PT1
40	PT0
39	PT7
38	PT6
37	PT5
36	PT4
35	PT3
34	PT2
33	PT1
32	PT0
31	PT7
30	PT6
29	PT5
28	PT4
27	PT3
26	PT2
25	PT1
23	PT0
21	PT7
19	PT6
17	PT5
16	PT4
15	PT3
13	PT2
11	PT1
9	PT0
7	PT7
5	PT6
3	PT5
2	PT4
1	PT3

Free Scale HCS12C128A

59	PM0
57	PM1
55	PB0
53	PB1
54	PB2
52	PB3
49	PB4
47	PB5
48	PB6
46	PB7
45	PA0
43	PA1
44	PA2
42	PA3
41	PA4
40	PA5
39	PA6
38	PA7
37	PM3
36	PM4
35	PM5
34	PM0
33	PM1
32	PM2
31	PM3
30	PM4
29	PM5
28	PM0
27	PM1
26	PM2
25	PM3
24	PM4
23	PM5
22	PM0
21	PM1
20	PM2
19	PM3
18	PM4
17	PM5
16	PM0
15	PM1
14	PM2
13	PM3
12	PM4
11	PM5
10	PM0
9	PM1
8	PM2
7	PM3
6	PM4
5	PM5
4	PM0
3	PM1
2	PM2
1	PM3

Free Scale HCS12C128A

59	PM0
57	PM1
55	PB0
53	PB1
54	PB2
52	PB3
49	PB4
47	PB5
48	PB6
46	PB7
45	PA0
43	PA1
44	PA2
42	PA3
41	PA4
40	PA5
39	PA6
38	PA7
37	PM3
36	PM4
35	PM5
34	PM0
33	PM1
32	PM2
31	PM3
30	PM4
29	PM5
28	PM0
27	PM1
26	PM2
25	PM3
24	PM4
23	PM5
22	PM0
21	PM1
20	PM2
19	PM3
18	PM4
17	PM5
16	PM0
15	PM1
14	PM2
13	PM3
12	PM4
11	PM5
10	PM0
9	PM1
8	PM2
7	PM3
6	PM4
5	PM5
4	PM0
3	PM1
2	PM2
1	PM3

TB8 Terminal Block

1	PT7
2	PT6
3	PT5
4	PT4
5	PT3
6	PT2
7	PT1
8	PT0
9	PT7
10	PT6
11	PT5
12	PT4
13	PT3
14	PT2
15	PT1
16	PT0
17	PT7
18	PT6
19	PT5
20	PT4

TB7 Terminal Block

1	PT7
2	PT6
3	PT5
4	PT4
5	PT3
6	PT2

TB10 Terminal Block

1	PT7
2	PT6
3	PT5
4	PT4
5	PT3
6	PT2
7	PT1
8	PT0
9	PT7
10	PT6
11	PT5
12	PT4
13	PT3
14	PT2
15	PT1
16	PT0
17	PT7
18	PT6
19	PT5
20	PT4

TB9 Terminal Block

1	PT7
2	PT6
3	PT5
4	PT4
5	PT3
6	PT2

TB3 5V Out

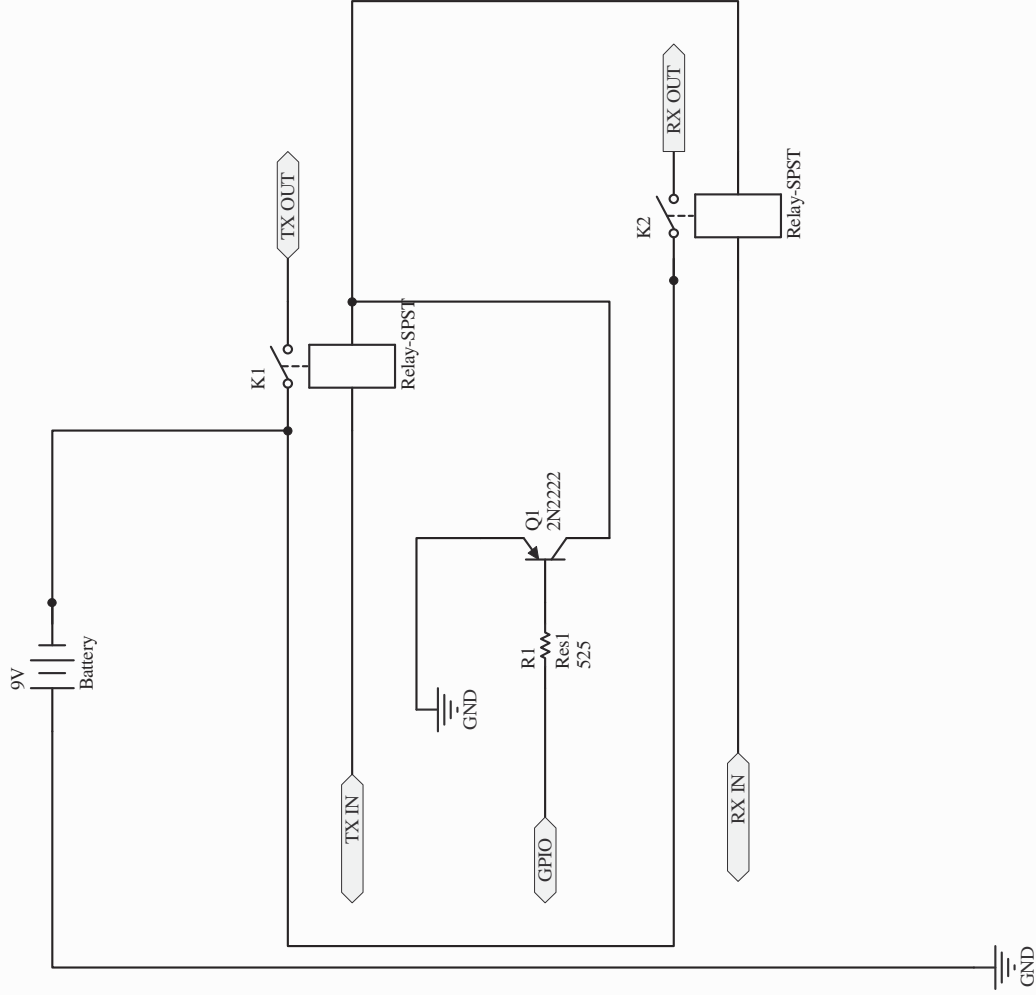
1	5V
2	5V
3	5V
4	5V
5	5V
6	5V

TB6 GND

1	GND
2	GND
3	GND
4	GND
5	GND
6	GND

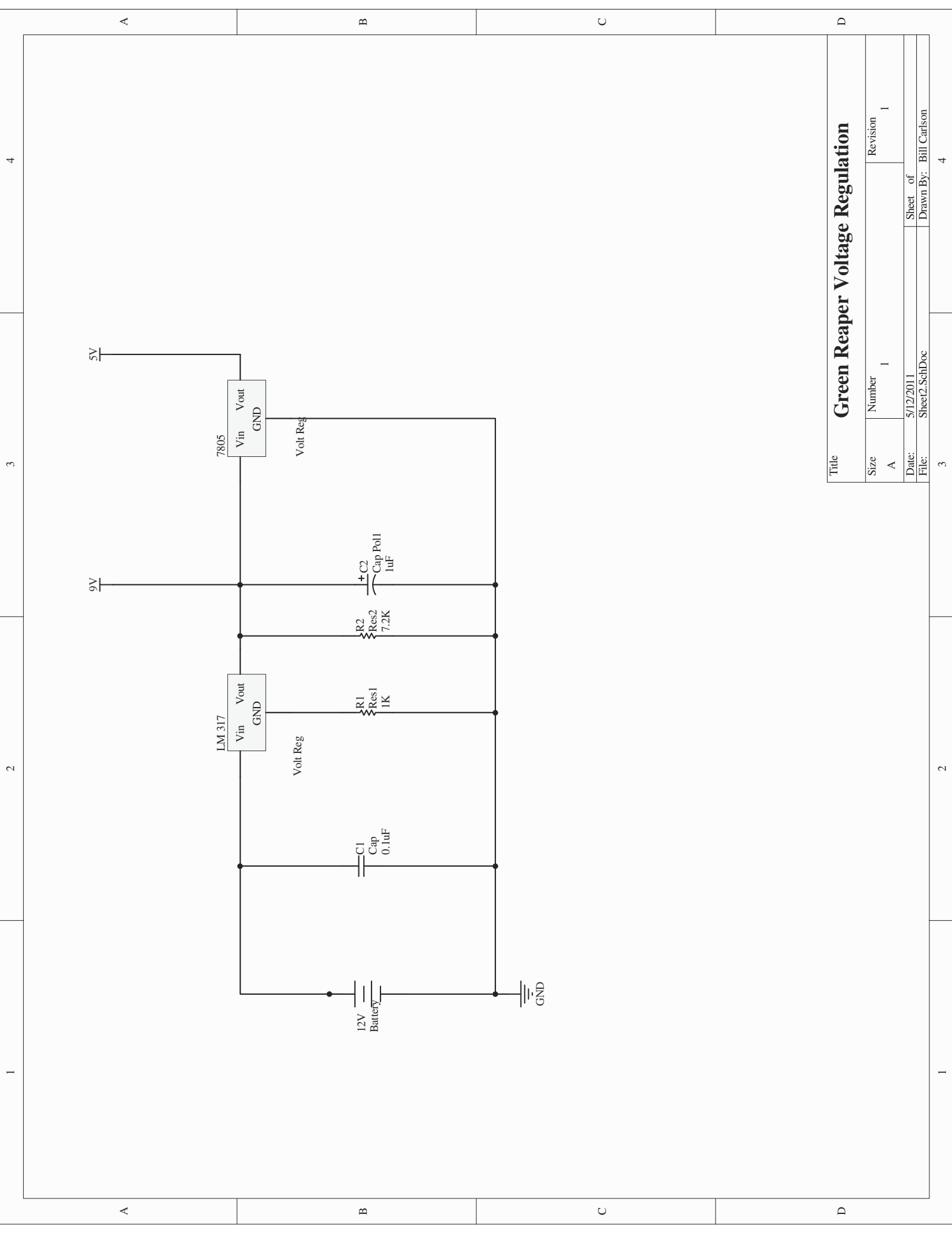
TB5 GND

1	GND
2	GND
3	GND
4	GND
5	GND
6	GND



**Green Reaper SCI Multiplexing**

Title		Green Reaper SCI Multiplexing	
Size	Number	Revision	
A	1	1	
Date:	5/12/2011	Sheet of	
File:	Sheet4.SchDoc	Drawn By:	Bill Carlson



Title			<b>Green Reaper Voltage Regulation</b>		
Size	Number	Revision			
A	1	1			
Date:	5/12/2011		Sheet	of	
File:	Sheet2_SchDoc		Drawn By:	Bill Carlson	