The Virginia Tech Biplanar Bicycle

Required Faculty Advisor Statement

I hereby certify that this is an original design. Four of the student designers working on the project received two semesters of senior design credit. The other two student designers received credit for one semester of independent study.   These students were fully responsible for the design, construction and testing of this device, including the electrical and mechanical fabrication.

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1 – INTRODUCTION

The Virginia Tech Autonomous Vehicle team has attempted to extend the boundaries of autonomous vehicle design by developing a capable and inexpensive two-wheel vehicle to compete in the 2001 Intelligent Ground Vehicle Competition. The team has adopted the term "Biplanar Bicycle" to describe this new vehicle concept and to distinguish it from the typical bicycle with coplanar wheels.

Although the Biplanar Bicycle is a remarkably simple mechanical device, developing this radical concept into a competitive entry in the Intelligent Ground Vehicle Competition was a major undertaking. From the outset of the project, the student design team attempted to set ambitious, but realistic, goals for the academic year. After considerable research and deliberation, the team decided to develop the Biplanar Bicycle for the purpose of competing in only the Design Competition and the Navigation Challenge at this year's IGVC. We made this decision only after reviewing the successes and failures of past first-time vehicles in competition and also after receiving permission to focus on these events from the IGVC Design Judge Chair. Nevertheless, the Biplanar Bicycle was purposefully designed to facilitate the addition of sensors and software in future years to allow for competition in all events of the IGVC.

We believe the Biplanar Bicycle takes innovation to a higher level than any of our past vehicles. Through a unique design that uses only two wheels and a single axis of rotation, the Biplanar Bicycle is a surprisingly nimble, capable, and powerful autonomous vehicle.

The Biplanar Bicycle is propelled by lifting a reaction mass. The reaction mass is made up of the functional components of the vehicle, such as the motors and the batteries. In static mode, the vehicle will roll until the reaction mass is positioned as close to the ground as possible. This puts the system in a minimum potential energy state. Using the reaction mass as resistance, two independent chain drive motors propel the vehicle forward. Using position and velocity feedback from a global positioning system (GPS) the vehicle calculates the course heading. This report describes both the design and the design process used to create the Biplanar Bicycle.

2 – DESIGN PROCESS

2.1 – Design Process

The Biplanar Bicycle Team adopted the design process taught in a required sophomore mechanical engineering design class at Virginia Tech. A detailed discussion of this design process can be found in *Product Design and Development* [Ulrich and Eppinger 1995]. The process includes the following five main steps: concept development, system-level design, detail design, testing and refinement, and production ramp up. The concept development process represents the most significant step in the design process. A flow chart of the concept development process is shown in Figure 1.

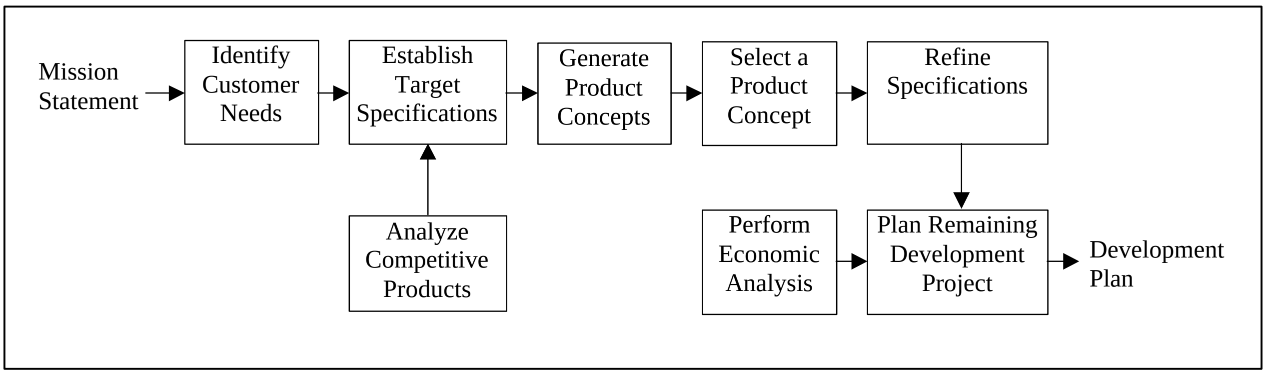

Figure 1: Flow schematic of the concept development phase.

Our unifying vision for the Biplanar Bicycle Team was to design and build a two-wheeled, single-axis vehicle capable of winning both the Design and GPS-based Navigation Challenge portions of this year's Intelligent Ground Vehicle Competition. We also desired a vehicle that could be enhanced to include other sensors and navigation schemes for future competitions. With these goals in mind, the team consulted individuals involved with past and current autonomous vehicle designs to determine what features were needed in such a vehicle. The perceived needs for the vehicle were then translated into specifications by attaching measurable values. An example of a perceived need was the need for higher ground clearance compared to earlier vehicles. This was transformed into a specification by setting a minimum ground clearance requirement of 10" for the new design. Having specifications allowed the team to rate how well various concepts for the Biplanar Bicycle could satisfy the needs. Also, previous autonomous vehicles and similar systems were rated for their ability to meet the specifications. Concepts that rated well were considered for possible implementation on our vehicle. One important input point came from Mr. William Agnew, Chair of the Design Judging Panel, who confirmed that the new vehicle would be allowed to compete in only the Design and GPS-based Navigation Challenge portions of the Competition this year. In addition to concepts from external sources, team-brainstorming sessions provided a wealth of ideas that could be incorporated into the design. To gain a better understanding of the functional requirements of the new vehicle, we divided the overall design into the areas of sensors, drive system, power source, navigation schemes, and motion control. Internal brainstorming and external research were conducted to generate possible concepts for each area. The concepts were then entered into concept classification trees. These trees provided a logical and visual grouping for the ideas, and permitted careful consideration of each concept. Clipping off some of the branches and eliminating certain concepts that did not adequately fulfill the concept specifications narrowed the search.

The concepts that remained after pruning the concept classification trees were rated in a concept selection matrix. The selection matrix involves establishing a relative importance for each specification and assigning a weighted score to each concept for its ability to meet the given specifications. This permitted a quantitative analysis of the options, leading to rational decision-making.

2.2 - Design Team Organization

The Biplanar Bicycle Team consisted of four mechanical engineering students, an electrical engineering student, and a computer engineering student. In order to gain detailed knowledge of each aspect of the design, the Biplanar Bicycle project was divided into the following four major categories: structural, electrical, sensing, and navigation. Each team member was responsible for developing one of the categories listed above. Table 1 shows a list of the Biplanar Bicycle Team members, responsibilities, major, and class level, and hours worked.

Table 1: Biplanar Bicycle Team Members

Biplanar Bicycle Team Member	Responsibility	Major	Class Level	Hours
Jason Badgley	Electrical System	EE	Senior	119
Jessica Chillas	Structural and Electrical System	ME	Senior	255
Patrick Forman	Structural and Electrical System	ME	Senior	365
Daniel Graves	Navigation System	ME	Senior	248
Shawn Gunsolly	Navigation System	CpE	Senior	56
Joseph Trout	Sensing System	ME	Senior	246

2.3 - Design Methods

Hand drawings were used initially in the design process to rapidly generate a variety of concept sketches and to quickly communicate the design among the team members and sponsors. Computer-aided design using Autodesk Mechanical

Desktop™ permitted relative ease in modifying the design. Solid modeling with CAD was essential due to the limited space available on the vehicle. An example of this method is shown as Figure 2.

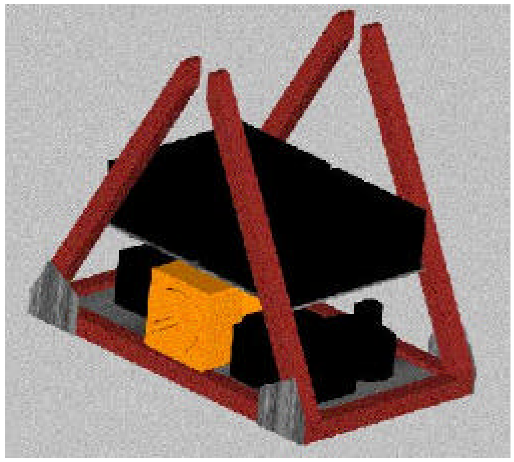

Figure 2. Isometric view of the left-hand reaction mass

3 - MECHANICAL SYSTEM

3.1 – Mechanical System Overview

Conceptually, the Biplanar Bicycle differs significantly from typical vehicles. The single-axis, two-wheel configuration requires the vehicle to use its own mass to provide a propulsive torque. The drive motors are configured to raise the swinging, but non-rotating, reaction mass of the vehicle in front of the center axis. This generates a mass imbalance, causing the vehicle to roll. Motion is dynamically sustained for propulsion by continued motor rotation, which holds the reaction mass above its minimum potential energy state. Each wheel is independently driven by a motor that reacts against the reaction mass, producing a differential drive capable of zero-radius turns.

The reaction mass contains many components of the vehicle including the motors, batteries and navigation hardware. Space is optimized on the Biplanar bicycle to allow for a variable size payload, and to carry various intelligence systems.

3.2 – Control Structure

The Biplanar Bicycle is built using 2” O.D. x 1 ¼” I.D. structural aluminum tube as the backbone and center axis of the vehicle. This tube is rigidly connected to the reaction mass frames through a section of 30mm Bosch Automation extruded aluminum. The Bosch extrusion system provides a connection point for the mounting of the reaction mass and payload carrier. The Bosch extrusion is also used to fabricate the reaction mass frames, which allow equipment to be added to the vehicle using stock fasteners.

3.3 - Reaction Mass

The reaction mass provides the necessary eccentric mass imbalance for vehicle propulsion. To obtain optimal vehicle acceleration and performance, the team chose to include the majority of the vehicle components, such as the drive train, motor controller, GPS and emergency stop receivers as part of the reaction mass.

The reaction mass frames are constructed of 20mm by 20mm extruded T-slotted aluminum bar stock donated by Bosch Automation. This material is cut to length and assembled using a variety of gusset plates and other stock connector elements. This allowed rapid fabrication and easy modification. Bosch provides detailed information on the load carrying capacity of the extrusion and each of the connector elements. This enabled us to design a strong structure with relatively few design calculations. Modular components can also be added or removed as necessary, after construction, adding versatility to the design. The right side of the reaction mass is shown in Figure 3.

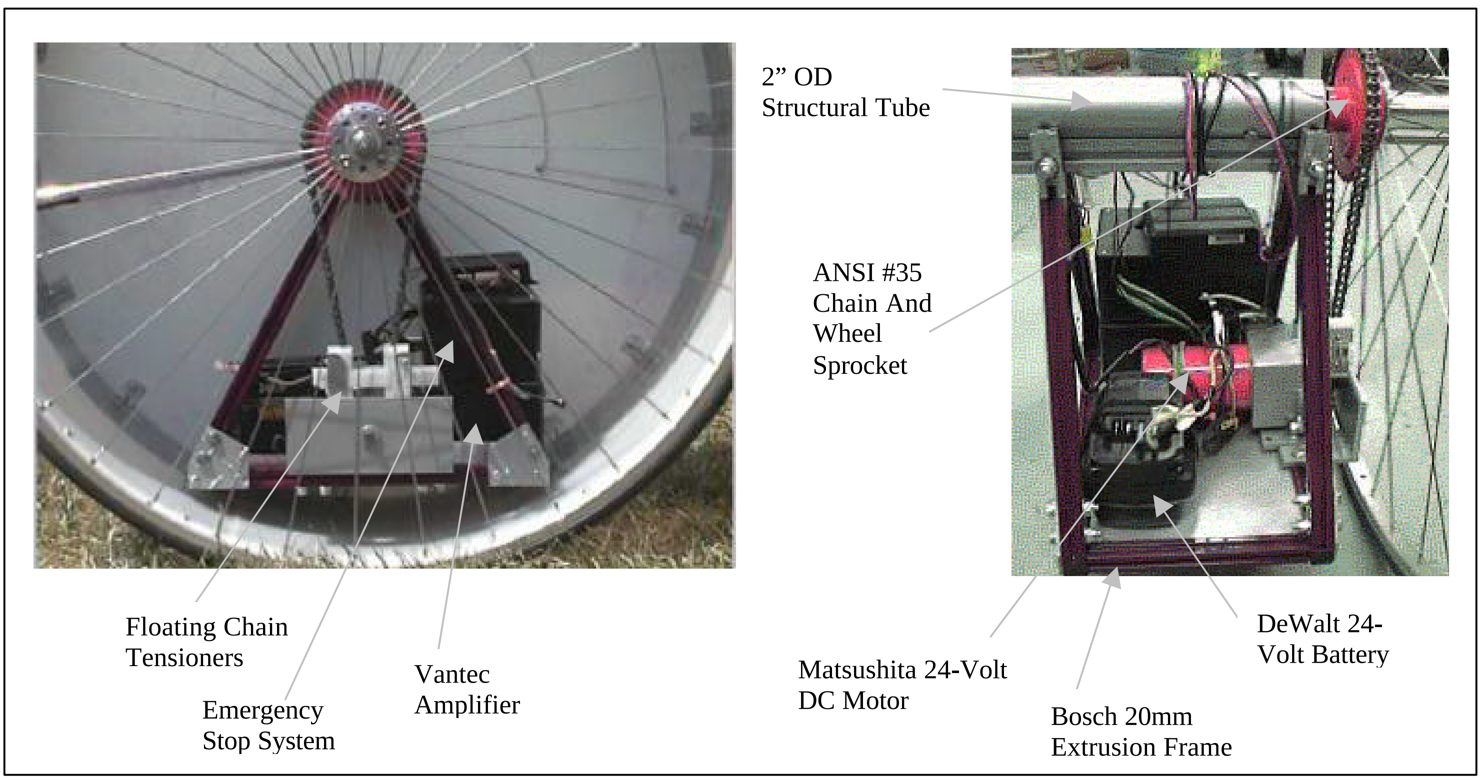

Figure 3. The right side of the reaction mass shown in profile at the left and from the rear at the right.

3.4 – Wheels

The wheels on the Biplanar Bicycle were designed to help accommodate many aspects of the design criteria. Standard 26-inch bicycle wheels, which were used on an earlier prototype, did not provide adequate space for the onboard equipment and the payload. The current design uses 35-inch diameter wheels, which allow space to distribute the components of the reaction mass and payload. The only object extending past the wheels to extend the length to 36 inches is the manual emergency stop switch. This gives easy access to the E-stop in an emergency and allows the vehicle to satisfy the 3-foot minimum length required by IGVC rules.

The stock wheels have been modified to include modular shells constructed of low-density polyethylene hoops and styrene faces. This modification allows the wheels to engulf the reaction masses, which include most of the electronic components of the vehicle. This innovative feature, which can be seen in the cover photograph, serves four important purposes. First, it safeguards all pinch points caused by the drive train and reaction masses. Second, it provides a weather resistant cover for most of the sensitive vehicle components. Third, it provides impact protection to the reaction mass platforms. Fourth, it greatly increases the vehicle ground clearance by housing the lowest lying components within the wheel cavity. This fourth feature addresses one of the most significant concerns about the Biplanar Bicycle concept, namely, that the swinging reaction masses would interfere with the ground on rough terrain. The vehicle is shown in Figure 4 without the modular shells. Note that impact with the reaction masses could damage hardware and compromise safety. What was a potential weakness has now been turned into a significant strength. Wheel rigidity is provided by the styrene, while the low-density polyethylene provides impact resistance as a bumper surrounding the vehicle.

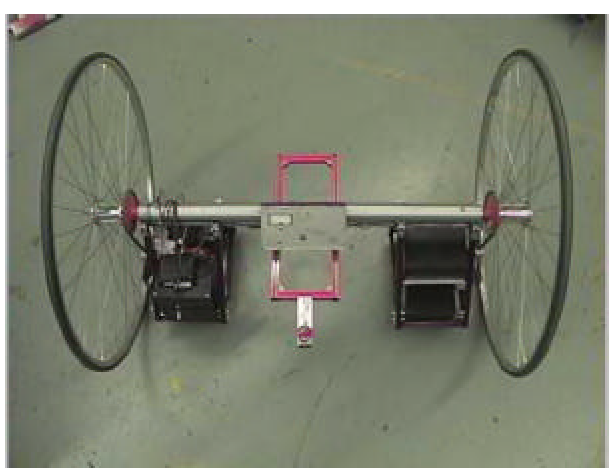

Figure 4. The Biplanar Bicycle without modular wheel shells

3.5 – Drive Train

The torque required to lift the reaction mass and propel the Biplanar Bicycle is provided by two Matsushita 24 Volt brush-type DC motors equipped with 12.1:1 gear heads. Mounted in a differential configuration, these motors give the vehicle exceptional steering ability. Power is transferred from the motor shaft to the wheel by a chain and sprocket drive that gives an additional 2:1 mechanical advantage. The wheel sprockets are mounted directly to the wheel hub to conserve space and minimize the bending moments in the wheel shafts. Floating chain tensioners are mounted to the #35 ANSI Roller chain to eliminate backlash in the drive train. The configuration of the drive train permits motion of the Biplanar Bicycle equally well in both the forward and backward directions.

4 – ELECTRICAL SYSTEMS

4.1 – Electrical Systems Overview

In order to compete in the Navigation Challenge event and to fit within the constraints of the vehicle, it was necessary to make the electrical system robust and streamlined. The electrical system design includes the sensing, navigation and motion control systems. The vehicle senses its environment, makes navigation decisions based on the sensory information, and controls its motion to achieve the desired navigation.

4.2 – Electrical Components

A primary goal in the vehicle's design was to make the simplest possible vehicle that could complete the Navigation Challenge event. As a result, the design of the electrical system incorporates only the essential components as displayed in Figure 5. A GPS sensor supplies all the sensory input to the vehicle. All processing takes place in a Motorola 68HC11 microcontroller and a DELL 600 MHz laptop computer. The laptop makes the navigation decisions, and the microcontroller performs the motor control functions. The laptop receives information from the GPS unit via a serial connection and runs the navigation algorithm. According to the decisions made by this algorithm, the laptop sends commands to the microcontroller, which is dedicated to motor control. The motor controller then sends signals to a Vantec amplifier, which regulates the power supplied to the two Matsushita motors using pulse width modulation. The power source for the main components of the electrical system is a rechargeable Dewalt 12-Volt NiCad battery. The electrical system also includes additional components for radio control operation, fail-safe braking, and remote emergency stopping. Figure 6 shows the main components of the electrical system.

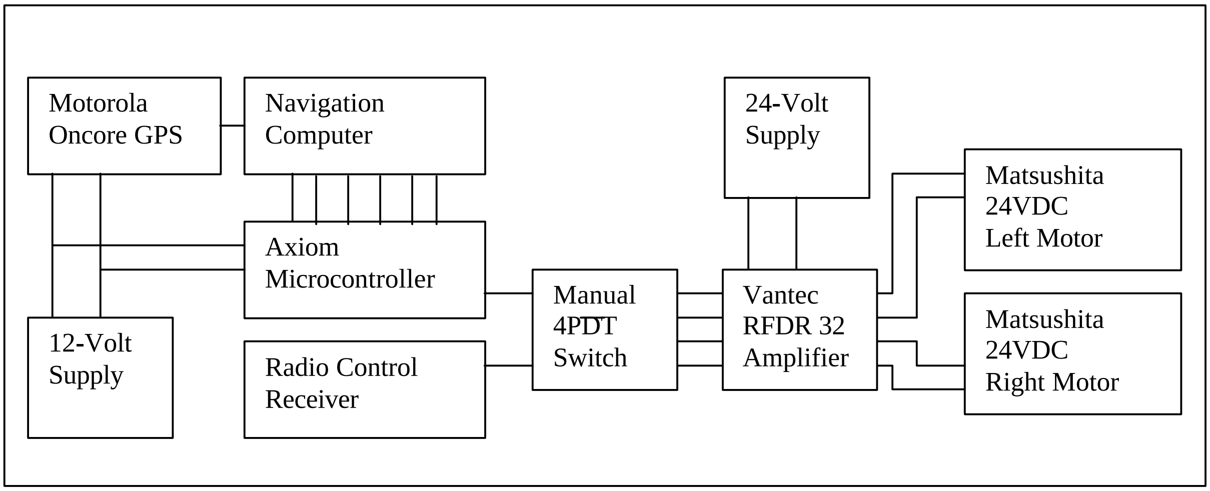

Figure 5: Schematic representation of the Biplanar Bicycle's electrical components

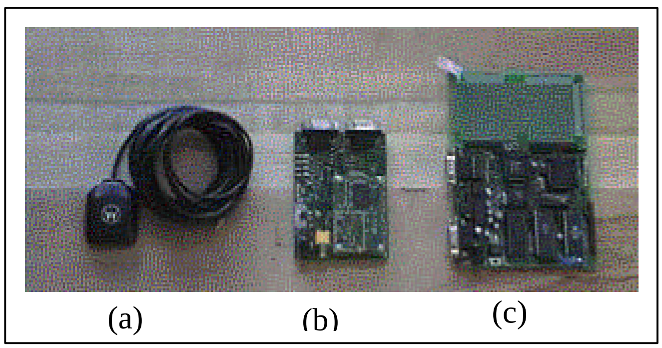

Figure 6: The electrical components: (a) GPS antenna, (b) GPS receiver, and (c) Axiom microcontroller

4.3 – Sensors

The vehicle's sensor system applies specifically to the Navigation Challenge. The rules for this event prohibit using visual sensing. Therefore, the design of the sensor system includes no cameras or obstacle detectors. The vehicle relies entirely on a GPS sensor to supply all the information needed to navigate through the series of waypoints on the course. Most importantly, the GPS sensor indicates the current position of the vehicle, but it also can sense speed and heading while it is in motion.

4.4 – Navigation Components

The navigation processing occurs in the DELL 600 MHz laptop computer with 128 Megabytes of memory installed as part of the easily accessible payload area on the vehicle. The navigation algorithm writes and reads to and from the GPS through a serial port. The incoming data is parsed and stored in an active buffer. The desired information is extracted for use in the navigation algorithm. The serial communication, data processing and navigation algorithms are programmed in C++.

4.5 – Motor Control

While running autonomously, the microcontroller will control the motors based on heading and velocity commands from the laptop computer. Because the power requirements of the two Matsushita motors are too great for the microcontroller to run them directly, the motor control system uses a Vantec amplifier to regulate power to the motors. The motor controller sends signals to the amplifier, which then sets the throttle and steering ratio of the motors. One advantage for using the microcontroller and the Vantec amplifier rather than a conventional amplifier or motor controller is the compact size of the Vantec device measuring 1-3/8"x 3" x 4-1/4". Another significant benefit of the amplifier is that it is intended for radio control applications. Thus, the amplifier can receive input directly from a radio control receiver or the microcontroller. Changing between radio control and autonomous navigation simply involves activating a switch to alternate the inputs to the amplifier from the receiver and microcontroller.

Because the amplifier is intended for radio control, it requires input in the form of a servo-control pulse, the standard form of output from traditional radio control receivers. Therefore, the microcontroller program outputs signals in the servo-control format. Two signals are sent to the amplifier, one to set the throttle and one to set the steering ratio.

The program that generates the pulses from the microcontroller includes thirty possible throttle and steering combinations. This program was written in assembly language and creates the pulses by setting an output pin high, and then running a delay loop before clearing the output pin back to a low state. Because operations in the program control the timing of the pulses, the microcontroller cannot perform any other operations, such as navigation processing. The previously described laptop computer is used to make navigation decisions. It sends commands to the microcontroller using five parallel lines. The digital signal sent through these five pins indicates to the microcontroller which of the thirty settings it should send to the Vantec amplifier. A sixth pin serves as the interrupt line to alert the microcontroller of a new command coming from the laptop. Dividing the navigation and motor control functions between two components has allowed the programming to remain relatively simple. This allows modular improvements to each individual program.

5 – NAVIGATION SYSTEM

The navigation software operates on the on-board DELL 600 MHz laptop computer. The main tasks of this computer are to communicate with the GPS and microcontroller and to make navigation decisions based on the current and desired headings. User input is required to program the navigation scheme with its desired waypoints. As the vehicle drives, the navigation controller receives information from the GPS in the form of latitude, longitude and velocity. Initially, the vehicle begins the course by driving forward in a straight line. As the first set of moving data from the GPS is processed, the navigation controller calculates the distance and angle to the next waypoint. The Biplanar Bicycle will stop and perform a zero-radius turn in the direction of the next waypoint. After completing the turn, the vehicle will continue driving straight ahead until the next set of data is received from the GPS. The repeated verification of position and heading will compensate for the accuracy of the GPS as well as any slip that may occur as the vehicle is turning. As the vehicle enters the designated three-meter perimeter around the waypoint, the navigation controller will restart the navigation scheme in search of the next waypoint. A sample pathway for the vehicle is shown in Figure 7.

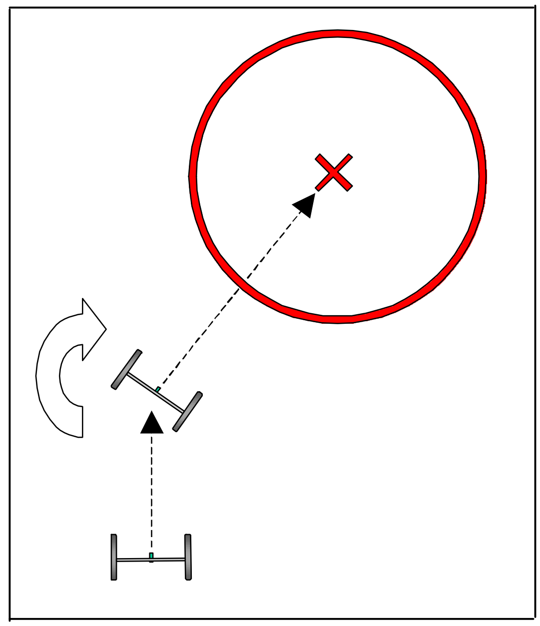

Figure 7. A sample pathway taken by the navigation algorithm

6 – SYSTEM INTEGRATION

The design objectives of the Biplanar Bicycle called for meeting three main objectives: vehicle performance, ease of operation, and low cost. In order to fulfill these objectives, a unique interdependence of components was necessary. Each component of the vehicle is directly related to the propulsion system by being part of the reaction mass. For this reason, a small computing system was chosen over the more conventional personal or industrial computer. The computing system is electrically isolated from the propulsion system so that any power fluctuations from changing motor loads will not affect the supply to the intelligence system.

The computing system connects directly to the amplifier to control the motion of the vehicle based on a servo-control pulse architecture similar to the radio control mode. The emergency stop system isolates the amplifier and computing system by disconnecting the supply power to the amplifier during a stop. All components are attached to the frame of the vehicle through non-permanent fasteners, such as 3M Dual Lock. This modular architecture allows easy servicing of the components.

7 – DESIGN RULES

7.1 – Safety

The safety of the Biplanar Bicycle was held paramount throughout the design process. A unique braking system disconnects the power system and dissipates energy of the vehicle by driving each motor against each other in opposing polarities. This restricts translation of the vehicle and permits only rotation about the vehicle center until the energy of the vehicle is dissipated. In testing, the vehicle was able to stop on a 15% grade decline in less than 5 seconds. The emergency-stop manual switch is located at the rear center of the vehicle for optimum accessibility. A remote control variant of this system allows stopping of the vehicle from a greater range.

The reaction mass and drive system lie within the diameter of the large wheels and shells. This eliminates potential pinch points. Should impact with an object occur, the rubber tire or wheel shell provides a bumper to protect both the vehicle and the object. The wheel shell also protects the intelligence system from foul weather and impact. The power system limits the top speed of the vehicle to 5 mph under a no load condition.

7.2 – Innovations and Features

The Biplanar Bicycle is clearly a radical concept. The two-wheel design about a single axis visibly differs from all previous autonomous vehicle designs. Every functional component contributes to the driving force of the vehicle. The symmetry of the vehicle enables motion equally well in both the forward and backward directions. The differential drive design also provides the ability to perform zero-radius turns. The low center of gravity and the inherent symmetry of the vehicle about its drive axis make it virtually impossible to capsize. Keeping most of the critical components of the vehicle within the modular wheel shells allows it to remain functional under rainy weather conditions. The design of the vehicle also permits it to translate extreme terrain. Unlike any other autonomous vehicle, the Biplanar Bicycle can safely descend stairs as well as climb a five-inch curb starting from a standstill. The GPS system itself may not appear innovative, but integrating this into an intelligent vehicle is particularly novel, as it has not been done in previous competitions. The simple navigation algorithm, utilizing zero-radius turns, will demonstrate the ability to successfully integrate GPS in an autonomous vehicle.

The Biplanar Bicycle was also uniquely designed to maximize serviceability, especially away from the shop. Access panels on the modular wheel shell faces provide a quick and easy way to service the reaction mass. Also, the entire shell is capable of being removed using just a screwdriver. A small on-board tool kit is included on the reaction mass to allow the operator to completely assemble or disassemble the vehicle. This allows easy service to individual parts on the structure, a key feature of the system during the testing and refinement phase of design. The vehicle is also capable of being hand-towed, by a single operator, using a custom-made harness. This is practical feature for transport without applied power. The emergency stop switch is capable of being stowed along the payload frame to allow all the vehicle components to lie within the wheel diameter. This produces an even more rugged design, as no elements can impact obstacles other than the wheels. During the testing of the Biplanar Bicycle, a lot of interest was stimulated on campus. This new concept not only qualifies as an autonomous vehicle, but also promotes public interest by demonstrating a unique mechanical concept.

7.3 - Reliability and Durability

The Biplanar Bicycle has been designed for rugged outdoor use in nearly all weather conditions. Use of commercial off-the-shelf items allows a measure of ruggedness and quality with each individual component. The wheels containing the vehicle components provide a bumper 360° around the central axis of the vehicle. The centerline and wheel shaft system enables the vehicle to negotiate rugged terrain while ensuring vehicle integrity. The use of CAD permitted an early analysis of the structure and contributed to the reliability of the design by predicting vehicle behavior.

7.4 - Predicted Performance

Performance of the Biplanar Bicycle was based on the competition guidelines with special attention to safety. In testing, the actual no-load speed was confirmed at 5 mph operating at maximum battery power. Through testing, it was determined that the vehicle will climb an incline of 29.9% without the payload, and an incline of 36.5% with the payload. This unusual improvement in performance results from incorporating the payload into the reaction mass. The Biplanar Bicycle can also drive over a typical five-inch high sidewalk curb from a standing start, a feat that would be impossible for nearly all previous vehicles entered in the IGVC. Battery life for the vehicle was calculated at approximately 1.51 hours based upon maximum throttle on flat terrain for a fully charged system. Reaction time for the emergency stop is nearly instantaneous using relays to control the circuit. Starting from a stopped condition, the vehicle can turn a complete 360° in under 1.5 seconds. This remarkable turning reaction is a direct result of the two-wheel design.

Since the vehicle was developed exclusively for GPS navigation, some aspects of the design for the autonomous challenge were purposefully omitted. The omitted components were the strobe light, signifying obstacle recognition, the distance detection systems, and the follow the leader systems. Omission of these systems permitted more dedicated efforts to producing a vehicle dedicated to GPS navigation.

7.5 – Planned Addition of Computer Vision and Rangefinder Sensors

The Biplanar Bicycle includes a GPS sensor, which is necessary for this year's IGVC Navigation Challenge. Further development of this vehicle will require the addition of a computer vision system and a range-finding sensor. Throughout the design process, the team has considered the addition of these sensors as future requirements and has designed the vehicle accordingly. Surprisingly, the vehicle's center tube and attached platform provide a relatively stable attachment point with ample space to mount these additional sensors. The platform and central axis of the vehicle must rock forward to cause acceleration, but this is a brief transient motion. At constant velocity on relatively level or constant slope terrain, the platform orientation is also constant, providing an inertially stable platform for mounting the camera and rangefinder. The team has also developed conceptual designs for an independent gyroscopically stabilized platform and a computer vision system with built-in inclination adjustments to account for rugged terrain. By test-driving the vehicle on modestly rough terrain simulating a typical obstacle course, we estimate transient camera tilt of about 30 degrees and steady state camera tilt of just a few degrees. The laptop computer used on this vehicle has ample processing power and memory to allow the addition of a computer vision system and rangefinder

7.6 – Cost

Throughout the design and construction of the Biplanar Bicycle, cost was an important concern. Each component was optimized for maximum performance and minimum cost. In comparison to previous autonomous vehicles, the Biplanar Bicycle costs significantly less to build and operate. Table 2 shows the cost summary for the vehicle.

Table 2: Cost Summary

Intelligence System	**Qty.**	**Unit**	**Unit Cost**	**Total**
Axiom 68HC11 Development Board	1	1	190.00	190.00
Motorola GPS Receiver	1	1	200.00	200.00
Dell Laptop Computer	1	1	1,000.00	1000.00
E-Stop System				
Sidewinder Car Alarm	1	1	70.00	70.00
Miscellaneous E-Stop System	1	1	70.00	70.00
Power System				
DeWalt 24V XR Battery	2	1	99.00	198.00
DeWalt 12V XR Battery	1	1	60.00	60.00
Vantec RFDR22 Amplifier	1	1	273.95	273.95
Drivetrain				
Matsushita 24V DC Brush Motors	2	1	25.00	50.00
Wheels				
Sun Rims 34 7/8" Custom Wheels	2	1	70.00	140.00
US Plastic Corp. 1/8" LDPE Sheet	1	96x48" Sheet	35.47	35.47
US Plastic Corp. 1/8" Styrene Sheet	1	40x72" Sheet	22.95	22.95
Frame and Structure				
McMaster Carr 2x1.25"x6' Aluminum Tube	1	1	57.38	57.38
Bosch Automation 20x20 Extrusion	4	3000mm	25.00	100.00
Bosch Automation Miscellaneous	1	1	75.00	75.00
Miscellaneous				
Tower Hobbies Radio Control Tx and Rx	1	1	99.99	99.99
Miscellaneous	1	1	725.00	725.00
Total Cost				$ 3,651.78

8 - SUMMARY

Through creativity, team cooperation, and hard work, the Biplanar Bicycle Team designed and built a unique and innovative new autonomous vehicle. Without careful consideration, this radical design may seem absurd to some people. Our intent has always been to create the most practical, economical autonomous vehicle possible. The low cost and mechanical simplicity of this vehicle are among its many attributes. Because all of the vehicle weight is on the driving wheels, the Biplanar Bicycle has optimal traction in all conditions. Although the vehicle can rock slightly about the two points of ground contact, its low center of gravity makes it inherently stable. The Biplanar Bicycle is also inherently rugged, in part because the wheels are generally the only part of the vehicle to contact an obstacle. Setting our team goals towards competing in only the Design and Navigation Challenge events allowed us to concentrate on building a solid vehicle and demonstrating the important features and capabilities of this design. Our fascination with this novel concept has evolved into a passion to make it a practical reality. We now firmly believe that autonomous Biplanar Bicycles have a bright future.