RED RAVEN

RED Robotic Autonomous Vehicle Engineered at Northridge

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Faculty Advisor Statement

I certify that the engineering design of the vehicle described in this report, RED RAVEN, has been significant and equivalent to each team member earning four semester hours of senior design credit for their work on this project.

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1. Introduction

The Intelligent Ground Vehicle team of the College of Engineering and Computer Science at California State University, Northridge (CSUN) is proud to present RED Robotic Autonomous Vehicle Engineered at Northridge (RAVEN). RED RAVEN is an entirely new and innovative IGV that was designed, built, and programmed during the 2010-2011 academic year at CSUN. Many of the innovations of RED RAVEN include a linked-bogie frame, drive wheel decouplers, a custom printed circuit board, a dynamic color detection algorithm, and a radial path planning algorithm.

1.1 Team Organization

The IGV project at CSUN is a senior design course that is associated with the Mechanical Engineering Department and spans over two semesters. It is comprised of five sub groups: Mechanical, Electrical/Power, Cognition/Motion Control, Vision, and Navigation/JAUS (Figure 1.1). Each sub group has a leader that structures the organization of the group and enforces open communication with the other groups so that proper integration is achieved. In addition, three team leaders are democratically nominated and include a project manager, treasurer, and secretary. These three leaders hold the responsibility of organizing team meetings, promotional events, registration forms, and finances.

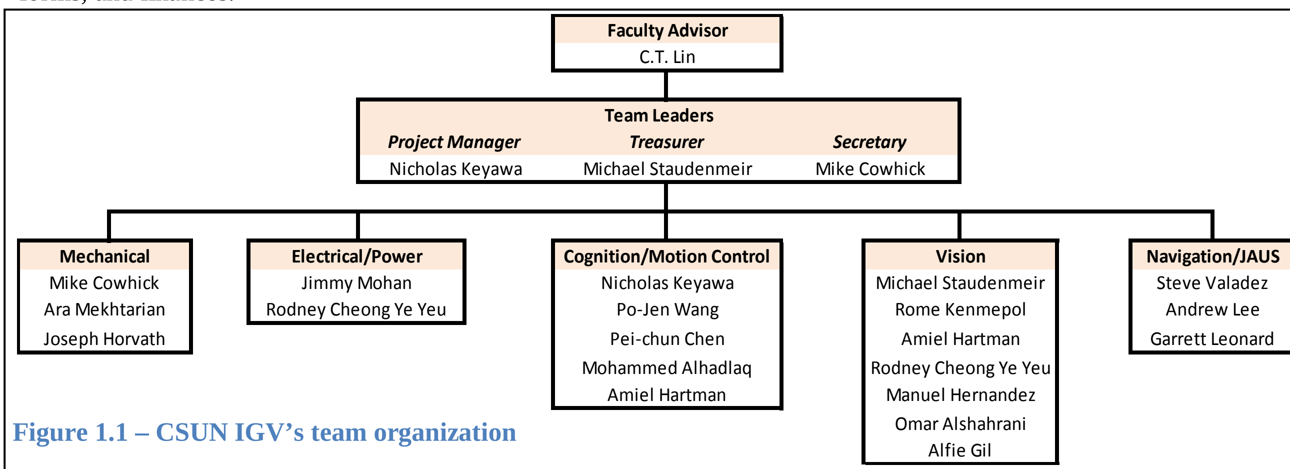

Figure 1.1 – CSUN IGV's team organization

1.2 Overall System Integration

Utilizing a camera, Laser Range Finder (LRF), GPS, and compass, RED RAVEN scans its immediate environment and sends this data to Cognition (Figure 1.2). Cognition integrates the sensory data and evaluates an instantaneous turning radius. Cognition sends this data to Motion Control to evaluate the required angular velocity and acceleration of the IGV's motors. Using the on board Li-Po batteries and mechanical drive wheels, the IGV navigates itself to a new location in the environment.

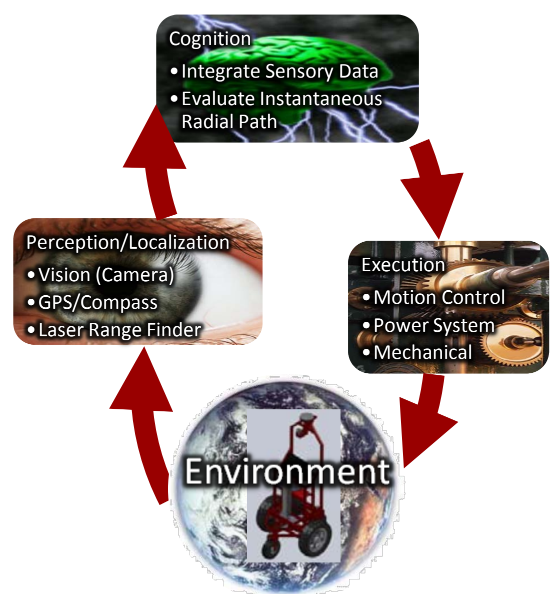

Figure 1.2 – System Integration Flow Chart

2. Mechanical Design

RED RAVEN is mechanically designed to navigate through an autonomous course fast and efficiently. The CSUN IGV Team designed the vehicle with an innovative Linked-Bogie dynamic frame, which minimizes platform tilt and movement. It also improves traction while maintaining all the vehicle's wheels in contact with uneven surfaces at all times. Its unique platform design makes the robot extremely maneuverable since it allows the vehicle's horizontal center of gravity to line up with the center of its differential-drive axle. The compact and lightweight ground-vehicle also features a rigid vertically stacked aluminum frame, drive axle decouplers, and a transparent polycarbonate weatherproofing shell.

In contrast to last year's three wheel IGV platform, RED RAVEN incorporates an additional caster wheel in the rear of the vehicle to allow the shifting of the horizontal center of gravity (HCG) to be over the driving axle. Since maneuverability and efficiency are the key aspects of the new design, the component layout of the new platform is centered over the driving axle, resulting in smoother turning.

2.1 Linked-Bogie Frame

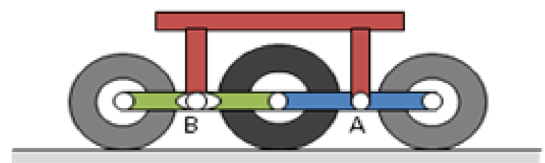

Figure 2.1 – Basic schematic of Linked-Bogie frame

During the design process, the Linked-Bogie frame design was found to be ideal. The Linked-bogie frame (Figure 2.1) is propelled by two driving wheels (Center), and balances itself with the help of two floating wheels (Front and Rear). The frame mechanism consists of two links (Green and Blue), which connect the center driving wheels to the front and rear floating wheels, and form two bogies linked together at the center of the driving axle. The configuration of the links allows each wheel to move in the vertical direction independently of the other wheels. Since the weight of the main platform (Red) is distributed equally between pivot point "A" at the center of the blue link, and slide "B" at center of the green link, the load on the driving wheels is doubled. This gives the ground vehicle better traction and the load on the floating wheels is minimized, which reduces negative caster-wheel effects.

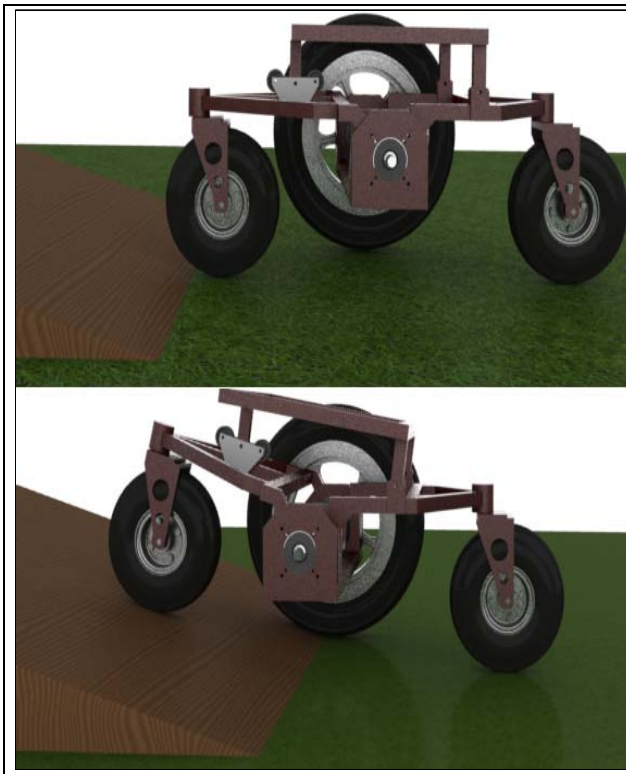

Figure 2.2 – Dynamic frame adapts for ramp

As a result of the dynamic frame, RED RAVEN's top platform tilts less than the front caster bogie when climbing. The vertical movement of the main platform is minimized since points "A" and "B" move half as much as the centers of the wheels. In addition, each wheel can move independently in the vertical direction, which allows RED RAVEN to maintain all wheels in contact with uneven surfaces at all times (Figure 2.2). The chassis is constructed from 1-inch 6063 aluminum tubing, which was chosen due to the material's high strength to weight ratio. The aluminum tubing is TIG welded with sealed corners, thereby maximizing the strength of the frame and minimizing oxidation.

2.2 Vertical Stacked Frame

When designing the component layout, there were two goals that drove the entire design. The first goal was to keep the CG located directly over the drive train and as low as possible. The second goal was to concentrate the mass as close to the center vertical axis as possible, thereby minimizing the robot's rotational inertia. In order to meet these requirements, RED RAVEN was designed with a vertical stacked frame (Figure 2.3). The vertical stacked frame allows for optimal component layout and accessibility; the heaviest components are placed at the bottom and the lighter components are placed at the top. The motors, gearboxes, batteries, and motor controllers are all mounted at the bottom of the robot since they are the heaviest components, while the lighter components (such as the PCB, laptop, GPS receiver, and antenna) are placed higher up on the vehicle. Though the IMU is a relatively heavy component, the device had to be placed at a centralized location in order to obtain accurate data. In addition, the PCB is mounted in a central location in order to minimize cable lengths. Overall, the CG is kept relatively low (Figure 2.3) and the concentration of mass is kept as close to the central vertical axis of the robot. As a result, RED RAVEN can perform quick turns and remain stable while doing so.

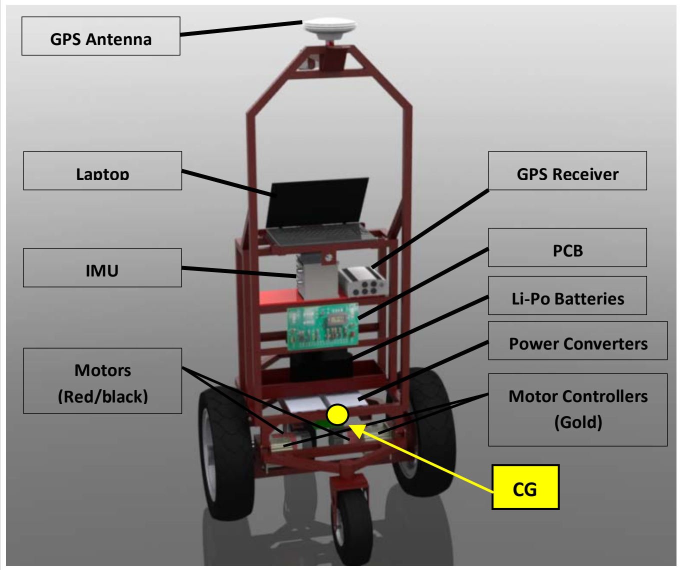

Figure 2.3 – Component layout on RED RAVEN's vertical frame

2.3 Drive Axle Decouplers

Another innovative aspect of RED RAVEN's design is the drive wheel decouplers. Most robots are designed with the drive train keyed directly to the drive wheels. The disadvantage to that design is that when the robot isn't powered on, it is not possible to roll the robot without risking damage to the drive train. In order to transport the robot, it would have to be lifted onto a dolly. Therefore, RED RAVEN features the innovative drive wheel

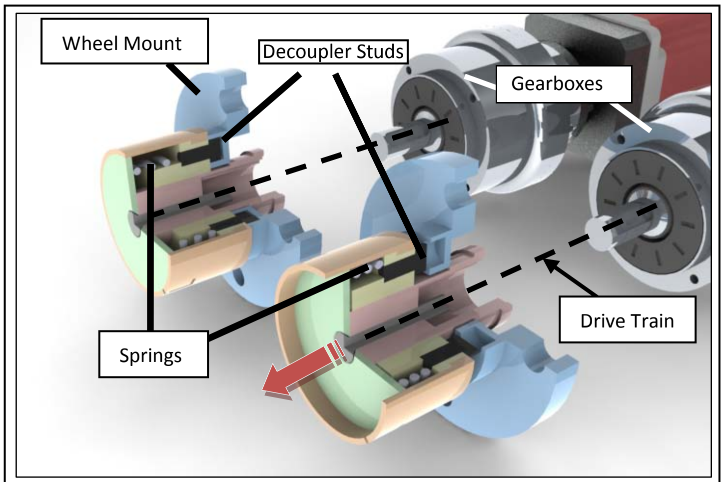

Figure 2.4 – The decouplers utilized on RED RAVEN in both the coupled (left) and decoupled (right) positions.

decouplers in order to give the user the ability to decouple the drive train from the drive wheels. As shown in Figure 2.4, the drive wheels are mounted to the blue hub (or wheel mount). The drive train is static with the pink inner shaft, which is coupled to the motor through a keyway on the gearbox shaft. The hub has four black studs that insert into the blue disk, thereby coupling the drive train to the wheels. Note in the left decoupler the black studs are coincident with the blue disk, whereas in the right decoupler the black studs have disengaged from the blue disk. Furthermore, the hub is spring loaded and has a locking slot (not shown) when decoupled. Overall, in order to decouple the motors, the user merely needs to pull out the spring loaded hub and turn it to lock the decoupler in the decoupled position. This allows the robot to roll freely wherever the user needs it to go. This feature significantly speeds up the testing process, eliminates the need for a dolly, and ultimately preserves the strength and energy level of team members from having to carry the vehicle.

2.4 Durability and Serviceability

The last major component that is featured on RED RAVEN is the polycarbonate weather-proofing. Polycarbonate is used because of its low weight and transparent properties. Since the material is transparent, all of RED RAVEN's components are visible despite being covered for protective purposes. Additionally, polycarbonate can simply be bent with a sheet metal bender; there is no need to heat the material in order to get a clean bend. As a result, the polycarbonate provides RED RAVEN protection from unwanted moisture and provides a clean, professional finish.

The ease of serviceability is a necessary feature that ensures the longevity of RED RAVEN's design. All the screws that secure the different polycarbonate panels to the frame are medium-sized thumbscrews, allowing any panel to be removed as needed without the use of any tools. Additionally, if there is a need to access the motor compartment below the top platform, a single pin needs to be removed from the main roller in the front of the robot. Once removed, the entire top platform can be pivoted down to allow full access for serviceability.

3. Electrical/Power Systems

Increased reliability, reduced weight, and reduced power consumption were all critical goals for this year's IGV robot, RED RAVEN. As such, the power team deviated from last year's robot design, NorMAN Jr., whose power system included a complicated and hybrid battery/fuel cell, to a simplified design using only reliable Lithium Polymer batteries as the main power source.

3.1 Electrical Configuration

All electrical components tie into RED RAVEN's power system through a custom made power distribution printed circuit board (PCB) (Figure 3.1). Main power is provided by a set of three series-configured Lithium Polymer batteries. Battery voltage is converted and regulated by two separate buck/boost DC to DC converters: 48V DC for the

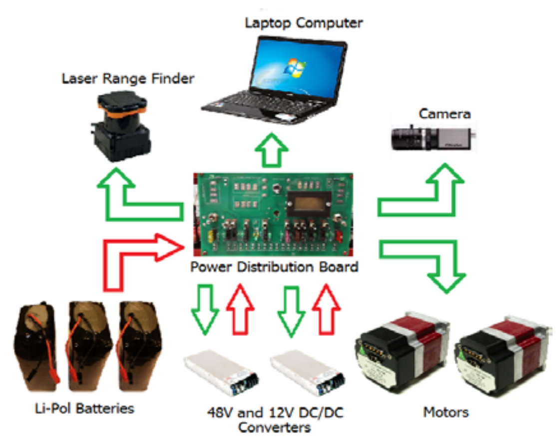

Figure 3.1 - RED RAVEN's Power System

motors and 12V DC for all other electrical components. This provides electrical isolation between the motors and sensitive electrical sensors, such as the Laser Range Finder. This also allows the motors to function at their ideal operating voltage of 48V DC.

The PCB itself is a durable design consisting of 2 oz/ft^2 copper for the electrical traces, and is able to handle currents as high as 60 A (Figure 3.2). A printed circuit board provides a much more stable and reliable platform compared with using terminals or wires only. Two trace layers were chosen in designing the PCB, the front traces all consist of positive voltages, while the entire back is one large ground plate. This simplifies trace routing considerably and allowed for a much more compact design compared to previous year's robots. All devices that receive power through the board are protected by fuses. LED lights are also present, indicating if power is flowing to an electrical device and also acting as an indicator for whether or not a fuse is blown.

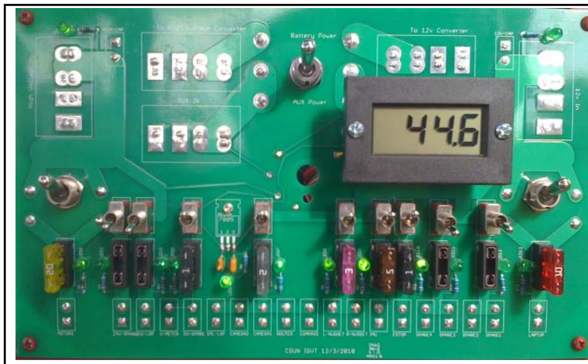

Figure 3.2 - Power Distribution Printed Circuit Board

3.2 Power Analysis

The power consumption of RED RAVEN was analyzed at both normal and extreme load conditions (Table 3.1). Normal load conditions consisted of RED RAVEN traveling at approximately 1 mph, and extreme load conditions with RED RAVEN traveling at a top speed of 6.5 mph. The data indicated that under extreme conditions RED RAVEN would need approximately 1235 W. In order to supply sufficient amount of power to RED RAVEN under these conditions, a minimum of three Lithium Polymer batteries are needed. Each battery has a nominal voltage of 14.8V and is over-current protected at 30A, which provides a nominal rated power of 444.4 W. A series configuration for the batteries, as mentioned previously, is chosen to limit overall current.

Table 3.1: Power Consumption

Type of Load	Power Normal (W)	Power Extreme (W)
Total Base Load	177	
Transient Motor Load	154	910
Total Load	331	1087
Total with 88% DC/DC Efficiency	376	**1235**

3.3 Emergency Stop

The emergency stop system on RED RAVEN functions by making use of the motor controllers' built-in stop conditions to bring the robot to a controlled and safe stop. When the emergency stop is activated, a logic HIGH (+5V) is sent to the motor controllers' input/output pins. When the emergency stop is not activated, a logic LOW (ground) is sent to the motor controllers. A series configuration is used for the pushbutton stop and the wireless remote stop (Figure 3.3) to ensure that either one does not conflict with the other.


Figure 3.3 – The push button (top) and wireless (bottom) e-stops utilized on RED RAVEN

3.4 Audio-Controlled Relay

In order to comply with the new 2011 IGVC rules, RED RAVEN must indicate when it is powered on through the use of a solidly lit light. When the IGV is autonomously running, the light must begin flashing. Since RED RAVEN is set into autonomous mode through software, a software hardware interface is required in order to determine the state of the IGV's light. Rather than tying up another USB port and devising how to interface with it, an audio output on RED RAVEN's laptop is utilized.

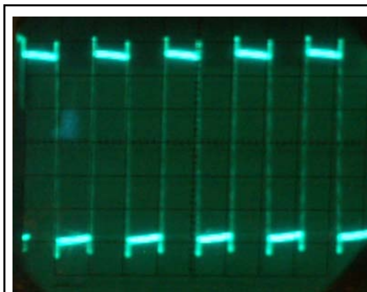

Figure 3.4 - 500 Hz Square-Wave Audio Output, 1.4$V_{p\text{-}p}$

When RED RAVEN is set into autonomous mode, a 500Hz square wave sound file is triggered in LabVIEW. This sound file creates an output voltage waveform with a peak to peak voltage of 1.4V (as shown Figure 3.4). This waveform is sent through an amplifier, filter, and rectifier in order to trigger a relay (Figure 3.5) from the solid lit light to the flashing light. Overall, this process provided a simplistic and easy solution; utilizing audio files in LabVIEW was extremely simple, and interfacing with the audio output of the laptop was effortless.

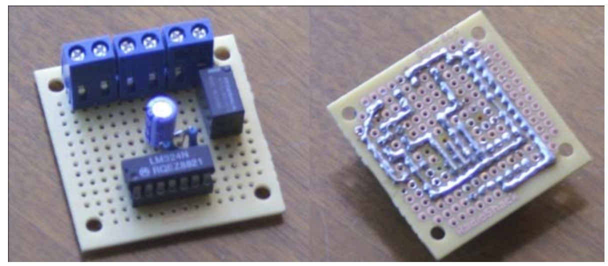

Figure 3.5 - Audio-Controlled Relay

4. Vision

The camera on the robot is used to capture real time images of boundary lines and obstacles that are necessary for completion of the autonomous task. While other sensors on the robot such as the LRF are useful for determining the location and distance of three dimensional objects within a specified plane, boundary lines and flags remain unseen without a camera. To detect and process environmental data, the camera is used to acquire a continuous video feed directed at the forward field of view of the robot. The camera is mounted at a height and orientation to maximize the field of view for useful data capture (Figure 4.1).

Figure 4.1 – Location of camera on RED RAVEN

4.1 Camera Hardware

The camera of choice is a FOculus FO124/TC color IEEE1394 camera with a 1/3" progressive scan CCD. The camera is capable of achieving frame rates of 60 fps and has an effective pixel resolution of 659 (H) x 494 (V) VGA. Both the resolution and frame rates meet and exceed current operating requirements. IEEE1394 FireWire is the selected data transfer and power input source for the camera; it provides for widespread compatibility and availability with multiple computer interface setups.

The lens chosen to accompany the camera is a Computar T2Z1816CS varifocal lens, which provides manual control for precise aperture and view angle adjustments. With the lens, the camera is capable of achieving view angles up to 144º horizontal and 109º vertical. Because of the small profile of the camera and the very wide view angles provided by the lens, the camera can be conveniently mounted on RED RAVEN to provide visual ground cover across a trapezoidal area of 308 ft^2 in the front view field of the robot. To further enhance the visual input of RED RAVEN via hardware, a polarized filter is used for outdoor sunny conditions when glare needs to be reduced for improved light balance.

Figure 4.2 – The FOculus Camera (top) and Computar lens (bottom) used on RED RAVEN

4.2 Vision Software Strategy

All algorithms utilized on RED RAVEN were programmed in LabVIEW due to its fast processing time and easy-to-use software to hardware interface. For the vision of the IGV, the innovative algorithm created to map the local environment was Dynamic Color Detection (DCD). DCD extracts boundary and obstacle data from a color image. Color data from a select template area of each image is extracted to determine average hue, saturation, and luminance values of the grass field (Figure 4.3). Tolerances are applied to these values to give acceptable data range. For each pixel in the image, the color values are compared to this range. If they fall within the range, they are removed from the image; otherwise, they are turned white. This produces a simple black and white (non-grayscale) image called the DCD image that is simpler to process.

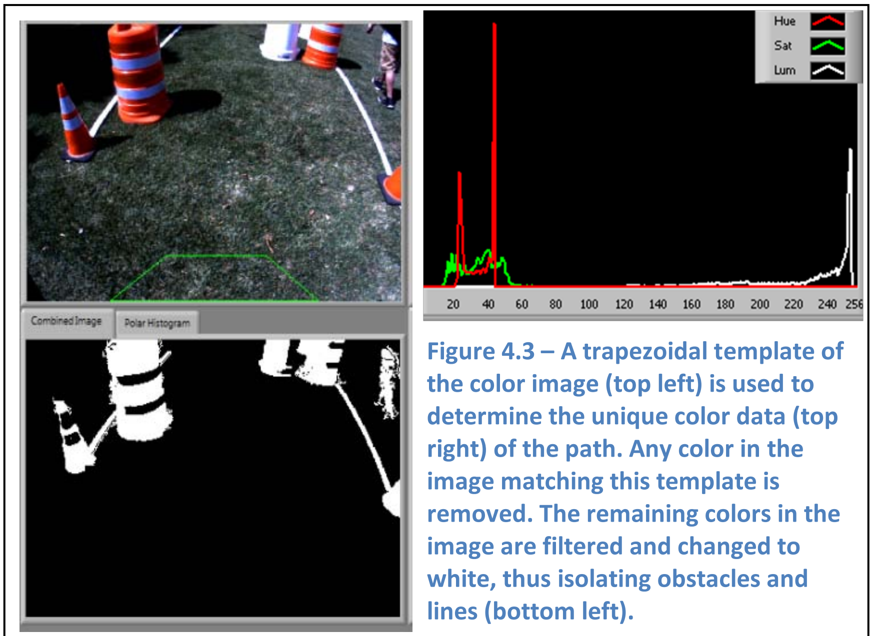

Figure 4.3 – A trapezoidal template of the color image (top left) is used to determine the unique color data (top right) of the path. Any color in the image matching this template is removed. The remaining colors in the image are filtered and changed to white, thus isolating obstacles and lines (bottom left).

While using the DCD algorithm, shadows cast on the field were interpreted as “obstacles” and provided inaccurate data. In order to correct this, a shadow detection process that uses a similar color range that matches darker shades of the ground color is performed and the results are removed from the DCD image. Small “noise” data often occurs on the non-uniform grass surface as well, so a particle filter that removes small objects is used on the combined image, resulting in a clean map of boundary lines and obstacles (Figure 4.3).

A flag detection algorithm is utilized to determine the locations and color of red and green flags. A color filter removes all pixels apart from a pre-set data range that corresponds to either a red or a green flag (Figure 4.4).

Figure 4.4 – Process of the flag detection algorithm (from left to right) that begins with the color image, removes all colors not associated with flags, generates solid shapes, and implements an area filter to isolate flags.

Due to possible wind or shadows, the flag sometimes appears with gaps or dark spots. A convex hull is performed on each flag image to fill in gaps and generate solid shapes. An area filter removes all obstacles that do not match the approximate area of a flag; this is done in order to eliminate objects that are of the same color as the flag. This process results in two image maps that are sent to Cognition to analyze: one for red flags and one for green flags.

Presenting this data in a readable interface to the Cognition system requires a separate process of data conversion. The wide angle lens and the camera's positioning angle result in high distortion that must be corrected. The distorted images are corrected using a pixel coordinate translation that is based on a calibration image. The calibration image consists of a controlled grid of data points taken from the camera at the same position and view angle. The image maps for DCD, flag detection, and white boundary lines are converted from Cartesian to polar coordinates, with the (180^{o},0 mm) corresponding to the front tip of the robot (Figure 4.5). The vision data consists of distances to obstacles for every 0.5^{o} in a 180^{o} field of view directly in front of the robot

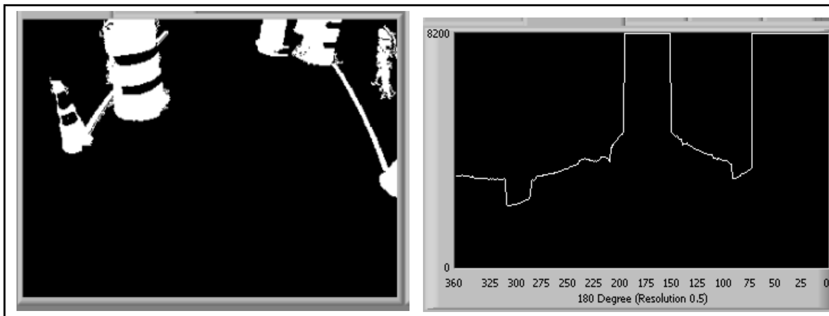

Figure 4.5 – The DCD image (left) is converted into polar coordinates (right) before sending the data to Cognition to analyze.

5. Navigation/JAUS

5.1 Navigation Hardware

RED RAVEN uses a NovAtel SPAN (Synchronized Position Attitude & Navigation) system for navigation. This system consists of a GPS-702L antenna (Figure 5.1a) and a LN200 IMU (Inertial Measurement Unit) (Figure 5.1b), which feed into a ProPak-V3 receiver (Figure 5.1c). OmniSTAR provides the IGV an HP differential GPS service, which increases the accuracy to 0.1 meters. The IMU provides position data when GPS data is unavailable, as well as increases the

Figure 5.1 – Navigation hardware used on RED RAVEN includes an (a) antenna, (b) IMU, (c) receiver, and (d) compass.

refresh rate up to 200Hz. The ProPak receiver merges the GPS and IMU data and provides latitude, longitude, and velocity data to the computer. The receiver interfaces with the computer via an RS232 serial connection at a baud rate of 460.8kBd while updating at 40 Hz.

RED RAVEN uses a True North Revolution 2X digital compass (Figure 5.1d) to identify heading and is used primarily to verify accurate data from the IMU. This compass provides heading data at 31.25 Hz, with an accuracy of 0.5°. It communicates with the computer via an RS232 serial connection.

5.2 Navigation Software Strategy

As shown in Figure 5.2, the overall software strategy for the Navigation challenge begins by accepting a list of waypoints along with the location and direction data. Navigating between waypoints in the shortest time possible is an application of the "traveling salesman" problem. For a large number of waypoints, approximation methods must be used to efficiently find the shortest path. However, the Navigation challenge contains a relatively small number of waypoints and can be quickly solved using a brute force algorithm. The Navigation program iterates through every possible path and chooses the one with the shortest total distance. An ordered list is created, and the vehicle uses the first point as its goal.

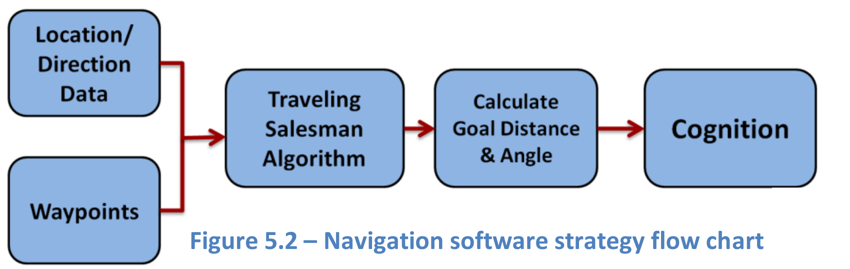

Figure 5.2 – Navigation software strategy flow chart

The Navigation program must continuously calculate the bearing and distance between the vehicle's current position and its current goal waypoint. This is done using the Haversine and Great Circle formulas. The vehicle's compass heading is compared to the bearing in order to find the relative direction to the goal (i.e. the goal angle). The goal distance is constantly monitored, and when it becomes half the radius given in the IGVC rules (2 meters in "the Valley" and 1 meter for "the Mesa"), the current waypoint can be checked off. This angle and position are provided to Cognition, where they can be used for path planning.

5.3 Joint Architecture for Unmanned Systems (JAUS)

JAUS is a protocol designed by the Department of Defense to facilitate the communication and cooperation between autonomous systems. The purpose of the JAUS Challenge is to program a platform for remote communication between the users and the robot. In order to ease management of the design process the set of used commands are split into two categories: Non-Navigation and Navigation. The Non-Navigation commands cover Transport Discovery, Capabilities Discovery, and System Management (i.e. commands not related to the navigation process). Since these commands are one-time linear processes, they are written within the main JAUS program and put under an array of cases to perform upon receiving the commands. On the other hand, Navigation commands cover Velocity State Report, Position and Orientation Report, and Waypoint Navigation (i.e. commands that relate to navigation and may need to recur upon request). Considering the complexity and recurring nature, these commands are modularized and then combined into the main program in both case structures and sequential structures, depending on the application. This strategy eases the management and debugging of recurring, non-linear processes.

As shown in Figure 5.3, the received signal is sent to two separate areas of the program: one to non-navigation queries to report the received information, and to local position and waypoint settings. The position and waypoint information is relayed to navigation queries, where it simultaneously executes the navigation data and reports information.

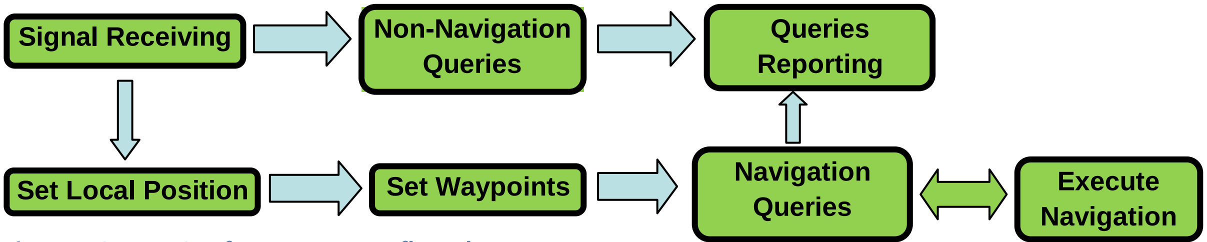

Figure 5.3 – JAUS software strategy flow chart

6. Cognition/Motion Control

The Cognition and Motion Control of RED RAVEN is responsible for calculating an optimal path and speed such that the IGV is able to navigate through the obstacle course autonomously. These algorithms utilize maps of the local environment generated in the form of polar histograms provided by vision and a Laser Range Finder. The LRF used on the robot is the Hokuyo UTM-30LX as shown in Figure 6.1. The LRF has a scanning range up to 270^{o} at a selectable scale of 0.25, 0.5, or 1 degree resolution and a range of up to 30 meters with an accuracy of 1cm. The setting selected is 0.5 degree resolution with an 8 meter range and a scanning rate of 25 milliseconds. Additionally, only 180^{o} of the scanning range is utilized to collect data (due to excessive processing time with the full 270^{o}). The LRF is connected to a USB 2.0 to receive data, and is mounted at the lower front of the robot (right above the IGV's front caster wheel).

Figure 6.1 – The Hokuyo LRF used on RED RAVEN

6.1 Cognition Software Strategy

Previous CSUN IGVs utilzied a linear goal point heading in order to determine a desired path to avoid obstacles. However, by developing a path planning and obstacle avoidance algorithm to approximate a curvlinear motion of the IGV into a series of instantaneous turning radii, the execution and accuracy of the IGV's Motion Control can be greatly improved (Figure 6.2). This enables the ground vehicle to achieve much higher average speeds and proficiently maneauver around complex obstacle arrangements. This innovative path planning and obstacle avoidance algortihm is coined as the Radial Polar Histogram (RPH). This algorithm's main function is to calculate the robot's

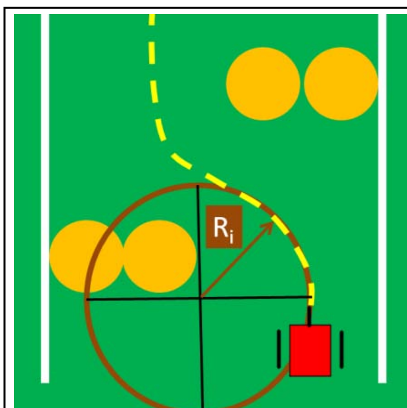

Figure 6.2 – Approximation of the path (yellow) into a turning radius (R_i).

desired turning radius and velocity as well as the accelerations of the robot's left and right wheels for Motion Control to execute.

The process of RPH begins with receiving data in the form of polar histograms from the LRF and the vision system. The histograms received contain distance data for obstacles and lines every 0.5^{o} from 0^{o} to 180^{o} in front of the IGV. RPH combines the two polar histograms and converts the data into cartesian coordinates. This generates a local map representing the robot's field of view (Figure 6.3). RPH uses a controlled filtering range to exclude data that is not within a specified distance from the robot; the filtering range is determined based on the robot's speed and the orientation of the obstacles. Once the appropriate filter range is selected, the obstacle data is grouped and potential open paths for the IGV to travel through are identified; these openings are referred to as open blocks. The program chooses one of the open blocks for evaluation based on factors that include navigational heading given by GPS, obstacle orientation, and the current location of the IGV. Taking into account the width and length of the IGV, the left and right most radial paths within the selected open block are generated. These left and right most radial paths define the radial boundary of the open block. Lastly, an optimization function selects one radius within the radial boundary and outputs it as desired turning radius to Motion Control. This process is illustrated during a standard test run in Figure 6.3 shown below.

Figure 6.3 – Using LRF and vision data, Cognition generates a cartesian coordinate map (right) of RED RAVEN's immediate environment (left). The yellow data points in the generated map indicate obstacles within the filter range, and RPH generates a desired turning radius based on this data. The blue lines indicate the projected path of the IGV based on the calculated turning radius.

6.2 Motion Control Software Strategy

The purpose of Motion Control is to execute the desired turning radius given by Cognition at a proper speed and acceleration. Motion Control utilizes the desired turning radius in a dynamic velocity function to determine the optimal angular speeds of the vehicle's wheels in real time. Depending on the calculated turning radius, the vehicle adjusts its velocity range to accommodate the current physical location. A rapidly changing and small turning radius forces the vehicle to lower its velocity range in order to safely navigate through a cluster of obstacles. Conversely, the velocity range increases if the calculated turning radius is large, indicating that few obstacles are present.

In order to further optimize the path planning and obstacle avoidance of the IGV, a dynamic acceleration function was added in parallel with the velocity function and RPH in order to determine the desired angular accelerations of the vehicle's wheels in real time. Based on the current location of the vehicle, a local map of the IGV at a future location is generated. At this future location, the RPH algorithm is able to generate a future turning radius and angular speed for each wheel (as shown in the top right corner of the cartesian coordinate map in Figure 6.3). Using these future calculations in conjunction with the current turning radius and wheel speeds, the angular accelerations of the IGV's wheels are determined. In addition, the future radius and velocity are also used by Cognition to continuously search if any obstacles have entered the predicted path. If obstacles are detected, RED RAVEN either performs an emergency turn or an emergency stop if a collision is imminent. Upon stopping, RED RAVEN will perform a zero radius turn until an open block is detected.

6.3 Complex Obstacle Arrangement Modifications

Though RPH proved to be a highly accurate path planning and obstacle avoidance algorithm, additional case structures had to be added to overcome certain obstacle arrangements. These complex obstacle arrangements included forks in the road, switch backs, dead ends, broken lines, and flags.

In the autonomous challenge, forks in the road are commonly present and the required direction to follow is specified by a navigational waypoint. In order to determine which path to follow, a navigational heading is incorporated into the RPH algorithm. Thus, when the robot detects multiple open blocks, the navigational heading dictates which open block the IGV travels through (Figure 6.4).

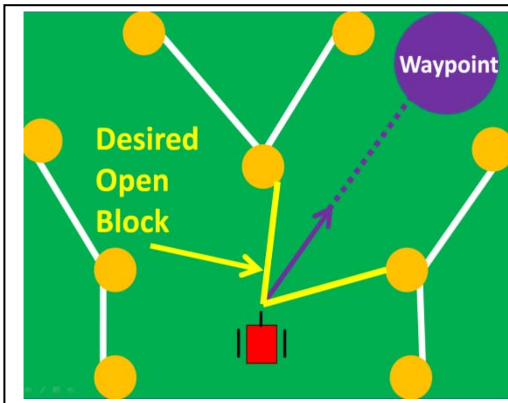

Figure 6.4 – Navigation heading dictates which open block to travel through.

During switch backs, the IGV has a tendency to overturn and hit the center dividing obstacles. This is due to the fact the obstacle is in the IGV's blind spot. In order to overcome this scenario, a case structure is added that increases the RPM of the inside turning wheel if the calculated turning radius is extremely small. The increased RPM allows the robot to perform a wider turn, and thus avoid obstacles in the vehicle's blind spot.

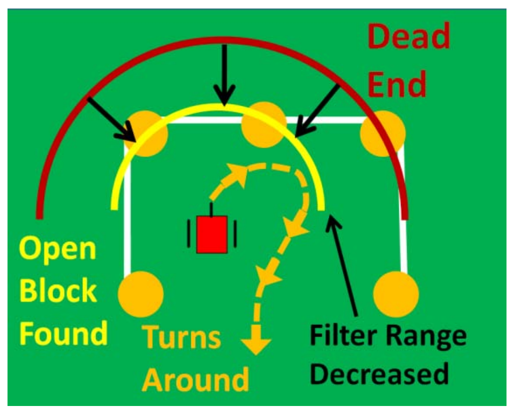

Figure 6.5 – Filter range detects a dead end (red), and thus decreases to find an open block (yellow).

In order to overcome a dead end, the range of the data filter was made to be dynamic (Figure 6.5). Currently, the data filter range (i.e. the range where the IGV analyzes obstacle and line data to determine an optimal path) is set to 5m. However, when the IGV sees a dead end, the data filter range is decreased to allow the vehicle to see an opening. This allows RED RAVEN to turn accordingly to avoid the dead end. If the IGV still cannot see an open block after decreasing the data filter range, the vehicle will stop and perform a zero radius turn until an open block is detected.

Lastly, in order to overcome broken lines and turn to the correct side of the flags, imaginary lines (or ghost lines) are generated within the RPH algorithm to guide the IGV in the correct direction. When a broken line is detected, the edges of the broken line are connected to close the gap. In addition, when the IGV detects a red flag, a ghost line is drawn to the right of the flag to guide the robot to the left (and vice-versa for green flags) as shown in Figure 6.6.

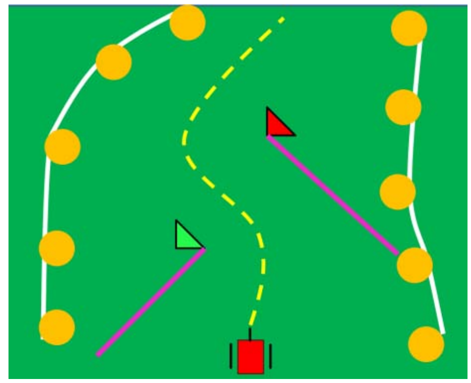

Figure 6.6 – Ghost lines (purple) drawn to guide the robot (red) to the correct path (yellow)

6.4 Map Generation and System Cooperation

In order to generate an accurate local map of RED RAVEN's environment, each of the IGV's on board sensors are integrated with one another in a checks and balance system (Figure 6.7). The sensor data from the LRF serves to provide information on the location of standing obstacles. Data gathered from the onboard camera provides information regarding the location of boundary lines and flags. The LRF and camera data is sent to Cognition where the instantaneous local map and desired ghost lines are generated and stored in short-term memory. Furthermore, the camera and LRF work together to overcome their individual weaknesses and blind spots. For example, an LRF may detect that the space between the legs of a saw horse is an open block for RED RAVEN to travel through (which is false). However, using the provided obstacle data from the camera, the generated map is able to indicate that the area between the legs of the saw horse is not an open block. In addition, if barrels on the course match the exact same color as the flags, the camera may indicate to Cognition that a red or green flag is present. However, using the obstacle data from the LRF, the generated map is able to indicate that a barrel is present and not a flag.

Figure 6.7 – System cooperation between the sensors of the IGV for generating an accurate local map

6.5 System Integration

Figure 6.8 shows the process that RED RAVEN uses for the complete integration of all onboard systems. RED RAVEN uses a LRF and a camera to scan for objects and line boundaries in the robot's environment. It also has a GPS onboard that gathers waypoint locations and the robot's heading information. These sensor data are being sent to Cognition for comparison and ghost line generation. In addition Cognition creates a local map, and by evaluating the open blocks in a selected area, a desired radius is determined and is sent to Motion Control for execution. While Motion Control moves the robot, it continuously feedbacks the robot's predicted turning radius and velocity to Cognition for determining the ideal motor acceleration for each wheel that optimizes the smoothness of the robot's motion. The sensors then rescan the environment and the process is re-iterated again.

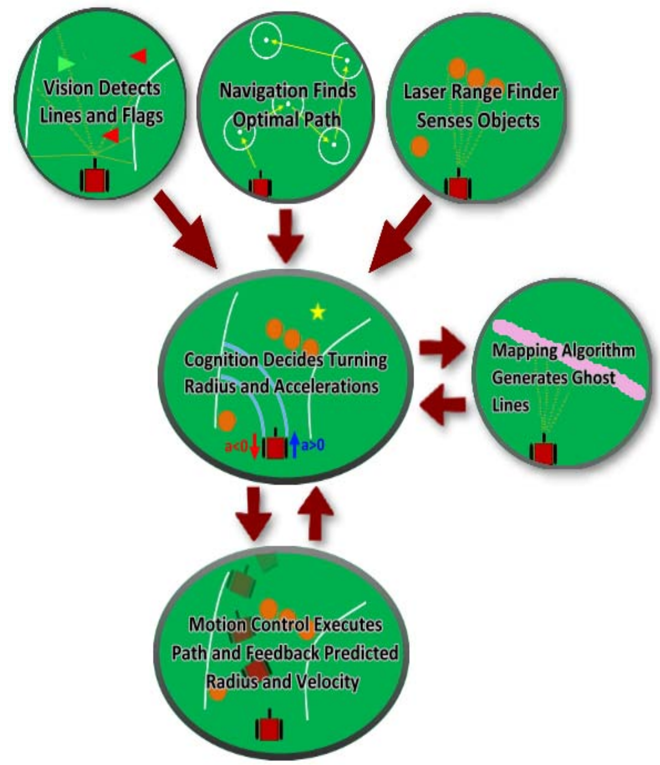

Figure 6.8 –System integration flow chart

7. Overall System Performance

RED RAVEN is a revolutionary IGV that has been designed, built, and programmed to achieve efficient maneuverability, high speeds, precise path planning, and near-perfect obstacle avoidance. The overall performance parameters of RED RAVEN are shown in Table 7.1. Due to a light weight chassis, the use of a 48V DC/DC converter, and three series-configured Lithium Polymer batteries, the motors are able to drive the IGV to a top speed of 6.5 mph on pavement. On grass, the top speed is around 5.5 mph, depending on the conditions of the terrain. Taking into account the data collection rate of each of the sensors and algorithm processing times, the reaction rate of RED RAVEN is clocked at around 100ms. Due to the IGV's Link-Bogie frame, RED RAVEN is capable of climbing 30^{o} ramps. Furthermore, the three series-configured Lithium Polymer batteries provide enough power to run RED RAVEN at top speed for 3 hours. Under normal operating conditions, the battery life is approximately 6 hours. The LRF detects obstacles up to 8 meters away, and the camera detects obstacles and lines up to 7 meters away. Lastly, through the use of a Differential GPS system (DGPS), the waypoint accuracy is approximately 10 cm.

Table 7.1 - RED RAVEN's Performance

Parameter	Value
Top Speed	6.5mph
Reaction Time	100ms
Ramp Climbing	30^{o}
Battery Life	3-6 hrs
Obstacle Distance Detection	8m
Waypoint Accuracy	10cm

8. Appendix

8.1 Total Cost Estimate and Person-Hours

The total retail cost of all the materials and components utilized on RED RAVEN is approximately $91,400 (Table 8.1). The most expensive components contributing to the cost are the IMU, GPS Antenna, and GPS Receiver. However, thanks to Northup Grumman, these components were obtained at severely reduced prices; the IMU is currently on loan to the IGV team at no charge. Additional discounts were obtained when purchasing new vision equipment. Overall, the total purchase cost for RED RAVEN is approximately $27,000. However, since many of the components were recycled from the previous IGV, the total cost to the team in constructing RED RAVEN this year is approximately $9,600. In addition, each of the students spent approximately 26 hours a week on the IGV project. Thus, during the 2010-2011 academic year, each of the students spent about 1040 hours working on RED RAVEN (Table 8.2).

Table 8.1 - Total Cost Estimate of RED RAVEN

Components	Retail Cost	Cost at Time of Purchase	Cost to Team This Year
Hokuyo LRF	$5,000.00	$5,000.00	$5,000.00
Nuggets	$1,600.00	$1,600.00	$0.00
Motors/Motor Cables	$2,437.00	$2,437.00	$0.00
Clamp	$200.00	$200.00	$0.00
Black/White Pack Batteries	$4,150.00	$4,150.00	$150.00
Toshiba 16" Laptop	$1,500.00	$1,500.00	$1,500.00
48V/12V DC/DC Converters	$300.00	$300.00	$150.00
Printed Circuit Board	$150.00	$150.00	$150.00
Misc. Electrical Items	$150.00	$150.00	$150.00
IMU	$44,000.00	$0.00	$0.00
GPS Receiver/Antenna	$28,079.00	$8,500.00	$0.00
Digital Compass	$467.00	$397.00	$0.00
FOculus Camera	$1,000.00	$430.00	$430.00
Computar Lens/Filter/Mount	$520.00	$255.00	$255.00
Gearboxes	$1,204.50	$1,204.50	$1,204.50
Driving Wheel Rims	$215.46	$215.46	$215.46
Driving/Caster Wheels	$135.98	$135.98	$135.98
Metal Materials	$133.16	$133.16	$133.16
Misc. Mechanical Materials	$159.64	$159.64	$159.64
Total	**$91,401.74**	**$26,917.74**	**$9,633.74**

Table 8.2 - Hours worked per student

Time Period	Hours
In Class (per week)	12
Out of Class (per week)	14
Total Per Week	26
2010-2011 Academic Year	**1040**