ReWIRED

Return of Wisconsin Robotic Exploration Device

IEEE Robot Team
University of Wisconsin - Madison

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

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TABLE OF CONENTS

1. Introduction

The IEEE Robot Team from the University of Wisconsin – Madison would like to introduce ReWIRED, an improved version of our 2006 entry, WIRED. ReWIRED will represent the team's fourth appearance at IGVC.

2. Innovations

In creating ReWIRED the team sought to improve upon already successful systems from WIRED. This year significant upgrades were made to essential sensory components. The single web camera was replaced by two new board cameras which greatly increased our viewing angle and produced higher quality images while still keeping costs low. The GPS system was also upgraded from non-differential to differential GPS, which vastly enhanced the precision of GPS data and decreased the vehicle's reliance on encoder feedback.

ReWIRED is built upon a solid chassis which has served the team well. The compartmentalized nature of the chassis has allowed for the modification of individual systems without forcing changes to the overall vehicle structure. Moreover, the distinctive mast was replaced with a low profile sensor module. By using two cameras to enlarge the field of view, the sensor module could be placed at half the height of the original design greatly reducing ReWIRED's clearance.

For the electrical system, new power supplies were built to include fault tolerance, protection, and recovery, which greatly improves safety and reliability. Additionally, features were added to allow for the monitoring of battery state, 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.

In software, notable improvements were made to an already successful system. The platform was migrated to Linux in order to keep costs low. Additionally, features were added to make calibration considerably less complex. Similarly, data processing algorithms were streamlined and simplified in order to maximize reliability and speed.

Lastly, to increase the usability of ReWIRED and any other JAUS compliant vehicle, an Operator Controller Unit (OCU) was developed. The OCU is a remote device which allows the user to directly control ReWIRED as well as monitor and modify its state during testing. The OCU has made the calibration and configuration of ReWIRED safer and more efficient.

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 created a very successful design with WIRED last year, the team focused primarily on improving upon it. 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.

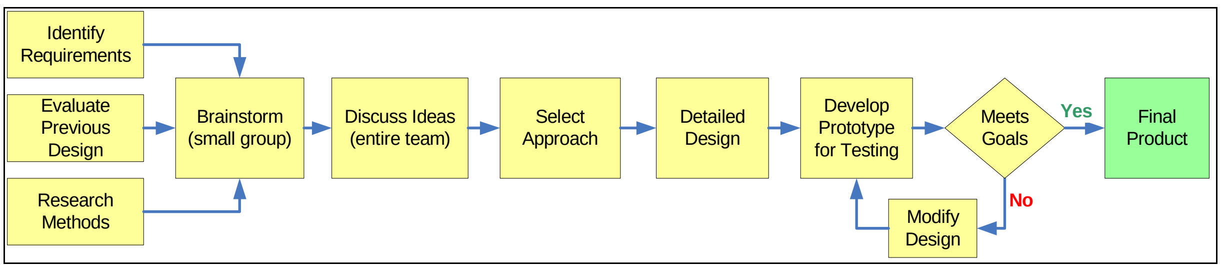

Figure 3-1: Design Process

3.1. *Team Organization*

To accomplish our tasks efficiently the team was divided into four subgroups (mechanical, power, embedded electronics and software) as illustrated in Figure 3-2. The hierarchical structure of leadership allowed groups to focus on specific sub-projects, while leaders coordinated their efforts to ensure compatibility and functionality of all robot systems.

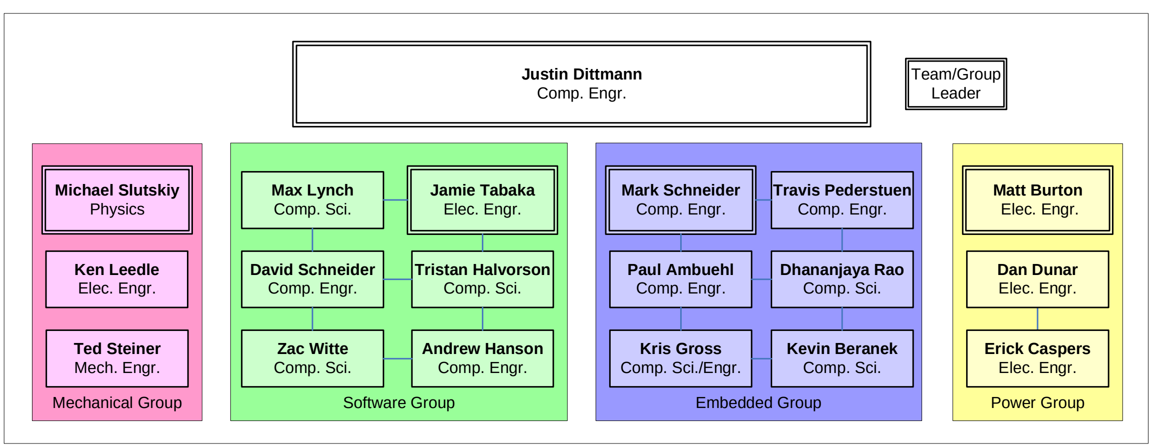

Figure 3-2: Team Organization

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. Meanwhile, the redesign and addition of new components was greatly eased by the spacious compartmentalized chassis. In order to utilize space more efficiently, WIRED's mast was removed from the design and replaced with a Forward Sensor Module, reducing the robot's clearance significantly. 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.

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.

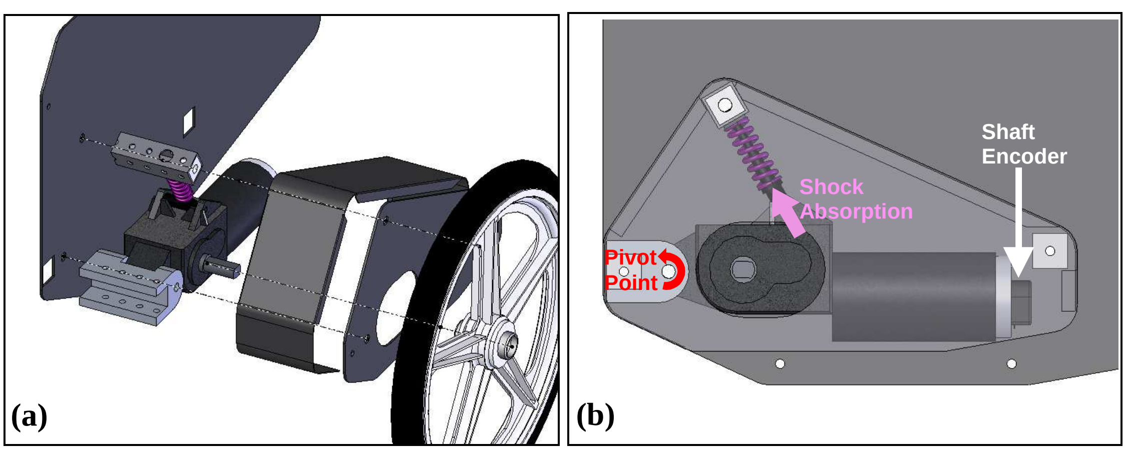

Figure 4-1: Left Motor Compartment (a) Exploded view (b) Side view

Like its predecessors, ReWIRED is differentially steered with motion feedback provided by the attached optical shaft encoders (Figure 4-1b). 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 11-1.

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.

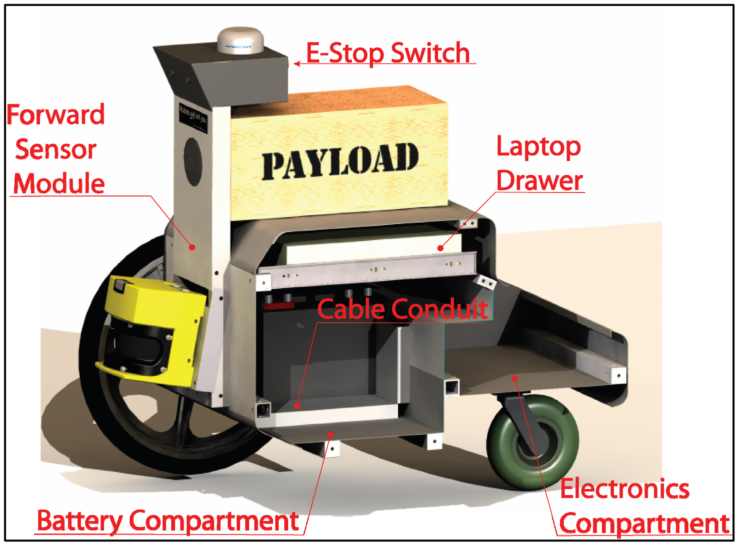

Figure 4-2: Main Chassis Compartments

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.

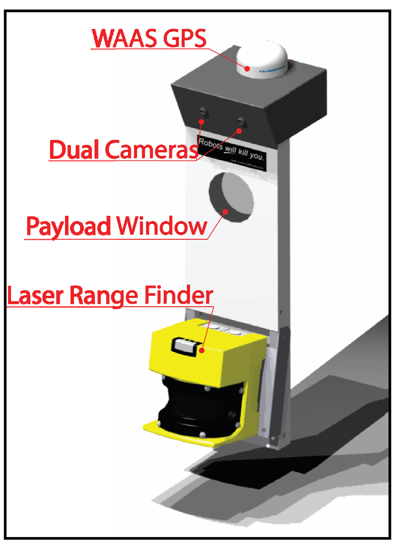

Figure 4-3: Forward Sensor Module

4.1.3. Forward Sensor Module

A brand new addition to the robot this year is the Forward Sensor Module (FSM); this low-clearance section replaces WIRED's mast. By increasing our field of view with dual cameras, we were able to design a more compact and visually appealing sensor carrier. The modification is made possible by a simple predefined mechanical interface which allows differently configured modules to be attached to the robot. Internally, the FSM houses the dual Fire-i cameras; externally, it provides a mount for the Garmin 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.

5. Power System

The power system for ReWIRED is an improved version of the previous year's design. Two 12V deep-cycle lead-acid batteries provide over six hours of battery life. Switching power supplies were chosen for their low heat dissipation and high efficiency, which extends battery life. The previous year's designs were modified to take new component demands into consideration, and were improved to be more robust and stable. Regulated 5V, 12V and 24V supplies were built to provide all necessary voltage levels. The new power supplies have dedicated fault protection circuitry which guards against voltage and current fluctuations, as well as reverse polarity. The power supplies also allow for components to be selectively powered on or off by the embedded system to conserve power when these components are not being used. To improve usability, a battery monitoring circuit was designed to monitor the condition and usage of the two lead-acid batteries on the vehicle. Two ten-segment LED bar displays provide quick indication of the power levels of each battery.

Power Supply	Component	Current (mA)	Power (W)
Regulated5V	AVR Microcontroller (3)	6	0.030
	HCTL2017 Quadrature Decoder (2)	3.4	0.017
	HEDS5540 Encoder (2)	19.1	0.096
	Receiver	11.20	0.056
	RS232 Transceiver	13.85	0.070
	LCD	1.20	0.006
	LED bars (2)	200	1
Regulated 12V	GPS 17HVS	40	0.48
	Fire-i Digital Board Cameras (2)	150	1.8
Regulated 24V	SICK LRF	800	30
24V Direct Battery Connect	Victor 883 Speed Controllers (2)	10	0.2

Table 5-1 Power Requirements

6. Electronics Design

6.1. Cameras

To satisfy our visual sensor needs, the team chose to use 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). However, in order to increase processing speeds the resolution is limited to 160x120. Additionally, the cameras are small in size and have very low power consumption. Each of the cameras can be fitted with a 4.3mm focal length lens that has a diagonal view angle of 42.25°; alternatively, these can be replaced with 2.1mm focal length wide-angle lenses which have twice the field of view (85°). The cameras are arranged side by side to increase the horizontal viewing angle and the images are spliced together into a single panoramic view. The cameras are used primarily to detect ground obstacles, lane boundaries and construction equipment.

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

The GPS unit being used is the Garmin GPS 17HVS. This GPS unit features a 12-channel receiver that reports its precise position through the continuous tracking of satellites. It is capable of receiving WAAS differential corrections, improving its horizontal precision to less than 3 meters. The sensor resides in a rugged waterproof housing allowing it to be mounted without additional enclosures. The GPS 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 and positioning data. 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. Additionally, the data is used to supplement the GPS positioning data.

6.5. Computer

WIRED's computer, last year, was a Dell Inspiron 600m with a 2.0GHz Pentium M Processor with 1GB of DDR memory. This was deemed sufficient for the robot's processing requirements and was chosen again for ReWIRED.

6.6. Embedded System

To interface the computer with the low-bandwidth sensors an embedded system was designed. A single board system was chosen for efficiency and simplicity of design, though the board includes network connections to ensure an expandable and modular design. An Atmel ATmega16 microcontroller (AVR) was selected, due to its relatively low cost, high performance, and ease of development. The AVR features multi-channel pulse-width modulation (PWM) used to control the motors, and supports many standard communication protocols (I^2C, SPI, RS232) for a flexible interface. To help implement these protocols, the Procyon AVRlib was selected as a stable, proven development platform to interface to the AVR's peripherals. A defining feature of the ATmega series is the ability to use standard development tools that are freely available via the GNU Compiler Collection project.

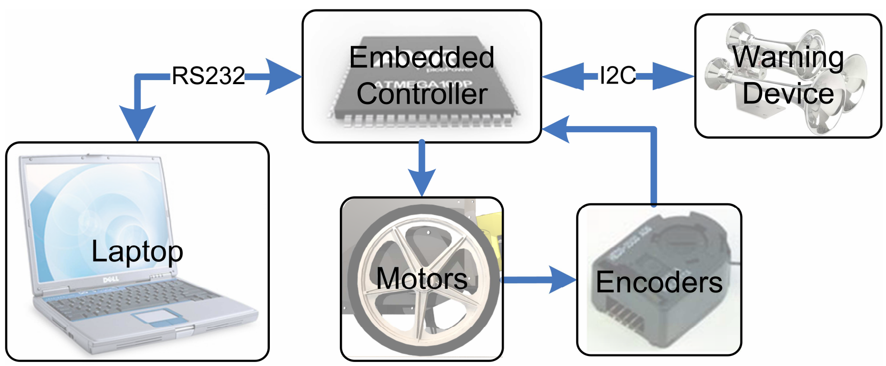

Figure 6-1: Embedded Network Structure

As demonstrated in Figure 6-1, the embedded board's primary function is to convert commands from the laptop into PWM 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. A secondary function of the embedded controller is to engage the audible warning device.

6.7. Safety Measures

Multiple safety measures were taken to ensure that ReWIRED is always under full control of an operator and will 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. Finally, an air horn was incorporated into ReWIRED to be used as a warning device to alert people of its presence.

7. Software Design

7.1. Overview

ReWIRED's core software platform is a continuation of previous year's efforts, with significant improvements in functionality, efficiency and usability. The main control application was developed in Java to take advantage of its cross-platform compatibility as well as the language's ability to facilitate modular design. The software structure is based on the open-source Robot Simulation and Control Lab (RSCL) framework, which was adapted for ReWIRED's particular needs. RSCL assists with the modularization of processes and systems within the software package and provides the user with the ability to easily interchange processing stages within the data path. This has provided the team with a consistent, configurable and extensible system for obstacle avoidance and navigation.

7.2. Robot Simulation and Control Lab

RSCL is an open source robotics framework that resulted from the team's work in previous years. It provides the necessary backend components to simulate and control a robotic vehicle including a convenient graphical interface for debugging, a 3D simulation structure for extensive testing, and modular organization for ease of programming. This software platform makes it easy to concurrently program as a team and provides a reusable and reliable framework.

7.3. 3D Simulation Environment

A 3D simulation application was written to allow for easy testing of new software modules, and to allow for testing when outside conditions or work on other systems in ReWIRED made real world tests difficult. The simulation software used the Xith3D Java extension that allows creation of an OpenGL virtual world complete with the models of a varied terrain, 3D obstacles and line boundaries similar to those that the autonomous and navigation competitions would present the robot. This simulated world was used to generate artificial vision, laser range finder, GPS and encoder data for the robotics application and responded appropriately to the control signals that were calculated from this data input.

7.4. Sensory Obstacle Detection System

7.4.1. Vision

The vision processing algorithms rely on data from two FireWire cameras directed at exclusive halves of the 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. A low-level C program was written to merge the two images together. The resulting panoramic image is fed into the core Java software using the Java Media Framework (JMF).

Figure 7-1: Panoramic Camera View

Image processing is done on the wide-angle image to detect both lines and obstacles. Most filtering operations performed on the image take advantage of the Java Advanced Imaging (JAI) API. Initially, color filtering is done on the raw image to separate obstacles (converted to white) from clear space (converted to black). The HSI (hue, saturation, intensity) color space is used for these operations rather than RGB because the hue of objects is affected very little by light, making it less sensitive to varying light conditions. A dynamic threshold is used to binarize any remaining sections of the image. Next an edge preserving median filter is applied to the image to eliminate speckling and “salt and pepper” noise. The camera is able to detect the lanes and the construction equipment quite well due to their vibrant color, but is unable to detect those objects that are dull in color. This data is combined with information from the LRF, greatly increasing the reliability of the obstacle detection system.

7.4.2. Laser Range Finder

Although our vision system is capable of recognizing a large number of obstacles appearing on the course by color alone, another sensor was desired to identify obstacles difficult to identify visually. For this reason, a SICK laser range finder (LRF) was incorporated into the obstacle detection system. The LRF continuously transmits distances to the nearest obstacle detected, sampled every 0.5° for 180°. The data is analogous to the visual data after preprocessing, and hence no preprocessing on the LRF data is required. However, in order to facilitate merging with visual system the LRF data is processed to reduce the field of view to 180º and to ignore obstacles farther than 10ft away.

7.5. Robot Navigation

7.5.1. Autonomous Challenge

For the Autonomous Challenge, ReWIRED relies on a purely reactive method to navigate the course while avoiding obstacles using vision and the LRF. Both systems are designed to produce gaps, which represent those areas that are free of obstacles. For vision, gaps are formed from rays drawn on the preprocessed image from the position of the robot to the edge of the image or the first white pixel, which represents an object. The vision information is then combined with similar data from the LRF.

To reconcile possibly conflicting sensor information, a moderating system was developed to combine data from an arbitrary number of sensor inputs. The system takes input from the sensors in the form of gaps and merges them in a process similar to a logical AND operation: if all the sensors agree that an area is clear of obstructions, the gap is validated. A moderator assigns each sensor a priority corresponding to its perceived reliability. If the moderating system detects a conflict between sensors, then the higher priority data is treated as correct. In ReWIRED's sensor layout, the camera is highest priority because it is capable of detecting solid bodies in addition to lines, potholes, and sandpits. The priority of the sensor systems can be changed during runtime if needed.

After the gaps are merged and validated, the vehicle attempts to proceed to the middle of the chosen gap, giving priority to those gaps that are most closely aligned with the current trajectory (Figure 7-2).

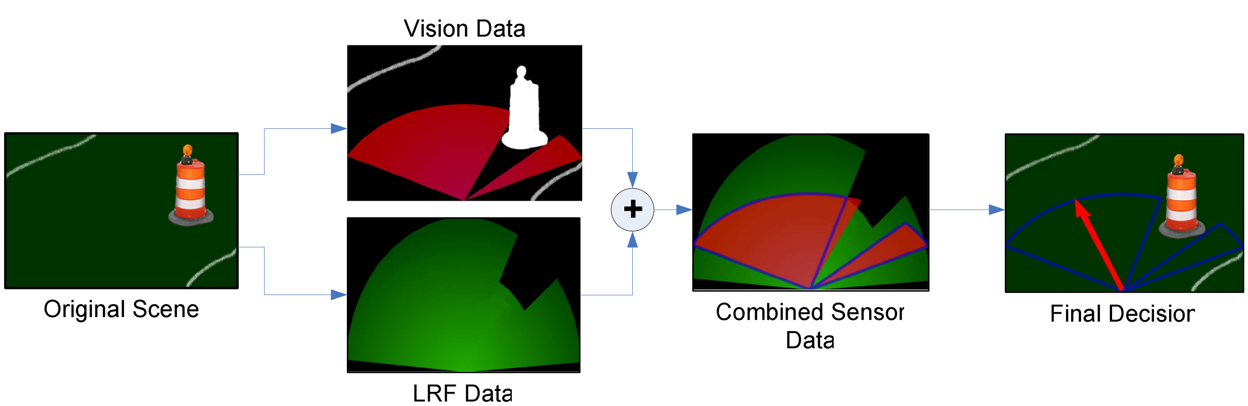

Figure 7-2: Obstacle Detection with Multiple Sensors

7.5.2. Navigation Challenge

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.

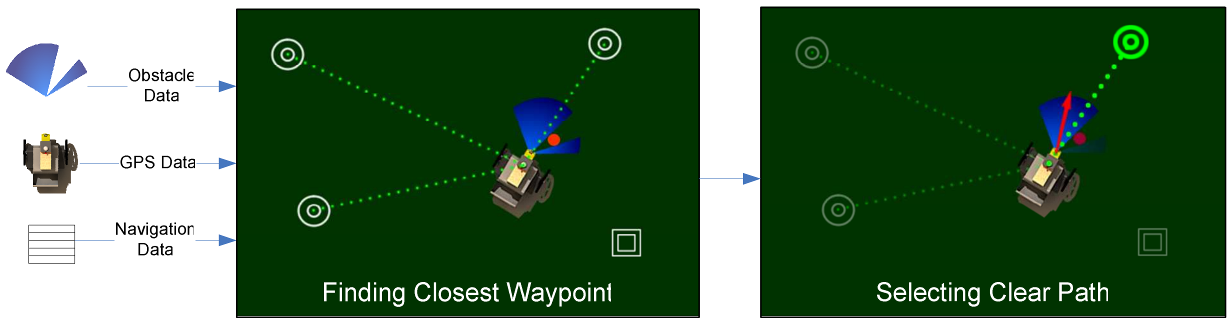

Figure 7-3: Navigation Procedure

The vehicle primarily relies on the information from the GPS to determine its position; however, if satellite lock is unavailable, ReWIRED relies on information from its encoders. This data is used by a dead-reckoning system to achieve an approximate location of the vehicle until the GPS signal is reestablished. The obstacles avoidance algorithm is identical to that of the Autonomous Challenge; the only exception is that gaps are prioritized based on their alignment with the target waypoint instead of the forward direction.

8. Joint Architecture for Unmanned Systems (JAUS)

ReWIRED continues the IEEE Robot Team's dedication to the JAUS architecture. Using OJJAUS, an open-source project which implements JAUS in Java, the software is able to send and respond to JAUS-compliant messages over any Ethernet or 802.11 interface. To develop a JAUS system, a dedicated team member studied the JAUS specifications to develop a thorough understanding of the protocols and methods involved and to convey the necessary ideas to the rest of the team. Each sub-group then developed their systems with JAUS communications in mind. For example, the software uses a coordinate system similar to the JAUS coordinate systems. Many internal structures were developed to be analogous to their JAUS counterparts so there is no loss of information during translation to JAUS messages.

The team originally planned to use JAUS for all communications on the vehicle, including RS232, I^2C, and SPI. However, it was decided that a sleeker, more elegant embedded design should be favored over complete JAUS compliance. Specifically, a complete JAUS implementation on the embedded system would be unnecessarily complex, and it was doubtful that a full implementation could fit in the limited memory offered by the microcontrollers. Instead, a full-custom embedded protocol was developed with JAUS in mind to facilitate easy translation from JAUS messages to the I^2C protocol.

In accordance with IGVC requirements, the vehicle is capable of handling three JAUS messages: Resume (Command Code 0004h), Standby (Command Code 0003h), and Set Discrete Devices (Command Code 0406h). Standby and Resume commands suspend and resume the vehicle's autonomous operation, respectively, while the Set Discrete Devices JAUS message activates the warning device.

In addition to the standard IGVC requirements, the IEEE Robot Team implemented an operator control unit (OCU) to send and receive JAUS messages over a wireless 802.11 network. The OCU is capable of handling all three messages recommended by IGVC as well as the Set Joint Efforts (Command Code 0601h), Query Joint Efforts (Command Code 2601h), Report Joint Efforts (Command Code 4601h), Query Global Pose (Command Code 2402h), and Report Global Pose (Command Code 4402h) messages. These messages are used to directly control the vehicle via two analog joy sticks located on the side of the OCU, as well as to receive status information from the vehicle.

9. Operator Controller Unit

While performing field tests on ReWIRED over the past year, the ability to view and modify software variables remotely became extremely desirable. Although ReWIRED's mechanical design features a pull-out laptop drawer allowing quick access to the computer, the laptop can be difficult to read while the vehicle is in motion. Furthermore, being able to stand at a distance from the moving vehicle both saves time and is desirable for safety reasons. For these reasons, a remote Operator Controller Unit (OCU) was designed.

Figure 9-1: Operator Control Unit

The core of the OCU is a WebDT 375 Tablet PC containing a 400MHz XScale processor and running Windows CE. Handles with thumb-sized joysticks were added on either side of the tablet to transform it into an ergonomic controlling device. The tablet communicates with the vehicle through a wireless 802.11 network.

Embedded Visual C++ application was developed to allow ReWIRED to be driven in manual mode with the thumb-sticks or to enable monitored autonomous mode. JAUS messages are interpreted by the OCU and continuously displayed to the user. JAUS messages are also used in the OCU's manual drive mode to send desired speed and directions to ReWIRED. A watchdog system was built into the vehicle's software systems to halt it in the event of communication loss. The OCU has made field testing of ReWIRED significantly more efficient and safe. Furthermore, the OCU represents an excellent investment for the team, as it will be used with future JAUS-compliant vehicles.

10. Systems Integration

By settling on predefined hardware and software interfaces early on, the systems integration process was greatly simplified. For example, the protocol used to communicate between the laptop and the embedded system uses custom variable-length messages for motor commands, status information and configuration. Defining a custom protocol that was specifically tailored for the task at hand ensured complete interoperability of our software and embedded systems while the variable-length capability leaves room for further expansion. In turn, the embedded system, itself, was developed in order to mitigate integration between the high level decision making by the software and execution by the mechanical systems.

Additionally, we were able to take advantage of standard industry interfaces such as RS232, FireWire, NMEA-0183, I^2C, and others. This saved us from having to develop other unnecessary custom interfaces, thus simplifying the integration process between the sensors and the software. Overall, these various standard protocols along with our embedded system, as a transparent layer for the underlying mechanics, allowed for a modular and extensible robotic vehicle.

11. Predicted Performance

Using data gathered at last year's competition 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.

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	1.5 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

Table 11-1: ReWIRED Statistics

12. Other Design Considerations

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

12.1. 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. Furthermore, checkpoints along long communication paths were built in to facilitate debugging of subsystems and to allow for problem sources to be more quickly determined. 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. A full 3D model of the vehicle was completed using SolidWorks, and component failure analysis was performed using COSMOS Express to guarantee a minimum Factor of Safety of 10.

12.2. 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 was approximately 1644 man-hours.

Category	Item	Qty.	Tot. Price	Team Cost
Computer	*Dell Inspiron 600m	1	$1200	$0
Power	*12V deep-cycle lead-acid	4	$400	$0
	*Charger	1	$300	$0
	Power Supply components	3	$45	$30
Chassis	*Sheet steel (1/8")	20sq.ft	$450	$0
	*Sheet metal (.04")	20sq.ft	$100	$0
	*Square aluminum tubing	12ft	$40	$40
	*Rectangular aluminum tubing	16ft	$60	$60
	*Wheels	2	$100	$0
	*Caster	1	$20	$0
	*Misc. Hardware		$300	$200
Motors	*24V right-angle gearmotor	2	$100	$80
Electronics	*Victor 883, 24V Speed	2	$298	$0
	Fire-i Digital Board Cameras	2	$222	$222
	Garmin 17HVS GPS	1	$112	$112
	ATmega16	2	$16	$16
	*Quadrature Shaft Encoders	2	$120	$0
	*Quadrature Decoders	2	$30	$0
	*SICK PLS	1	$4,500	$0
	Misc. Electronics		$100	$100
OCU	Operator Control Unit	1	$277	$0
Totals			$8790	$860

Table 11-1 Team Expenditures

13. Conclusion

The IEEE Robot Team has brought together a diverse team of students to design an autonomous robot, ReWIRED, to compete in the 16th Annual Intelligent Ground Vehicle Competition. The team developed the robot to exceed all specifications while holding to our team goals. We feel that through participation in this project and competition we have expanded student knowledge and experience while creating a safe, robust, and competitive intelligent vehicle.