

# WunderBot III



2006 Intelligent Ground Vehicle Competition  
Design Report

Elizabethtown College

Thomas Yeager

Brian Moran-Bernard

Justin Shade

Shane Rosencrance

David Coleman

Arindam Kanjilal

Amlan Banerjee

James Painter

Juan Pablo Rodriguez



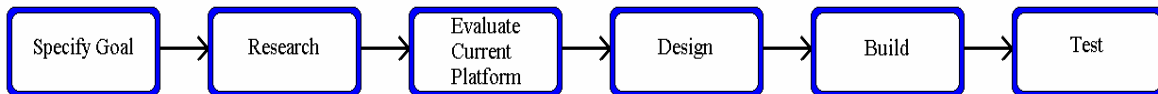
## 1. Introduction

WunderBot III is a versatile third-generation autonomous robot platform. Driven by two 1.75 HP DC motors by a Roboteq AX2550 motor controller, the 300 lb. robot uses a differential steering scheme and is highly maneuverable. Software and hardware redundancy is employed in sensor arrays; including a combinational logic collision detection system, laser range finder for proximity detection and machine vision camera for obstacle recognition and avoidance. High-level sensor data communicates with the robot PC directly through RS-232 serial or RJ-45 Ethernet connections. The high-level sensor array is comprised of a PNI TCM2-50 three-axis digital compass module, a Trimble differential global positioning system (DGPS) with DGPS service through OmniSTAR, a Cognex DVT high resolution color machine vision camera, and a STI OS3100 laser range finder. Using a wireless VLAN, a remote laptop can access the onboard computer and monitor all system parameters in real-time via a custom GUI interface that is made in National Instruments LabVIEW software, which includes real-time obstacle mapping, compass heading information, collision and low-battery alarms, plots of motor current and velocity vs. time and a path-planning simulation. Project goals include developing an autonomous robot capable of giving college campus tours or possibly commercialized tours, and to win the IGVC National Autonomous Robot Platform competition. The 14<sup>th</sup> Annual Intelligent Ground Vehicle Competition (IGVC) will be the second time that the WunderBot will compete.

Name	Contribution	Class	Major
Thomas Yeager (Team Leader)	<ul style="list-style-type: none"> <li>Mechanical and electrical design and implementation</li> <li>Digital Compass and DGPS implementation</li> </ul>	Senior	CE
Brian Moran-Bernard (Chief Programmer)	<ul style="list-style-type: none"> <li>Overall design and programming</li> <li>Path planning, mapping and component integration</li> </ul>	Senior	CE
Justin Shade	<ul style="list-style-type: none"> <li>Low level sensors and path planning</li> <li>Complete vision implementation</li> </ul>	Senior	CE
Shane Rosencrance	<ul style="list-style-type: none"> <li>Sponsorship/donation specialist</li> </ul>	Senior	CS
Juan Pablo Rodriguez	<ul style="list-style-type: none"> <li>Labview programming</li> </ul>	Senior	CE
Arindam Kanjilal	<ul style="list-style-type: none"> <li>Case design</li> </ul>	Junior	CE
Amlan Banerjee	<ul style="list-style-type: none"> <li>Case design</li> </ul>	Junior	CE
David Coleman	<ul style="list-style-type: none"> <li>Webmaster of the Wunderbot III webpage</li> </ul>	Sophomore	CE
James Painter	<ul style="list-style-type: none"> <li>Case design and 3D Solid Edge Schematics</li> </ul>	Sophomore	CE
<b>Total Team Hours</b>	<b>&lt; 2000</b>		

Table 1.1 Member Contributions

## 2. Design Process



### 2.1 Specify Goals

Our project goal was to fulfill the needs of our customers, namely the IGVC directors, officials, and judges as well as Elizabethtown College. IGVC had several safety requirements in addition to performance standards as specified by the Navigation Challenge and Autonomous Challenge. Elizabethtown College required the robot to remain versatile and implemented size constraints as well as safety regulations.

### 2.2 Research

Group members selected areas of study and appropriate assignments during the research phase. Several additions as well as mechanical changes were necessary in order to compete at IGVC. Initial research was performed on previous competing vehicles, and further research was completed on sensors, mapping, control, and decision-making. Consideration was primarily given to sonar, infrared, laser, and machine vision.

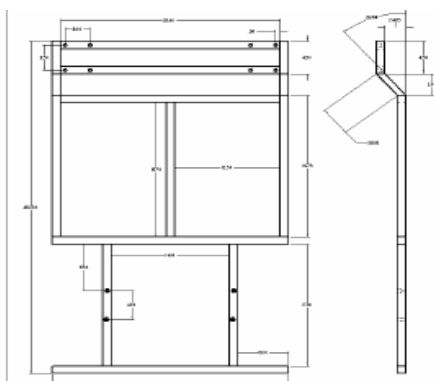
Component research included digital compasses, GPS receivers, machine vision cameras, and supporting parts such as DC-DC power supplies and microcontrollers.

## 2.3 Evaluate

Upon evaluation of the current platform, a new design was conceptualized through the following guidelines:

- Cost – Fundraising and donations totaled \$6000
- Aesthetics – Must be pleasing to technical and non-technical people
- Dimension Constraints
  - 1) Width: 28 inches – Must be capable of fitting through a standard doorway
  - 2) Length: 3 to 9 feet – As specified in Autonomous Challenge
- Accessibility – Components must be easily accessed for repair or service
- Maneuverability – Optimize length to width ratio for smooth turns
- Mobility – Performance in grass and sand is critical
- Versatility – WunderBot is a developing platform utilized for research and must remain upgradeable and adaptable.
- Resource Utilization – Preference must be given to previously used components
- Capability – WunderBot must be capable of competing in every challenge at IGVC
- Safety
  - 1) Components must be protected from electrical shock and disturbances.
  - 2) Bump switches must be included, but should be removable for competition.
  - 3) Emergency stop systems must be reliable and visible
  - 4) Durable and rugged materials must be used to ensure mechanical stability

## 2.4 Design



### 2.4.1 Mechanical

Based on our goals, research, and evaluation several mechanical drafts were constructed and the layout was sketched using solid edge design

software. The chosen design involved a two tier rectangular frame constructed out of solid aluminum. The raised rear casters are a result of the bump switch requirement desired by Elizabethtown College. Dimensions were optimized based on component size, component placement, and maneuverability. Optimum maneuverability was achieved by creating the width to be 62% of the length [2]. For mobility purposes weight was distributed evenly such that the batteries, electronics, and second level offset the motors, drive wheels, and PC. In order to achieve traction in wet grass and sand, 14” NPC Flat Proof tires are driven by two NPC 1.75Hp motors. Eight-inch pneumatic rear casters were selected to prevent over complicating the drive system. To facilitate proper airflow the ATX PC case was modified, and intake and exhaust fans were added to the fiberglass body.

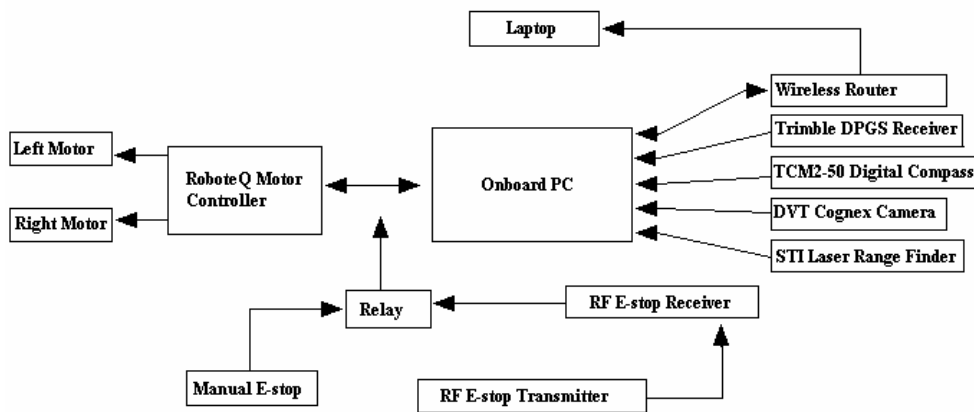
### 2.4.2 Electrical

Hardware selection was determined through weighted comparisons between device brands as displayed in table 2.1. Component additions to WunderBot included a motor controller, STI laser range finder, DGPS receiver, Digital Compass, RF E-Stop, and a DVT Vision System.

Appendix A						
Weight:	Parameters:	Model:				
		Dinsmore 1490 (Current Model)	PNI Vector 2X	PNI Vector 2Xe	PNI TCM2-50	Honeywell HMR 3000
Value:	<b>MCU</b>	MCU and design already exist				
25	On-board MCU? (Y or N)	N (10 points)	N (10 points)	Y (25 points)	Y (25 points)	Y (25 points)
15	External Clock Required? (N or Y)	Y (7 points)	Y (7 points)	Y (7 points)	N (15 points)	N (15 points)
20	External MCU Required? (Y or N)	Y (10 points)	Y (10 points)	N (20 points)	N (20 points)	N (20 points)
35	EEPROM (Y or N)	N (12 points)	N (12 points)	Y (35 points)	Y (35 points)	Y (35 points)
5	Min. Response Time (ms)					
Total(100)		<b>39 points</b>	<b>39 points</b>	<b>87 points</b>	<b>95 points</b>	<b>95 points</b>
	<b>Power Requirements</b>					
30	Power supply voltage needed (V)	5 (25points)	5 (25 points)	3 (30 points)	5 (25 points)	5 V (25 points)
40	Power Supply (via PSU / Y or N)	Y (40 points)	Y (40 points)	Y (40 points)	Y (40 points)	Y (40 points)
15	If MCU needed i min (mA)		4 mA (13 points)	.4 to .7 mA (15 points)	7 to 13 mA (10 pts)	2 mA (14 points)
15	If MCU needed i max (mA)	30 mA (7 points)	5.5mA (13 points)		15 to 20 mA (10 pts)	35 mA (5 points)
Total(100)		<b>72 points</b>	<b>91 points</b>	<b>85 points</b>	<b>85 points</b>	<b>84 points</b>
	<b>Heading Information</b>					
25	Accuracy (degrees RMS)		2 RMS (18 points)	2 (18 points)	1.0 RMS (22 points)	.5 to 1.5 RMS (25 pts)
25	Resolution (in degrees)		1 (10 points)	0.01 (25 points)	0.1 (20 points)	0.1 (20 points)
5	Repeatability (degrees)		2 RMS (5 points)		0.3 (3 points)	0.2 (3 points)
15	Axis (°)	2(10 points)	2 (10 points)	2 (10 points)	3 (15 points)	3 (15 points)
15	Tilt Range (Degrees)	12-with little error (8 points)	0 (0 points)	0 (0 points)	50 degrees (13 pts)	20 (10 points)
15	Dynamic Range (T)		90 uT (12 points)		(+/-)80uT (11 pts)	0.1mT(8points)
Total(100)		<b>28 points</b>	<b>60 points</b>	<b>53 points</b>	<b>84 points</b>	<b>81 points</b>
	<b>Ease of Use</b>					
20	Interface (Difficulty)	Easy (15 points)	Easy (15 points)	Easy (15 points)	Very Easy (20 pts)	Very Easy (20 points)
20	Example Code Available (Y or N)	Y (20 points)	N (0 points)	Y (20 points)	Y (20 points)	Y (20 points)
12	VB Language Supported				Y (12 points)	Y (12 points)
8	Mounting (Difficulty)	Easy (6 points)	Moderate (4 points)	Easy (6 points)	Moderate (4 pts)	Easy (6 points)
20	Integration with GPS (Y or N)	N (0 points)	Y (15 points)	Y (15 points)	Y (17 points)	Y (17 points)
20	PCB Fabrication (Y or N)	Y (7 points)	N (0 points)	N (0 points)	N (20 points)	N (20 points)
Total(100)		<b>48 points</b>	<b>34 points</b>	<b>56 points</b>	<b>93 points</b>	<b>95 points</b>
	<b>Physical Characteristics</b>					
5	Temperature	(negative)20 to 80 Celsius (5 p)	(negative)20 to 70 (4 p)	(negative)20 to 70 (4 p)	(negative)20 to 70 (4p)	(negative)20 to 70 (4p)
5	Solid State (Y or N)	Y (5 points)	Y (5 points)	Y (5 points)	Y (5 points)	Y (5 points)
25	Weight	2.25 grams (25 points)	11.36 grams (12 pts)		45.28 grams (6 points)	92 grams (3 points)
15	Dimensions (Volume)	12.7mm by 16mm (15 points)	1.5in by 1.43 by .39 (8p)	25.4by25.4by11.55mm(10)	2.5 * 2 * 1.25 in (5 p)	1.5 X 4.2 X .88in (6p)
50	Cost	Free (50 points)	50 (40 points)	55 (38 points)	769 (3 points)	750 (5 points)
Total(100)		<b>100 points</b>	<b>77 points</b>	<b>57 points</b>	<b>22 points</b>	<b>23 points</b>
	<b>Total Overall(500):</b>	<b>287 points</b>	<b>296 points</b>	<b>338 points</b>	<b>379 points</b>	<b>378 points</b>

Table 2.1 Digital Compass Comparisons

### 3. Electronics and Electrical Systems



Safety, reliability, and accessibility influenced the layout of the electrical system. Fuses prevent component damage as well as electric shock. Project boxes securely contain electronics and a waterproof fiberglass body ensures safe operation in wet conditions. All sensor components communicate directly to the PC or their respective information is relayed by microcontrollers. All communication data is passed through either RJ-45 or RS-232 serial ports.

#### 3.1 Power

Two 12V 60-amp hour batteries connected in series, provides approximately two hours of operating time. A 300W 24V DC-DC ATX power supply provides voltage regulation for the onboard PC and all system components.

#### 3.2 Control

Motor control was a source of numerous setbacks in previous WunderBot designs. Due to the critical operation of this component, a RobotEQ AX2550 motor controller was purchased. RS-232 serial communication transmits and receives information and instructions between the onboard PC and motor controller. Two independent channels allow control of each motor individually. Wunderbot's main PC control program monitors several built in sensors such as temperature, battery voltage, and current draw in order to ensure safe and dependable operation. Advanced safety features provided by the

motor controller include automatic shutdown due to electrical or software failure, programmable output current limit, and emergency stop notification.

### **3.3 Emergency Stop**

The Emergency Stop System includes an onboard push button and a RF remote stop. The RF receiver board controls a power relay, which along with the push button is placed in parallel between the control line of the motor controller and ground. When the e-stop is pressed or the relay tripped, the control line is shorted, the motors are halted, and the motor controller shuts off immediately. This system was thoroughly tested and has proven to be reliable.

### **3.4 Sensors**

A PNI TCM2-50 three-axis digital compass provides heading with 1.5° accuracy (at 0.1° resolution), and tilt information with 0.4° accuracy (at 0.3° resolution). The optical encoders are used in a proportional closed-loop control system, adjusting the speed every 50ms. The current speed and distance traveled are considered when adjusting the speed to the motor controller. For safety, the motor controller is on watchdog mode, which stops driving the motors if a new command is not received for more than a second.

The closed loop system is software implemented in LabVIEW. The closed loop system first seeks to match the wheel speeds to a goal speed, through a gain proportional to the error. In certain modes of travel the closed loop system attempts to make the distance traveled by the right wheel equal to the distance traveled by the left wheel.

Implementing the vision specifically for the IGVC competition is the first step in this subsystem's development. Obstacles can be recognized and calculated by using given information about dimensions and color. Intellect software 1.2.2 used with Cognex DVT EX544C machine vision camera will be used to filter an image and apply edge detection. Direction bearing to objects will be calculated by aligning the center of the picture with the current direction heading. Any deviation off center will be measured as the direction heading to the obstacle. Using distance and heading, along with our current DGPS location, a virtual map will be built and obstacles plotted with DGPS coordinates. This map will be used in path planning and optimization.

Line following will also be implemented for IGVC. Wunderbot will evade obstacles while remaining within bounds of a fixed path represented by dashed white lines. This is achieved through edge detection, shape analysis, and vanishing point detection.

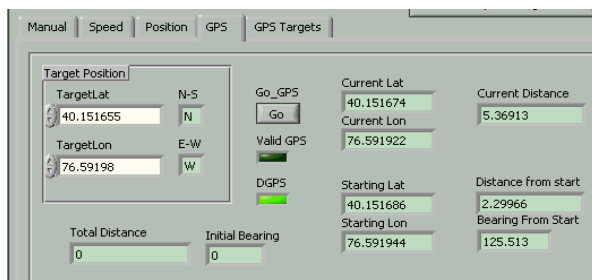
The Trimble AgGPS 114, a differential GPS receiver, offers positional output accurate within 30 centimeters. Important information about location, speed, and distance is interpreted from DGPS data.

Parameters for the onboard computer included cost, efficiency, and expandability. The system consists of an AMD Athlon XP Barton 2500+ CPU, 512MB of DDR Ram, 60GB IDE hard drive with 8mb cache, and a Netgear wireless router. Wireless access provides monitoring capabilities and critical debugging information.

#### 4. Software

LabVIEW 7.1 is programming software we have decided to use this year, rather than the Visual Basic code used in competition last time. Our LabVIEW 7.1 programs create a graphical programming environment that can be used for test and measurement, data acquisition, instrument control, data logging, measurement analysis, and report generation [1]. Intellect software 1.2.2 with Cognex DVT EX544C machine vision camera will be used to filter an image and apply edge detection in LabVIEW format.

##### 4.1 GUI

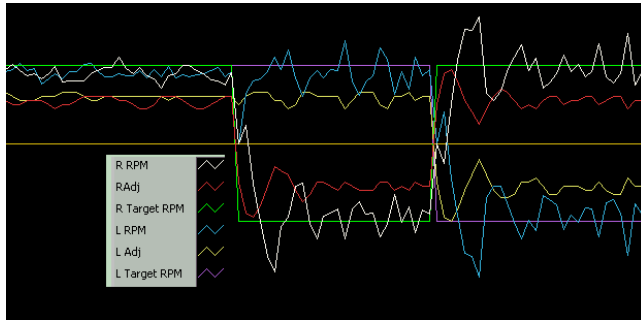


The graphical user interface consists of monitoring information, manual controls, sensory information, and configuration settings. Monitoring information read from the motor controller provides voltage, current, and power graphed in real-time.

The graphical user interface consists of monitoring information, manual controls, sensory information, and configuration settings. Data pertaining to the closed loop



system is graphed, including desired speed, actual speed, and the arbitrary speed value being sent to the motor controller.



The GUI is layed out as tabs, which contain manual controls, closed-loop speed graph, position graphing, GPS data, and a list of GPS waypoints.

The manual controls tab allow has controls to allow the robot to be driven, with closed loop assistance, in a straight line even over uneven terrain. These controls are only used in testing to get GPS readings of waypoints, and when moving the robot farther than is practical to push it. Also present are parameters for adjusting the proportionality constants of the closed loop system, the rate at which the GPS waypoint system corrects its course, and debugging information including execution time for each loop, and speed of each wheel.

The speed tab includes debugging information. The maximum speed, the percent overshoot, and the instantaneous percent error of each wheel is displayed, along with a graph of relevant speed data.

## 4.2 Mapping and Path Planning

Our obstacle avoidance systems will be operated by two pieces of hardware, STI OS3100 Laser Range Finder and the DVT Legend 554C Machine Vision camera. When we get data from this hardware we will then be integrating the information with LabVIEW 7.1 software to be able to know how far away each obstacle is and to determine when to start moving so that our vehicle does not disturb the obstacle in any way.

The DVT Legend 554C camera will mostly be used to detect the two dimensional objects that the OS3100 will not be able to detect. It has a TI DSP processor with 128 Mb of RAM and 16 Mb of flash onboard the camera for fast processing. The 1280x1024

resolution and 8 frames per second help us accurately and quickly process images that we see. For our competition this will include dashed white and yellow lines that represent



the boundaries of the course and imaginary sand traps and potholes that are spray painted onto the course. This will be done by using the Intellect 1.2.2 machine vision software that is onboard the DVT camera. We will be using a color detection that will be able to detect the white and yellow differences on the ground along with a pattern match that will be able to detect the different objects. This will have to be programmed into the camera once we are able to see the course and be able to get images of the objects. The camera will connect through a RJ-45 port which gives the camera 10/100

Mbps Ethernet connection. The data will be sent serially to LabVIEW where the information will be interpreted and an algorithm will calculate how far the object is away from the robot. Once the distance is determined another calculation will be made to determine where and when the robot will need to move to avoid the obstacle.



The OS3100 will be used to detect everything else that is three dimensional. This scanner has a 180° range and has a safety range of four meters. It is equipped with two scanners that both have a response time of forty milli-seconds. This finder will be able to

detect obstacles such as physical pothole and sand traps, construction barrels, chairs and much more. One application that will be helpful is the two separate detection zones that come equipped with OS3100, the safety zone and the warning zone. The safety zone radius is about fifteen meters and the warning zone is anything within four meters (user adjusted). This will let us know how far from an object we are and we it is in comparison to us. We will use this to send us warnings when obstacles get to close and another warning to let us know that we should change our barring to avoid the object. This data, like the DVT camera, will be sent serially to LabVIEW where constructed code and algorithms will help us integrate the OS3100 software with our own.

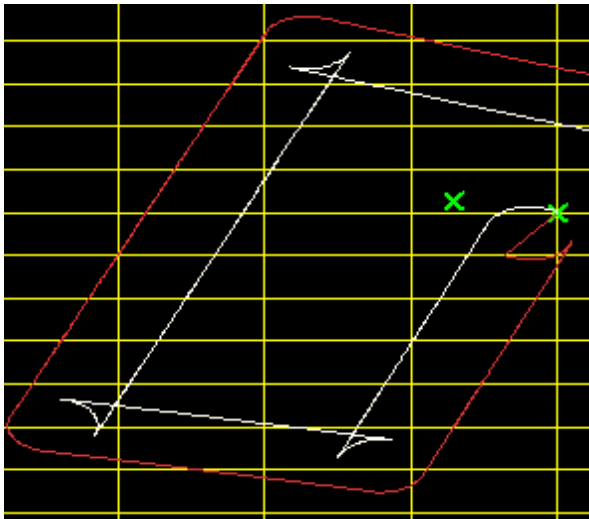
Once both the camera and the laser range finder are integrated with our robot we will be able to detect both two and three dimensional objects and be able to tell the distance they are away from our robot. This will guarantee that our robot will be as safe

as possible and will give us a great chance in being competitive in the IGVC and giving us a good prototype for our autonomous tour guide.

### 4.3 Simulation

The actual circular paths, in red, of the wheels are approximated as straight lines. The end result of the calculation is to find the angle, so the new bearing is known. As intermediate steps, all of the internal angles in the figure above are found, to accurately draw the lines for each wheel position.

Each iteration also includes code to rotate the result of these calculations to the graph maintains its accuracy with respect to magnetic north, so the positive Y-axis is magnetic north, and the positive X-axis is east.

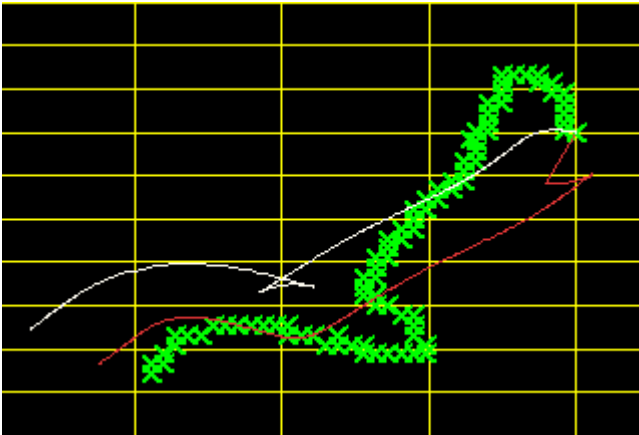


While the dead reckoning is accurate, there are possible sources of error. The control program doesn't analyze the current used by each motor, so it is unable to detect whether a wheel is engaged or is slipping. This means that wheel slippage will cause inaccuracy in the dead reckoning. Additionally, even under ideal circumstances, the laws of cosines calculations are performed on small triangles, which can lead to a compounding error because of limitations of floating point math.

DGPS data is analyzed to put it in a form that can be overlaid on dead reckoning information. DGPS distance and bearing from the DGPS starting point is desired. A new starting point is selected when a DGPS seek is initiated. The distance is calculated using the haversine formula to find the initial great-circle bearing to the destination coordinate.

A perfectly spherical earth with a diameter of 6,378,135 meters is used for our calculations. The distance between the points is necessarily small because of the nature of the application, so it is assumed that following this bearing will lead directly to the destination coordinates. The bearing calculation, which requires the use of the arctangent, must be corrected with conditional statements to insure that the correct quadrant is selected for the bearing.

In each loop iteration the distance and bearing from this starting point to the current location data from the Trimble AgGPS114 is calculated using the method described above. This polar information is then converted to Cartesian coordinates and plotted over the graph of the dead reckoning.

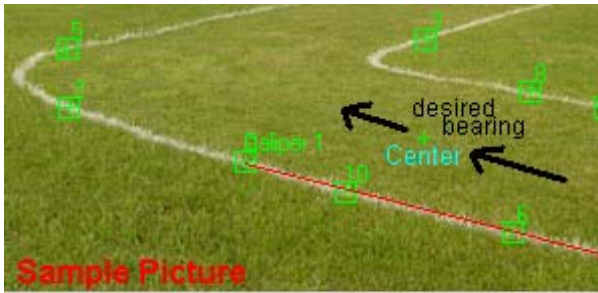


The DGPS data has a variable error because of environmental and signal processing factors. In addition to the complex causes of error in the data received, it is possible that there is a very minor error introduced by the assumption of a spherical Earth, but it is not reasonable to believe that this error is large enough to effect performance in any meaningful way.

## 5. Autonomous Challenge

The Autonomous Challenge requires a robot to traverse an obstacle course while remaining between two white boundary lines and carrying a payload of 20lbs. All subsystems are utilized during this challenge. Key components include Digital Compass, DGPS, DVT Vision System, and STI laser range finder.

## 5.1 Boundary Limits and Bearing



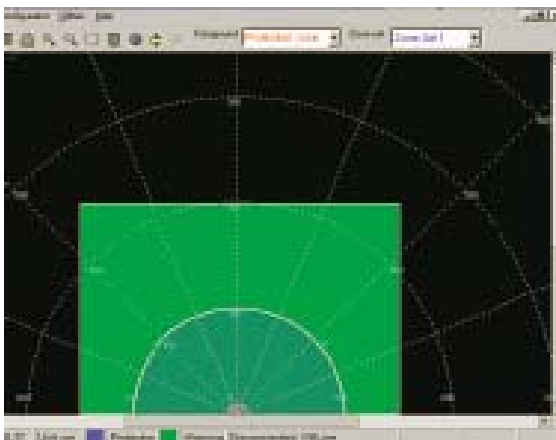
Results ...	
Center of Mass [1,2,3,4,5,6,7,8,9]	X = 315.75pix Y = 282.21pix
Line Fit [1,2,3,4,5,6,7,8,9,10]	Angle = 284.0 Dev. = 154.8

White boundary lines are discovered through white and green pattern matching. The image is scanned for a specified template, and corresponding areas are noted based on pixel location. Line fitting is then applied through the points in order to determine whether one line is detected or both boundary lines

are detected. If the line fits with negligible pixel deviation, only one line is in view. In this case, direction heading is adjusted using previous direction and line location. Movement is made in an attempt to view both lines while advancing along with course. Upon recognizing two lines, the midpoint between each line is calculated. Based on orientation of this midpoint, a desired direction vector passing through the center of the two boundary lines is fixed. WunderBot uses this desired bearing in the path planning logic described in section 4.2.

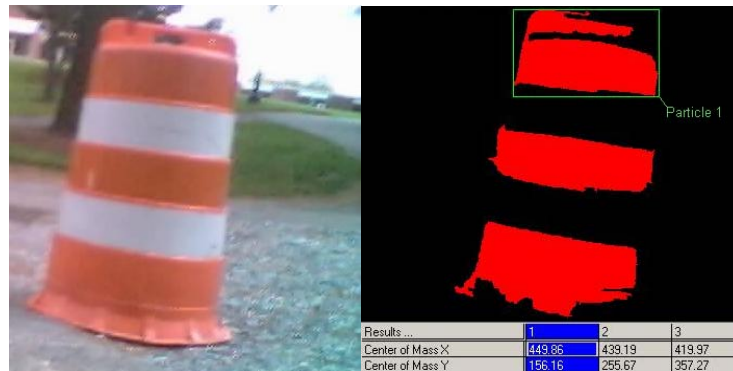
## 5.2 Near Object detection

Finally, data from the OS3100 laser area scanner, received through RS-232, will be converted to Cartesian coordinates and the corresponding data will be plotted. Since the sensor will be moving, the data will be shifted and rotated so the sensor's position between the two front wheels is represented, and the graphical representation of the environment remains correct.



The data is stored as an array, and so can be searched and analyzed to group points into blobs representing real-world obstacles. The lines representing the boundary lines of the course will be treated as boundaries, and a path planning algorithm will find a path to avoid obstacles while staying within boundaries. Using a strategy of analyzing obstacles as blobs should allow us to avoid traps which would force the robot to move backwards.

### 5.3 Distant Object detection and simulated potholes



Construction barrel location will be determined based on the relationship of varying image size and distance. The construction barrels are of uniform size and therefore measuring height or width can lead to barrel distance with respect to the robot. The barrel orientation is calculated based upon the location of the barrel in the image. Each object is recognized through a sophisticated process of threshold, filter, and analysis. In the image, the orange pixels are isolated, distance between orange bands measured, and based on a reference ratio of pixels to inches, distance to the barrel is calculated. Once a barrel is recognized, the center can be located and based on the pixel coordinates, a bearing to the obstacle can be calculated. Bearing information along with radial distance will be used to approximate the DGPS coordinate of the barrel. This coordinate will be used in mapping and path planning. White 5-gallon pails will be detected in a similar manner. In the instance of several barrels side by side, a significant area of orange pixels will be isolated. When this information is recognized, a new direction heading away from the trap is calculated. This direction calculation is once again based on pixel coordinates. In this way, a concentration of pixels is avoided and open space is sought out. Potholes are specified to be 2 feet in diameter and can be

simulated by white circles. The vision system detects simulated potholes through threshold and pattern matching. Once detected, diameter based on pixel length is measured, and distance to a pothole is determined through utilizing a reference ratio of pixels to feet.

## 6. Navigation Challenge

The Navigation Challenge requires a robot to meet specified waypoints and return to a home coordinate while avoiding obstacles. WunderBot’s digital compass and differential GPS are key components in this challenge. Based on current DGPS location, current direction bearing, and waypoint location, WunderBot is directed toward the nearest DGPS coordinate using simple trigonometric relations. As WunderBot moves and the relative DGPS coordinate changes, a new desired bearing is calculated every second. In this way the path remains direct. To prevent returning to home base accidentally, a flag is set as WunderBot approaches the home coordinate. If additional coordinates need to be met, WunderBot avoids home base and continues toward the necessary waypoint. All previous obstacle avoidance measures are in use. Once all locations have been met WunderBot is directed home.

## 7. Performance

Category	Required Results	Expected Results	Confirmed Results
Speed	5 mph	5mph	5mph
Ramp Climbing	15° slope	45° slope	30° slope*
Stopping Distance	6 feet, 15% incline	Immediate	Immediate
E-Stop Range	50 feet	1000 feet	Over 100 feet*
Payload	20 lbs	Over 20 lbs	Over 100 lbs*
Battery Life	30 minutes	4 hours	2 hour*
Vision Detection Dist.	25 feet	100 feet	100 feet

\* Indicates maximum performance was not measured

The performance table includes results required, expected, and confirmed. In few cases the maximum performance was not measured since the confirmed result exceeded the required.

## 8. Budget

W I	W II	W III	Product	Qty.	Act. Total	Our Total	Savings
•			NPC T-74 Motor	2	\$598.00	\$598.00	\$0.00
•			NetGear Wireless PCI Adapter	1	\$59.99	\$59.99	\$0.00
•			Linx RF Development Boards HP-II Series	2	\$298.54	\$298.54	\$0.00
	•		MK M34 Batteries	2	\$500.00	\$147.20	\$352.80
	•		Trimble AgGPS 114	1	\$3,000.00	\$0.00	\$3,000.00
	•		Roboteq AX2550 Motion Controller	1	\$495.00	\$468.00	\$27.00
	•		PNI TCM2-50	1	\$769.00	\$0.00	\$769.00
	•		Over-Current Protection	1	\$31.55	\$31.55	\$0.00
	•		80A Connectors & 8 AWG wire	1	\$95.64	\$95.64	\$0.00
	•		6061 Aluminum Frame	1	\$550.00	\$350.00	\$200.00
	•		NPC PT-5306 Flat Proof Wheel	2	\$146.00	\$146.00	\$0.00
	•		8" Pneumatic Caster (Series 5000)	2	\$133.66	\$133.66	\$0.00
	•		24-12V Power Supply Unit	2	\$400.00	\$400.00	\$0.00
	•		Omnistar DGPS Subscription	1	\$1,600.00	\$0.00	\$1,600.00
	•		LabVIEW Prof Dev System	1	\$3,495.00	\$0.00	\$3,495.00
	•		NI Vision Development Module for LabVIEW	1	\$2,595.00	\$0.00	\$2,595.00
	•		(Book) Img Processing with Labview and IMAQ	1	\$80.00	\$0.00	\$80.00
	•		Laptop for remote monitoring	1	\$1,500.00	\$0.00	\$1,500.00
	•		Silicon 8ga Wire (Black)	15	\$22.50	\$22.50	\$0.00
	•		Silicon 8ga Wire (Red)	15	\$22.50	\$22.50	\$0.00
	•		Hella Contour Master Power Switch	1	\$21.49	\$21.49	\$0.00
	•		Replacement Soldering Tips	4	\$20.24	\$20.24	\$0.00
	•		12 V 10A Battery Charger	1	\$100.00	\$100.00	\$0.00
	•		Misc Frame and Body Materials	1	\$527.49	\$527.49	\$0.00
	•		OS 3100 Laser Area Scanner	1	\$5,030.00	\$0	\$5,030.00
	•		Phoenix Contact Wireless Router	1	\$200	\$0	\$200
	•		Phoenix Contact IPC5500	1	\$3,000	\$0	\$3,000
	•		DVT Legend 554C XE w/ lens and I/O board	1	\$6,000	\$0	\$6,000
	•		Phoenix Contact Connectors and Fuses	1	\$300	\$0	\$300
	•		Motor Controller Repair	1	\$250	\$250	\$0
			<b>Total</b>		<b>\$31,841.60</b>	<b>\$3,692.80</b>	<b>\$28,148.80</b>

## 9. Conclusion

All project goals were achieved as well as customer requests through thoughtful design, quality parts, creative programming, and a variety of features. The result is a sophisticated project that is fully capable of participation at IGVC.



## REFERENCES

- [1] National Instruments, "LabVIEW 7 Express User Manual," Austin Texas: National Instruments, April 2003.
- [2] P. E. Sandin, "*Robot Mechanisms and Mechanical Devices*" New York:McGraw-Hill, 2003, pp..237.