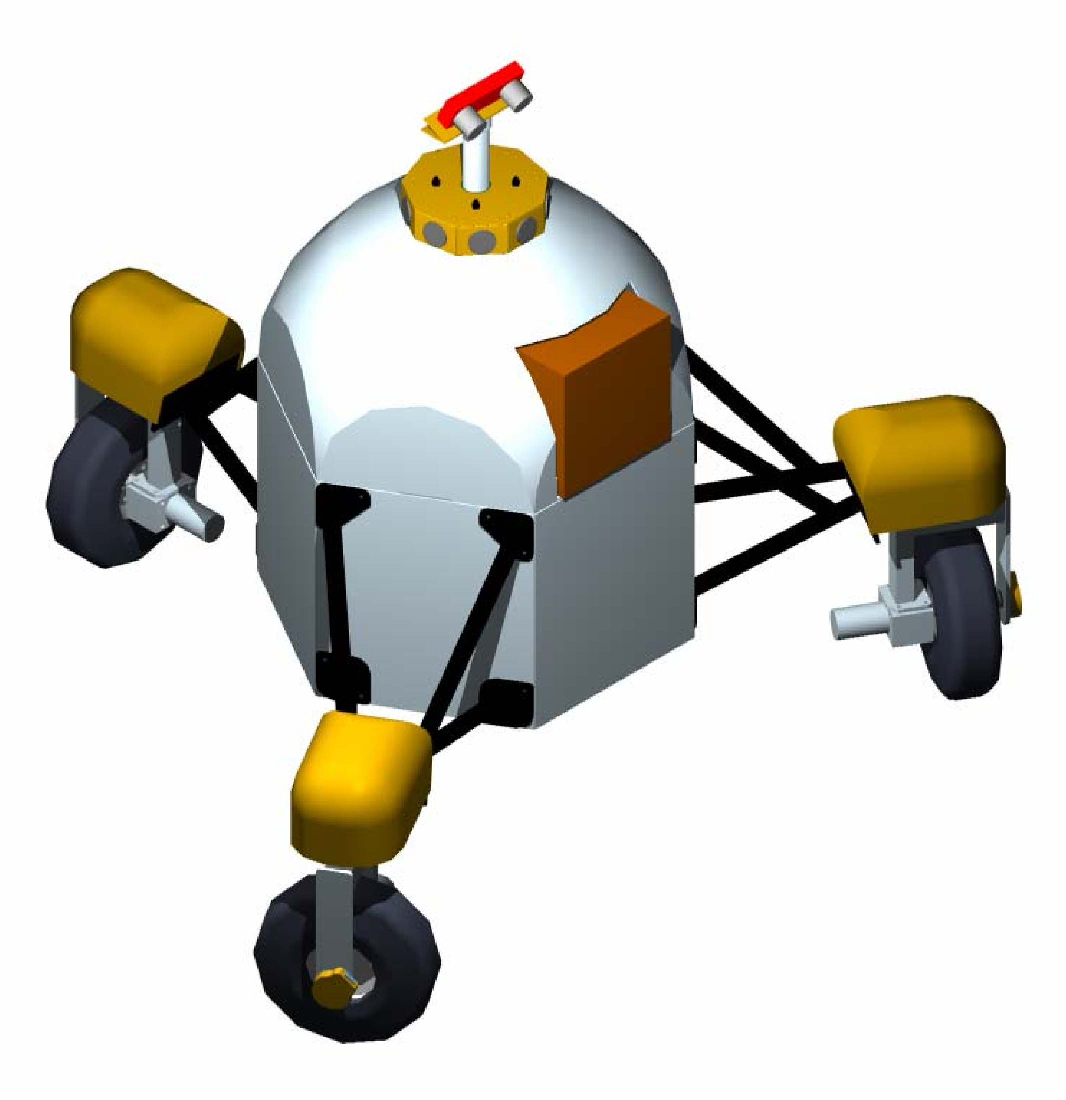
13th Annual Intelligent Ground Vehicle Competition

ρ-bot



University of Missouri – Rolla
Robotics Competition Team

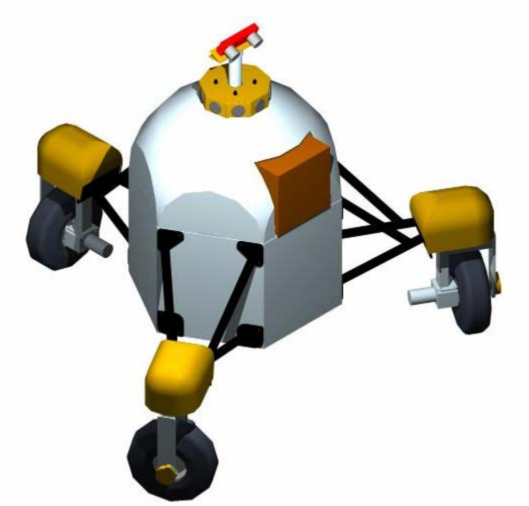
2005 Design Report

1.0 Executive Summary

The University of Missouri – Rolla Robotics Competition Team proudly presents Rho-bot, an innovative autonomous platform designed to take on the challenges of the 13th Annual Intelligent Ground Vehicle Competition. This is the first year the team is competing, and brings to the competition new ideas and innovations. Rho-bot is a highly maneuverable vehicle capable of movement in any direction at any time, and employs a novel environment modeling and path planning system. This robot is designed and constructed with an emphasis on maneuverability, durability, safety, modularity, and professionalism.

2.0 Innovations

Figure 1: Rho-bot



The completed Rho-bot is shown to the right in Figure 1. This platform represents one of the most maneuverable and stable platforms developed to date for this competition. The source of its exceptional maneuverability is the three independently powered and steered wheels. Each wheel can have a unique heading and speed, which permits smooth, gradual turns as well as tight turns of various radii, including a zero turning radius. The robot also has the ability to move in any direction regardless of which way the chassis is oriented.

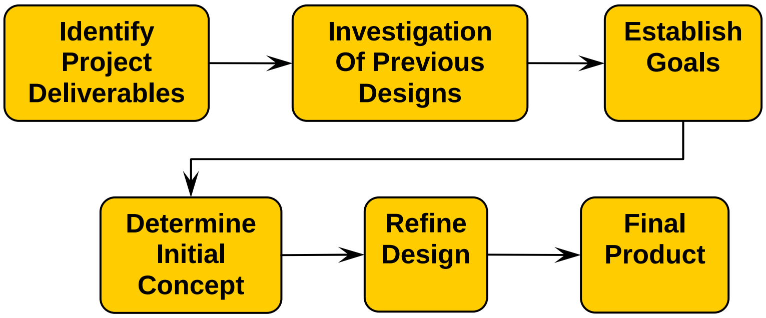
In addition to the maneuverable drivetrain, stereovision cameras capable of rotating 180° to the left and right, along with sonar and infrared sensors arrayed around the entire robot, allow the robot to see in any direction. This capability means that the entire robot does not necessarily have to turn to observe what is next to or behind it, which can save a significant amount of time when navigating in tight areas.

Another important innovation is the smart motion controller designed and built for this robot. Rather than forcing the computer to go through the entire decision making process of determining the speed and direction of each wheel, the computer simply sends to the motion controller a heading and speed. The controller then does the rest of the thinking. This saves computer-processing time for other tasks, and allows for simple and fast communication over a single serial port.

3.0 Design Process

Before beginning work on the robot, a design process must be established in order to ensure that vehicle is constructed in an efficient manner. See Figure 2 below for an outline of the procedure implemented by the team.

Figure 2: Design Process



3.1 Identify Project Deliverables

Rho-bot is engineered to compete in the 2005 Intelligent Ground Vehicle Competition. Therefore, the rules for this competition serve as the primary source for identifying project deliverables. Early on the team decided that the robot would compete in both the autonomous and navigation challenges. In addition to the rules outlined for the competition, there are three other important objectives that must be met; the robot must be reliable, cost-effective, and professionally manufactured.

3.2 Investigation of Previous Designs

Since this is UMR's first entry in the Intelligent Ground Vehicle Competition, it is important to thoroughly investigate previous designs to determine what problems have been encountered and what has performed well. Some common features of designs that have been successful include high maneuverability, accessibility to internal components, a reliable and adequate power supply, and sound mechanical design and fabrication.

Another important aspect investigated is the cost of constructing a robot. Previous top ranking robots in this competition ranged in cost from approximately $10,000 to $30,000, although some teams spent as little as $1,500. One of the primary expenses most of the top entries invest in is a scanning laser range finder, which costs around $4,000 to $8,500, depending on the model. Based on the team's previous research on vision systems, stereovision is a much more versatile and less costly method of finding distances to obstacles than a scanning laser range finder, and is still exceptionally reliable despite the extra noise. A stereovision system also eliminates the need for separate sensors for range finding and line detection.

3.3 Establish Goals

In addition to designing a robot that has the successful features identified from previous designs, another important goal is to set a target weight. This helps primarily to determine the size of the drive motors that are needed. The team established a target weight of 220 lbs (100 kg) by looking at the weights of previous vehicles and an estimation of the weights of major components, including the 20 lb payload. Another objective set by the team is that the robot be highly modular because it allows for greater flexibility when designing each component, more efficient work division, and greater portability when transporting the vehicle.

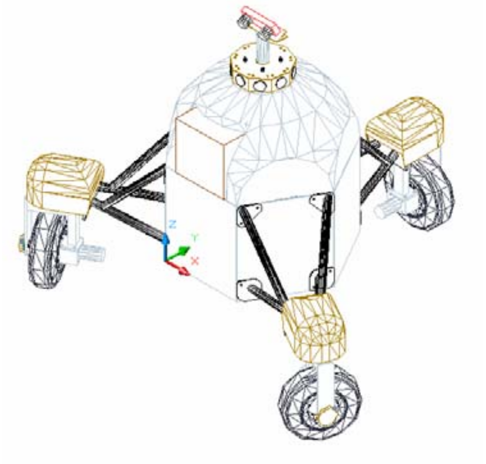
3.4 Determine Initial Concept

After carefully analyzing the project deliverables, looking at previous designs, and several brainstorming sessions, the team generated a basic three-wheel, omni-directional vehicle design. The team decided that the robot should not only be modular with respect to the mechanical systems, but also with respect to the software systems. The mechanical system modules include the main chassis, three support legs, the yoke and drivetrain subsystems; the upper support structure, the rotating camera system, and the sonar mount. The software systems are broken down by each type of sensor, the environment modeling system, and the computer to motor controller interface.

3.5 Refine Design/Final Product

From the basic mechanical design agreed upon from the brainstorming sessions, the robot is refined, module-by-module, in an iterative approach using AutoCAD 2005 to aid in the design process. Since the robot is designed to be modular, once the dimensions of the connection points between the modules are established, construction can begin on one part of the robot while another part is being refined. Once a particular module's design is completed, the necessary dimensioned drawings are generated from the AutoCAD models and fabrication can begin. See Figure 3 to the left for the final AutoCAD design.

Figure 3: Final Design



3.6 Team Organization

The team consists of a management core and two divisions. The management core consists of the team president, vice president, treasurer, secretary, and public relations, and is responsible for organizing the team's schedule, managing its finances, and addressing logistical issues. The tasks associated with the design, development, and construction of the robot are divided up into the two divisions: mechanical/electrical systems and computing/electronics. See Figure 4 below for a graphical representation of the team's organizational structure. Table 1 below lists all of the team members.

Figure 4: Organizational Structure

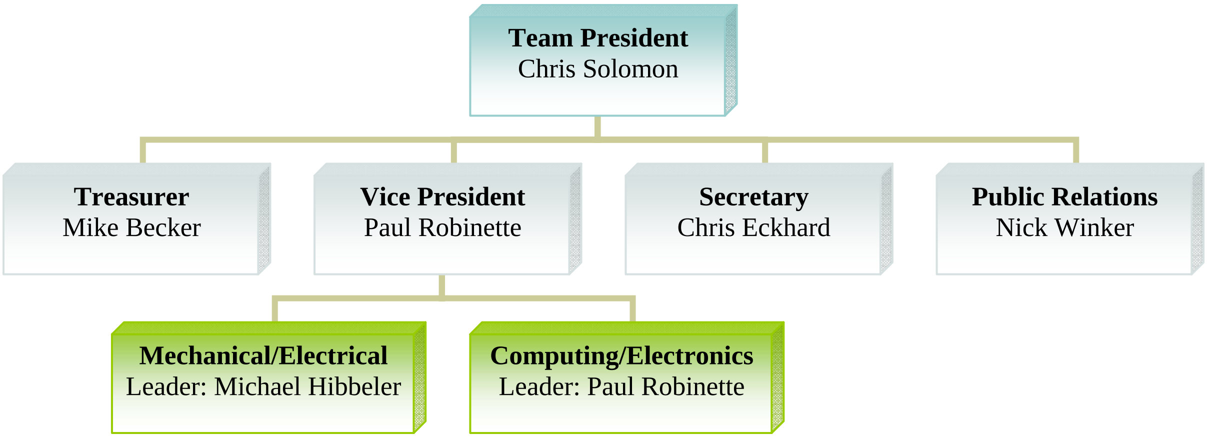


Table 1: Team Members

Brian Dobbs Casey Porta Chris Eckhard Chris Jacobsen Chris Solomon Dan Krus	Dave Brown Grant Wallace Igor Izyumin Jason Parker Jason Weil Jennifer Moentnish	Joel Harms Josh Anderson Joshua Crawford Kerry Geisz Luke Watson Matt Hawkins	Michael Hibbeler Mike Becker Nick Winker Paul Drews Paul Robinette Phillip Ponzer	Russ Bockhorst Ryan Meuth
Faculty Advisors: Dr. Daniel McAdams, Dr. Sanjeev Agarwal				

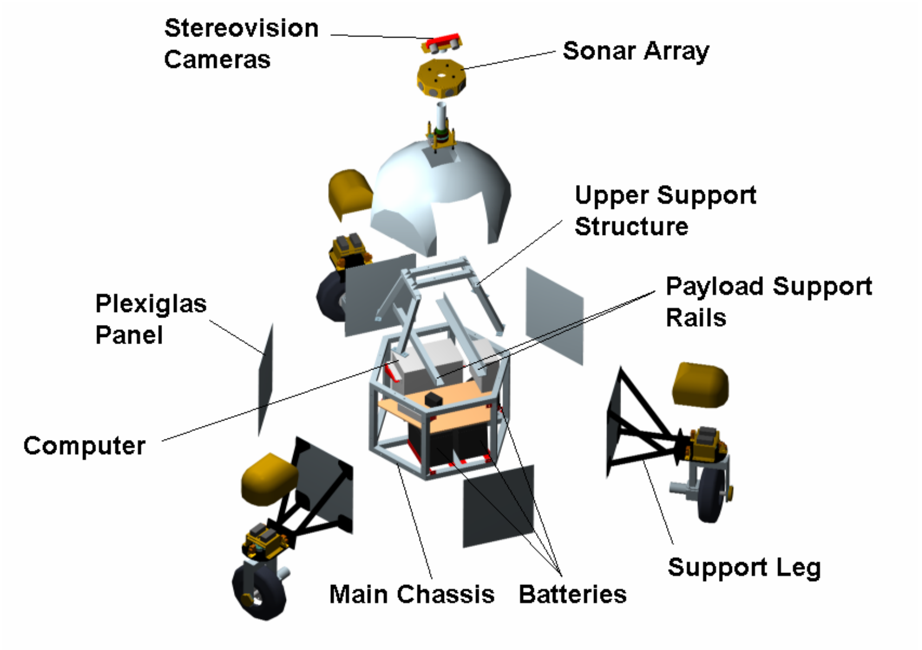
4.0 Mechanical Systems

4.1 Chassis

The main chassis is hexagonal in shape, and constructed primarily out of 1" square steel tubing. There are three support legs for the wheels, fabricated out of 1" round steel tubing and ¼" steel plates. The 0.065” wall steel tubes are welded together, creating a very rugged and durable frame. The frame is covered in a Plexiglas and fiberglass shell for visual appeal.

One of the main goals for this robot is to be as modular as possible. Each leg is attached to the main frame with ¼” bolts and the legs are all identical, which allows for them to be interchangeable and easily replaced if one should be damaged. Detaching the legs is the primary method of making the robot more portable. The upper support structure is also removable from the main chassis, which allows for easier access to the internal components. In addition, the rotating camera module and sonar array are also detachable to make working on those components easier. See Figure 5 below for an AutoCAD rendering of the robot disassembled into its primary components.

Figure 5: Disassembled Rho-bot AutoCAD Rendering



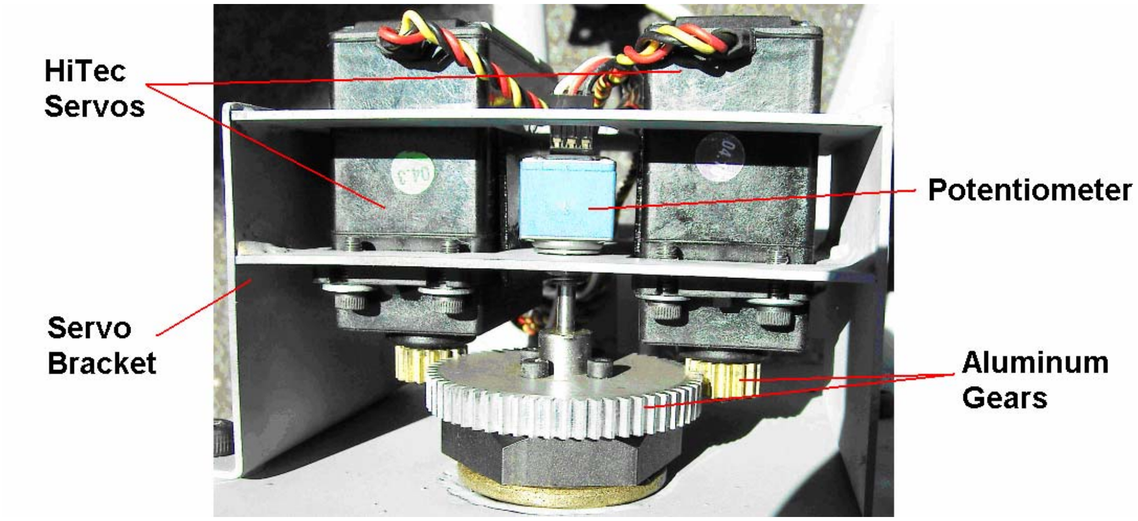
4.2 Drivetrain

Each wheel is powered by an SS2 gear motor capable of providing a maximum of 1.43 horsepower at 24 volts using a gear ratio of 35:1. The mechanical group selected this particular motor and gear combination because of its compact size and strong construction. The output shaft of the gearbox is attached directly to the wheel shaft. This assembly is mounted to the yoke, and can be easily detached if the motor or gearbox ever needs replacement. An optical encoder is mounted to opposite end of the drive shaft, and provides feedback to the motor controller about wheel rotation rate and direction.

4.3 Steering

Each wheel is steered via two ¼ scale, HiTec HS-805BB servos. A single-turn potentiometer is mounted to the end of rotation shaft, allowing for precise control over the direction of the wheel. See Figure 6 below for a close-up of the steering mechanism. Each wheel is capable of rotating 270°, which allows for the entire robot to move in any direction and even turn about its own axis. The 270° limit prevents excessive twisting of the wires running to the motor and encoder around the yoke.

Figure 6: Steering Mechanism



4.4 Stability and Vibration Isolation

The minimum mechanically stable platform consists of three contact points with the ground, so the team selected a three-wheel configuration to reduce the number of physical components. A three-wheel design also has the advantage of all wheels being in contact with the ground at all times. With any vehicle it is desirable to have the lowest center of gravity possible in order to handle quick acceleration or deceleration, especially on a slope. As a result, the robot has a wide wheelbase and a compact central chassis. The most crucial weight factor in the stability of the platform is the batteries, which have a combined weight of 60 lbs. Therefore, the batteries are placed as low as possible inside the main chassis.

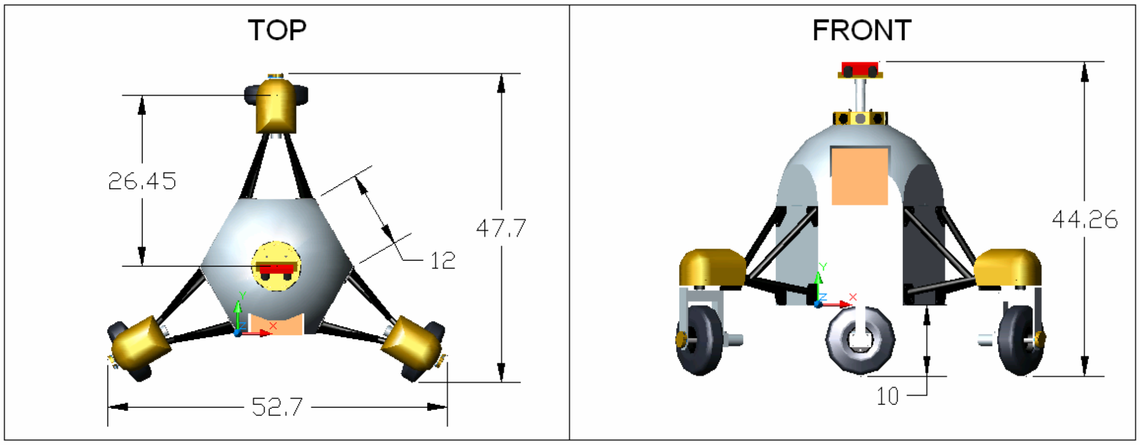
The only component on the robot sensitive to vibrations is the computer. The inflated wheels absorb most major vibrations, given the 5 mph speed limit, and can be inflated/deflated to change their vibration handling characteristics. In addition, the computer itself rests on rubber shock absorbers, thus further reducing vibrations.

4.5 Physical Parameters

The robot has a total weight, including the 20 lb payload, of 195 lbs, which is 25 lbs under the target weight of 220 lbs. After completing the vehicle, the team noted that the frame could be significantly lightened by using more expensive, thinner walled steel without compromising structural integrity. However, the low cost and ease of fabrication of the steel used on this platform served as the main material selection criterion. A future chassis would be constructed that minimizes weight in order to enhance overall performance.

The robot has an overall width of 52.7 inches at the widest point, and has a height of 44.26 inches. The main chassis has a ground clearance of 10 inches. See Figure 7 below for the dimensioned vehicle.

Figure 7: Dimensioned Vehicle

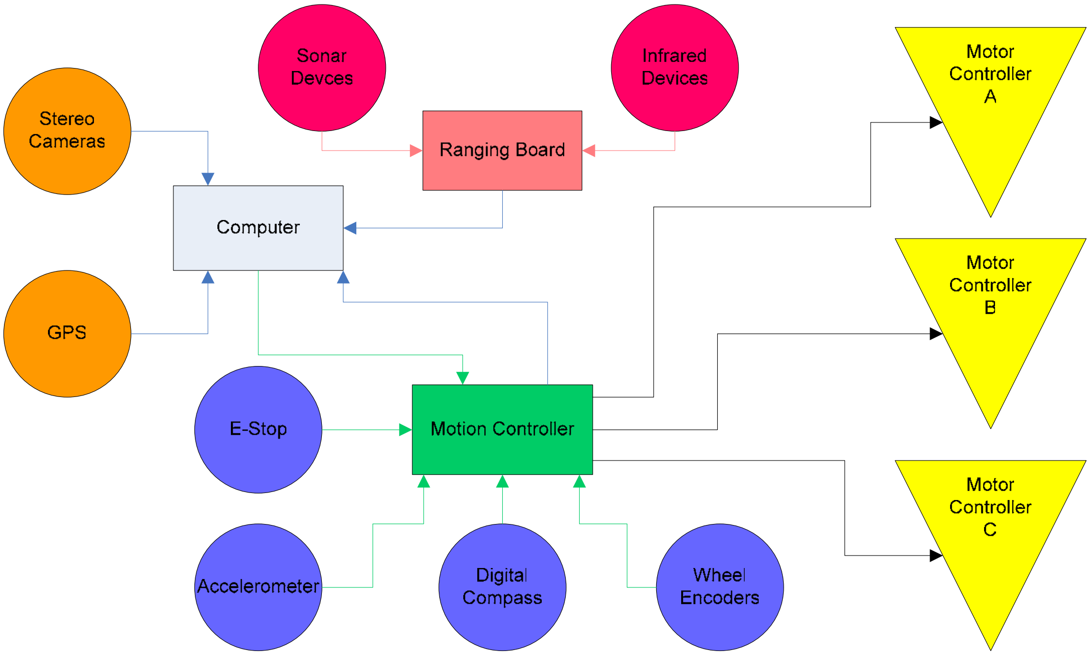


5.0 Electrical Systems

5.1 Power Source/Distribution

Power for all motors and servos is provided by two Helios 12 VDC, 35 A-hr, deep-cycle, sealed lead acid batteries. These two batteries are connected in series to a terminal block, providing a total of 24 VDC. The computer is powered by a similar Helios 12VDC, 12 A-hr battery. Having a power supply for the computer separate from the motors provides a cleaner source of power and enhances the robot's modularity since the computer can continue to run while the main batteries are charging. The sonar and infrared sensors receive their power from the 5 VDC power supply, which is connected to the 24 VDC terminal block. The stereovision cameras get their power from the computer over the IEEE 1394 cable. See Figure 8 for the layout of the vehicle's electrical system.

Figure 8: Electrical System



5.2 Motor/Servo Controller

A large amount of computing power is needed for stereovision and navigation, so this mandates a more intelligent approach to motor control. Hence, the main computer is only required to output direction and speed to the motion controller. The controller takes this information and determines how fast and what the orientation of each wheel should be. It then decides how to make the necessary adjustments, and sends appropriate signals to each of the three Innovation First Victor motor controllers that power the drive motors. The motion controller directly actuates the steering and camera servos.

5.3 Electrical Safety

Since high current will be going from the batteries, through the motor controller, and out to the motors, it is important to make sure that the electrical system will not be damaged in the event of a short or one of the motors stalling for an extended period of time. This issue is resolved by using current sensors that monitor the current level, and will shutdown a circuit in the event of an overload. Additionally, in-line fuses are connected to the batteries as a backup. Since the batteries only output 24 VDC, there is minimal risk of electrocution; however the fuses will help to limit any harm to a person.

6.0 Software Systems

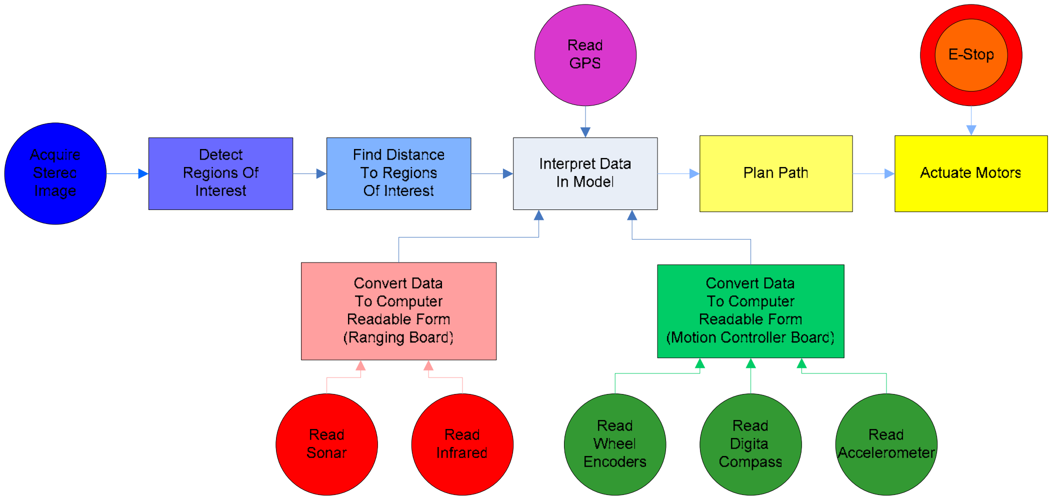
6.1 Computer Hardware/Platform

The robot utilizes a 2.8 GHz Pentium 4 computer mounted in a custom-built box. The stereovision cameras are connected to an IEEE 1394 port and data to and from the motion controller, sonar sensors, and infrared sensors is sent over RS232 serial ports. The autonomous software runs on Gentoo Linux, a flexible operating system that allows for significant performance optimization.

6.2 Software Operation

The robot will begin moving once the “START” button is pressed. If no GPS waypoints are loaded ahead of time, then the robot will start in autonomous mode. At this point the computer will take data from its sensors and process them into the environment model. The path planning module calculates the best route, and the motion controller actuates the motors. If either the wireless or onboard E-Stop is activated, the motion controller sends a signal to the motor controllers to brake, and informs the computer of this action. Once the computer is notified that the E-Stop has been triggered, it stops running the autonomous software. See Figure 9 below for the software layout.

Figure 9: Software Layout



6.3 Sensors

There are three sensors that provide information to the robot about its surroundings: sonar, infrared, and stereovision. Stereovision is the primary obstacle detector and detects all potholes, both real and simulated. It is also used for detecting lines. The array of nine sonar sensors provides data for medium range obstacles. The nine infrared sensors, located at strategic points on each leg of the robot, detect close proximity obstacles and objects missed by the sonar. Infrared sensors are particularly useful when navigating in tight areas.

The sonar array is connected to a microcontroller that continuously reads information from each of the individual sensors and calculates the location of any obstacles found. This information is then added to the model upon request. Data from the infrared sensors is acquired in a similar manner. The stereovision system transmits data across the IEEE 1394 bus to the computer, and is processed by software developed by the team that utilizes the Stanford Research Institute Small Vision System and Intel Open Computer Vision libraries.

6.4 Environment Model & Navigation

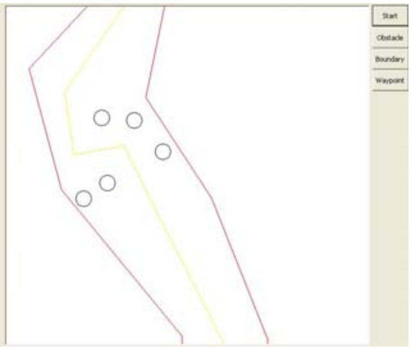


Figure 10: Model

The environment-modeling module is a highly innovative method of storing information about the robot’s surroundings and selecting the best path possible. The model gathers data from all of the sensors and stores the information in a potential field, which records the position of obstacles and assigns them a potential, or threat level. The model then determines the best possible path to take by finding the lowest points in the potential field and creates a path following it. Since the line finding algorithm outputs “obstacles” to the model, a path is created between the peaks in the potential field. Similarly, simulated and real potholes are considered “obstacles” by the model, and the software will navigate around them. See Figure 10 to the right for a top down, simplified representation of the model with the path plotted as a yellow line.

6.5 Trap/Dead End Avoidance

In the event that the robot winds up in a dead end, it merely has to either rotate the stereovision cameras or make a zero-radius turn to back out of the dead end and then search for a new path to take. Due to the model’s long range planning, such a trap will typically not be a problem. If the robot must turn around, the digital compass will assist in determining which direction on the path is forward.

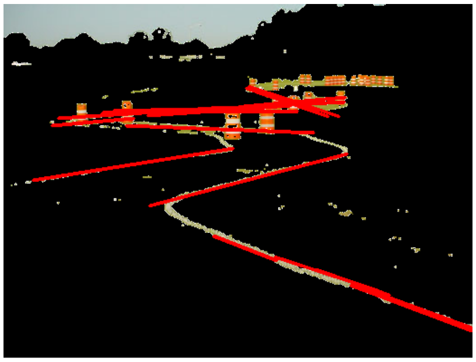
7.0 Autonomous Challenge

Detecting lines is one of the most crucial tasks for this challenge since the lines define the course layout. Unlike obstacle detection, line detection can only be accomplished using a vision system**.** A color filter is then applied to eliminate all colors but whites, yellows, and oranges. Figure 10 below shows an example of the color filter applied to an image.

Figure 10: Color Filter

Original Image **Filtered Image**

Figure 11: Detected Lines



The Canny edge detection algorithm is applied to another copy of the original image to find major edges. An output image is created using data points that appear in both filtered images. Dominant lines are found using the Probabilistic Hough transform. Using information from previous frames, a region of expectation is generated, and the detected lines are matched up to this region. Finally, stereo data is used to find the location of the lines in 3D space. See Figure 11 to the right for an example of an image with lines detected highlighted in red. Short, dashed lines are not a problem since the Hough transform will inherently connect those lines. Longer gaps also do not pose a problem since the path planning algorithm is constantly looking ahead as far as possible in the model. Thus, the robot will automatically align itself with the next set of lines.

8.0 Navigation Challenge

The navigation challenge requires that the robot quickly, accurately, and efficiently reach as many waypoints as possible in the shortest amount of time. For this challenge, the robot relies on a GPS unit to provide position information and a digital compass to determine its current heading. The stereovision, sonar, and infrared sensors provide the robot with information about any obstacles it encounters. Initially the computer will receive a list of waypoints, which are fed into the model one at a time in the order they must be reached, as determined through initial analysis. The model will then process the waypoint as a negative potential, or essentially the opposite of an obstacle. The robot will be attracted to the negative potential, analogous to a ball rolling to a low point on the ground. When obstacles are encountered, the software will accordingly plan a course around them. As soon as the waypoint is reached, the next waypoint is added to the model.

9.0 Safety

The robot has an emergency stop that can be activated both by a button on the robot as well as by remote via radio signal. When the emergency stop is activated, either wirelessly or mechanically, the motor controller shorts the motor terminals, which causes the motors to experience very high impedance, thus causing the robot to electromagnetically break to a stop. Without this breaking system the robot would just coast to a stop. In other words, the absence of a breaking system means that the robot might not stop at all if it is rolling down an incline.

10.0 Predicted vs. Actual Performance

10.1 Speed

The SS2 gear motors have a maximum output shaft rotation speed of 800 rpm. This translates into a maximum speed of 23 mph with the 10 inch wheels. However, for the competition there is a strict speed limit of 5 mph, so the motion controller will not allow the robot to exceed this speed limit.

10.2 Ramp Climbing Capability

According to the rules for the competition, the robot must be capable of climbing a 15% grade (8.5 degrees). Since the robot has approximately 115 pounds of thrust at the wheels, it is capable of climbing a grade of 50%, limited by the coefficient of friction, which is assumed to be 0.6. In addition, the vehicle is capable of driving over ground discontinuities, such as curbs, that are three to four inches in height.

10.3 Reaction Time

The model will refresh as often as it can receive data from its sensors. The vision software, for example, is able to send data at around 5 Hz. This means the robot covers a distance of about 1.5 feet between frames. Each sonar sensor reports data to the model approximately twice per second in a sequential order around the array, and all of the infrared sensors are sampled a minimum of 5 times per second. When the E-stop button is activated, approximately 1.2 seconds elapse until the robot comes to a complete stop from 5 mph.

10.4 Battery Life

When selecting the batteries, the team initially estimated a power consumption of approximately 2.2 kW. The power consumption is based on the computer running at full speed, all sensors running continuously, the drive motors running at maximum, and all of the servos operating continuously. The batteries are selected assuming a 30-minute minimum running time. Under normal operating conditions, the computer battery and motor batteries have an actual runtime of approximately 30 minutes and 1 hr, respectively.

10.5 Accuracy of Waypoint Navigation

The robot uses a Garmin GPS 18 unit that is able to receive a WAAS signal for differential capability. Given a good differential signal, the device is accurate to within approximately 1.5 meters after the Kalman filter is applied. This filter coordinates GPS and dead reckoning data, acquired from the accelerometer and digital compass, to give a more accurate vehicle position.

11.0 Systems Integration

Through careful planning of the mechanical, electrical and software systems, all of the various components are able to interact with one another. A highly modular design allows for individual components to be easily modified without changing the entire design of a system. Using a smart motion controller is vital to developing a software system that is independent of the physical platform. This means that the software is portable to another vehicle that has a motion controller that can accept a heading and speed.

12.0 Vehicle Component Costs

The team initially estimated that the total budget for constructing the robot would be approximately $5,400. This figure then increased to about $7,000 once the computing group determined that the stereovision cameras would be purchased as a whole unit, rather than as individual components. The robot actually cost $5,963 to build, at a cost of $4,010 to the team. These totals show that the robot is under budget and costs significantly less than the $10,000 to $30,000 budget other teams have. See Table 2 for a breakdown of the estimated and actual costs.

Table 2: Cost Breakdown

Component	Vendor	Predicted Cost	Actual Cost	Cost to Team
Mechanical				
Steel Components	Rose Metal	$150.00	$245.75	$245.75
Drive Motors	RobotCombat.com	$600.00	$515.10	$515.10
Servos & Gears	ServoCity.com/Maxx Products	$350.00	$430.66	$430.66
Wheels	Northern Tool	$50.00	$49.09	$49.09
Fiberglass/Plexiglas	Wicks Aircraft/Aircraft Spruce/Lowes	$50.00	$171.34	$171.34
Bearings	Igus/McMaster-Carr	$50.00	$32.51	$11.64
Bolts/Fasteners	McMaster-Carr/Lowes/MSC Ind. Supply	$100.00	$200.15	$200.15
Subtotal		$1,350.00	$1,644.60	$1,623.73
Sensors				
Cameras	Videre Design	$500.00	$1,415.00	$0.00
Digital Compass	Acroname	$90.00	$51.00	$51.00
Accelerometer	Analog Devices	$60.00	$20.00	$0.00
Optical Encoders	USDigital.com	$100.00	$158.60	$158.60
Sonar	Senscomp	$300.00	$425.70	$425.70
Infrared	Acroname	$150.00	$140.04	$140.04
GPS	Garmin	$300.00	$94.99	$0.00
Subtotal		$1,500.00	$2,305.33	$775.34
Computing System				
Pentium 4 Processor	Newegg.com	$200.00	$158.00	$158.00
Motherboard	Newegg.com	$100.00	$70.00	$70.00
RAM	Newegg.com	$150.00	$134.25	$134.25
Hard Drive	isellsurplus.com	$100.00	$78.97	$78.97
Other Hardware	Various Companies	$1,000.00	$167.72	$167.72
Subtotal		$1,550.00	$608.94	$608.94
Electrical Systems				
Batteries	Batteries.com	$150.00	$153.54	$153.54
Electronics	Digikey/Futurelec/Circuit Specialists	$700.00	$559.81	$559.81
Wire	Igus/MSC Industrial Supply Co.	$100.00	$469.25	$66.95
Connectors	Home Depot/AlliedElec.com	$50.00	$221.82	$221.82
Subtotal		$1,000.00	$1,404.42	$1,002.12
Total		**$5,400.00**	**$5,963.29**	**$4,010.13**

13.0 Conclusion

Rho-bot combines exceptional mobility with an innovative modeling system to handle the challenges presented in the Intelligent Ground Vehicle Competition. The robot represents the combined design and manufacturing efforts of students from the University of Missouri – Rolla from a diverse set of disciplines, primarily consisting of computer engineers, computer science, and mechanical engineers, but also including students majoring in math, physics, aerospace, and business. A total of approximately 2,900 person-hours went into the design and development of this vehicle. Rho-bot will continue to serve as a reliable and adaptable platform for future autonomous development.