NAVIGATOR

Vehicle Design Report

Autonomous Vehicle Team of Virginia Tech

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1 – Introduction

The Virginia Tech Autonomous Vehicle Team has a history of developing new and innovative vehicles for entry into the Unmanned Ground Robotics Competition. Navigator, our newest vehicle, draws upon many of the best features of past designs and the knowledge gained through four years of competitions and exhibitions. Our intent throughout the design process was to produce a modular vehicle that could be easily programmed and adapted to be successful in performing a variety of autonomous tasks. In this way, we hope Navigator will be successful in all phases of the expanded and increasingly complex Unmanned Ground Robotics Competition. The result, we believe, is a vehicle that is more powerful, capable and adaptable than any of our prior vehicles.

Navigator is built on tubular steel chassis to which all the other components are mounted. Course markings and obstacles are sensed through a pair of color video cameras operating in parallel and a scanning laser range finder. Navigator uses a pair of differentially driven front wheels and a single rear caster wheel for locomotion. Through careful attention to vehicle size and component layout, Navigator has excellent stability and ample space for mounting and accessing hardware. This helps to make the vehicle more modular and computationally more powerful than any of our past vehicles. For example, Navigator uses an industrial programmable logic controller to handle low-level motor control and a separate dual Pentium III PC for high-level control and navigation. The new layout also allows room for an improved user interface, with such features as a high intensity fifteen-inch LCD monitor and a fold-down style keyboard tray. All of these features are a direct result of our effort to make Navigator modular and easy to program, test, and validate, especially at the sub-function level.

The student group charged with developing this vehicle dubbed itself the **N**ew **A**utonomous **V**ehicle Team, or *NAV-team* for short, with the resulting vehicle being known as Navigator. This report describes both the design and the design process used to create Navigator.

2 – Design Process

2.1 – Design Methods

To make the most efficient use of time and effort, the NAV-Team adopted a familiar design process know as the "Seven Stages of Engineering Design" formulated by G.N. Sandor[1]. **Figure 1** is a graphical representation of these seven stages.

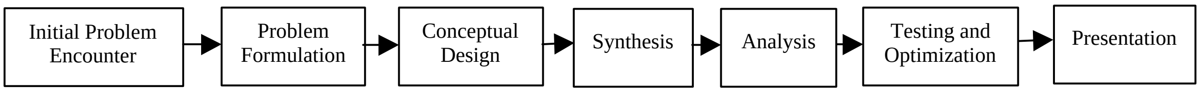

Figure 1 – The Seven Stages of Engineering Design

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[1] Sandor, G.N., "The Seven Stages of Engineering Design," Mechanical Engineering, April, 1964, pp. 21-25.

Sandor noted that design is not a linear process, and that iteration and backtracking are likely to occur between stages. The extensive use of parametric CAD software and computer assisted analysis allowed the team to test many design concepts before parts were fabricated. This helped to reduce the amount of iteration and shortened the design cycle.

Primary criteria considered throughout the design process were safety, simplicity, reliability, durability and conformity with the competition rules. All these criteria were considered in light of the constraints imposed on the design by the academic schedule and by the desire to make the vehicle modular and easy to adapt to a variety of tasks. A number of design and scheduling tools were generated to assist in this process. For example, an extensive Gantt chart was created to show the flow and scheduling of the work. All team members were required to participate in regular meetings and periodic design reviews.

2.2 – Design Team Organization

The *NAV-Team* consisted of nine mechanical and three electrical/computer-engineering students. The design process was broken into tasks, each corresponding to one or more elements of the modular system. Each member had responsibility for at least one task. The *NAV-Team* roster is shown in **Table 1**, including the responsibilities of each member.

Table 1 – *NAV-Team* Roster

NAV-Team Member	Responsibility(s)	Major	Class Level
Yohannes Ambaye	Frame Structural Specification/Design	ME	Senior
Colin Campbell	Frame Design, Mechanical Systems Integration, CAD-Data Management	ME	Senior
David Conner	*NAV-Team* Leader, Electrical Systems Integration, Administration, Software Development	ME	Grad
Kevin DeMarco	Laser Range Finder Mount	ME	Senior
Ryan Fong	PLC Interface, R/F Remote	CpE	Junior
Stephen Horney	Camera Housing and Mount	ME	Senior
Philip Kedrowski	Shell Finishing, Vehicle Testing	ME	Grad
Joseph Payne	PLC Interface, Electrical Schematics	EE	Senior
David Poe	Drive Modules, User Console	ME	Senior
Shawn Rosengrant	Vibration Isolation, Glass-Fiber Shell	ME	Senior
Kelly Sweeney	Rear Caster, Glass-Fiber Shell	ME	Senior
Jeff West	Laser Range Finder, PLC-to-Amp Interface	EE	Senior

2.3 – Computer Aided Design Tools

After several weeks of conceptual designing and brainstorming, computer aided design (CAD) software was used to create parametric, feature-based solid models using Autodesk Mechanical Desktop. The extensive use of Mechanical Desktop's 3D parametric capabilities allowed the team to easily change the design and make quick, clear presentations to communicate ideas to other groups, including project sponsors. Once the group accepted a design, the software was used to automatically generate the detail drawings for manufacturing. **Figure 2** is an image from a December 1999 design presentation. **Figure 3** is a screen shot from Mechanical Desktop. MATLAB was used for camera placement analysis and dynamic vehicle modeling. Microsoft Excel was used for the vehicle stability calculations.

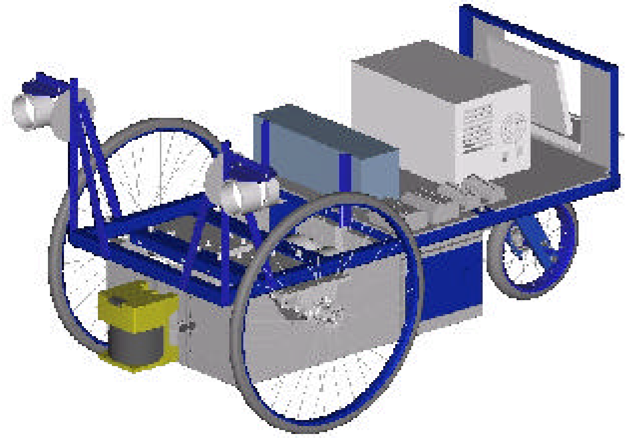


Figure 2 – Three Dimensional CAD Rendering of Navigator

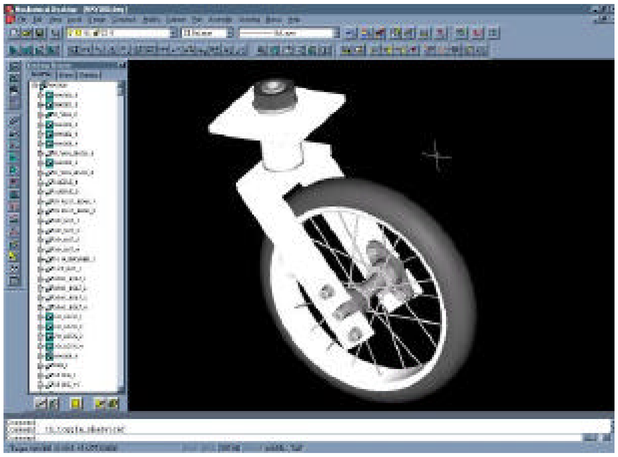


Figure 3 - Screen Capture from Mechanical Desktop During the Caster Design Process.

3 – MECHANICAL SYSTEM

3.1 – Design Process Overview

A key goal throughout the design process was to make the vehicle modular. With this in mind, all the major components were designed to be easily removable from the chassis, allowing for easy redesign or replacement of subassemblies. Modularity also provided a natural task breakdown for the team members. **Figure 4** on the following page is a photograph showing the main modules of the vehicle before assembly. The Navigator chassis is a planar, welded steel tubing structure. All the sub-assemblies, including the lower bay, drive modules, caster, and console, require four bolts or fewer to assemble to the chassis. All bolts are conveniently located to allow for quick assembly and disassembly.

Our previous three-wheel, differentially driven vehicles would tip forward during fast stops. This year, with the help of CAD and Microsoft Excel, the center of gravity of the vehicle became a known parameter during the design process. Mechanical Desktop was used to quickly analyze the assembly and determine the center of gravity. By moving components around in CAD, we were able investigate options for vehicle layout while assuring that the center of gravity was in a stable location.

3.2 – Drive Train

Navigator uses two Bodine 24-volt, 15-amp, 0.45 hp, brush-type DC servomotors to drive the wheels. Each motor transfers power directly to a drive wheel through a 90-degree, 33:1 gearhead, which is directly coupled to the motor housing. The wheels are attached to 3/4 inch drive-shafts via custom-made hubs. The motors include shaft encoders, which are used to determine the position and velocity of each wheel for closed-loop control.

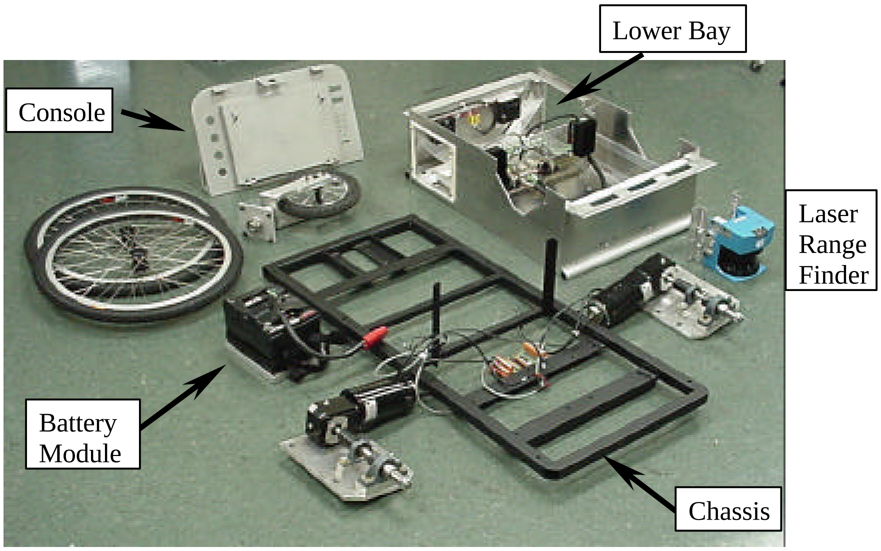


Figure 4 – Navigator Components Just Prior to Assembly.

An important feature incorporated in each drive-train module is a fail-safe brake directly coupled to each motor. During operation, the braking system is held in a disengaged state by electromagnets. In an emergency stop or power loss situation, the electromagnets lose power and the brakes are engaged, bringing Navigator to a rapid, stable stop.

3.3 – Lower Bay

One of the ways the team managed to stabilize the vehicle was by placing a significant fraction of the vehicle weight below the axle height of the drive wheels. This was accomplished by making an aluminum cage, or lower bay, that bolts to the bottom of the chassis and holds several of the heaviest components. This was shown in **Figure 4**. The lower bay was designed to hold the batteries, motor amplifiers, and other drive-related electrical equipment. The sides and bottom of the bay were covered with 1/32” aluminum sheet using pressure sensitive 3M VHB (Very High Bond) tape. This created a weather proof cover, without the need for welding or exposed fasteners. The battery units slide through hatches on either side of the bay. The hatches are sealed, but easily accessible by removing four butterfly nuts on each hatch door.

3.4 – Caster Wheel

The caster wheel has been custom designed from a 12 inch street-class bicycle tire and can handle a static load of 200 lbf. Although 12 inch industrial caster wheels are commercially available, they are designed to carry loads much heavier than Navigator and, as a result, are much wider than necessary. This added width makes them more difficult to turn, reducing the steering responsiveness of the vehicle. Also, the custom designed caster wheel assembly has been created to allow it to be instrumented with encoders that will give feedback on steering direction and wheel rotation. Analytical studies have shown that this added feedback can be used to help reduce dead-reckoning errors. Although the team felt this would be too complex for initial implementation, we believe it represents an excellent opportunity to upgrade the vehicle for next year's competition.

3.6 – Console

The console, shown in **Figure 5**, gives the operator control over the PLC communication, frame grabber data, and all the navigation software through a custom Windows interface. On the left side of the monitor, user input switches are conveniently organized. The console has two key switches, one for the main system power and one for the computer and monitor. An operation mode select switch allows for selection between protected, manual, and computer modes. A manual monitor on/off switch allows for power savings whenever the operator is not interacting with the software tools. Status and feedback indicators are located on the right side of the monitor. Battery voltage indicators give feedback for both battery packs. Bright LED indicators display the current status of the Computer-to-PLC communication, control mode, R/F signal quality, "Brakes disengaged" warning, and several other statuses.

Figure 5 – Operator Console on Rear of Navigator.

3.7 – Weatherproofing

To prevent electrical failure and maintain safety, the team worked diligently to ensure that the vehicle would be unaffected by weather. This requirement influenced many aspects of the overall vehicle design and fabrication, including camera enclosures and component locations. The glass fiber composite shell cover, as well as sealed aluminum paneling on the lower bay and operator console, provide the necessary protection. The paneling is permanently sealed on the lower bay since the bay can be easily removed and accessed. The composite shell rests on four shoulder bolts. The shell tilts up for easy access to the computer, PLC, and wiring, and is easily removed. The shell, made to be rigid and durable, also serves as a mounting surface for the two video cameras, which are enclosed in weatherproof PVC housings.

4 – ELECTRICAL SYSTEM

4.1 – Computational Hardware

The team received several generous donations that helped us optimize the electrical hardware configuration. GE-Fanuc donated a Programmable Logic Controller (PLC). Industrialcomputer.com donated an industrial, dual CPU Pentium III computer. NEC donated a fifteen inch LCD flat-panel monitor. These donations proved extremely valuable during preparation for competition. For example, the PLC and the dual Pentium computer allow for rapid and extensive data logging, which is convenient for testing and troubleshooting. The PLC handles all of the details associated with controlling the motion of the vehicle, while the computer analyzes all the sensor data. The NEC monitor is bright enough to be viewed in direct sunlight, which is a significant advantage during testing and calibration. Even the computer operating system, Windows NT 4.0, was selected to enhance software development and testing. This system combines a familiar operator interface with a stable, multi-processor capable platform. A simple schematic representing the computational hardware architecture is shown in **Figure 6**.

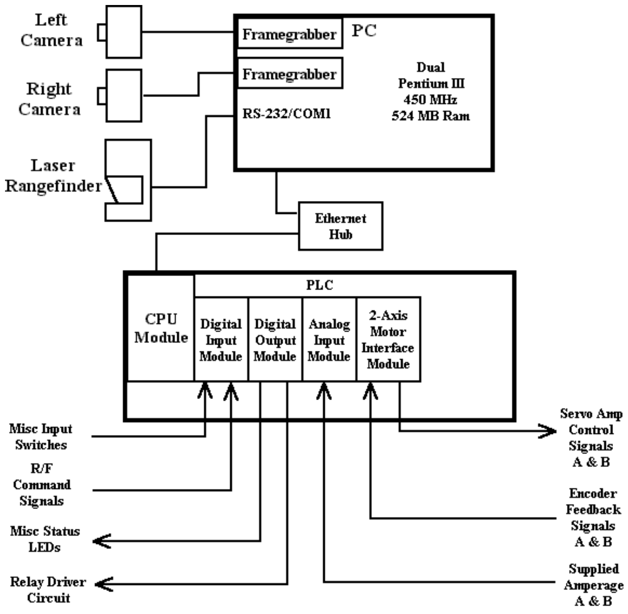


Figure 6 – Hardware Architecture Diagram

4.2 – Power System

Navigator has two onboard, rechargeable, non-spillable 24 volt Lead-Acid battery modules that power everything on the vehicle. One battery module powers the two drive motors via the amplifiers. The second module powers everything else. The batteries are mounted in custom aluminum frame “cartridges”, which easily slide out of the vehicle for change out. A DC-to-AC inverter was required to go from 24vDC to 120vAC for the NEC Monitor. A 24vDC to 12vDC converter was also required for the PLC outputs and radio signal controller. Fuses, sized for the current load and wire size, were used to provide over-current protection for the vehicle.

4.3 – Control System

The low level motor controls are performed by the PLC, based on speed and steering commands received from higher level routines. The PLC converts these values to required rates of rotation for each drive wheel, based on the kinematic model of the vehicle. The actual wheel speeds, measured by the encoders, are regulated by a proportional+integral+derivative (PID) control algorithm programmed into the PLC logic. The vehicle is capable of operating in three basic modes: protected, manual, and computer controlled. The software architecture is shown in **Figure 7**.

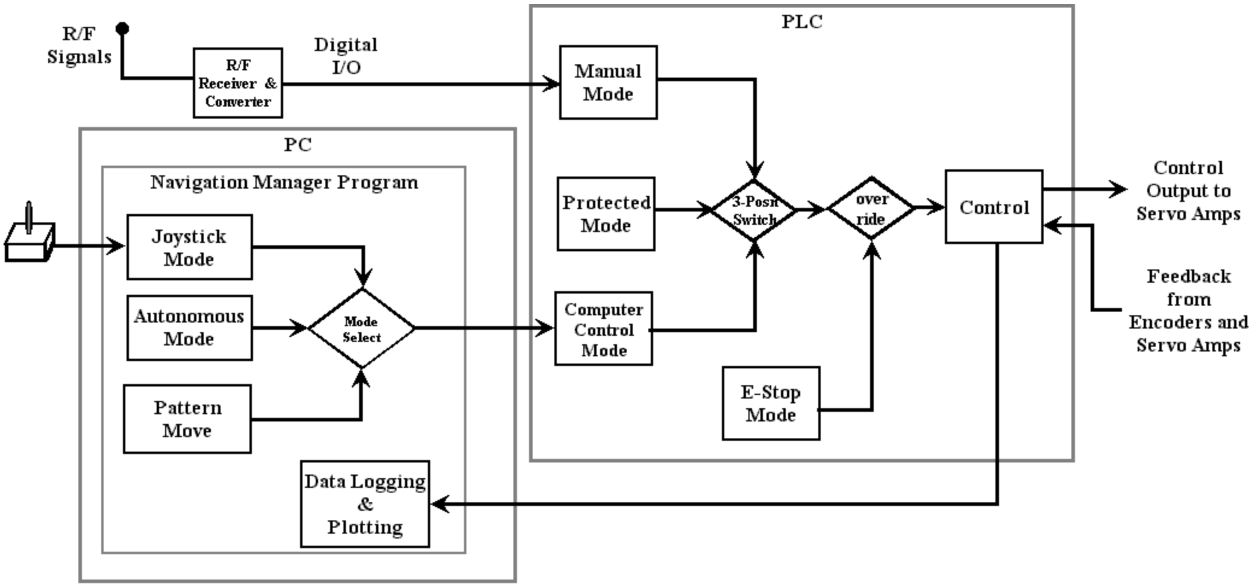


Figure 7 - Software Architecture

In protected mode, the vehicle is stopped, the speed and steering commands are set to zero, and the drive and brake relays are de-energized. This is a software mode, used for programming and debugging, that tells the PLC to ignore all speed and steering inputs from any device.

In manual mode, the steering and speed commands are input by a standard FM radio frequency (R/F) transmitter and receiver. Custom microprocessor code interprets the received R/F signal and outputs two 4-bit digital signals to the PLC. The PLC interprets the 4-bit values, and calculates the speed and steering commands used by the PID algorithm. Manual mode only uses the PLC controls, and can be run without the PC in operation. This conserves power during test setup.

In computer control mode, the computer sends the speed and steering commands to the PLC. The computer operates in one of three modes: joystick control, pattern move, or autonomous. Joystick mode allows the operator to test the vehicle communications and control via the PC, without having the full navigation software. In pattern move mode, the computer generates the required speed and steering commands to move the vehicle in a pattern, such as a line, arc, or figure eight. In autonomous mode, the program analyzes the environment map and determines an appropriate direction and speed.

All of the control modes use the same motor control algorithm. This modular design allowed the vehicle controls to be tested, debugged, and tuned, prior to the implementation of the navigation software. This also allows navigation problems to be separated from underlying problems with the vehicle controls, thus speeding the testing cycle.

4.4 – Safety Interlocks

Since safety is such a critical part of our design, Navigator incorporates four different ways to activate the stop routine. All four methods remove power from the motor and brake relays, which activate the brakes and cut power to the motors. A large emergency stop button centered above the console provides the most obvious method for signaling an E-stop. It mechanically removes power from the relays. During normal operation, when the E-Stop is deactivated, the PLC controls the brake and motor relays. Interlocks programmed into the PLC logic prevent the vehicle from energizing the relays, and starting the vehicle, unless the vehicle is in the correct mode. The PLC will de-energize the relays and stop the vehicle based on a stop command from the PC Navigation Manager software or the wireless pushbutton remote. These are the second and third methods to signal a stop. Finally, PLC logic is used to halt the vehicle during any abnormal conditions. For example, the loss of a good quality radio control signal or the loss of communication with the PC will signal a rapid stop. Once halted, a subsequent start command must be given to the PLC before the vehicle resumes operation.

4.5 – Sensing

Navigator uses three sensors to obtain information about the external environment: two color video cameras and a Sick Optic LMS laser range finder. These sensors are shown on the vehicle in the cover page photo. The dual CPU computer uses two separate frame grabbers, which allows it to process both camera images simultaneously. The cameras are mounted on adjustable mounts. As configured, the cameras provide about 2.5 meters of forward view, and 4 meters of lateral view, as shown in **Figure 8**.

The laser range finder communicates with the computer serially, via the RS-232 serial port. It scans 180 degrees in a plane approximately 10 inches from the ground and returns a sequence of 361 values representing radial distances at ½ degree increments. Objects shorter than 10 inches are detected by the vision system. The laser range finder operates using an eye-safe Class I laser, again showing the emphasis on safety.

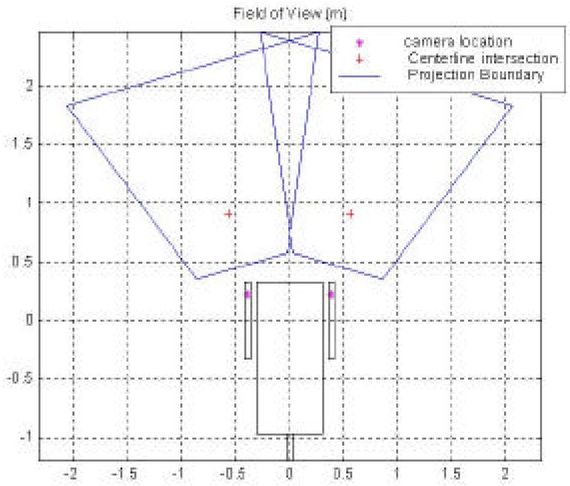


Figure 8 – Plan View of Camera Coverage

5 – SOFTWARE DESIGN

5.1 – Software Design Goals and Requirements

The major goals in the development of Navigator's software were to make it fast, effective, reliable, easy to use, upgradeable, and amenable to testing. Because the development of an entirely new vehicle in one year is an extremely ambitious challenge, the team recognized that time available for implementing and testing the software would be limited. This mandated the development of modular software system that could be tested incrementally on the vehicle or its subsystems. For example, code was developed to compare a planned vehicle path with the actual path traversed. This allowed us to test and tune the motor controllers well before the navigation software was fully implemented.

Navigator's software, called *Navigation Manager*, was written using Microsoft Visual C++ 6.0 under Windows NT. Based on the Microsoft Foundation Classes, the program uses an interface familiar to users of Microsoft Windows. Real-time access to sensor and operational data is available through on screen displays, including parameter plots. Additionally, the data can be saved for later review, either by loading the data into other programs for analysis, or through plots generated by the program. Navigation Manager allows configuration files to be saved and loaded. Camera parameters are available for editing. The modular, object oriented design simplifies future upgrades. **Figure 9** shows the interface of Navigation Manager.

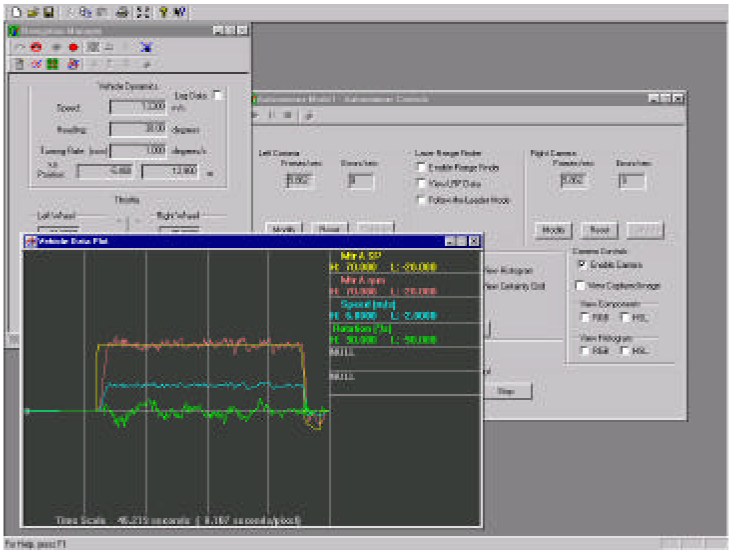
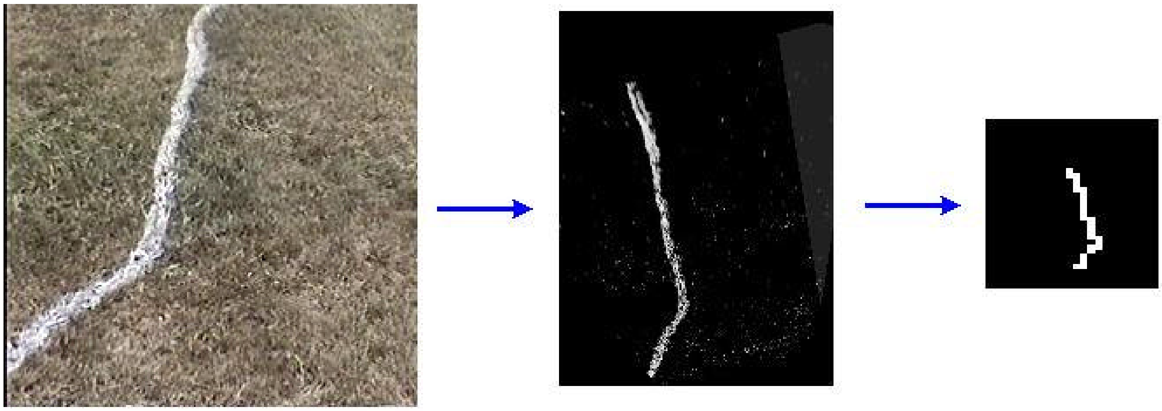


Figure 9 – Navigation Manager Screen Shot

5.2 – Image Processing

In order to successfully navigate the course, the computer vision system must be able to pick lines and obstacles, such as potholes and debris, out of the images obtained by the camera. The Navigation Manager uses several innovative image processing techniques to extract the lines and obstacles from the background. The images are converted to gray scale according to a custom conversion, and then processed to isolate relevant features. The image resolution is then reduced, in an operation called decimation, to provide a more manageable data set. This process is shown in **Figure 10**.



Raw Image

Remapped, blurred, and thresheld

Decimated

Figure 10 - Line and Obstacle Finding Technique Demonstration

Additionally, the Navigation Manager software transforms and composites the two images from the left and right cameras into a single ground plane image. The ground plane image, when decimated, serves as an evidence grid representation of the ground plane. The evidence grid is then used by a sensor fusion algorithm, to be discussed later, to determine valid paths for the vehicle. By using the evidence grid, no prior assumptions are required about line location, shape, or size. Obstacles are handled equally well by the algorithm. To maximize speed, software libraries optimized for the Intel Pentium III MMX instruction set were used for the image processing operations. The use of the optimized libraries allows both images to be processed and combined at over six frames per second.

To find objects in the road debris event, a thresholding algorithm removes pixel values in the middle of the intensity spectrum, while highlighting pixels at the lower end. In this way the algorithm acts as an inverted band pass filter, looking for both light and dark portions of the image. This intensity based method has proven to be more reliable than edge detection methods used on some vehicles.

5.3 – Laser Range Finder Processing

As mentioned previously, the laser range finder returns obstacle data over a 180 degree range in 1/2 degree increments. Objects more than five meters away from the sensor are ignored. The remaining obstacle data is sent to the sensor fusion algorithm. Based on the distance to the object, and the angular dimension of the object, the approximate size and placement of the object can be determined relative to the vehicle.

To improve the robustness of our follow-the-leader algorithm, the navigation software looks at the time history of a tracked object. Objects not matching the expected next position of the tracked object are rejected. This allows the algorithm to ignore people who might walk between the vehicle and the followed target. To ensure safety, a collision avoidance routine will slow and stop the vehicle should an object come within a predefined safety zone, normally set to about 18 inches in front of the vehicle.

5.4 – Sensor Fusion and Navigation

Once the sensor data is collected from the cameras and laser rangefinder, the data from each sensor is translated into a Vector Field Histogram. The Vector Field Histogram is a representation of the obstacle or line density at a given angle. If a line, pothole, or debris is detected, the polar location and distance is used to calculate the obstacle density. A composite Vector Field Histogram for both the laser range finder and camera data is created, using the maximum obstacle density at a given angle. The Navigation Manager then selects the best path from the given data. **Figure 11** shows a screen shot of Navigation Manager with the sensor fusion data displayed.

If a valid path is not detected, the vehicle pauses for a short period of time in case of momentary problems caused by glare or noise. If the path is still blocked after this delay, the Navigation Manager recognizes a trap situation an implements a trap escape algorithm. The program analyzes the data further for a recognized trap condition, and then steers the vehicle accordingly until the trap is escaped.

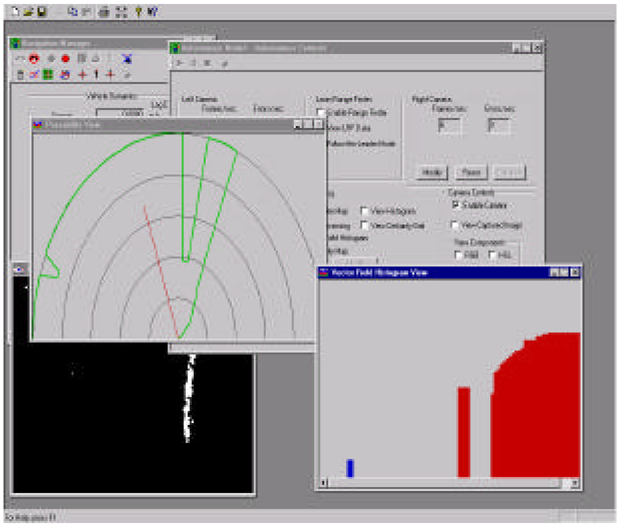


Figure 11- Navigation Manager with Navigation Data Shown

6 – DESIGN TOPICS

6.1 – Safety

Safety was our most important consideration in all aspects of design, fabrication, and operation of the vehicle. Since this topic is so pervasive in the design, discussion of safety is distributed throughout this report. Especially important at competition are the fail-safe emergency brakes and E-stop interlocks. The vehicle is hardware limited to approximately 5.8 miles per hour. Software is used to limit the top speed to 5 mph to conform to competition rules. The attention to safety includes such details as rounded corners and deburred parts. As part of the design program at Virginia Tech, safety is also taught and emphasized in all students machine shop, welding shop and laboratory work.

6.2 – Innovations and Features

Our intent in designing Navigator was to capture the best ideas from previous designs, while avoiding the problems encountered in the past. This led us to focus on the total product development cycle, including programming and testing as an integral part of the design. Experience and attention to detail are evident in all aspects of the design. Although the vehicle is larger than our most recent vehicles, it is designed to fit through a standard 36 inch doorway, and will fit through a 32 inch doorway with the cameras removed. This makes it much more convenient to transport through buildings. All wiring is clearly labeled and documented, allowing problems to be quickly diagnosed and repaired. The vehicle can operate in manual mode, without the computer present, via the remote R/C transmitter. During development, this allowed early testing of the mechanical systems and motor controls. It also helps to isolate drive system problems independent of the navigation software.

The extensive use of the Graphical User Interface (GUI) capabilities of Windows NT and user interface enhancements make the Navigation Manager software easy to use. Innovative image processing techniques and laser range finder data processing give Navigator an advantage over similarly equipped systems. The vehicle’s sensor fusion and map building capabilities allow the software to use histogram information in making future navigation decisions. The use of two cameras allows for a wide view of the course, without subjecting the camera to glare and horizon effects evident in other designs. The modular software design allows for quick upgrades, and the ability to test a variety of algorithms on the powerful computing hardware. Real time plotting and data logging are built into the Navigation Manager, enhancing the operator’s ability to test and evaluate the vehicle performance.

Navigator has also been designed as a general purpose autonomous vehicle test platform. As a demonstration, Navigator has been equipped to carry optional landmine or unexploded ordinance detectors, which will be demonstrated at the competition. The design allowed for this capacity, while still retaining the ability to fit through doorways.

6.3 – Reliability and Durability

Navigator has been designed for rugged outdoor use, starting with the base frame that is constructed from 1/8" wall thickness carbon steel tube. Standard, industrial-quality components were used whenever possible to ensure reliability and maintainability. For example, commercial Bodine motors with integral gearboxes, brakes and encoders provide an industrially proven drive train. The 26-inch diameter rugged mountain bike tires use a triple-cross pattern of spokes. This arrangement is intended for high-torque, rough-terrain applications. The PLC and industrial computer are designed for use in extreme environments. Even simple components like switches and terminal blocks are industrial grade. The simple, modular design and the use of premium-quality standard components helps to ensure the reliability of the vehicle.

6.4 – Predicted Performance

The vehicle drive system was designed so that Navigator could traverse up a 15 percent grade at 5 mph. Because the vehicle weighs more than originally predicted, the maximum ramp climbing speed is actually closer to 4 mph. Navigator is also designed to clear the peak of the 15 percent grade ramp. Stability analysis correctly predicted that the vehicle is stable under even the most severe braking and turning conditions. The dual battery modules give a expected life of approximately 90 minutes, which has been verified in testing.

The use of a dual CPU computer, along with optimized image processing routines, allows the navigation system to calculate steering commands over 6 times per second. This rate is significantly faster than previous vehicles, increasing the vehicle responsiveness on the course. The vision and navigation algorithms are programmed to be flexible enough to handle both the main obstacle course and the road debris course. The use of the laser rangefinder gives the vehicle a competitive advantage in the follow the leader course.

6.5 – Problems and Solutions

The estimated weight of the vehicle during conceptual design was 250 pounds, however the actual weight is approximately 380 pounds. The conceptual design called for a lightweight vehicle. However, because the actual dynamic forces that the vehicle would experience were unknown, a large factor of safety was applied to the design of the chassis and other load-bearing components. Additionally, the available material and limited welding experience of the students fabricators led the team to select steel rather than aluminum tube. As part of the design process, it is planned to instrument Navigator with strain gauges to develop a more realistic model of forces encountered by the vehicle during dynamic operation. This will allow the design to be optimized so that unnecessary weight can be removed. The modular design allows this incremental optimization approach to minimally impact the vehicle's usefulness as a test platform during this process. Fortunately, because of the conservative design approach, the drive motors still have ample power and torque even with the additional weight.

Despite our significant design effort to optimally locate the vehicle's center of gravity, problems were encountered during testing that necessitated moving the batteries to shift weight off the caster wheel. We discovered that very short radius turns (approaching zero radius) required more torque to re-orient the caster wheel than the drive motors could deliver. This was primarily due to the vehicle being heavier than originally planned, as already mentioned. The modular design allowed the batteries to be shifted, while still conserving stability.

Our initial goal was to use only DC power for all vehicle systems. Unfortunately, we were unable to directly power the LCD monitor with DC voltage due to the complexity of the circuitry inside the monitor. For this reason, a 300 watt DC to AC inverted was needed.

6.8 – Cost

Table 2 shows a complete cost breakdown for all the components of Navigator. Donated items are noted as such. Also, totals are shown for donated and purchased items. In addition to monetary costs, over 3500 student-hours were spent from July of 1999 to July of 2000 doing hardware design, software design, and manufacturing.

Table 2 – Cost Estimate

Item Description	Team Cost	Donated
GE-Fanuc PLC	$0.00	$7,815.00
SICK LMS 200 range finder	$0.00	$3400.00
industrialcomputer.com PC	$0.00	$3,078.00
NEC LCD Monitors	$0.00	$3,000.00
Bodine Motor (2 plus spares)	$0.00	$2,450.00
Imagenation Frame grabber (qty 2)	$495.00	$495.00
Copley Controls Amps	$0.00	$290.00
Wheel rims (qty 2)	$0.00	$250.00
Electronic Components (cables, etc)	$743.00	$200.00
Material (aluminum and steel)	$768.00	$0.00
Mechanical Components	$312.00	$0.00
Batteries (qty 10) and chargers	$850.00	$0.00
Totals	$3,168.00	$20,978.00
Vehicle Cost (without student hours)	$24,146.00	