polaris II

Virginia Tech AVT

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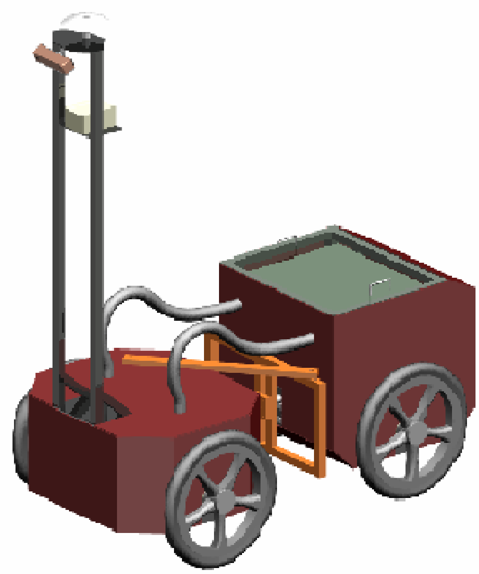

Required Faculty Advisor Statement

I certify that the engineering design of the vehicle described in this report, Polaris II, has been significant, and that each undergraduate team member has earned six semester hours of senior design credit for their work on this project.

Charles F. Reinholtz, Alumni Distinguished Professor
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1 Introduction

The Autonomous Vehicle Team of Virginia Tech is proud to introduce Polaris II, a redesign of the original Polaris vehicle for entry in the 2007 Intelligent Ground Vehicle Competition (IGVC). The name Polaris comes from *Stella Polaris*, the Latin form of its common name Polar Star. Also called the North Star, Polaris has been used as a navigational beacon for centuries.

Polaris was originally constructed for entry in the 2005 IGVC at Traverse City, Michigan. Polaris performed well that year, winning second place in the Design Competition and third place in both the Autonomous Challenge and the Navigation Challenge. The original Polaris platform was excellent in almost every respect. It was carefully designed and fabricated, and it proved to be among the most rugged and reliable vehicles ever developed at Virginia Tech. Polaris was used in 2006 as a research platform for both an acoustic detection project and as an inspection robot for a broccoli harvester. Its articulated twin-body, four-wheel configuration gave it an outstanding combination of stability and maneuverability. Unfortunately, Polaris had one serious flaw. To keep the center of gravity low, it was made slightly wider and longer than Gemini. In narrow passages on the Autonomous Challenge course, the trailing body of Polaris would sometimes clip or sideswipe obstacles that the front body had avoided.

Polaris II includes many noteworthy innovations, but the most obvious is the new four-bar linkage "joint" that connects the front and rear body. This remarkable feature allows the rear body of the vehicle to track the path of the front body, effectively eliminating the lone deficiency of the earlier version of Polaris. All the other advantages of the articulated twin-body, four-wheel design have been preserved. The four-bar linkage rear steering mechanism will be discussed in greater detail later in the report. The improved Polaris II design also features a custom integrated E-board, smaller, less expensive sensors options, fail-safe brakes, and refined software. The goal of the redesign was not only to improve Polaris's performance, but also to provide greater value to the customer by investing in engineering development and by offering a wider variety of options for performance versus cost. We believe these features will make Polaris II highly competitive in the 2007 IGVC.

2 Innovations

Polaris II returns to the 2007 competition with a many innovation features that were developed for the 2005 competition. These include an articulated two-body platform, integrated “smart” motors, and reliable system architecture. Building upon previous successes, Polaris has been updated to meet the demands of the IGVC with improved intelligence, a new printed circuit board power distribution system, enhanced mobility using the four-bar linkage, and many other refinements that will be discussed in this report.

The mobility platform has been improved with the implementation of a new mechanical linkage between the two bodies of the robot. The original revolute-jointed design exhibited a trailer-like motion that resulted in the rear body of the vehicle cutting corners and clipping obstacles. Figure 1 is an example of a familiar safety warning sign found on trucks that helps to illustrate this undesirable behavior. This behavior has also been observed on many competing IGVC vehicles, typically when the rear of a vehicle sideswipes an obstacle. This was enough of a problem with Polaris that it was temporarily retired after the 2005 competition.

Figure 1. Safety Warning Illustrating Corner-Clipping Behavior (http://www.bradyid.com/)

The earlier version of Polaris and virtually every other vehicle having four or more wheels suffers from this corner-cutting behavior. While it is possible to plan a path where the front of the vehicle swings wide around the turn or an obstacle, this complicates the path planning and increases the overall tracking width of the vehicle along its path. This is obviously detrimental in the tortuous turns and obstacle traps typically found in the IGVC Autonomous Challenge course. A better solution, the one developed for Polaris II, uses a four-bar linkage to guide the rear of the vehicle in nearly the same track as the front of the vehicle.

Figure 2 is a photograph of the initial prototype model of a four-bar-linkage-based articulated vehicle design. The simple crossing linkage is easier to see in this photograph than it is on the actual vehicle. The links of the four-bar generally act as tension or compression (two-force) members, which is an improvement over the cantilever beam connection between the two bodies used in the earlier version of Polaris. Figure 3 shows CAD models of both Polaris II and Polaris to help highlight the newly developed four-bar linkage based interconnection.

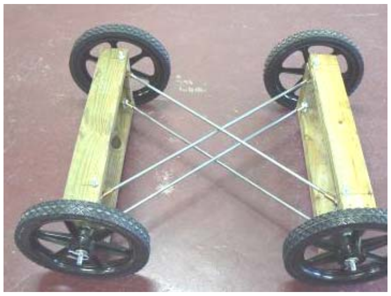


Figure 2. First Prototype of the Four -Bar Linkage Connection.

Figure 3. Polaris II (left) and the Original Polaris (right). Note the Crossing Links of the Four-Bar Linkage on Polaris II (shown in orange) versus the Rigid Connecting Beam and Revolute Joint on Polaris

The new four-bar linkage still allows for roll between the two bodies. Having this degree of freedom between the bodies allows the wheels to remain in contact with the ground without the need for a suspension. Roll between to the bodies is achieved by incorporating a longitudinal revolute joint connecting the rear body to the four-bar linkage. Figure 4 shows how this joint connects to the four-bar linkage and allows roll between the two body segments.

Figure 4. Location of roll axis

The four-bar linkage is not the only significant improvement on Polaris II. A great deal of work has also gone into improving the sensing capabilities and offering the customers added value and a range of performance options. The original sensor suite on Polaris offered only a Sick Optic laser range finder for obstacle avoidance. At approximately $6,000 and 13 pounds, this system was expensive, cumbersome, and power hungry. Instead, Polaris II uses a smaller and lighter Bumblebee stereovision camera for obstacle avoidance. The Sick laser range finder remains a high-end option for user wishing to run at higher speed and with greater look-ahead distances.

The application of a new electronics board (E-Board) and refined software gives Polaris II an upgraded central nervous system. The new E-Board allows for power conditioning to ensure uninterrupted operation. It also incorporates a modular design, allowing for various types components to be powered off the board. Software was updated to handle the new E-Board and sensory components. Two 12V and two 24V auxiliary ports provide power for optional components that may be added to the vehicle.

3 Design Process

Constraints on time and resources in conjunction with the demands of the IGVC necessitate the implementation of a rigorous design process. Building on past success, the team chose to utilize the Definition, Design, and Produce method. This method has been used by previous Virginia Tech teams and has contributed to the success of their vehicles. Figure 5 shows this custom-developed iterative process that relies heavily on past experience and examination of design solutions that were successful in previous competitions. The process holds the design team to a methodical approach to design with milestones and deliverables providing checkpoints along the way. Milestones included identification of proposed improvements by December 2006, completing reconstruction of a frame and drive train by March 2007, completion of software upgrades by April 2007, and testing and evaluation rounded out the academic year. A competition-level demonstration of all vehicle capabilities was scheduled for mid-May 2007.

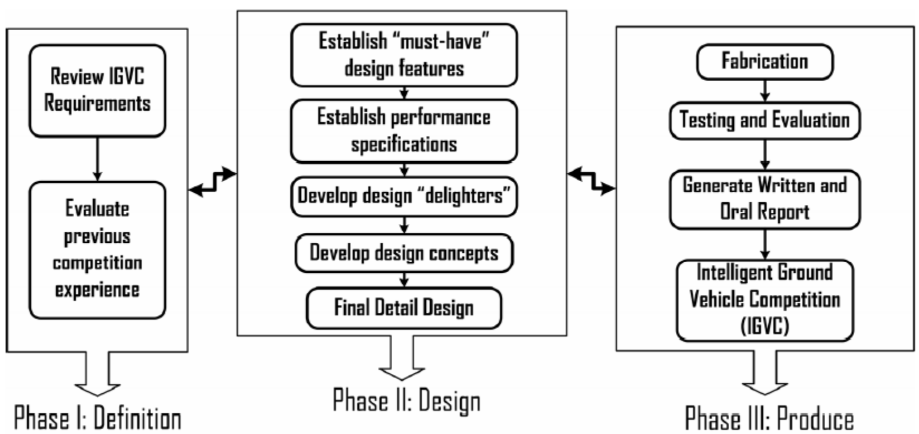


Figure 5. Layout of iterative Definition, Design, and Produce (DDP) design process.

3.1 Definition Phase

The Definition phase of the design process leverages the unique aspects of design for the IGVC by incorporating competition rules and the experience gained from previous competitions. The process begins with an initial review of the competition rules, a review of previous competition performance, and a dissection of previous IGVC vehicles. A holistic approach to design development is applied during the design phase and carried through to the Produce phase where the vehicle is finally constructed and validated. In the Definition phase, the team identified the following customers: the IGVC judges, project advisors, sponsors, the Virginia Tech research community, and the design team.

3.2 Design Phase

As part of the Design phase, the team used the KANO design methodology, described in *Attractive Quality and Must-Be Quality Method*, (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996) to study customer needs. Figure 6 shows this methodology. This design method consists of three main components: “must haves”, “linear performance features” and “delighters”.

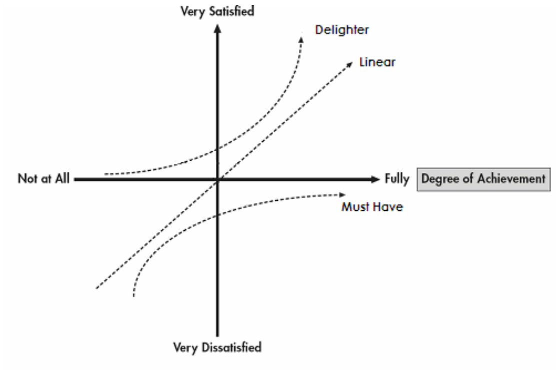


Figure 6. KANO design methodology

The KANO model predicts the customers’ satisfaction as a function of particular design features. The team’s goal is to design a vehicle that performs well and includes all of the “must have” features, such as an E-stop and speed control. Beyond these goals, the team strives to generate innovative “delighter features” that are beyond the expectations of the customer. The KANO method help provide motivation for the innovations described in Section 2. During this step in the design process the team focused on customer needs, including performance in the dynamic events, improved vehicle mobility, options that reduce cost while providing the level of performance required by the customer (value engineering), and simplified design and operation.

3.3 Production Phase

The Production phase of the design process consists of the manufacturing, testing, and evaluation of the vehicle. Using design specifications and a Unigraphics 4.0 CAD model, the optimal component locations were determined. Figure 7 shows the CAD model that was in the development of Polaris II along with a photograph of the actual vehicle. The vehicle’s performance was tested and refined during extensive field trials. The final step of the Production phase is attending the 15th annual IGVC.

Figure 7. Unigraphics rendering of Polaris II along with the working vehicle

3.4 Design Team Structure

A functional decomposition of the team's organizational structure is shown in Figure 8. Team members migrated between sub-teams as needed to complete tasks and integrate systems. In total approximately 2000 person hours were spent developing Polaris II.

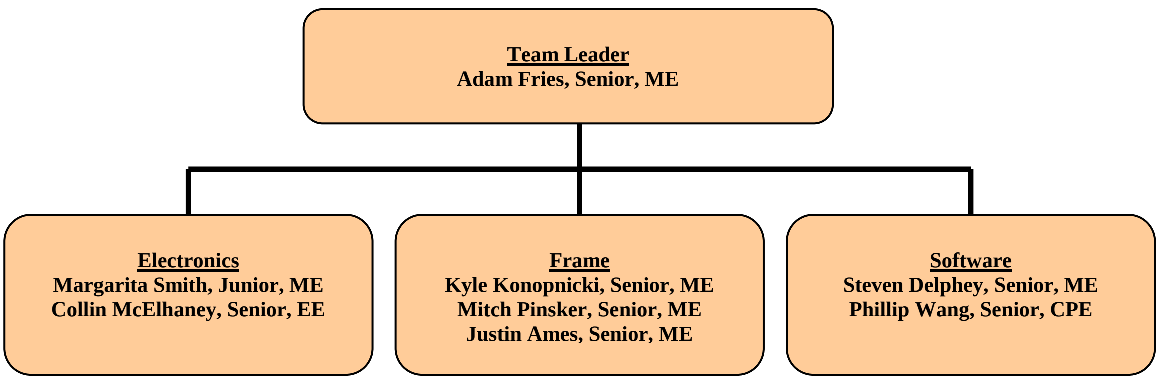


Figure 8. Team organization structure.

4 Base Vehicle

A custom frame was developed for Polaris when it was originally constructed in 2005. Polaris weighs 210 pounds without the competition payload. Weight is distributed in a ratio of 60/40 between the front and rear wheels, respectively. Since the front wheels are driven, this ratio provides superb traction on a wide variety of surfaces. Heavier components such as the motors and batteries are mounted in line with or below the axles to improve stability. In operation, Polaris II is 56 inches long, 34 inches wide, and 68 inches tall with the collapsible mast extended.

4.1 Chassis Features

The chassis of Polaris II incorporates a foldable mast that allows it to be easily transported in a van or sport-utility vehicle without having to remove components. This is an excellent example of an unexpected "Kano Delighter" feature that does not directly affect vehicle performance, but it makes the vehicle easier to store and transport, which contributes to overall customer satisfaction. Another example of a subtle but useful feature is the five-spoke composite wheels that also serve as handles for lifting and loading Polaris II. Solid wheels, or wheels with many spokes, are far more difficult to grasp and control than the wheels used on Polaris II.

4.2 Drive Train

Polaris II is propelled by two Quicksilver I-Grade 34HC-2 brushless DC servomotors. The motors have a maximum power of 0.76 horsepower at 2.03 ft-lb of torque with a continuous stall torque of 6.78 ft-lb. The motors are controlled by QuickSilver I-Grade N3 SilverNugget controllers. Connected to each motor is a 5:1 reduction NEMA 34 gear head. The gear heads are connected to a Timken polycarbonate eccentric locking bearing through a 0.25 inch aluminum mounting plate. A custom-made aluminum drive shaft connects the wheel, through the bearing and mounting plate, to the gear head as shown in Figure 9.

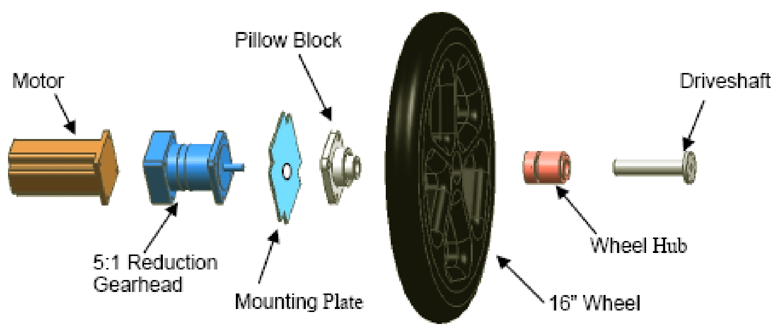


Figure 9. Assembly drawing of the Polaris II drive train.

4.3 Steering and Mobility

Excellent vehicle mobility is achieved using the twin-body design with a four-bar linkage assembly and longitudinal revolute joint. The four-bar linkage system allows the back end of Polaris II to closely follow the path of the front end. The top view photographs in Figure 10 show that, as the front body enters a turn, the four-bar linkage initially directs the rear body away from the turn and along the intended arc of the curve. This causes the rear body to track nearly the same path as the front body.

Figure 10. Polaris II front and rear body connected by a four-bar linkage

The advantage of this tracking is clearly illustrated in Figure 11, where Polaris II is able to avoid a barrel that Gemini, with a similar articulated design but lacking the linkage, cannot avoid.

Figure 11. Polaris II rounding a barrel (left) and Gemini (without the four-bar linkage) clipping the barrel while attempting the same maneuver

This surprising and complex behavior can be controlled by tuning the dimensions of the four-bar linkage. This was done by developing a kinematic model of the mechanism and coupling this to a time-based simulation of the constrained vehicle motion. Jesse Farmer, a graduate advisor to the team, performed this work as part of his Master's program research.

Figures 12 and 13 are sample output plots from the simulation software. Figure12 shows the locations of the front (red) and rear (blue) axle along with the locations of the crossing links of the four-bar linkage as Polaris II executes a turn. Figure 13 is a plot from simulation of the wheel paths of Polaris and Polaris II executing an identical turn, as shown by the single set of red front-wheel paths. It is again clear that the rear wheels of Polaris (paths shown in blue) has the tendency to

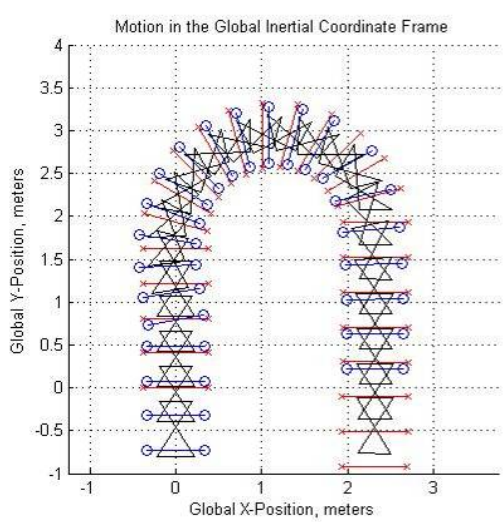
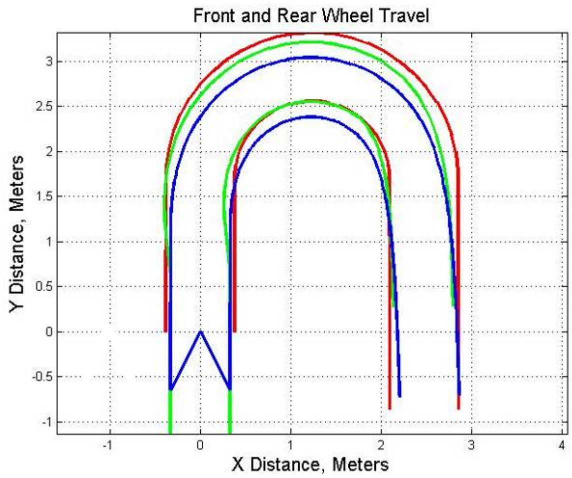


Figure 12. Plot from simulation showing the front and rear body motion of Polaris II

cut the inside corner of the turn, while the real wheels of Polaris II (green) closely track the front wheel paths.



Red: Front Wheel Paths for Polaris and Polaris II
Blue: Polaris Rear Wheel Path
Green: Polaris II Rear Wheel Path

Note that the front track (red) is slightly wider than the rear track (blue and green) on both Polaris and Polaris II

Figure 13. Improved Tracking of Polaris II in a 1.25m radius turn. Note how the rear wheels of the original Polaris (blue lines) cut the corner by about 0.2m compared to the front wheel path (red lines). The rear wheel of Polaris II (green lines) generally tracks to the inside of the front wheel paths.

4.4 Safety

A new safety feature added to Polaris II this year is a fail-safe braking system. Each rear wheel has an independent axle that is connected to a 10:1 gear reducer which is connected to electric brakes. When the emergency stop is activated, the brakes engage the axle and stop the vehicle with 150 lb·in of torque. This system is shown in Figure 14.

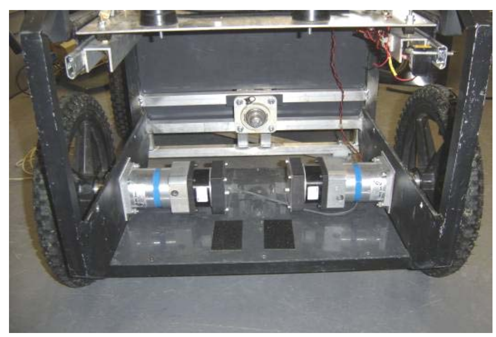


Figure 14. New Fail-Safe Brake System

5 Electrical System

The electrical system provides the appropriate power for each vehicle component and supports communication between the computer, sensors, and actuators. Safety, durability, simplicity, and efficient use of space were all considered during the development of the electrical system.

5.1 Power Distribution

The power distribution for the vehicle is accomplished through the custom designed circuit board shown in Figure 15. This board is 6.4 inches by 4.6 inches and is fixed inside a vented enclosure in the vehicle during operation. The board is responsible for power input and regulation.

Two 12 Volt sealed lead acid batteries connected in series supply the board with 24 Volts at one main power input. The main power input sends the 24 Volts through one 24 Volt and one 12 Volt DC to DC regulators. Also, the main power input is used to send an unregulated 24 Volts to the motors and the brakes. This power can be interrupted by a remote emergency stop or a hard-wired button which also triggers the brakes and immediately stops the vehicle. The vehicle uses one main power switch to control the entire electrical system.

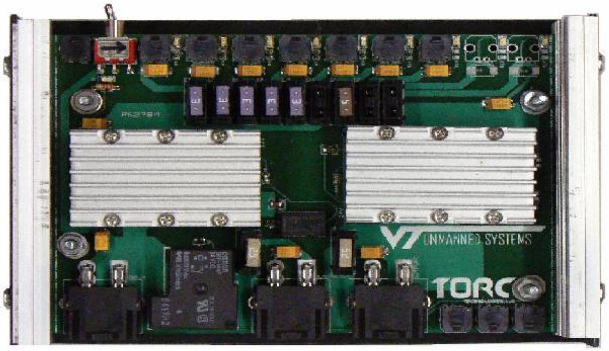


Figure 15. Power distribution board

The distribution section of the board receives regulated 12 and 24 Volts and is responsible for power distribution and monitoring. The regulated 24 Volts is distributed to the optional laser range finder and to an auxiliary connector. The regulated 12 Volts is sent to the compass, GPS, Firewire hub, remote control E-stop, and to a two auxiliary 12 Volt connector. Each of these connectors has an individual fuse to avoid damage from a power surge. The entire power distribution system is outlined in Figure 16.

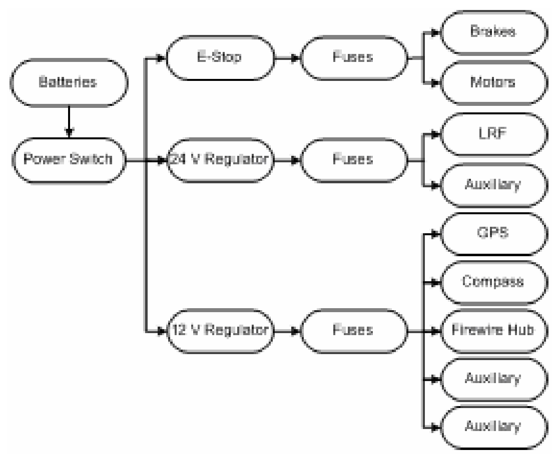


Figure 16. Power distribution system

5.2 Power System

The power system is supplied by two UB-12180NB 12 Volt 18 Ah rechargeable sealed lead acid batteries. Figure 17 shows the basic power system architecture of Polaris II. The batteries connect to the electrical system via finger-safe genderless plugs. A 30 amp in-line fuse on the positive lead of each battery provides an added measure of safety. Voltage clamps are included in the motor line to protect the circuitry from the back EMF generated by the motors. The batteries provide 12 Volts and 24 Volts to the motors, relays, and the power distribution board. A fresh battery set provides four hours of vehicle run time.

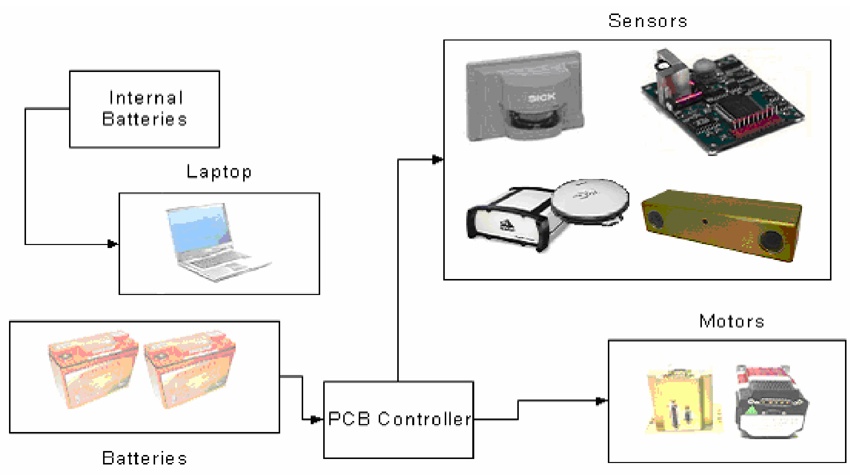
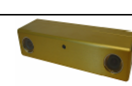


Figure 17. Power system block diagram

6 Sensors

Sensors are mounted on Polaris II to perceive the vehicle's environment. Data from the sensors is sent to an onboard Toshiba Portégé M400 tablet computer with a 1.83 GHz Intel Core 2 Duo processor and 2 GB of RAM. Table 1 provides information on each sensor.

Table 1. Summary of sensors used on Polaris II

Sensor	Description	Image
SICK LMS-221 Laser Range Finder [Optional]	The optional laser range finder scans in a horizontal plane and returns the distance to any obstacle. Because of the cost, this option is only utilized if a resolution of 1 degree is needed.	
PNI TCM2-20 Digital Compass	The digital compass senses vehicle heading relative to magnetic North. It is tilt compensated and can give pitch and tilt values up to 30 degrees.	
Novatel Smart Antenna, or Novatel ProPak-LB Differential GPS	This dual frequency GPS system is able to improve position information by using the Omnistar HP correction service. Using these corrections, 99% of all position readings will be within 50cm (15cm for the Propak) from the true position.	
BumbleBee Camera System	The BumbleBee is a stereo vision system developed by Point Grey Research. The system is being used to detect both obstacles and lines on the course.	

7 Sensor Architecture

The method for communication between the electrical components is presented in Figure 18. The GPS system and the digital compass output are passed through serial-to-USB converters before being connected to the tablet computer. The Firewire output of the BumbleBee is passed directly to the tablet computer. The use of industry standard communication protocols provides a reliable, inexpensive solution that has proven to be successful on several previous vehicle platforms.

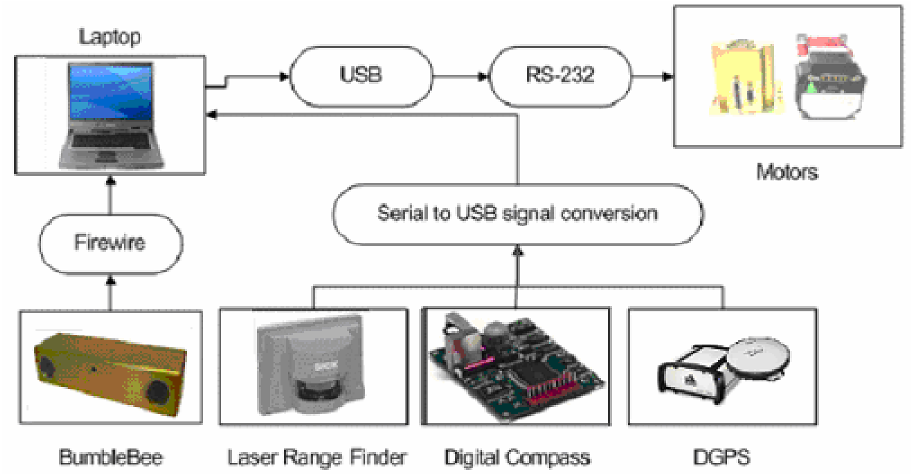


Figure 18. Sensor communication diagram with the optional laser range finder installed.

8.0 Software

The National Instruments LabVIEW development environment was used for all software development. The virtual-instrument based programming naturally compliments the modular system architecture of Polaris II.

8.1 Autonomous Challenge

The Autonomous Challenge software uses only the BumbleBee stereo vision camera to navigate through the course. Since both cameras in the BumbleBee see similar images, only the right camera image was acquired for the line detection algorithm. The acquired image is resized to 160x120 and converted to a monochrome image and thresheld to separate the white lines from the rest of the image. A Hough transform is then applied to the thresheld image to identify the most dominant line in the image. Figure 19 shows the result of the Hough Transform applied to an image of a line on grass. Line characteristics are examined and the information is passed to a decision tree where heading and speed are determined. Once heading and speed are determined, this information is processed through an obstacle avoidance filter.

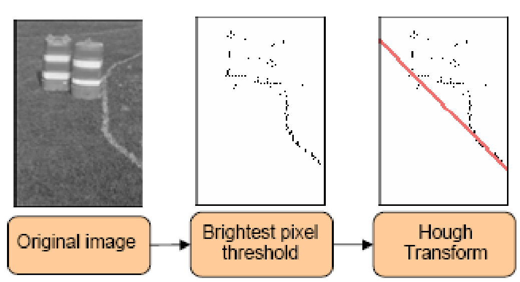


Figure 19. Original Image, After Threshold, Detected Line.

The final step is to combine the heading and speed with the information about any obstacles in front of the vehicle. A heading is selected that is closest to the one suggested by the line following algorithm while avoiding the obstacles.

8.2 Obstacle Avoidance

Both the Autonomous Challenge and the Navigation Challenge depend on detecting and avoiding obstacles. Polaris II utilizes the BumbleBee stereo vision camera as a “BumbleBee Virtual Laser Rangefinder” system to detect obstacles. The software for Polaris II is designed so that either system can be used. The Bumblebee stereo camera system provides a significant cost and weight savings over a separate monocular camera and laser range finder. We believe the performance of the BumbleBee virtual laser range finder will be adequate for the IGVC challenges, although it has a shorter range and a lower resolution. The BumbleBee unit comes with its own image processing software that is specifically tailored for the system. This software has been integrated into the vehicle’s LabVIEW software to make the BumbleBee and laser range finder interchangeable.

The obstacle avoidance software begins by mapping detected obstacles into a single Cartesian-style occupancy grid. The BumbleBee system is able to use depth perception to identify the distance to obstacles along the course. By knowing the angle that the BumbleBee is pointing down, and its height above the ground, the distance from the front of the vehicle to the obstacle can easily be calculated. During the Autonomous Challenge, lines and potholes, as well as objects detected by the BumbleBee vision system, are considered to be obstacles. A supplemental analysis of the acquired digital image identifies potholes; regions of the image that contain more than 80 white pixels are labeled as such. The lines and potholes detected by the camera are mapped into the same Cartesian occupancy grid as the course line data. Doing so puts all obstacle information in the same mathematical form, simplifying the obstacle avoidance process.

The second stage of the obstacle-avoidance software is to examine possible arc-shaped paths. The program analyzes possible paths from -90 degrees (directly right) to +90 degrees (directly left) in five-degree increments. Possible paths are compared against the ideal vehicle heading and the occupancy grid. Once each path is checked for obstacles, the final path of the vehicle is chosen by a cost function that combines the following factors for each path: distance to closest obstacle along path, deviation from the ideal vehicle heading, and deviation from the last heading chosen. After being chosen, this final path is broken down into left and right motor speeds, which is sent as a serial command to the motors.

8.3 Navigation Challenge

The Navigation Challenge software uses either a Novatel Smart Antenna GPS or an optional, but more expensive, Novatel ProPak LB system unit to determine the latitude and longitude of the vehicle. Information from the digital compass is used to find the vehicle's heading. Once the vehicle identifies its current position and heading, it determines the direction and distance it needs to travel to the next waypoint.

In previous Virginia Tech IGVC vehicles, the information from the GPS unit is fed directly into the Navigation Challenge software to identify vehicle position. GPS can have serious error, however, so a form of GPS error-correction is included in the Navigation software of Polaris II. The software incorporates information from the wheel encoders to create dead-reckoning estimates of the vehicle's change in position over short periods of time. Dead-reckoning is very accurate over small time intervals. Based on these estimates, the error of individual GPS can be estimated. GPS points identified as having a relatively large chance of being in error will be used less, or even not at all, when formulating the final estimate of the vehicle's latitude and longitude. Instead, the software relies on dead reckoning and a backlog of previously outputted vehicle coordinates to determine its current position.

Once the desired heading is determined, the vehicle will continue towards the waypoint until an object enters the BumbleBee's field of vision. The BumbleBee's field of vision is broken up into the five distinct regions shown below in Figure 20. The vehicle's behavior is dependant on which regions contain obstacles.

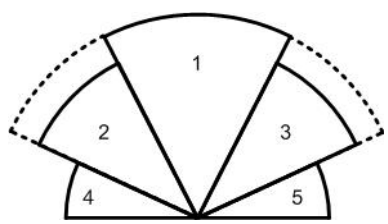


Figure 20. BumbleBee regions for Obstacle Avoidance in Navigation Challenge

Because obstacles directly in front of the vehicle are of the greatest concern, BumbleBee data is processed to a 16-foot distance in this central region, region one. Obstacle data from regions two and three is initially truncated to 11 feet, which allows the vehicle to avoid obstacles in its direct path while placing less of an emphasis on obstacles to either side. During testing in the software simulator, the vehicle tended to oscillate around an object detected in the central region. To remedy this, once an obstacle is detected in region one, the look-ahead range in regions two and three is increased to 16 feet, as shown by the dashed lines in Figure 17. Implementing this modification allowed the vehicle to circumvent obstacles without the oscillations. Regions four and five, are used to prevent the vehicle from turning back into a previously avoided obstacle. Motion commands to the motors are issued based on which of the five regions is reporting an obstacle present, and the heading to the next waypoint.

JAUS Competition

9 JAUS Implementation

Virginia Tech has intimately involved in the development of the JAUS standard for several year. AS part of this effort, we have developed a LabVIEW toolkit that can parse the JAUS header and handle many of the defined JAUS messages. Having worked with JAUS in the previous competition, the learning that took place was mostly reviewing the specific messages needed in the reference architecture.

Level 1 of the JAUS competition was completed last year and has remained unchanged. As dictated by the rules, the team wrote a separate JAUS component that will be running on the vehicle node to respond to the global waypoint query after validation of the message header. An OCU from last year was also modified to be able to send the query and interpret the response. No problems were encountered in the implementation of JAUS.

10 Vehicle Component Costs

Table 2 provides the retail cost of each component and actual costs incurred team for all major components but not including labor. We are grateful to our many sponsors for providing equipment at reduced cost or at no cost to the team.

Table 2: Summary of vehicle component costs.

Part Description	Retail Cost	Cost to Team
Toshiba Portege M400 Tablet	$2,500	$2,100
(2) QuickSilver 34HC-2 Servo motors and Controllers	$3,000	$2,700
(2) Odyssey PC AGM lead acid batteries	$105	$105
Electrical Components	$500	$500
IGUS flex cables	$1,000	$0
PNI TCM2-20 digital compass	$700	$0
Novatel DGPS Smart Antenna	$1,795	$0
Point Grey Research Bumblebee Camera	$2,000	$0
Custom welding - Piedmont Metal Fabricators	$1,000	$0
(4) 16" Skyway Tuffwheels	$250	$0
Aluminum and frame materials	$700	$700
Total	**$13,550**	**$6,300**

11 Conclusion

Polaris II is a fully autonomous robotic vehicle, designed and manufactured by engineering students at Virginia Tech. Polaris II. The vehicle features a novel four-bar linkage jointed two-body articulated platform that combines the maneuverability of a differential drive system with the ability to traverse rough terrain and ascend steep grades. The four-bar linkage system also offers the future prospect of a vehicle with dynamically adaptive geometry. This would involve actuating (lengthening or shortening) one link of the four-bar linkage to produce optimal tracking of the rear body in response to the currently desired path and obstacle field. The four-bar linkage based design also lends itself to a four-wheel drive version of the platform.

The use of an integrated brushless motor, controller and amplifier system and a BumbleBee camera simplified the overall design, allowing a tablet computer to directly read all the sensors and command the drive motors through existing communication ports. The use of the BumbleBee camera instead of the laser range finder has reduced the cost of sensor suite by $3900. In addition, the vehicle's new E-Board is much smaller and less costly than the board it replaced.

Through continued testing and development, Polaris II stands as an example of a robust, effective, and professionally constructed autonomous vehicle. By following a methodical engineering design process, and using the latest software tools, the team was able to create a vehicle that should compete favorably in all three events at the 15th annual IGVC.