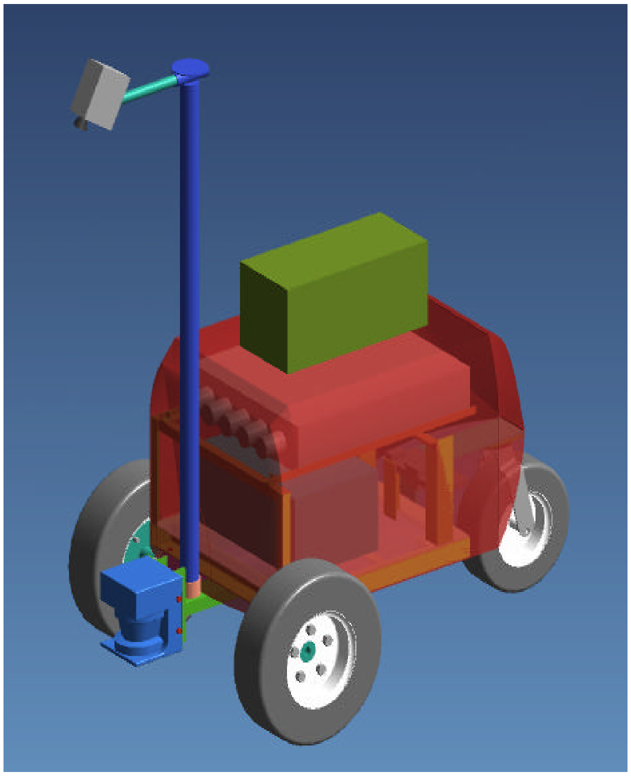
OPTIMUS 2003



2002-2003
Autonomous Vehicle Team
of
Virginia Tech

TEAM MEMBERS:

Andrew Bacha
Michael Gossler
Matthew Minner
Rush Sutherland

Marc Bielak
Ruel Faruque
Jamie Riggins
Justin Wetterhall

Michael Carr
Pelle Duong
Ankur Naik
Sam Wood

Required Faculty Advisor Statement

I, Dr. Charles Reinholtz of the Department of Mechanical Engineering at Virginia Polytechnic Institute and State University, do hereby certify that the engineering design of the new vehicle, Optimus, has been significant and each senior team member has earned six semester hour credits for their work on this project.

Signed, (Date)

Dr. Charles F. Reinholtz
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1 – INTRODUCTION

The Virginia Tech Autonomous Vehicle Team (AVT) proudly presents Optimus, an innovative, new vehicle designed and built to become the standard for utility and reliability. The vehicle name is derived from the popular television cartoon series *Transformers*. In this cartoon, robot characters change their form to overcome challenges. Optimus has the ability to transform from a three-wheel, two-wheel drive configuration to a four-wheel, four-wheel drive configuration. In addition, Optimus can use large, low rolling resistance wheels or smaller, more rugged wheels, depending on the course condition and event.

Optimus is designed with several key goals in mind, including serviceability, upgradeability, and originality. The chassis of Optimus is designed for easy access to all vehicle components, including the electrical system, power system, computational hardware, and sensors. Sensors include a camcorder, laser range finder, digital compass, and differential global positioning system receiver.

Perhaps the most significant innovation in Optimus is the exclusive use of the LabVIEW software package from National Instruments. LabVIEW is based on an easy-to-follow graphical block-object programming language, but it still maintains the functionality to build sophisticated programs. LabVIEW was selected because it provides a reliable real-time control environment that is well accepted in industry. A major additional benefit of LabVIEW is that it is far easier to use than text-based languages such as C++.

This report presents the mechanical, electrical, and computational design of Optimus, Virginia Tech's most advanced autonomous vehicle to date.

2 – DESIGN PROCESS

2.1 – Design Methods

The mission statement of the team was to build an autonomous vehicle that could compete favorably in the 11th Intelligent Ground Vehicle Competition, reflect well on Virginia Tech, and be marketable outside of the university. To achieve the goals set forth in this mission statement, the team followed the design process described in *Product Design and Development* (Ulrich and Eppinger, 2000), shown in Figure 1. The steps in this process are iterative, meaning that one or more steps may be repeated until satisfactory results are obtained.

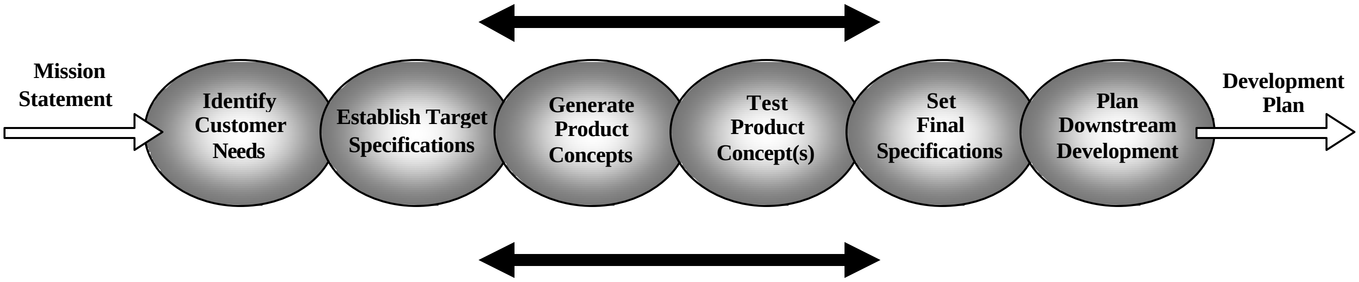


Figure 1.1 – The design process used for Optimus

Optimus was designed and built with the customer in mind. The team targeted three primary groups of customers, namely, the US military, research agencies, and educational institutions. A set of customer needs was identified from the IGVC rules and from surveys taken by members of previous autonomous vehicle teams. Interviews were conducted to follow up on survey responses. The primary customer needs were transportability, reliability, serviceability, and expandability.

Target specifications were established by benchmarking Virginia Tech vehicles from prior competitions. The following vehicles' strengths and weaknesses were studied: Virginia Tech Daedalus (2002), Virginia Tech Biplanar Bicycle (2002), Virginia Tech Maximus (2001), and Virginia Tech Artemis (2001). By comparing the characteristics of these vehicles, the team was able to set target specifications. These specifications focused on creating a stable, easily accessible, well-organized, and compact vehicle.

Conceptual designs were generated based on target specifications. A three-wheeled, differential drive design, with an option for four wheels, was chosen for further development. Figure 2.1 shows a *Unigraphics* drawing of the concept vehicle in its three-wheel configuration.

With an initial concept defined, the team pursued detailed design and fabrication of the vehicle to meet the target specifications. Testing was performed at each stage of construction to ensure quality in the vehicle design. If a problem was encountered, modifications were made to the target specifications, resulting in a new set of specifications. Two such modifications were the addition of more powerful amplifiers to enhance ramp performance, and larger wheels to increase top speed during the Follow-the-Leader competition.

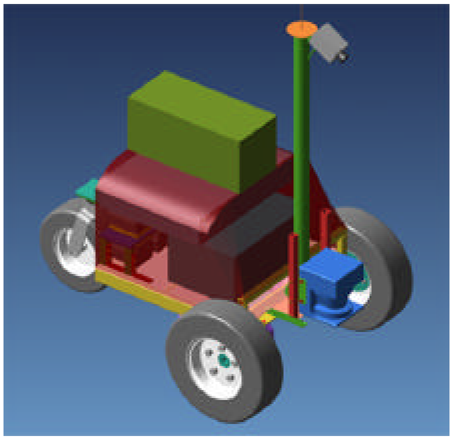


Figure 2.1 – Conceptual vehicle design of Optimus

2.2 – Team Organization

The team was divided into three subteams: mechanical, electrical, and software. Table 2.1 lists the members of each subteam, along with their major and academic level. Approximately 4,000 hours were spent designing, building, and testing Optimus.

Table 2.1 – The team organization of Optimus (* subteam leader)

Mechanical Subteam			Electrical Subteam			Software Subteam		
Name	Major	Year	Name	Major	Year	Name	Major	Year
Andrew Bacha	ME	Senior	Marc Bielak	ME	Senior	Michael Carr*	ME	Senior
Mike Gossler	ME	Senior	Ruel Faruque	ME	Senior	Pelle Duong	ME	Senior
Matt Minner*	ME	Senior	Jamie Riggins	EE	Senior	Ankur Naik	ME	Senior
Rush Sutherland	ME	Senior	Justin Wetterhall*	ME	Senior	Sam Wood	ME	Senior

3 – DESIGN INNOVATIONS

To give Optimus maximum flexibility as a research testbed, the vehicle was designed with two distinct drive configurations. The first configuration is a four-wheel drive skid steer and the second configuration is a differentially driven two-wheel drive with a caster wheel. Figure 3.1 shows the base of the vehicle frame in both configurations, as well as two different wheel sizes for the three-wheel configuration. Our research showed that in past competitions, many vehicles had difficulty traversing the sand pit, wet grass, and ramps. To improve traction in these situations, Optimus is the first vehicle from Virginia Tech to support four-wheel drive. Optimus also improves upon past three-wheel designs by using a 12-inch caster wheel, compared to the 8-inch caster wheel used on several prior vehicles. The larger caster is less prone to sticking in small ruts, and it provides less rolling resistance when executing a zero radius turn.

Figure 3.1 – The vehicle base of Optimus in 4-wheel and both 3-wheel configurations

The electronics used in Optimus are simple and easily serviced. After analyzing the interconnectivity and repair/debugging needs of the electrical components, an aluminum box was fabricated to enclose the components. This box organizes the wiring of the electrical components, making the electrical system easy to understand and repair. Figure 3.2 shows the organization of the electronics box. Each wire is labeled to match an *AutoCAD* schematic, making the purpose of each wire clear during repair or upgrading.

Another key element in simplifying the electronics system is the use of a National Instruments PXI-1000B computer chassis. The PXI chassis houses all computer hardware as well as an analog I/O and data acquisition module, two camera frame-grabbers, and a motor controller module. With all additional modules packaged into the PXI, component layout and integration is simplified.

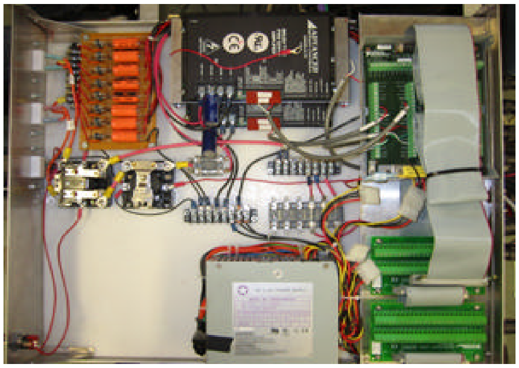


Figure 3.2 – Electrical enclosure

4 – VEHICLE DESIGN AND CONSTRUCTION

The vehicle frame was designed to provide a flexible and stable platform to facilitate research related to autonomous vehicles. The 24-inch by 22-inch by 15-inch space inside the vehicle shell allows internal components to be cleanly arranged. The frame is constructed from welded steel tubing and angle. A lightweight fiberglass shell covers the frame, protecting internal components from the weather. Optimus weighs 220 pounds when fully outfitted for competition.

The modular design of the frame makes Optimus easy to maintain. The layout of each major component is shown in Figure 4.2. The electronic systems of the vehicle are inside a single electronics box that can be easily removed. The camera, GPS, and laser range finder are mounted on a single mast in front of the vehicle shell. This allows the shell to be removed without disturbing these components or disconnecting wires. An equipment rack on top of the shell carries the payload and is adjustable to support payloads of different shapes and sizes.

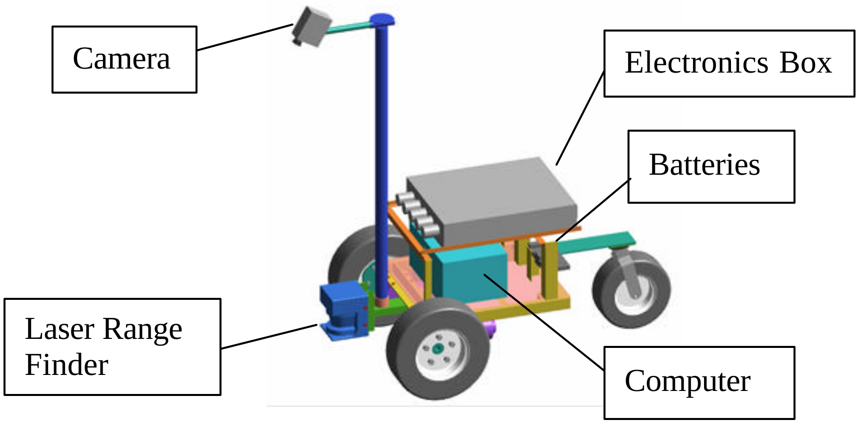


Figure 4.2 – CAD image of component layout

The drive train of Optimus can switch between a three-wheel and a four-wheel configuration. The three-wheel configuration uses a 12-inch rear caster wheel and two drive wheels that can be either 16 inches or 26 inches in diameter. The four-wheel configuration uses 16-inch wheels with each side linked by a roller chain. The 26-inch wheels are used for higher speeds in the Follow-the-Leader competition. Optimus uses 16-inch wheels for the other competitions. The three to four wheel drive conversion can be accomplished with a single halfinch wrench in a few minutes. The back wheels of the four-wheel setup are pinned in a sleeve on the bottom of the frame as shown in Figure 4.3. The caster mount is bolted to back of the frame.

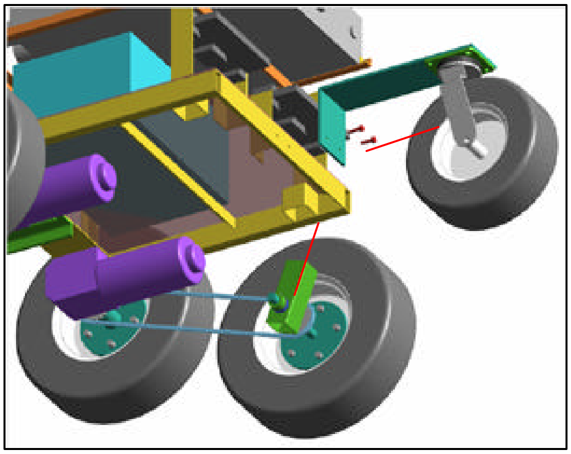


Figure 4.3 – Rear Wheel Assembly

5 – ELECTRICAL SYSTEM

5.1 – Power System

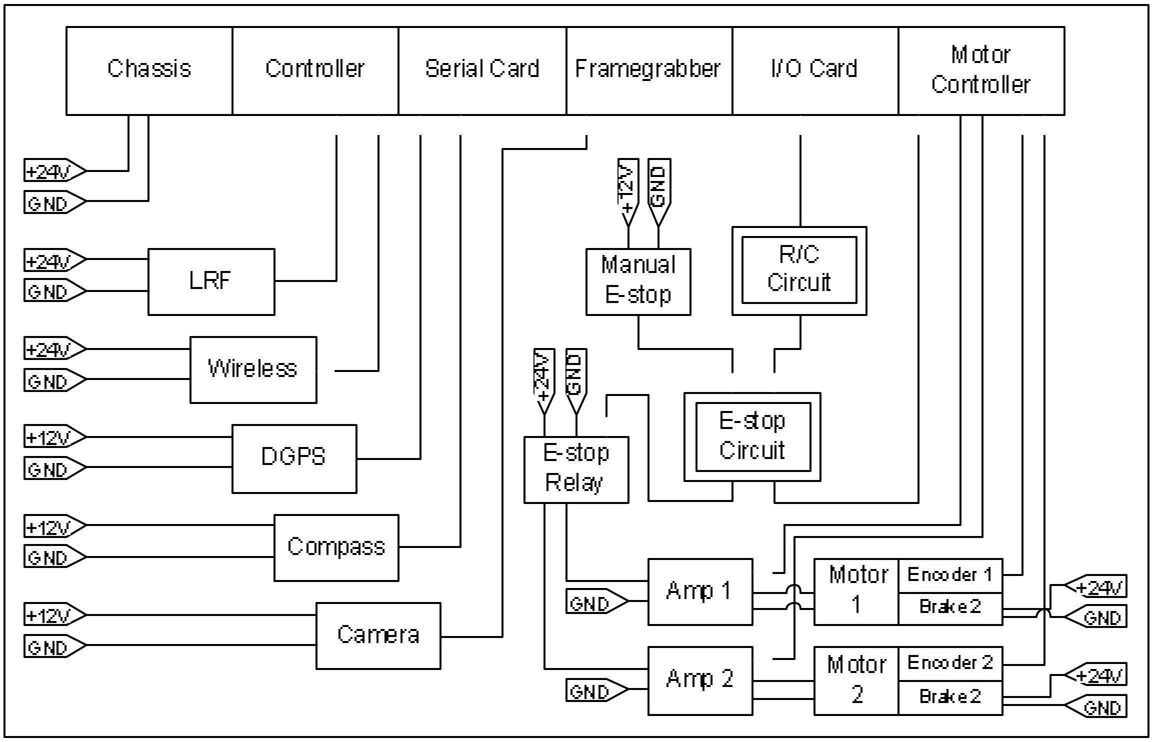
The power system of Optimus consists of eight 24-volt DeWalt nickel-cadmium batteries in parallel, providing power for two separate buses. The component bus, which uses five batteries, provides power to the PXI main computer and all of the electronic equipment and sensors. The motor bus, which uses three batteries, provides power to the amplifiers and motors. The electrical system was designed so that the number of batteries assigned to each terminal bus can easily be changed to accommodate various types of testing.

The main power for both buses routes through a 30-amp mechanical relay controlled by a key switch. This relay is double pole, providing a way to turn on both the component equipment and the motors, while at the same time keeping the two buses separate. The motor bus routes through a second relay controlled by the e-stop system and continues on to power the amps and motors. The component bus routes straight to a connection board and from there powers the computer and all sensors. To power the various onboard devices that require less than 24 volts, a DC to DC converter is used to break the 24-volt component bus into 5 and 12 volts.

One of the most important features of the battery system on Optimus is that the batteries are hot-swappable. All eight batteries can be monitored for charge status using LabVIEW software. When a weak battery is detected, the hot swap battery circuit allows it to be replaced while maintaining component and motor power, thus preventing electrical surges to sensitive equipment and eliminating the need to restart devices.

5.2 – Control System

The control system of Optimus is based on a PXI-7344 National Instruments motion controller. The controller is a single module located inside one of the chassis slots, directly integrated with the main computer. In addition to four axis controls, the controller has several digital I/O pins. The control and sensor system is shown in Figure 5.1.



the computer, which outputs the corresponding speed signal to the motor amplifiers. If no signal is received, this is interpreted as an E-stop. In the case of an E-stop, the stamp triggers an E-stop circuit-board relay. This E-stop circuit-board relay is connected directly in line with the main E-stop relay, which cuts power to the motors.

5.3 – Sensors

Optimus uses four sensors to obtain external data: a Canon ES75 8mm camcorder, a SICK LMS-200 laser range finder (LRF), a Honeywell HMR-3000 digital compass, and a Trimble AgPS 124 differential global positioning system (DGPS) receiver. The camcorder is used to find lines during the Autonomous Challenge. Video images are captured by the camera, converted to digital format by a National Instruments frame grabber, and sent to the navigation software. Optimus uses a LRF to detect all obstacles. The LRF scans a 180° plane in front of the vehicle, detecting all obstacles within a specified range up to 30 meters. The data from the range finder is sent to the computer via a serial (RS-232) connection. The digital compass is used to determine the vehicle's heading during the Autonomous and Navigation Challenges. The compass is a three-axis, tilt-compensated compass that uses a two-axis accelerometer for enhanced performance. The DGPS receiver is the primary means of determining vehicle location during the Navigation Challenge. The receiver sends the vehicle's location, heading, and direction to the computer via a serial (RS-232) connection.

6 – SOFTWARE

6.1 – Introduction to LabVIEW

Software development took priority in the design of Optimus. All software was developed using the National Instruments (NI) line of software development tools. Among these is a product called LabVIEW, which uses a graphical block-object environment development platform to build software that integrates Data Acquisition (DAQ), system peripherals, and automated devices. An example of a LabVIEW program is shown in Figure 6.1.

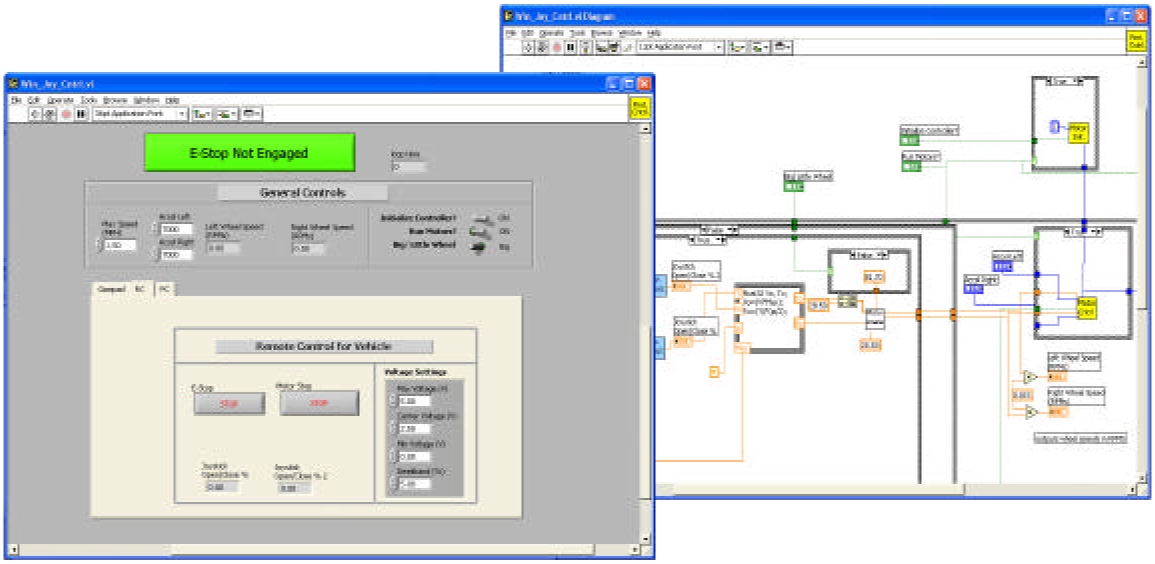


Figure 6.1 – Example of a LabVIEW program

6.2 – Autonomous Challenge

To perform well in the Autonomous Challenge, Optimus uses a combination of software programs that work together. Figure 6.2 illustrates the interaction of the codes required to run the vehicle.

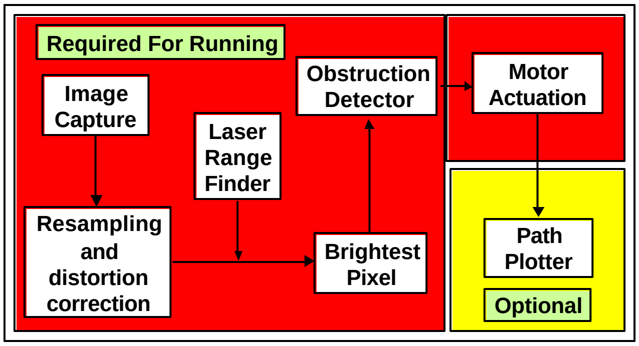


Figure 6.2 – Flow diagram of the Autonomous Challenge software

Image Processing

To capture the image for processing, Optimus uses a camcorder, which has an auto exposure feature that compensates for varying lighting conditions. To ensure that the vehicle vision captures the course lines, Optimus uses a Pro-Optic super fisheye lens that gives the camera a 75° field of view. Furthermore, the frame grabber extracts the blue plane from the color image and applies an inverse-log lookup table to provide better contrast in the bright regions. That image is then re-sampled to 320x240 and corrected for perspective distortions using the NI IMAQ Vision builder functions.

The LRF detects solid obstacles and reads the data in the form of a polar array. The array is then converted to Cartesian coordinates and mapped onto the previously processed image as blocks of white pixels. That image is then passed to the *Brightest-Pixel Code*, which takes the top half of the image and splits it vertically. The code locates the brightest pixel on each row of both halves and outputs the average coordinate, which defines the heading of the vehicle. Then a pathway as wide as the vehicle is projected in the direction of the coordinate defining the heading of the vehicle. While the *Brightest-Pixel Code* can project a heading between the two course lines, it does not avoid obstacles or handle tight curves. This is where the O*bstruction-Detector Code* comes into play.

The *Obstruction-detector* code scans blocks of the image within the pathway projected by the *Brightest-Pixel Code*. If too many pixels above a specific threshold value are present, the code assumes that there is an obstruction and scans for alternate headings as shown in Figure 6.3. If the code fails to find a clear path, then the vehicle stops and initiates a zero radius turn until the next frame. A major difference between this and previous codes is that it scans along curved paths rather than straight paths. These curved paths provide the vehicle with additional path options. If more than a certain number of white pixels are detected in the field-of-vision, the software code alerts the vehicle of a sandpit ahead. In this case, the *Obstruction-Detector Code* will be turned off, the vehicle will line up perpendicular to the sand trap and travel straight for a pre-specified distance. At that point, the *Obstruction-Detector Code* is turned on again and the vehicle returns to regular running mode. Finally, the *Motor-Actuation Code* acquires the heading information and parameters and translates them into wheel speeds. The wheel speeds are then sent to the motor control board to commence the turning of the wheels. A Path-Plotter code overlays the selected route on top of the finalized image, making it easier for the operator to see the projected pathway of the vehicle while testing.

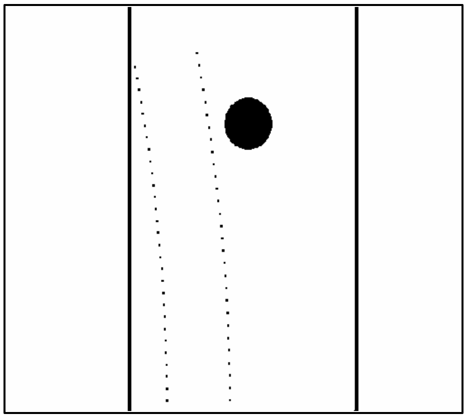


Figure 6.3 – Obstruction Detector

6.4 – Follow the Leader

The Follow-the-Leader algorithm is split into two parts: finding the heading and setting the speed. The *Finding the Heading* algorithm uses the data from the laser range finder to locate an object with a specific width, which is the leader vehicle. The polar array from

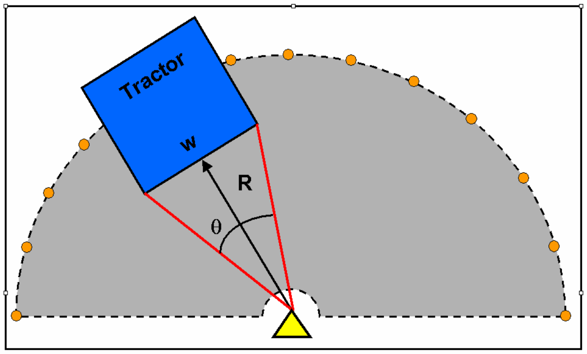


Figure 6.4 – Normalization of LRF data

the LRF is normalized to the width of the leader such that a small object near the LRF does not appear larger then a large object that is further away. A graphical representation of the LRF normalization is shown in Figure 6.4.

The second part of the Follow the Leader code is *Setting the Speed.* The speed of the vehicle is controlled using a simple equation that sets speed as a function of the distance from the lead vehicle, according to the function shown in Figure 6.5. If the leader is less then 3 meters away, the vehicle stops.

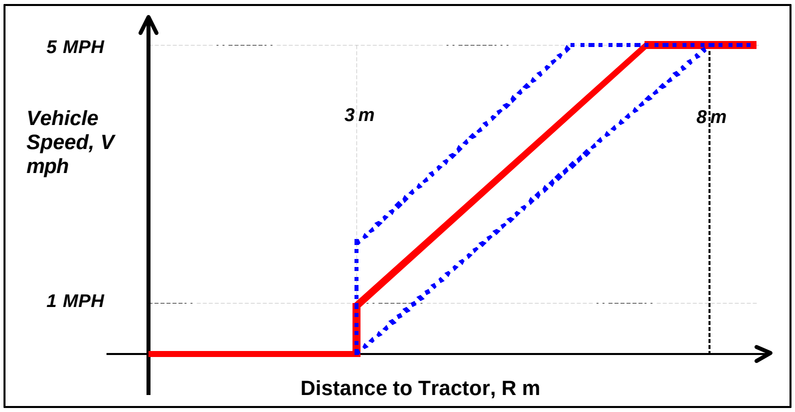


Figure 6.5 – Velocity as a function of distance from the lead vehicle

6.5 – Navigation Challenge

There are two main algorithms in the Navigation Challenge software: a *path finding* algorithm and an *obstruction finding* algorithm. These two algorithms allow the vehicle to traverse the navigation course quickly and reliably.

The *path finding* algorithm uses the data from the DGPS receiver and the digital compass to determine the current vehicle position and heading. Then the algorithm determines a path to the next waypoint. If the current heading of the vehicle is not in line with the path, the vehicle will perform a turn to bring it into alignment. If the current heading is in line with the path, the vehicle will travel in a straight line towards the waypoint.

After a tentative path is selected, the *obstruction finding* algorithm begins. This algorithm scans the path for barrels and other obstructions using data from the LRF. The LRF data is plotted as white blocks on a black background, over which is plotted the tentative path. If there is an obstruction, the algorithm selects a useable path close to the tentative path and moves the vehicle in that direction. When the vehicle reaches the waypoint it immediately moves on to the next point.

7 – PREDICTED PERFORMANCE AND TESTING

7.1 – Speed

Optimus is powered by two 0.45 horsepower Bodine motors equipped with 33:1 reduction gearheads. The no-load output speed rating for these gearmotors is 75 rpm. When using 16-inch tires, the vehicle can obtain a maximum rated speed of 3.57 mph. The maximum speed increases to 5.8 mph when using the larger 26-inch tires. For both wheel sizes, the motor controlling software will enforce the 5 mph speed limit.

7.2 – Ramp Climbing Ability

While the largest ramp incline specified by the IGVC is a 15% grade (8.5 degrees), a 15-degree incline was used in ramp-climbing calculations to account for the possibility of the ramp being on a slope or discontinuities, such as uneven plywood panels, in the ramp surface. With 16-inch wheels, Optimus requires 228 lb-in of torque per motor to maintain its position on the ramp. The motors on Optimus output 269 lb-in of torque, allowing the vehicle to advance up the ramp.

7.3 – Battery Life

The Dewalt batteries used on Optimus are rated at 2.4 amp-hours each. During testing, it was determined that it was best to use five batteries for the component bus and three for the motor bus. This provides approximately 30 minutes of run time for the computer and electronic components, and 20 minutes of actual run time for the motors.

7.4 – Reaction Times

The Autonomous Navigation code runs at 5 hertz update rate. This means that, when a boundary or obstruction comes into view, it will take from 0.2 to 0.4 seconds for the code to react and send a signal to the motor control board. Once the motor control board receives the command, it takes up to 0.2 seconds for the motors to accelerate to the required speeds. This gives a maximum total response time of about 0.6 seconds. Higher refresh speeds up to about 15 hertz can be achieved with a faster, more expensive processor. At 5 mph, the 0.6 second response time means the vehicle can move approximately 4 feet before reacting. Although it is possible to navigate under these conditions, reliability decreases. As a result, slower speeds will generally be used in the early runs of Autonomous Challenge. Should another vehicle finish the course with a better time, the maximum vehicle speed will be increased.

7.5 – Distance at Which Obstacles are Detected

An important factor in the Autonomous Challenge is the distance at which Optimus can detect obstacles. The large field of view of the camera, along with image processing, provides Optimus with the ability to detect potholes, sand traps, and course lines as far as 12 feet ahead. The LRF has a range of up to 30 meters, but the current navigation algorithm ignores objects more than 12 feet away. This range is sufficient to see the second barrel in a barrel trap before the vehicle determines the best path around the first barrel.

7.6- Dead Ends, Traps, and Potholes

Optimus uses a resourceful method of dealing with barrel traps and pot holes. To avoid barrel traps, Optimus maps the locations of the barrels to the processed image. As a result, the *Obstruction-Detector* code can clearly read the image as a whole and choose to avoid the trap. If an apparent a dead end is encountered, the *Obstruction-Detector* program is designed to execute incremental zero radius turns until a clear path can be found.

7.7 – Navigation Accuracy

Preliminary testing shows Optimus can consistently navigate to GPS waypoints to within less than one meter, given good quality GPS signals and a reliable differential correction. Since our test site in Blacksburg, Virginia is landlocked with no nearby correction beacon, we have subscribed to the new satellite-based OmniSTAR wide-area differential GPS service. Data from many widely-spaced reference stations is used to achieve reliable sub-meter positioning over most land areas worldwide.

8 – OTHER DESIGN ISSUES

8.1 – Safety

Safety was the most important concern in all aspects of the design, fabrication, and operation of Optimus. Three modes of stopping Optimus in case of an emergency were implemented into the vehicle design. The first mode is a manual E-stop button, located at the rear of the vehicle, which opens a relay disconnecting power to each amplifier. Thus, no power reaches the motors when the manual E-stop is engaged. In addition, the motor brakes are automatically engaged when power is disconnected from the motors, stopping the vehicle in less than one foot from 5 mph. The second mode is a remote E-stop feature programmed onto a wireless remote joystick. This remote E-stop is independent of the software, and works up to 50 feet away. The third E-stop mode is controlled via software using a laptop computer connected to the PXI main computer using *PC Anywhere*. Software detects when any of the E-stop modes have been activated, and no power is sent to the motors.

8.2 – Costs

Table 8.1 shows a cost breakdown for the components used to build Optimus.

Table 8.1 – Cost breakdown for Optimus

Components	Retail Cost	Cost to Team
PXI 1000B Chassis	$2,795	$0
PXI 8175 Controller	$3,695	$0
PXI 7344 Motion Controller	$1,695	$0
PXI 6025E I/O Connector	$895	$0
(2) PXI 1411 Frame Grabber	$2,190	$0
PXI 8422 Serial Expansion Card	$495	$0
PXI Accessories	$350	$0
Trimble DGPS	$2,995	(loan)
Digital Compass	$675	$0
Sick Laser Range Finder	$3,400	$0
Wireless Hub	$120	$0
Wireless Client Adapter	$70	$70
Cannon 8mm Camera	$220	$220
Voice Synthesizer	$120	$120
(8) Dewalt 24V Battery	$880	$0
(2) Bodine Motors	$1,200	$0
(2) AMC Amplifier	$1,120	$560
(3) Wheels	$75	$75
Frame	$200	$200
Shell	$150	$150
Electrical Components	$400	$400
Total	$23,740	$1,795

9 - CONCLUSION

Optimus is a fully autonomous robotic vehicle, designed and manufactured by engineering students at Virginia Tech. The key aspects of the vehicle platform are safety and versatility. The electrical system focuses on safety, simplicity, and efficiency. The software systems are designed for lane following, obstacle detection and avoidance, and GPS navigation. By following an engineering design process, the team was able to create a vehicle that will compete favorably in all four events of the 11th IGVC.