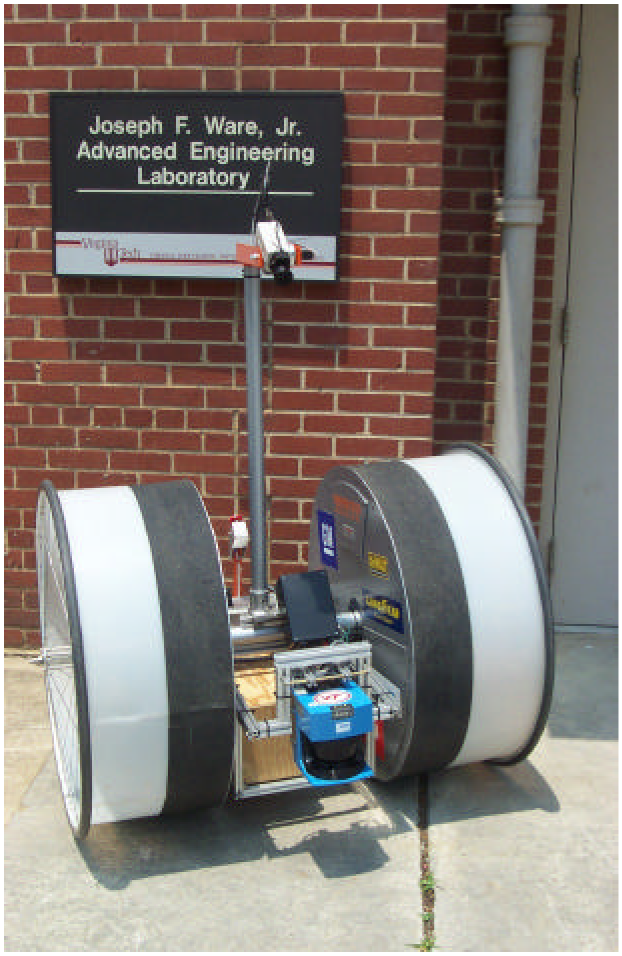
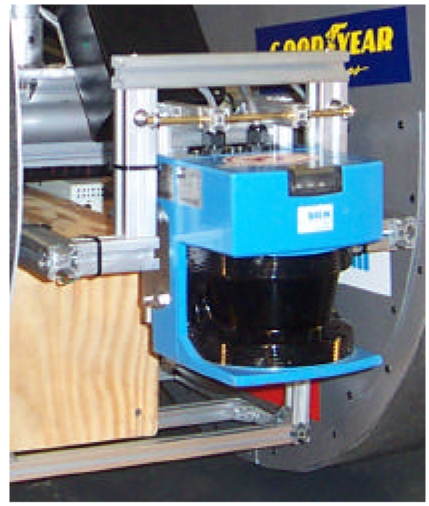
Biplanar Bicycle 2002

2001 – 2002
Autonomous Vehicle Team
Of
Virginia Tech





Team members:

Eric Slominski
Joong-Kyoo Park
Christopher Terwelp
Patrick Forman
Ian Hovey
Jared Mach
Joseph Roan
Merritt Draney

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 re-design of the vehicle, Biplanar Bicycle, by the current Biplanar Bicycle team, has been significant and each senior team member has earned six senior design project credits from this University.

Signed, (Date)

Dr. Charles F. Reinholtz
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1. Introduction

The Virginia Tech Autonomous Vehicle Team extended the boundaries of autonomous vehicle design with the introduction of the Biplanar Bicycle at the 2001 competition. This unique two-wheel, single axle vehicle uses motors to lift a reaction mass, which creates a force imbalance that propels the vehicle in the desired direction. Last year, the vehicle was only equipped to compete in the design and navigation portions of the Intelligent Ground Vehicle Competition. In 2001 the Biplanar Bicycle failed to compete in the navigation portion of the IGVC due to a circuit board failure.

Many improvements and refinements were made for the 2002 competition to allow the Biplanar Bicycle to compete in all three phases of the competition, namely, design, navigation and autonomous challenges. The most apparent changes are the laser rangefinder and camera that have been added to the Biplanar Bicycle. These sensors are actively mounted, allowing them to maintain a nearly constant horizon. Less apparent but noteworthy modifications include a motion controller and amplifier setup that allows precise control of the vehicle. Tying all the motion control components together and commanding the navigation of the vehicle is a new robust industrial computer. A redesigned electrical system includes a chassis ground to reduce the number of wires and a fuse system for added safety to the operator as well as onboard components. To improve operator access to components the wheel shrouds are improved with larger access panels as well as user-friendly hardware. The components, ultimately protected by the wheel shrouds are removed from individual boxes facilitating easier access for adjustments and wiring.

2 Design Process

2.1 Design Process

One key to success in any engineering project is an organized approach to the design process. The conceptual development process used to modify the Biplanar Bicycle as outlined by *Product Design and Development* (Eppinger & Ulrich, 2000) consists of 8 stages shown connected by solid arrows in Figure 1. This design process is both iterative and reflective – as each phase is completed, the team reflects on the results and decides how to continue the project.

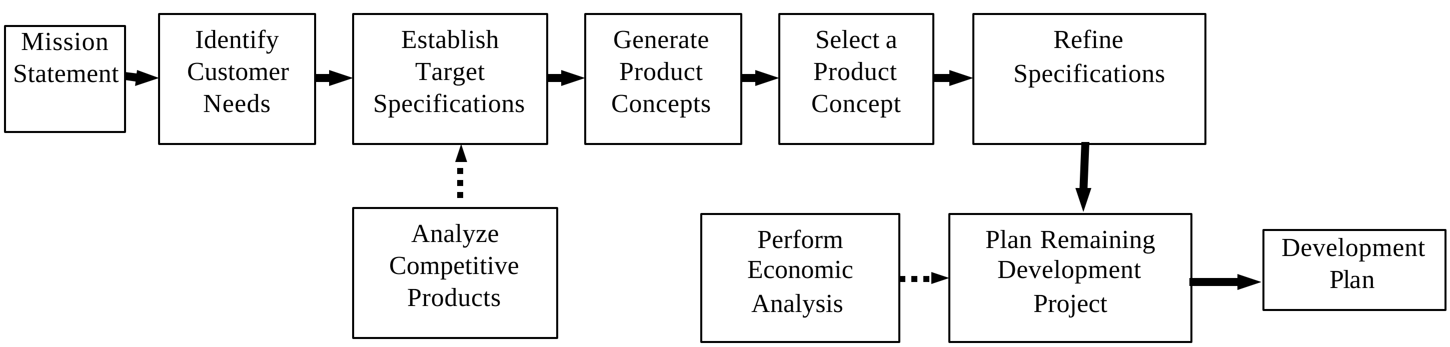

Figure 1: Flow schematic of the concept development phase

The mission statement for the 2002 Biplanar Bicycle Team was to redesign the existing two-wheeled, single-axis vehicle, ultimately making it a capable contender in all three events of the IGVC. With this mission in mind, the team set out to identify the customer needs. The customers are defined as the 2002 IGVC judges, the project advisor, Virginia Tech, and the vehicle's initial designers. The customer needs were determined by studying the rules of the competition and by interviewing team members from last year. These needs include mounting and stabilizing the sensors, a new method of motor control, increased safety, and better weatherproofing. The team then followed the rest of the design process to generate multiple concepts for each modification, select final concepts, and finally create a final plan to improve the vehicle.

2.2 Design Team Organization

The Biplanar Bicycle design team consists of seven engineering students. In order to gain a greater understanding of how each system operates, the team is divided into 6 sub-teams. These sub-teams dealt with Motion Control, Camera Stabilization, GPS, Software, Vehicle Frame, and Electrical System. Each sub-team is responsible for researching and developing their respective system. Due to the small size of the Biplanar Bicycle Team, members were assigned to multiple sub-teams. Table 1 shows a list of the team members and the responsibilities they undertook throughout the year. Approximately 1200 person hours went into the redesign and development of the 2002 Biplanar Bicycle.

Table 1: Biplanar Bicycle Team Member Information

Team Member	Responsibility	Status	Major	Class Level
Chris Terwelp	Camera Stabilization Motion Control Software	Volunteer	ME	Graduate Student
Patrick Forman	Camera Stabilization Vehicle Frame	Volunteer	ME	Senior
Ian Hovey	Motion Control Camera Stabilization Vehicle Frame Electrical System	6 hr. Senior Design	ME	Senior
Jared Mach	Motion Control	Volunteer	EE	Graduate Student
Eric Slominski	Camera Stabilization Motion Control Electrical System	6 hr. Senior Design	ME	Senior
Joseph Roan	Motion Control Electrical System	6 hr. Senior Design	ME	Senior
Joong-Kyoo Park	GPS	6 hr. Senior Design	ME	Senior
Merritt Draney	Camera Stabilization Vehicle Frame	Volunteer	ME	Junior

3. Drive Train and Structural Improvements

The 2001 Biplanar Bicycle drive train centered around 2 Matsushita 24V Brushed DC motors proved to be robust. The existing drive system on the 2001 Biplanar Bicycle was repeatedly tested using remote control. Test conditions included negotiating down stairs, running through mud, colliding with stationary objects, and climbing over curbs. Although the vehicle will probably not be subjected to these conditions in competition, it is reassuring to know that its structure and drive system can withstand such abuse. The motors include integral 12:1 gear reducers, which provide ample torque to raise the reaction mass and propel the vehicle. Also internal to the motor design is a common HP encoder that allows easy interface with our motion control system.

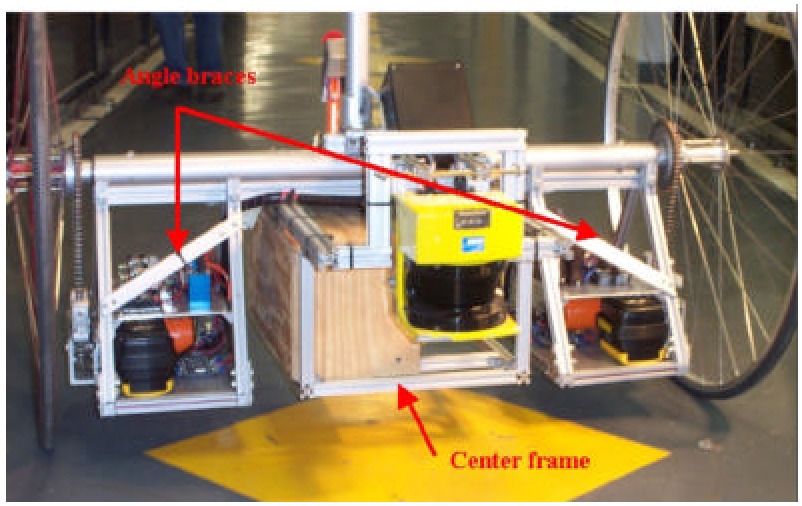

Figure 2. Structural design changes

Slight improvements were made to the vehicle's frame to mount new components and increase rigidity in some areas. Angle braces were added to increase the horizontal strength of the right and left sub-frames. Braces were also added to stiffen the motor mounting. A new center frame was built to house the computer, payload, and laser range finder. A camera mast was fabricated to hold a camera and its associated active leveling system. Finally the wheel shrouds were improved, thus simplifying access to internal vehicle components. Figure 2 shows some of the added bracing and the new center frame that holds the payload, computer and laser rangefinder.

4. Design Innovations

Design innovation was a focused objective in the redesign of the Biplanar Bicycle. In order to meet competition and senior design project requirements, the vehicle needed to be significantly changed from the previous year. The vehicle configuration itself obviously demonstrates innovation compared to conventional vehicles. While this year's design team did not develop the basic vehicle concept, every phase of our design was radically affected by the constraints and opportunities presented by this novel concept. For example, ramp climbing ability is directly dependent on both the overall mass of the vehicle and on the location of the center of mass. This constraint made nearly every subsystem of the vehicle a unique challenge to design and implement.

As noted earlier in the report, last year's vehicle was designed with only GPS navigation capabilities. Unfortunately, after the failure of a circuit board, the vehicle could only be demonstrated operating through remote control at the 2001 competition.. This year, the vehicle is equipped with a new motion control system and an upgraded version of a previously implemented software system called *Navigation Manager.*

An integral part of the vehicle's aptitude to navigate lies in its capacity to sense the world around it. Thus, implementing these components on an unstable platform oscillating in a non-linear manner posed many significant challenges. Avenues such as gyroscopic stabilization and servo stabilization were pursued.

A novel, inertially stable camera platform was developed using a Futaba S9303 high-torque servo and closed loop control system. The camera and servo are shown in Figure 3. The inclination of the support pole is measured using a US Digital inclinometer which provides a digital signal proportional to the angle of the camera mast. A Microchip PIC16F84 microprocessor reads data from the inclinometer and employs a proportional digital control loop to stabilize the camera. The microprocessor outputs a servo control pulse to the leveling servo, which attempts to keep the camera at a constant horizon. In order to verify the robustness of the control design, a dynamic model of this system was developed and simulated using control theory. This step was a crucial part of the design to ensure that the non-linear dynamic nature of the Biplanar Bicycle would not cause the camera stabilizer to go out of control. With the addition of the camera stabilizer, it is now possible to capture stable computer images needed for lane following and obstacle detection.

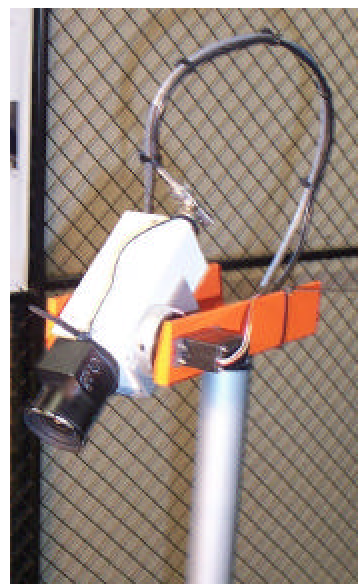

Figure 3. Camera stabilizer

Another design innovation implemented on this year's Biplanar Bicycle is the addition of a laser rangefinder. Due to the large mass and inertia of the laser range finder, it was impractical to utilize the same method of servo correction as used on the camera. Rather, the laser rangefinder was mounted on a pivot about its horizontal center of mass, as shown in Figure 4. The inertia of the range finder helps make it insensitive to the angular and linear acceleration of the base vehicle. Software-imposed acceleration limitations are implemented to prevent this sensor from reaching a resonate frequency created by vehicle accelerations. The maximum angle of rotation of the laser range finder is limited mechanically to prevent the sensor from interpreting the ground immediately in front of the vehicle as an obstacle when large oscillations occur.

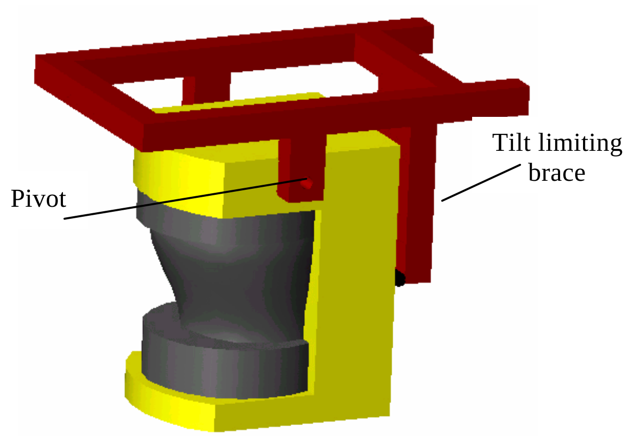

Figure 4: Mounting for Sick Optics laser range finder

5. Electrical System

5.1 Computational Hardware

The onboard computer used for all vehicle navigation and control decisions is an industrial PC that uses a 1.2 GHz Pentium III processor with 256 MB memory running Windows 2000. This system and its components were selected for their inherent reliability. Of particular importance is the ability of the system to reboot without user intervention in the case that power is lost. A significant innovation is the use of a Cisco Wireless LAN PCI card, which facilitates debugging and monitoring via a remote computer running over a local area network. With this system, it is not necessary to have a keyboard or monitor on board the vehicle, which reduces both weight and power consumption. It also means that a programmer can sit comfortably at a table while working on the vehicle.

5.2 Power System

The safe, low-voltage power system using 24-volt Dewalt NiCad batteries employed in last year's vehicle was modified slightly in the 2002 Biplanar Bicycle. The number of batteries was increased from two to four, and a new fuse system was implemented to protect individual electrical components at ratings specified by the manufacturer. Additional power relays were implemented so that individual components could be turned off to save battery power. A set of relays also allows the vehicle to be switched between remote and autonomous modes. Additionally, the power system was improved by adding a chassis ground, which significantly decreased the number of wires and complexity of the electrical system. Diode gates were implemented to protect the batteries from back-charging each other, and arcing during battery changes was minimized by the introduction of capacitors. Further protection of the components is accomplished by separating high current devices from low current devices. The computer, motor controller, power relays, laser range finder and camera stabilizer are powered from a different system than the amplifiers and motors.

5.3 Control System

The control system is a completely new to this vehicle. Last year, an effort was made to employ an AXIOM board with a Motorola HC11 microprocessor, but these components proved to be complex and difficult to integrate as a system. For the 2002 Biplanar Bicycle, a stand-alone motor controller from Precision Microcontrol (PMC) was implemented on the vehicle. This device communicates to the PC via a serial (RS-232) connection. The controller actuates the motors by producing a voltage proportional to the desired speed of the wheels. This voltage is passed to a set of Advanced Motion Control (AMC) servo amplifiers, which in turn produce a pulse width modulated signal (PWM) that drives the motors. The motor controller then reads the data from the motor-mounted HP encoders in order to close the control loop and facilitate speed control. The flow of this control information is shown in Figure 5.

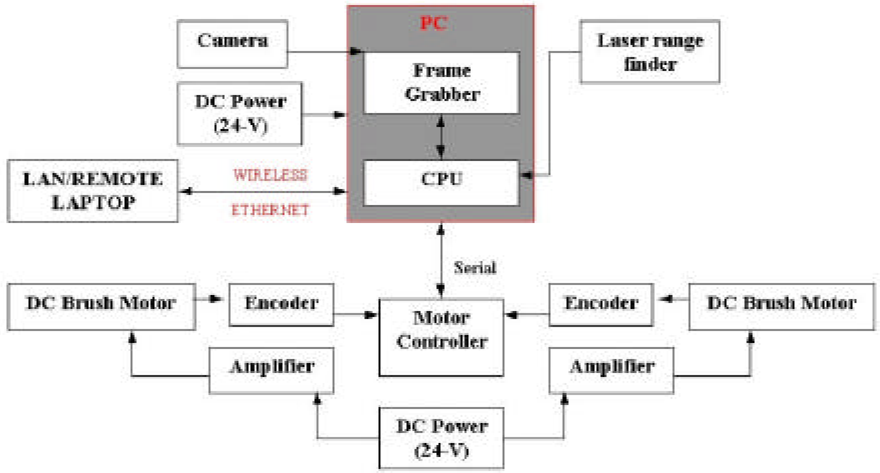

Figure 5. Control system flow diagram

5.4 Sensors

The new sensors incorporated on the Biplanar Bicycle include a laser rangefinder, a Panasonic black and white CCD camera, and Trimble Differential Global Positioning System (DGPS). Video images are captured using an Imagenation frame grabber, which converts the images into a digital format that are sent to the *Navigation Manager* for interpretation. A black and white camera was selected for its ability to produce high contrast images in a wide range of lighting conditions by lens and aperture adjustments as well as yellow and red lens filters. The onboard computer thresholds these images in order to distinguish between high and low intensity pixels that helps to discern the location of white or yellow lines in the image. A Sick LMS-100 laser range finder communicates with the PC via a serial (RS-232) connection. The LMS-100 scans in a 180° plane in ½° increments in front of the vehicle to detect obstacles. Again this information is sent to the *Navigation Manager* for interpretation. The final sensor is an agricultural-grade differential GPS unit. This unit communicates the vehicle's location in degrees of latitude and longitude via a serial (RS-232) connection to the onboard PC. The implementation of a differentially corrected GPS signal on this year's vehicle should greatly improve accuracy. In 2001 the conventional GPS data had a standard deviation of greater than 10 feet, which made navigation exceedingly difficult. With it's array of sensors, the 2002 Biplanar Bicycle will be able to compete in all competition events.

6. Software

6.1 Software Design Goals

The software written for the 2001 vehicle was limited to a relatively simple GPS based navigation algorithm. In developing software for this year's vehicle, a modular system that could be upgraded and had proven reliability was highly desired. The team based the new navigation software on code that was proven in two previous vehicles. This software, *Navigation Manager*, which was originally written by David Conner in 2000, has been designed with modularity in mind. This software was adapted to run the Biplanar Bicycle, by changing the motor controller interface, adding GPS navigation and by modifying the kinematic parameters of the vehicle..

6.2 Software Operation and Navigation

Navigation Manager is written in Visual C++ under Window NT. Through graphical user interfaces (GUI) information such as motor speeds and parameter plots can be communicated to the user. Data can be saved for later review in simulation mode or it can be used to generate a global map for the additional dead reckoning control algorithm. A typical view of the graphical interface of *Navigation Manager* is shown in Figure 6. Inputs to *Navigation Manager* come from the laser range finder, the camera (via the frame grabber), the DGPS system (during the navigation challenge), and from the motor controller. All information is collected and translated into a vector field histogram, which is a graphical representation of the course ahead of the Biplanar Bicycle. The desired

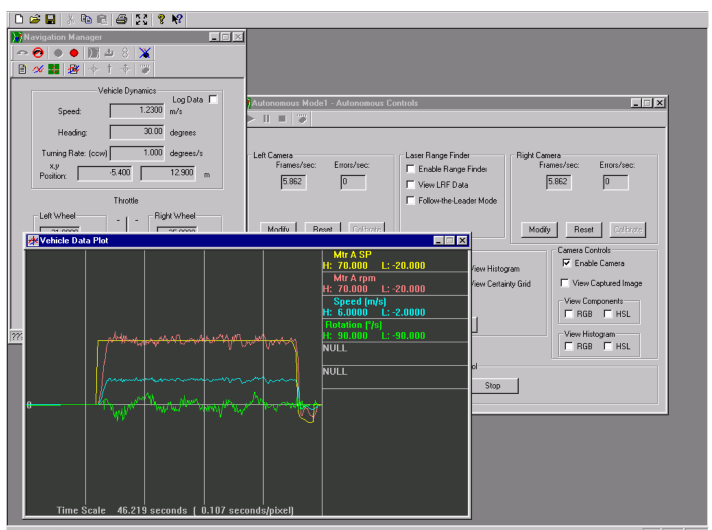

Figure 6 – Navigation Manager Screen Shot

velocity and heading of the vehicle is computed by minimizing the cost algorithm generated by the vector field histogram. Lines, potholes, and three dimensional obstacles are all considered to obstacles in Navigation Manager. As a result, the vehicle is always viewing obstacles during normal operation. When any type of obstacle (line, pothole, barrel or bucket) is detected, the size, polar location and distance are used to calculate an 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. *Navigation Manager* then selects the best path from the given data. Figure 7 shows a screen shot of *Navigation Manager* with the fused sensor data displayed. If a valid path is not detected, the vehicle pauses for a short period of time to acquire additional data from the sensors. If the path is still blocked after this delay, *Navigation Manager* recognizes a trap situation and implements a trap escape algorithm. The program analyzes the data further for a recognized trap condition, and then steers the vehicle accordingly until the vehicle escapes.

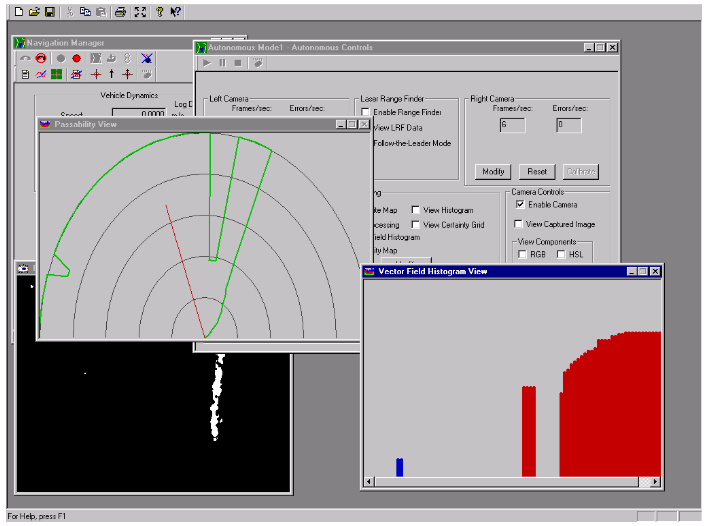

Figure 7- Navigation Manager with Navigation Data Shown

A new implementation to the software is the ability to incorporate GPS data. For the navigation challenge, *Navigation Manager* loads a global map file generated by the user. This map represents a series of lines the vehicle must follow in order to reach waypoints. Differentially corrected GPS data is weighed against dead reckoned data in order generate a path that will cross all of these waypoints. The navigation algorithm written for this section also employs a look-ahead algorithm written by Phillip Kedrowski. This algorithm allows the vehicle to stray from the global map path file in order to avoid obstacles by looking ahead to a distant point and navigating to that point while plotting a course around any encountered obstacle.

7. Predicted Performance of the Vehicle

7.1 Speed

The competition guidelines specify a maximum vehicle speed of 5 mph. Prior testing shows that this vehicle will not exceed 4.83-mph under no-load conditions operating at maximum battery power. To further ensure that this design criterion is met, speed and acceleration limits are imposed by software in *Navigation Manager*. If, for example, the vehicle is going down a hill, *Navigation Manager* will decelerate the vehicle to prevent it from breaking the speed limit.

7.2 Ramp Climbing Ability

The rules indicate a maximum slope of at least 15 percent. This equates to 8.53 degrees. Target specifications indicate an ideal maximum negotiable slope be 30 percent or 16.7 degrees. The target vehicle weight is 100 pounds including the payload. It was calculated that the reaction mass must provide a minimum of 29 N-m and a maximum of 56 N-m of torque. This torque corresponds to a reaction mass weight between 18.85 and 37.52 pounds at a radius of 13.75 inches. Therefore under the new design the original motors produce adequate torque to raise the reaction mass 90 degrees from its resting position.

7.3 Reaction Times

The Biplanar Bicycle is expected to have very quick reactions times due to the ability to use both drive motors to perform a zero radius turn in order to avoid an obstacle. Through software the vehicle can be command to respond very quickly to a line or physical obstacle. The camera has a very large field of view and the laser range finder can perceive obstacles at a great enough distance to avoid them all together.

7.4 Distance at Which Obstacles are Detected

A critical factor in successful autonomous navigation is the detection of three-dimensional obstacles, since this will affect both the Navigation and Autonomous challenge. The camera will be able to detect obstacles such as potholes and barrels at close range for fine maneuvering. At long range, the laser range finder will play a crucial role. The laser range finder has the ability to sense obstacles at a range of up to 75 ft. *Navigation Manager* will threshold this data to only incorporate obstacles within 15 feet. .

7.5 Battery Life

The Dewalt division of Black and Decker donated two sets of batteries to use at competition. The first set is rated at 2.3 amps/hour (55.12 W), and the second set is rated at 2.7 amps/hour (64.7 W). The power-sourcing capabilities of these batteries were compared against the power consumption ratings of the various electronic components to determine the required number of batteries. It was found that the batteries connected to the low power device bus, consisting of the motor controller, PC, power relays, laser range finder, and camera stabilization unit will produce enough power to run these components for a maximum of 40 minutes. The high power battery bus, which powers the amplifiers and motors, produces continuous run times on the order of 15 to 30 minutes, depending on speed and load. These batteries will be changed after every 10th run. Although these components draw higher current, they will consume less total power since they are not always running and will experience varying loads.

7.6 Dead Ends, Traps, and Pot Holes

The Biplanar Bicycle has the ability to recognize traps and dead ends before reaching them through the use algorithms such as the escape algorithm as well as the long distance obstacle detection capability of the laser rangefinder. The software interprets the potholes in the same manner as lines, which it avoids crossing. The vehicle will have no problem traversing sand traps, since all the weight of the vehicle is, by definition, on the driving wheels. In the detection algorithm, if no distinct line or pothole is picked out against the background, the vehicle continues to drive forward under the assumption it has encountered a sand trap.

7.7 Navigation Challenge

The vehicle is expected to perform well in the Navigation challenge. The new navigation algorithm, based on differentially corrected GPS data along with dead reckoning based on wheel encoder data is robust and easily adapted to varying quality GPS signals.

8. Other Design Issues

8.1 Vehicle Cost

Throughout the redesign of the Biplanar Bicycle cost was an important concern. Cost was kept to a minimum by seeking donations from companies and researching products for the lowest costs. A summary of the overall cost of the vehicle is shown in Table 2.

Table 2: Component cost breakdown

Intelligence System	**Retail Value**	**Actual cost to the team**
PNC DC2-ST	$1,700	$0
Trimble DGPS	$2,200	$0
Industrial Computer	$2,000	$0
Panasonic Camera	$150	$0
Sick Optic Laser Range Finder	$5,000	$0
Power System		
Dewalt 24V XR Battery	$738	$0
AMC Amplifiers	$590	$590
Drive Train		
Matsushita 24V DC Brush Motor	$25	$0
Wheels		
Sun Rims 34 7/8" Custom Wheels	$140	$140
Frame and Structure		
McMaster Carr 2x1.25"x6' Aluminum Tube	$57	$57
Bosch Automation 20x20 Extrusion	$200	$0
Bosch Automation Miscellaneous	$120	$120
Camera Stabilization		
Futaba Servo	$65	$65
US Digital *ECOUNT*	$99	$99
US Digital inclinometer	$75	$75
Miscellaneous	$500	$500
Total Cost	$13,659	$1,646

8.2 Safety

There were limited changes made to the existing safety system on the Biplanar Bicycle. The E-STOP switch was mounted in a different position to facilitate easier run termination, and with the addition of the new navigation software, the vehicle will stop if it encounters any obstacle within three feet of its path. The E-STOP will bring the vehicle to halt by reversing the polarity of one of the two motor leads. This causes any stored energy within the motor to be discharged into the opposing motor. This effect will cause the vehicle to stop immediately or do a zero radius turn until all energy is dissipated. If the vehicle loses power on a hill, the vehicle will turn sideways preventing any further motion down the hill. Also, a remote E-STOP has been implemented via a radio modem connection to a computer.

9. Conclusion

The changes made to the Biplanar Bicycle have changed the entire look and operation of the vehicle. These changes have made it possible for the vehicle to compete in all portions of the competition. The most significant changes took place in the addition of sensors and a complete navigation system. The addition of multiple sensors allows the vehicle to navigate autonomously. The accuracy of these motions has also been improved with the new system of motion control.