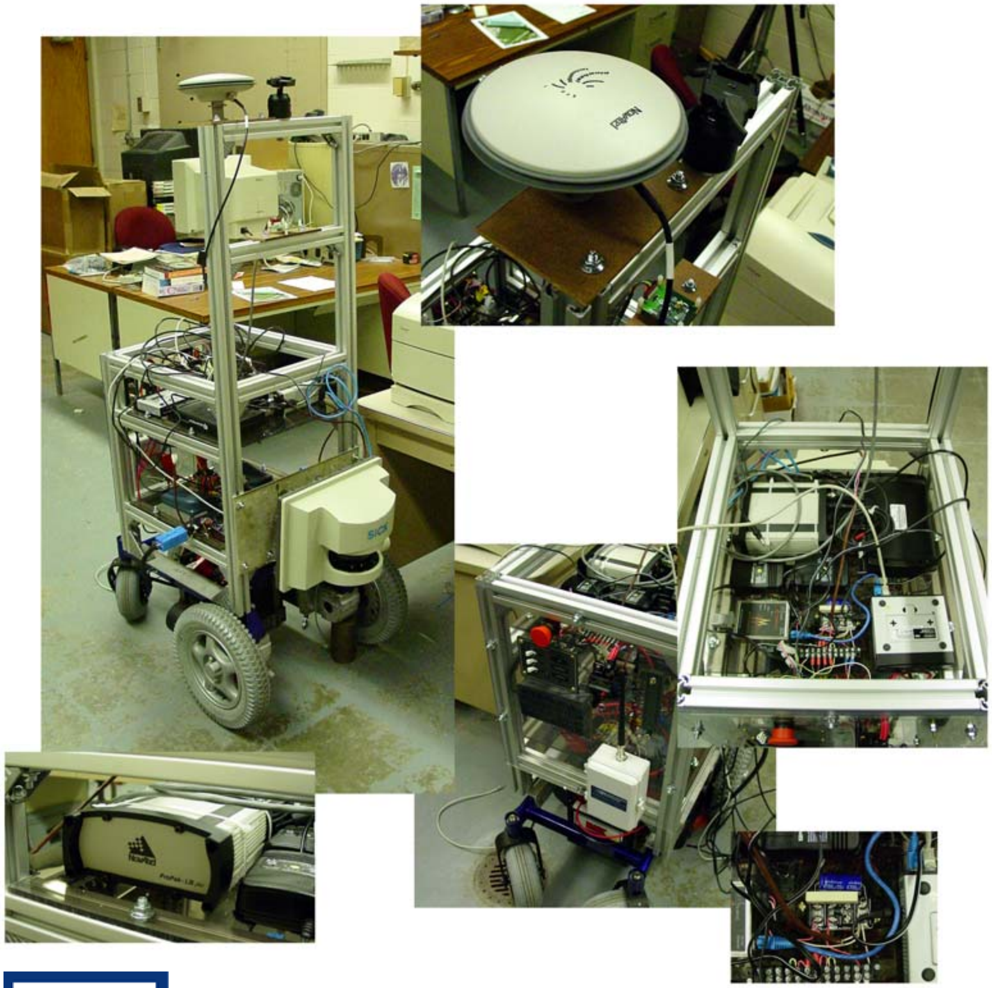
Roberto



CASE

CASE WESTERN RESERVE UNIVERSITY

Faculty Statement

“Roberto” was designed by a team of 6 senior-project students at Case during the Spring semester of 2006. The original 6 members contributed significant engineering design and each received 4 semester-hours credit. At the time of this writing, substantial additional software work is in progress, being contributed by new, additional team members.

Prof. Wyatt Newman, EECS Dept, CWRU

1 Introduction

Case Western Reserve University and the Case Autonomous Robotics Team are proud to introduce Roberto in the 14th annual Intelligent Ground Vehicle Design Competition. Roberto is Case's first entry to the competition. The vehicle is the culmination of a semester long senior project as well as continued effort during the summer.

2 Design Methodology

To design Roberto, the team examined the rules of the competition, identified requirements, and enacted a plan to fulfill those requirements. The requirements were organized into components and each member of the team took responsibility for one or more specific components.

3 Physical Design

The framework of the vehicle consists of a lower frame and drive unit as well as an upper frame with mounting for sensory and control equipment. Specifications for the frame were decided early in the production cycle because the frame was needed to integrate the remaining components. The design emphases were stability, maneuverability, ease of modification and safety.

3.1 Lower Frame and Drive Unit

The lower frame, wheels and motors were graciously donated by Invacare. The steel frame was custom built to meet the specifications set forth by the

Figure 1: Lower frame

team. Two large front drive wheels are independently powered by electric motors. Stability is provided by two castor wheels in the back. Figure 1 shows the lower frame assembly. Thanks to the design of the drive system, the vehicle is able to turn in place and maneuver in tight spaces. The weight of the lower frame provides a solid base for the upper frame and assures that the vehicle is not top heavy.

To hold the pair of 12V sealed AGM batteries, a battery box was drawn and manufactured. The custom design allows it to fit in a relatively small space and provides for easy replacement of the batteries. Mounted in the middle of the frame, the battery box provides stability to the vehicle.

3.2 Upper Frame

Bosch 40mm extruded aluminum structural framing components were used to construct the upper frame. This option was chosen because it is both light and strong. The design of the bars provides for easy repositioning of components and simple modification of the frame itself. It was also important that the upper frame be non-magnetic. In the front of the vehicle, two bars extend up to near the maximum allowable height. The boom allows the GPS antenna to avoid interference from other devices. It also places the compass away from magnetic interference from the steel lower frame, motors, and other devices. Finally, the raised section enables the camera to view the course from a high vantage point.

Behind the instrumentation tower, the upper frame provides several polycarbonate shelves. Each shelf hosts different components and provides protection from weather and debris. The shelf supporting the laptops is mounted on a system of springs and dampeners. That shelf is also lined with vibration isolation material to protect the laptops from excessive shock or vibration.

4 Sensor and Control Design

The sensor array was designed for accurate detection of markings and obstacles as well as ease of use and modification. The processing requirements of each potential sensor were also considered. The motor control was designed to be safe, responsive and accurate.

4.1 Vision

Machine vision is the most intensive computational process within our software system. Vision processing is comprised of three major components: color mapping, geometric transformations, and template matching. For color mapping, the system is “trained’ with manual assistance. Representative snapshots are acquired and displayed for user interaction. The user selects locations in the scene that are judged to be examples of key colors (notably, green, white, yellow and orange), and the corresponding (neighborhood-averaged) RGB values are stored as examples. Subsequently, in live processing, pixels are classified as color types based on closest similarity to one of the training values. The result is illustrated in Figs 2 and 3, below.

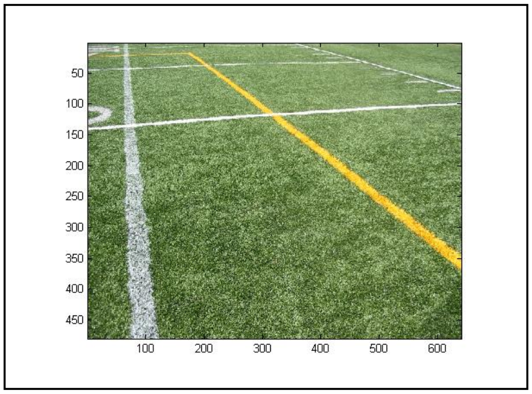


Fig 2: original scene

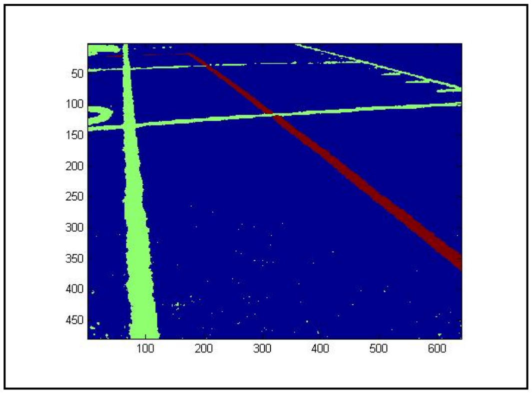


Fig 3: color-mapped scene

The second major processing task is geometric transformation. The camera mounting pose and the wide-angle lens introduce warping and perspective distortions. Images are transformed into equivalent top-down (plan) views, aligned with world coordinates. This transformation is performed on the basis of training images (snapshots with fiducials located at known coordinates with respect to the robot) and 2-D isoparametric interpolation.

The third image-processing module performs object recognition. Templates for lines, barrels, barriers and potholes are compared against regions within images, and labels are assigned to objects on the basis of template correlation values.

In addition to a plan-view Cartesian representation, the vision system also expresses an interpretation in terms of polar coordinates. Polar coordinates permits simple transformations to world coordinates based on robot GPS and compass values.

4.2 Obstacle Detection and Ranging

The primary means of obstacle detection and ranging is the SICK LMS 221 laser range finder. The LMS (Laser Measurement System) scans up to a 180 degree sweep in front of the vehicle. Data is taken at 1 degree increments, and each point is accurate to within 10cm. Using the data gathered during each sweep, obstacles in range are mapped using polar coordinates. In order to increase throughput, the standard RS-232 interface was replaced by RS-422 which will allow communication at 500kbaud. The LMS is mounted low to the ground and the scanning beam is angled up slightly to avoid detecting inclines or ramps as obstacles. Figure 4 shows the LMS mounted on the front of Roberto.


Figure 4: SICK LMS 221

Data from the LMS will be combined with vision information to provide an enhanced model of the world. The camera will help detect low lying obstacles, as well as simulated pot holes that would not be detected by the LMS. The LMS provides faster updates than the vision system and has very accurate distance measurement, so it works well as the primary obstacle detection sensor.

4.3 Heading and Position Determination

A PNI Corp. TCM 2.5 digital compass was chosen because it performs reliably under most conditions and can provide accurate readings even when on a moderate slope. The compass also allows for true north correction which is important when working with the GPS unit. The compass and its mount are shown in Figure 5.

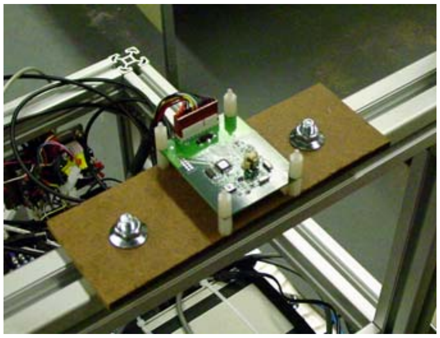


Figure 5: PNI TCM 2.5 Compass

NovaTel generously offered the ProPak LB-Plus GPS unit at a reduced price. The model was selected because of its good accuracy, as well as its ability to receive differential correction signals. Because the vehicle is required to pass very close to each waypoint in the competition, the accuracy of the NovaTel GPS unit augmented with differential correction will be essential. During testing, free Canadian differential signals were used. For the competition OmniSTAR has provided their commercial service at no charge. The signal received from OmniSTAR allows sub-meter accuracy. Figures 6 and 7 show the GPS base unit, and the antenna mounted to the top of Roberto’s sensor boom.

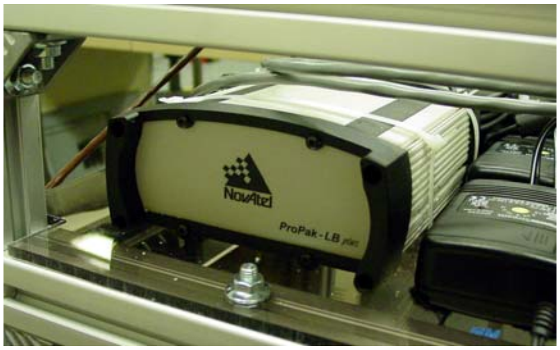


Figure 6: NovaTel ProPak LB-Plus

Figure 7: GPS Antenna

4.4 Motor Control

To transform low-power computer command signals to high-current motor control, two Curtis 1228 drives were chosen. The drives were chosen because they match the power requirements of the motors and they can be controlled with a simple analog signal. The drives use pulse width modulation (PWM) and back-EMF feedback to control the speed of the motors. The control information is sent to the motor drives from the control computer via National Instruments USB-6008 analog and digital I/O devices. Figure 8 shows the two motor controllers, the two NI units, and the wiring in between.

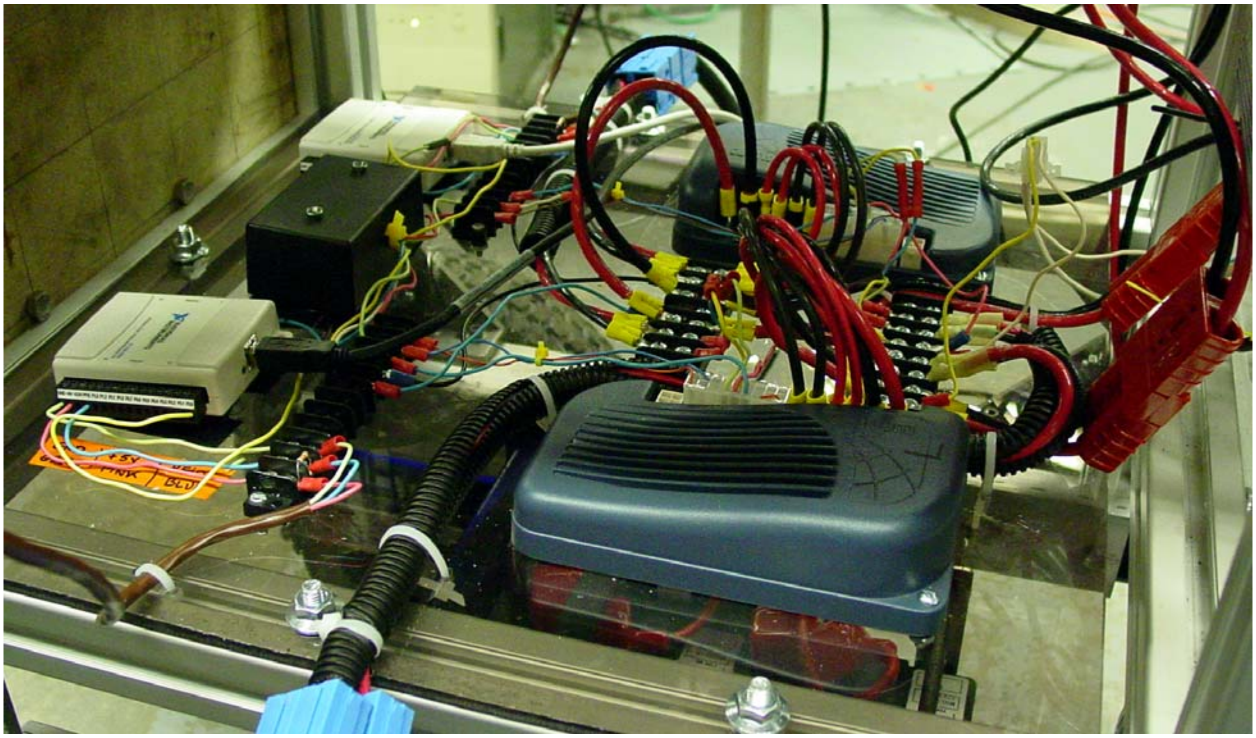


Figure 8: Motor Control assembly

4.5 Speed and Distance Monitoring

A Hall Effect sensor is mounted next to each drive wheel. Fixed to the wheels are ferrous disks with 22 holes drilled at regular increments. As the wheel turns, the sensor generates a square wave that represents the frequency at which the holes and solid parts of the encoder disk are passing by it. The USB-6008 is used to count the falling edges and a multimedia timer is used to provide an accurate estimate of time elapsed. With knowledge of how many holes have passed by the sensor, and how much time has elapsed, the vehicles current speed can be calculated. A related technique is used to determine how far the vehicle has traveled. The current hole count is recorded, and then after traveling the new hole count is recorded. By finding the difference, the total distance driven in that period can be determined.

5 Electrical System Design

Two 12V sealed AGM batteries are wired in series to provide 24V to the entire vehicle. The power supply from the battery is routed through a 100-Amp circuit breaker/cut-off switch. Past this breaker, the 24V supply is routed to the motor drives and to a breaker/distribution panel. Enabling the motor drives requires not only 24V power (via the main breaker), but also a 24V enable signal. This signal is routed in series through a manual E-stop button and a wireless-remote E-stop.

Several devices require voltages other than 24V. The wheel encoders require 5V, which is provided by the NI USB-6008 directly. The LMS needs 24V, which should be isolated from power-supply noise introduced by motor current draw. Simple power conditioning for the LMS is done with a single rectifier diode and a large capacitor. Additional devices (remote E-stop, network switch and GPS) require 12V, which is derived from the 24V supply via a DC-to-DC converter. Similarly, 9V power is supplied to the electronic compass and to the camera via a separate DC-to-DC converter. Finally, 120VAC is provided by an inverter. No devices currently require this power, but it is available for convenience (e.g. for laptops). Power for the LMS, the DC-to-DC converters and for the 120VAC inverter are routed through three separate 15-A breakers/switches.

6 Software Design

The main goals for the software design are reliability, modularity, and extensibility. Because Roberto will be used not only in the 14th annual IGVC, but also ongoing projects involving research in artificial intelligence and other fields of computer science, the framework for the software must be flexible. Each component of the vehicle that interacts with the computer is encapsulated and most implementation details are hidden from the user.

6.1 Software Organization

The control software is broken down into many parts. An interface for each sensor hides the hardware and communication details and provides a simple interface to desirable data or to allow commands. That interface is further encapsulated as a TCP/IP server so that each individual piece of the control system can run on a different machine and still be able to communicate with the rest of the system. Again, all details of the socket communication is hidden, and only useful data or command responses are provide to the rest of the code.

A central server maintains the processes that run the interface routines for each subsystem. When a client requests a connection to a certain subsystem, either a sensor or an output to the motors, the server connects the two and serves as an intermediary that can cache the communication and buffer it when needed. The server is designed for high throughput and low

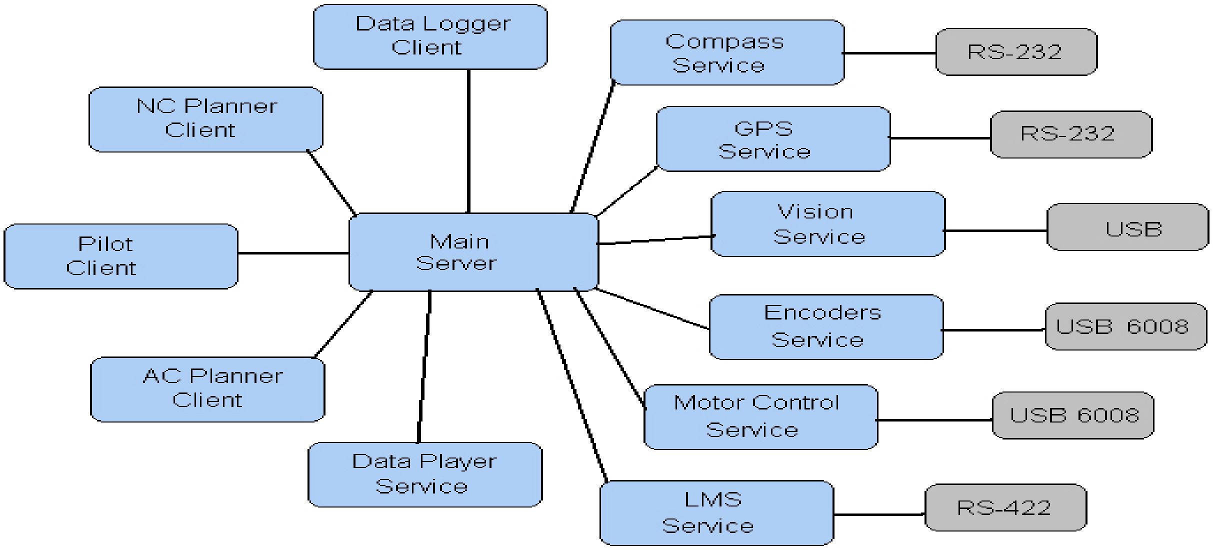


Figure 9: Software Layout Illustration

processor utilization. Priority of CPU time is given to the sensor data processing components such as the vision system.

Each subsystem can also be a client of the server. If one subsystem needs information from another to complete its task, it can gain access to that information through the main server. Once connected to the server, a client can request data from any currently running subsystem and it can expect to receive that data very quickly. There are three very important clients, the Navigation Planner, the Obstacle Course Planner, and the Pilot.

The Navigation Planner is active during the navigation challenge portion of the competition. It reads data from all of the sensors, compares its current position to the position of the waypoints, and then sends goal positions to the Pilot. The Obstacle Course Planner functions in much the same way, but is only active during the Autonomous Challenge portion of the contest. The planning clients are described in more detail in sections 6.3 and 6.4.

The Pilot takes the goals from the planning systems and moves the vehicle towards them. The pilot is responsible for keeping the vehicle traveling a true course, without excessive deviation from the intended path. The waypoints sent by the planners are not overly far apart, so the job of the Pilot is made easier. The pilot client is the only client allowed access to the motor output during the competition runs. Figure 9 details the design and layout of the software system down to the interface with the physical device.

6.3 Navigation Course Decision Making

We represent the environment in terms of an array of cells aligned with true north along the y axis, with the lower-left corner pinned to specified GPS coordinates. Within this world map, each cell is initialized to status “unknown”. As the robot acquires sensory data, cells are relabeled as Blocked or Open. Additionally, a list of goal points is maintained, expressed in terms of world-map coordinates and sorted in the order to be visited. GPS, compass and encoder data is used to identify the robot’s position and heading with respect to this world map.

The first goal in the list is used as the current subgoal, and this goal is pursued until it is achieved. Upon establishing a subgoal, a default plan is constructed, consisting of a straight-line path plotted from the robot's location to that goal, ignoring any possible obstacles. This default path is used to generate finer sequential subgoals, and a wall-following algorithm is applied to respond to obstructions in the default path.

Under the wall-following algorithm, subgoals are specified along the default path until encountering an obstacle, at which point the robot is commanded to turn clockwise and move forward along the edge of the obstacle. The robot is commanded to follow the obstacle boundary until the robot once again encounters an intersection with the original straight-line path plan. At this point, the robot resumes execution of its original plan.

Once the current goal is reached, the next goal in the list is selected, and the same algorithm applied. The final goal on the list is the “home” state to which the robot should return.

6.3 Obstacle Course Decision Making

The “autonomous challenge” obstacle-course planner leverages the representation and planning techniques from the navigation planner. The sole difference is that subgoals are not defined in terms of a priori GPS coordinates, but are defined as observable points along the pathway. By specifying a goal point roughly 30’ ahead of the robot, the path planner can invoke the navigation planner to define higher-resolution subgoals. If a trap is discovered, newly “blocked” cells in the world map will cause the planner to react to perform wall following to reach a point forward along the route (which may include backing up while following obstacle boundaries). Since a world map is maintained, planning for trap escapes can be performed in the map space without the obstacles being immediately perceived.

7 Performance Predictions

At the time of this writing, Roberto is still undergoing construction and testing. Though the full performance of Roberto will not be known until it is run in competition, there are several parts of its performance that can be predicted and tested.

7.1 Speed and Reaction Time

Each motor is geared to drive the standard tires at a maximum speed of 4.5MPH. By doing so, safety is assured as the vehicle can not be driven over this speed by the motors. Due to the gear reduction, the motors produce significant torque and will be able to drive the vehicle at or near its top speed in most conditions. Testing has shown that the vehicle is able to reach and maintain its top speed in a straight line.

While performing autonomously, the speed of the vehicle is limited by the rate at which the vehicle can react to stimuli. The vehicle's reaction time is controlled by several factors. First, the rate at which the vehicle receives data varies by each sensor, but each causes some delay in the reaction. Next, the control logic takes a finite amount of time to process the data and make a decision regarding how to react. Finally, the motor amps in use perform automatic speed profiling which slows the rate at which the vehicle can change its velocity. During preliminary tests of the LMS and the vision system, it was shown that the response time of the vehicle was adequate for moderate speeds, but it is hoped that recent improvements have reduced the reaction time and will allow for faster operation.

7.2 Battery Life

Measurements of the power drawn by the vehicle were taken while the vehicle was in three different states. The first was while the vehicle was powered on, but stationary. In this standby mode, 1 amp was drawn from the batteries. While driving at what is expected to be the average speed during the competition, the vehicle drew 18 amps. At full speed, 32 amps were drawn in total.

All power for the vehicle is provided by a pair of 12V batteries with a rating of 32 amp-hours each. When wired in series, these batteries provide 24V and maintain 32 amp-hours of life. Calculations based on that rating lead to the estimate that while stationary, the vehicle could monitor its surroundings for well over a day. While moving at the normal speed for the competition, the vehicle would be able to run for slightly less than 2 hours. At full speed, the vehicle would go through a full charge in about an hour.

7.3 Obstacle Detection Range

The distance at which obstacles are recognized by the vehicle is set by the software as opposed to limitations of the sensory equipment. For example, the LMS is capable of looking ahead 80 meters, but only objects detected within five meters are recognized in the software. Five meters is our chosen look-ahead for both the vision system and the LMS. After obstacles are detected, their positions are stored so that if that section of course needs to be revisited, those obstacles may be dealt with before they reach the five-meter detection range. Calculations have shown that a five-meter look-ahead will provide sufficient time to react to objects without requiring excessive memory and processor resources.

7.4 Ability to Handle Traps, Dead Ends and Potholes

The planner module transforms sensor values (notably, vision and laser range data) from the local robot coordinate frame into an absolute, GPS-based world frame. This transformation allows for reconciliation of sensors, and also provides a means for memory in map building. Typically, our five meter look-ahead should support avoiding traps by allowing the path planning module to see the traps in advance and steer clear of them. However, since the planner operates on the world map data, the planner does not care whether the current environment representation is the result of immediate sensing or of formerly-populated cells. As a result, the planner should be able to recover from unforeseen traps and dead ends. However, actual performance remains to be tested.

The vision system will be used to detect potholes that are simulated by painted circles. Pothole detection depends on color matching (white), on blob detection, and on template matching (circles). Potholes are represented as obstacles occupying cells in the world model map.

7.5 Accuracy of Navigation

The Novatel DGPS unit is quite powerful and provides reliable data. The requirement for the GPS unit is less than 2 meters of error for any given point. During initial testing, the Canadian differential signal was used. That signal is rated for two meter accuracy, and the vehicle achieved accuracy of approximately 2.5 meters. Subsequently, the GPS augmented with the commercial OmniSTAR corrections was tested. The OmniSTAR correction signals are provided to the team free of charge for the competition. On a clear day, 7 satellites were visible, and the error standard deviation decreased over 40 minutes to approximately 10cm.

8 Team Organization and Time Spent

The original senior-project team members, listed below, invested approximately 10 hrs/wk over the semester. The team leader invested significantly more time. At the time of this writing, 7 additional students are volunteering work on unfinished software. We anticipate an additional 400 person-hours to be invested before the competition.

Team member	Responsibilities	Total hours
Mike Lustig	Senior project lead, software layout and implementation	300
Alex Converse	Compass, GPS, testing	200
Jason Amistadi	Mechanical design, laser rangefinding	200
Josh Gabet	Machine vision	200
Sean Amick	Sensor integration	200
Eldred Lopez	Power; sensor interfacing	200

9 Budget

Below is a chart that details the cost of the vehicle. It shows both the retail cost of the component, as well as how much it cost the team.

Item	**Retail Price (USD)**	**Cost to Team (USD)**
Vehicle base donated by Invacare	Est. $3000	$0
Bosch aluminum framing and components	$500	$500
Curtis 1228 motor driver (x2)	$182 each	$364
Sealed 12V AGM batteries (x2)	$60 each	$120
Custom machined battery box, encoder disks and sensor mounts, frame mounts	$1,400	$1,400
SICK Laser measurement system LMS 221	$6,868	$5,422
Sick RS-422 to Ethernet converter	$500	$370
Laptop: HPT4200	$2,300	$0 (loaned)
Matrix DX-7811HRS Camera	$140	$140
Camera Lens	$40	$40
KWorld DVD Maker USB capture device	$60	$60
NovaTel ProPak LB-Plus DGPS	$5,490	$2,700
OmniSTAR differential signal	$800	0
PNI TCM 2.5 electronic compass	$769	$769
RCT Remote Switch System 1 wireless E-stop	$410	$410
National Instruments USB-6008 (x2)	$145 each	$290
RS-232 hub	$199	$199
Network router	$43	$43
Misc electronic components (connectors, fuses, wire, E-stop, wheel sensors, etc)	Est. $200	Est. $200
100-Amp breaker & breaker/distrib panel	$150	$150
Power converters (24VDC to 12VDC, 9VDC and 120VAC	$60	$60
Grand Total	$20023	$13,250

10 Acknowledgements

The team would like to thank Drs. Wyatt Newman and Francis Merat for advising them through the semester. The continued support of Professor Newman has been invaluable. The Case Alumni Association provided much needed funding for the project. Appreciation also goes out to Novatel, OmniSTAR, SICK and Invacare for providing good and services at greatly reduced or no cost.

11 Conclusion

"Roberto" constitutes our first attempt at the Intelligent Ground Vehicle Competition. The vehicle design benefited from technical reports posted on the IGVC website. Notably, many sensor selections decisions were made easier with the availability of these postings. All mechanical, electrical and software components have been constructed modularly and have been interfaced successfully. The design incorporates an attractive array of sensing and control components. At the time of this writing, software is still under construction and testing. While software readiness will certainly present a limitation to Roberto's performance at the 14th IGVC, the platform will be useful for future research and future competitions.