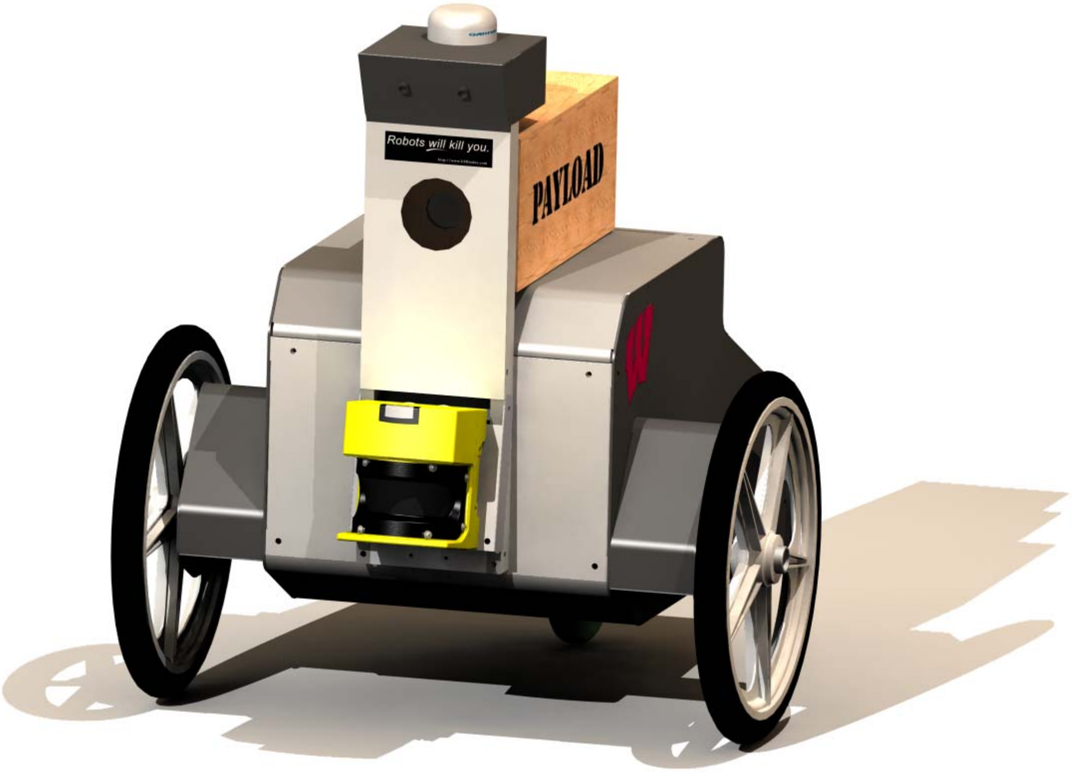
ReWIRED

Return of the Wisconsin Robotic Exploration Device



IEEE Robot Team
University of Wisconsin – Madison

Required Faculty Advisor Statement
I certify that the engineering design of the vehicle ReWIRED, described in this report, has been significant and equivalent to what might be awarded credit in a senior design course.

Professor Nicola Ferrier
Department of Mechanical Engineering

TABLE OF CONENTS

1. Introduction

The IEEE Robot Team from the University of Wisconsin would like to present ReWIRED, upgraded and refitted from its entry in 2007. This is the ReWIRED's third and the team's fifth entry in the IGVC.

2. Innovations

In creating ReWIRED the team sought to improve upon already successful systems from last year's ReWIRED. This year's significant upgrades include the implementation of an entirely new software platform and approach, new custom designed motor controllers, and substantial upgrades to essential sensory components. ReWIRED is built upon a solid chassis which has served the team well and hence was left unmodified.

The power system was completely redesigned and the old, worn out batteries retired and replaced with longer lasting batteries to improve ReWIRED’s running time. The most important changes include adding fault tolerance and moving from asymmetric to symmetric loading of the two onboard deep-cycle batteries to prevent future damage. Also, battery monitoring has been included, making battery maintenance more user-friendly.

Within the embedded system, the previous control scheme relied solely on proportional encoder feedback. This year a more complex proportional-integral (PI) control algorithm was used, providing smoother and more predicable movements. Furthermore, the new PI control is quicker to react to changes in desired speed and direction, improving the vehicle’s response time.

ReWIRED's software was completely re-imagined. A brand new framework was chosen and completely new strategies were implemented to handle the competition challenges. The autonomous strategy became more intelligent with the introduction of a new path finding navigation algorithm in place of the purely reactive model used last year. A mapping component aggregates all sensor data to build a persistent grid map of its environment and odometry data goes through a localization routine to correct for accumulated error. The line detection strategy was redesigned for better handling of noise. A brand new remote GUI application was implemented to make development and testing more straight forward.

3. Design Process

In the development of ReWIRED, the team followed the basic process as detailed in Figure 3-1 below. We began by identifying the requirements for the competition as well as evaluating the strengths and weaknesses of our designs in previous years. The team researched other approaches to the given problems and used the information to complement our own experience. Having worked with a relatively solid mechanical platform in ReWIRED last year, focus was placed primarily on improving the software design. The team used a bottom-up approach in redesigning systems, targeting specific functionality or feature and thereafter incorporating it into the overall system. When each design was sufficiently analyzed, a prototype was developed allowing preliminary testing of each new idea. Through careful planning and thorough testing, each subsystem was ensured to function correctly before integration into the final product.

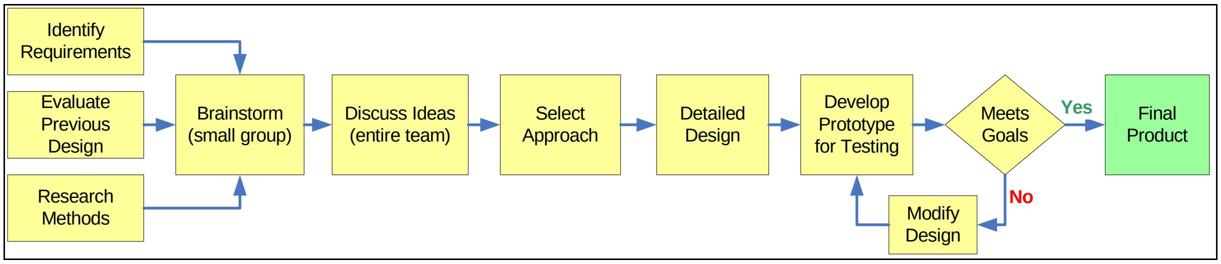


Figure 3-1: Design Process

3.1. *Team Organization*

The group of members from the IEEE Robotics Team working on ReWIRED consisted mainly of software developers, half of whom were new to the team this year. The ReWIRED team functioned as a sub-group under the IEEE Robotics Team leadership structure.

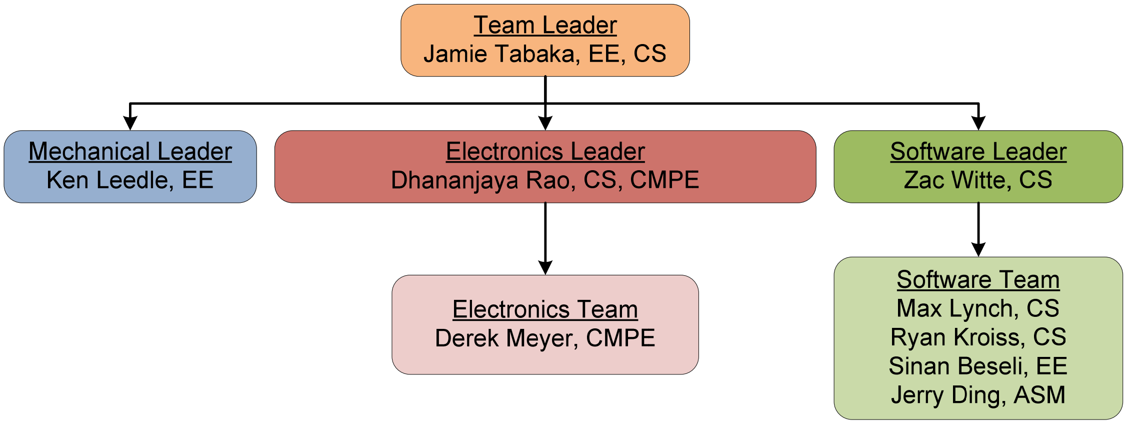


Figure 3-2: Team Organization

4. Mechanical Design

The previous year's mechanical design has proven to be an effective, reliable and versatile robotic platform. The original WIRED drive system has provided sufficient speed, power, and shock absorption and was thus left largely unmodified. Small modifications were made to make testing and general use of the robot easier, such as adding a magnet to the embedded compartment door to hold it in the open position. As in past years, special care was taken to ensure safety, reliability, and value in every step of the design.

4.1. Chassis

ReWIRED reuses the custom chassis designed for WIRED. The chassis is a hybrid combination of an exoskeleton body and an internal frame developed for superb rigidity and unobstructed access to even innermost components. Its logical division of space has proven to be an effective and secure way to house the various systems of the robot. Moreover, the original design was easily reconfigurable and extensible, as exemplified by the replacement of the six-foot mast with the compact forward sensor module in past years.

4.1.1. Drivetrain and Suspension

ReWIRED is propelled by two powerful 24V right-angle gear motors similar to the type used on many commercial wheelchairs. The built-in gearbox allows for a space-efficient and weatherproof drivetrain while requiring minimal maintenance. Rather than being rigidly attached to the robot, the motors are mounted using a spring suspension that drastically reduces shock and vibration from terrain roughness (Figure 4-1). The motors are intentionally placed exterior to the main section isolating actively moving components from the rest of the system.

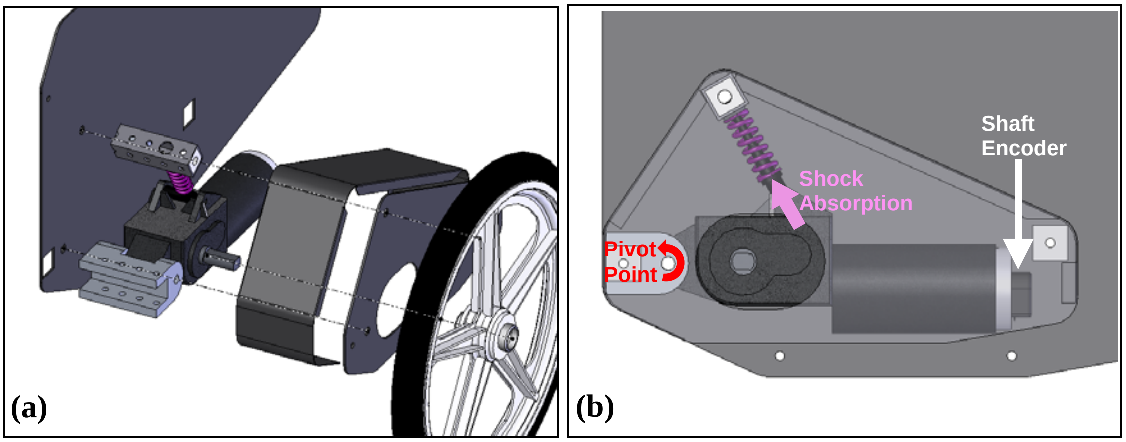


Figure 4-1: Left Motor Compartment (a) Exploded view (b) Side view

Like its predecessors, ReWIRED is differentially steered with motion feedback provided by the attached optical shaft encoders (Figure 4-1). This drive system has proved successful in the past and provides excellent power and maneuverability. ReWIRED can easily climb steep inclines, move quickly and precisely, and carry over one hundred pounds of payload. These and other vehicle statistics are given in Table 9-1.

4.1.2. Main Compartments

The main body contains three sections that house the majority of the robot's internal components. The largest compartment contains two lead-acid batteries, placing the bulk of the weight slightly behind the drive axles. This weight distribution provides excellent traction and balance. The compartment is recessed in order to keep a low center of gravity while maintaining sufficient ground clearance of 6". The batteries can be charged through the dedicated weatherproof charging port, and can also be easily accessed for maintenance or removal via the top door.

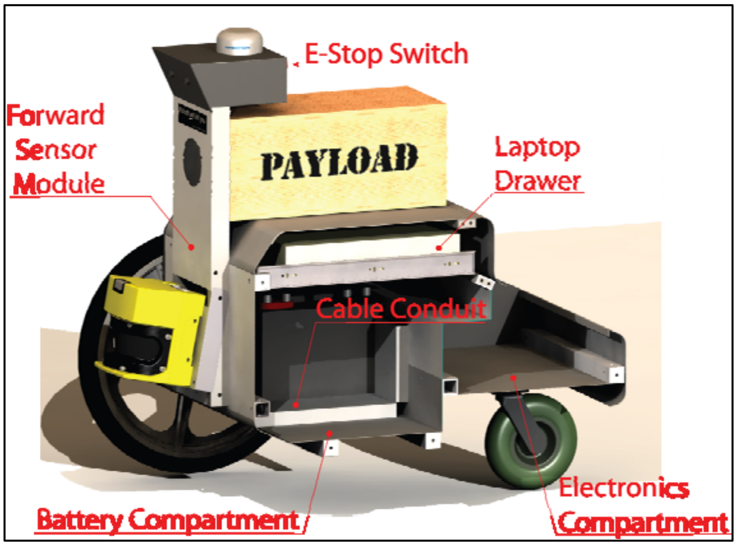


Figure 4-2: Main Chassis Compartments

Above the batteries, mounted on two 18-inch slides, is the laptop drawer. This design facilitates quick access to the computer without compromising the safety of other components. The enclosure retracts fully into the body of ReWIRED, stowing the laptop in a safe and space-efficient manner. A cable conduit along the bottom of the battery compartment houses and protects the wiring running between the laptop drawer, the Forward Sensor Module and the rear compartment which contains the power electronics, speed controllers, and the embedded system. Both the laptop drawer and the electronics compartment are easily accessible via independent doors.

4.1.3. Forward Sensor Module

The forward sensor module is a low-clearance module which holds all sensors on the robot. Internally, the module houses the dual Fire-i cameras; externally, it provides a mount for the GPS and SICK Laser Range Finder. Additionally, the manual E-Stop switch is located in an easily accessible location in the back of the module (Figure 4-2). Lastly, a transparent window is incorporated so as to not obstruct the payload camera. A taller structure was avoided by using dual cameras to increase our field of view. The lower profile is both more visually appealing and less conspicuous. Lastly, a simple predefined mechanical interface allows the module to be removed and possibly replaced with differently configured modules to hold a different set of sensors.

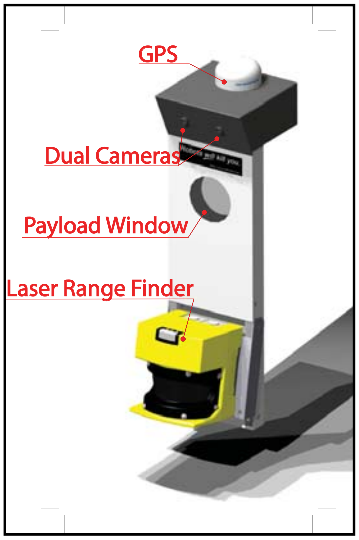


Figure 4-3: Forward Sensor Module

5. Power System

The new power system is again based around two car batteries in series supplying 24 volts. In order to implement the new symmetric loading scheme on the batteries the power converters needed to be able to receive a maximum of 30 volts, which occurs during charging, and a minimum of 10 volts or lower if possible, which can occur during heavy loading from the motors. The most effective regulator topology for reaching these requirements is a flyback design which replaces the combination of buck and boost converters previously used. In order to reduce the overall size of the design a high switching frequency of 500 kHz was selected which is five times the rate of the old converters. This speed is a good compromise between size and switching losses which grow linearly with the frequency chosen. Finally, since on two occasions inadvertent shorts destroyed a regulator, improved fault tolerance was implemented which includes over-voltage, reverse polarity, over-current, thermal overload, and electro-static-discharge protection. To improve usability, a battery monitoring circuit was designed to monitor the condition and usage of the two lead-acid batteries on the vehicle. One 10-segment LED bar display provides quick indication of the current capacity of the batteries while two 7-segment displays register the estimated time remaining.

Table 5-1: Power Requirements

Power Supply	Component	Current (mA)	Power (W)
5V Flyback	AVR Microcontroller (1)	2.00	0.010
	HCTL2017 Quadrature Decoder (2)	3.40	0.017
	HEDS5540 Encoder (2)	19.10	0.096
	Wireless E-Stop Receiver	11.20	0.056
	RS232 Transceiver	13.85	0.070
	LCD	1.20	0.006
	LED bars (1)	100.00	0.500
	Voltage Display	16.20	0.081
	Compass-HMC6352	10	0.050
12V Flyback	Fire-i Digital Board Cameras (2)	150.00	1.800
24V Flyback	SICK LRF	800.00	30.000
24V Direct Battery Connect	Custom Motor Controllers (2)	30,000.00	720.00

6. Electronics Design

6.1. Cameras

The team decided to continue using our two Fire-i Digital Board Cameras. These cameras feature a ¼” CCD sensor capable of outputting uncompressed color 640x480 VGA picture at up to 30fps and interface to the main computer over IEEE1394a (FireWire). The cameras are fitted with wide-angle lenses providing an 85° field of view. The power supply to these cameras has been vastly improved with the use of a powered FireWire hub, replacing the previous method of manually separating the power and data lines in the FireWire bus with jumper wires. The image processing technique of splicing the images from both cameras to create a panoramic view has been retained, as it's more than sufficient for detecting all manner of obstacles.

6.2. SICK Laser Range Finder

Supplementing the cameras is a SICK PLS101-112 laser range finder (LRF), which interfaces directly with the computer via an RS232 serial port. The device provides 180° single-plane sweep of the area in front of the robot with 0.5° angular and less than 70 mm (2.75 inches) radial resolution. Although the maximum scanning range of the SICK is almost 50 meters (164 feet), the scan radius is restricted to 10 feet to coincide with the camera's field of view. Although the LRF is a much more reliable sensor for detecting solid bodies, it is used to complement vision in detecting construction equipment and natural obstacles, such as trees and shrubs that are difficult to establish using vision alone.

6.3. GPS

We upgraded the GPS unit to a Trimble 4600LS. This survey-grade GPS unit features a 12-channel receiver that is also capable of receiving RTCM/RTK differential corrections, improving its horizontal precision to less than a meter. The sensor resides in a rugged waterproof housing allowing it to be mounted without additional enclosures. We selected this model for its relatively low cost and extra large surface area which improves signal reception. The unit interfaces directly to the computer via an RS232 serial connection using a standard NMEA-0183 protocol.

6.4. Encoders

Agilent HEDS-5500 optical shaft encoders were chosen for motion control feedback. These feature two-channel quadrature output with 1024 CPR (counts per revolution) resolution. Two 16-bit quadrature decoders (Avago HCTL2017) interpret signals from the encoders into meaningful data. The primary function of this sensor is to provide responsive motor feedback ensuring precise motion.

6.5. Computer

We decided to continue using a laptop computer for our processing needs. This was deemed sufficient for the robot's processing requirements and was chosen again due to the flexibility and efficiency these systems provide. Upgrades can be made easily and processing can be done independently of the hardware, which serves to lengthen the useful life of the mechanical platform.

6.6. *Embedded System*

To interface the computer with the drive system, an embedded system was used. The single board system from last year's entry was used with rewritten firmware for increased reliability and a better debugging interface. Procyon AVRlib was extended with additional functionality and drivers. The new code was written to be easily modified for use on the motor controllers as well as useful for future upgrades. In order to make debugging easier, a simple command line interface was implemented. Using this interface, a laptop can be connected to the board's serial debug port to run diagnostics.

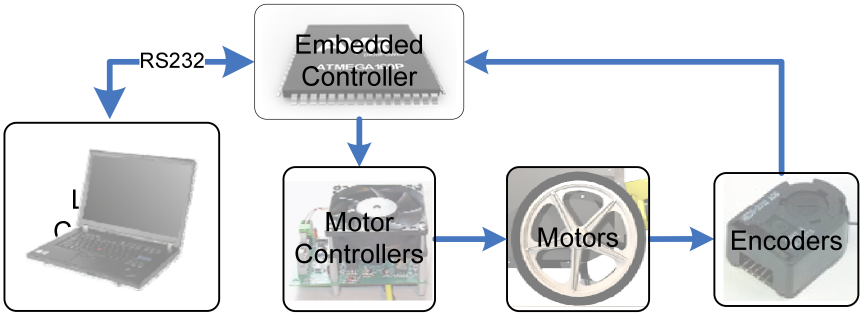


Figure 6-1: Embedded Network Structure

As demonstrated in Figure 6-1, the embedded board's primary function is to convert commands from the laptop into control signals used by the motor controllers. Optical encoders determine the position of each wheel, which is used to calculate its speed. This information is used by a proportional-integral (PI) closed-loop feedback algorithm. The PI control attempts to minimize the error between the desired speed and the actual speed of each motor while minimizing overshoot and maximizing motor agility. The PI algorithm maintains a responsive, precise control of the motors that is both flexible and easy to manage.

6.7. *Safety Measures*

Multiple safety measures were taken to ensure that ReWIRED is always under full control of an operator and does not threaten the safety of any bystanders. The vehicle speed is restricted to a maximum of 5 mph by the motor controller. A bright red emergency stop button is located atop the vehicle in a location easily accessible even when component lids are open. A wireless emergency stop is held by an operator whenever ReWIRED is in autonomous mode. Both emergency stops physically break the connection between the batteries and speed controllers, bringing the vehicle to an immediate halt. Additionally, the emergency stop signal is input into the embedded system so that it can be handled gracefully. This prevents the vehicle from behaving erratically after the emergency stop is released.

6.8. Motor Controllers

New motor controllers were developed to replace last year’s Victor 883 motor controllers. While the Victors were reliable, they have a 10% deadband which caused stability problems with the old control loop. The new motor controllers were based on the proven Open Source Motor Controller design. An Atmel AVR microcontroller was added to the design to increase flexibility by adding multiple input methods. The AVR performs PWM capture to accept signals from a standard R/C receiver for manual control, while interfacing with the embedded controller is done with an I2C bus.

7. Software Design

ReWIRED's software utilizes the open source Robot Navigation Toolkit, CARMEN, as a framework. It contains many drivers for standard sensor interfaces such as GPS, SICK laser range finders, which simplifies software design. Furthermore, it implements an extendable graphical user interface for these modules which serves as a base for additional GUI controls.

CARMEN divides tasks between processes that communicate via Inter-Process Communication (IPC) mechanisms. It passes messages over TCP sockets and each process can even be run on different physical systems if necessary. Persistent parameters are stored in a configuration file and can be changed in real-time. All processes using these parameters are updated with the new data immediately. The ReWIRED base module interfaces with ReWIRED's embedded systems and passes information as CARMEN formatted messages. The general robot server acts as a low-level control and reflexive safety layer between the higher level components and the base interface with ReWIRED's hardware. The laser and GPS modules are generic device drivers, which translate commands from our high-level modules into configuration commands and sensor data from the device into CARMEN formatted messages. High level modules including navigation, vision processing, and mapping also run as separate processes and are described in detail below.

ReWIRED runs on a conjunction of LRF and camera sensors with algorithms for obstacle detection, line detection, and mapping. All sensor data is aggregated on an environmental grid map after a probability-based localization process to correct for incremental odometry error. All sensor and map information is displayed in real-time on a remote graphical user interface application written in the Qt windowing library.

7.1. Obstacle Detection and World Mapping

ReWIRED utilizes a SICK laser range finder to detect all raised obstacles in front of it. An LRF is the simplest, least processor intensive and most reliable way to discover obstacles. After obstacles are detected, simple geometry is used to add them to a probability world map. Simultaneous mapping and localization (SLAM) is performed on this map to prevent collective errors in the odometry from destroying the map. Because the LRF used is meant for industrial purposes and takes quite accurate measurements, localization works quite well to produce a clear map of the areas traversed. The world map can then be saved for use in the CARMEN simulator. The ability to use the simulator on past data proved useful in the testing of path planning algorithms.

7.2. Lane Detection

The vision processing algorithms rely on data from two FireWire cameras aimed to cover the widest possible area in front of ReWIRED. Coriander, an open-source application for use with FireWire video devices and Linux, was used to capture from the two cameras. Each camera's feed is read in separately and stitched together to make a wide-angle view. This allows the robot to view both line boundaries nearly all of the time.

In the past, noise introduced by grass often interfered with ReWIRED's ability to detect the lane boundaries. This year an entirely new strategy was devised to overcome the limits of the past line detection methods. Because most of the noise occurs in the bottom third of the image, the image was broken into thirds vertically and horizontally and image processing is done on each of these sections independently. For each section an automatic threshold is chosen according to the Otsu method. Each section is binarized according to this threshold. In the lower third, where the grass produces speckling, blob analysis is done to throw out any blob below a certain size. To pick out the lines, each of the image sections in the upper two-thirds is compared to a set of binary images of lines at various angles. If the two are similar enough, the line is overlaid on a map containing only line boundary data. The map is periodically adjusted according to the localization done on the LRF data map. This method serves to perform line detection and interpolation in one pass.

7.3. Path Planning

In both challenges a map containing the combined LRF and lane boundary data is used to predict the shortest path to a desired location. The map is probed short distances in front and to the sides of the robot to determine the path which has the least probability of containing an obstacle. In the autonomous challenge, the desired location is a point a short distance down the lane. In the navigation challenge, the desired location is the closest waypoint. However, the map is only probed a short distance in the direction of the waypoint because the map may contain unexplored regions farther from this.

7.4. Objective Prioritization

For the Navigation Challenge, ReWIRED prioritizes the list of waypoints based on their distances from the vehicle’s current location. The closest waypoint is chosen as the next target. Priority is given to the currently chosen waypoint to avoid contention that occurs when two waypoints are equidistant from ReWIRED. As the vehicle moves, the priorities of the waypoints are continuously updated. Once ReWIRED reaches its intended target, the waypoint is removed from the list and the algorithm only considers those that are remaining.

8. Joint Architecture for Unmanned Systems (JAUS)

The team continues to be committed to the JAUS standard. We have improved on our previous JAUS implementation by writing our own message-handling libraries to interface with the CARMEN toolkit. The main reason behind developing a new framework was our shift from a Java-based software architecture to the C/C++-based CARMEN. We based our efforts on the OpenJAUS project, and have collaborated with the developers from the project in creating a reliable JAUS framework using C/C++. The new JAUS framework is still in development, and as such is not completely stable yet. This was however the only choice as a stable version of OpenJAUS only supported the JAUS Reference Architecture version 3.2, which is outdated.

ReWIRED is intended to participate in the 3rd level of the JAUS Challenge. We considered implementing JAUS level 3 as specified in the Reference Architecture, but decided against it since this would introduce significant overheads in communications within our embedded system. To handle the requirements of JAUS level 3 we would have had to add additional memory and processing capability to our embedded system, which would drive the cost up significantly. However, we have implemented a JAUS message parser in our embedded controller board that acts as a transparent proxy between the JAUS controller and the embedded system. While direct access to the embedded system components is not provided, the embedded controller provides the appearance of such access. In the future, with a more complex and powerful embedded system, we would be able to easily upgrade the individual components to handle JAUS messages.

9. Predicted Performance

Using data gathered at past competitions and from testing throughout the year a table has been compiled of ReWIRED’s performance benchmarks. Many of the target benchmarks were set during the original design of the robot and remained suitable goals during the redesign process.

Table 9-1: ReWIRED Statistics

Tests	Target	Measured
Vehicle Height	~36 inches (3 feet)	37 inches
Vehicle Length	Min 36 inches (3 feet)	39 inches
Vehicle Width	Max 36 inches (3 feet)	35 inches
Battery Life	Min 1 hour	>6 hours
Laptop Battery Life	Min 1 hour	3 hours
Maximum Speed	5 mph	Restricted to 5mph
Stopping Distance (down 15% grade)	Max 6 feet	<3 feet
Ramp climbing ability	Min 15% grade	>30% grade
Obstacle detection distance	10ft	Restricted to 10ft

10. Other Design Considerations

Beyond safety and solid mechanical, electrical and software design, the team has always strived for vehicle that is reliable, durable, and cost effective.

10.1. Reliability and Durability

All systems within ReWIRED were designed with reliability and durability in mind. Embedded and software systems were designed modularly, and rigorous testing of new modules was performed before integration. Durability of the electrical and mechanical systems comes from careful component selection and attention to strong mechanical design. Additionally, computer-aided design was utilized to ensure the sturdiness of ReWIRED’s mechanical design.

10.2. Cost

The cost of creating an autonomous vehicle from scratch can be a substantial investment. The team has always attempted to choose components with the best value to cost ratio possible. This has often involved designing and building systems from smaller components rather than customizing larger ready-made systems. Also, many of the parts and materials used to build ReWIRED were either donated or are on loan. Total time spent for design and implementation of ReWIRED this year was approximately 500 man-hours.

Table 10-1: Team Expenditures

Category	Item	Qty.	Tot. Price	Team Cost
Computer	Lenovo ThinkPad T61p	1	$1130	$0
Power	12V deep-cycle lead-acid	2	$120	$120
	*Charger	1	$300	$0
	Power Supply components	2	$45	$30
Chassis	*Sheet steel (1/8")	20sq.ft	$450	$0
	*Sheet metal (.04")	20sq.ft	$100	$0
	*Square aluminum tubing	12ft	$40	$0
	*Rectangular aluminum tubing	16ft	$60	$0
	*Wheels	2	$100	$0
	*Caster	1	$20	$0
	*Misc. Hardware		$300	$0
Motors	*24V right-angle gear motor	2	$100	$80
Electronics	Custom Motor Controllers	2	$160	$140
	*Fire-i Digital Board Cameras	2	$222	$0
	Trimble 4600LS GPS	1	$2,500	$0
	*ATmega16	2	$16	$0
	*Quadrature Shaft Encoders	2	$120	$0
	*Quadrature Decoders	2	$30	$0
	*SICK PLS	1	$4,500	$0
	Powered Firewire/USB Hub	1	$30	$30
Total			$10,343	$400

11. Conclusion

The IEEE Robot team has brought together a team of hardworking, motivated, and dedicated undergraduate students to deliver ReWIRED, a competitive and effective entry. The primary benefit to ReWIRED is that it builds on the modularity of the previous design and saves on a host of costs while integrating in new innovative systems.