polaris

Virginia Tech AVT

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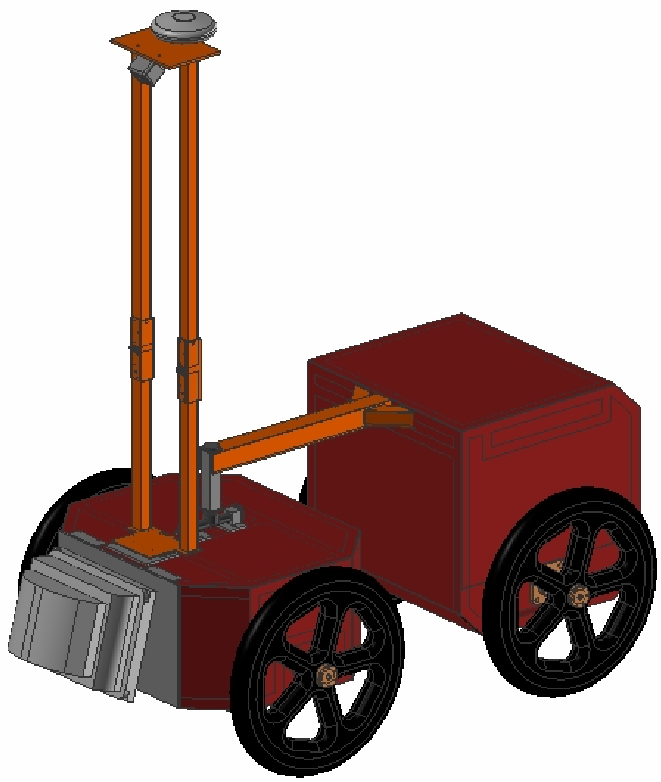

Required Faculty Advisor Statement

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

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1 Introduction

The Autonomous Vehicle Team of Virginia Tech is proud to present Polaris, a vehicle designed for entry in the 2005 Intelligent Ground Vehicle Competition (IGVC). The vehicle is named after the North Star, the steadfast celestial body that has been used as a navigational beacon for centuries. The Polaris design features superior vehicle mobility, a robust hybrid electric power system, a custom-developed operator control unit and emergency stop, an integrated power distribution board and refined software. We believe these features will help make Polaris highly competitive in the 2005 IGVC. We hope that Virginia Tech's prior experience and success in the IGVC will be evident in the attention to safety, quality, reliability, and durability seen throughout the Polaris design.

2 Innovations

While Polaris is designed to operate autonomously in competition, a human operator must take control during setup or in emergency situations. Polaris is the first Virginia Tech IGVC entrant to feature a custom-designed wireless handheld Operator Control Unit (OCU). The OCU includes an integrated, two-level, fail-safe emergency stop (E-stop) with a line of sight range up to one mile. A photograph of the OCU is shown in Figure 1. The red and yellow mushroom buttons are both emergency stops. The red button is a more conventional "hard" E-stop that releases a normally open relay on the vehicle, cutting power to all vehicle systems. The yellow button provides a "soft" E-stop that signals a pause command to the control software. When the soft E-stop is depressed, Polaris will come to a controlled stop and await the release of the soft E-Stop actuator before continuing autonomous operation. This soft E-stop eliminates the need to re-initialize electronic components, and it allows us to continue to collect sensor and systems diagnostics data. This data can be exceedingly helpful in understanding the root causes of navigation errors or subcomponent failures. The multi-function OCU also has an integrated serial data link. The data link can be used to monitor vehicle parameters such as voltage, sensor status or global position. The multi-function OCU has also been developed to be compatible the Joint Architecture for Unmanned Systems (JAUS) messaging standards.

Figure 1: Polaris operator control and E-Stop unit

A second innovation is the consolidation of the Polaris vehicle's low-current power system onto a single printed circuit board (PCB). This board is shown in Figure 2. The introduction of PCB power distribution greatly reduces the required size of the


Figure 2: Power distribution board

electronics box. The PCB also increases vehicle reliability by significantly reducing the number of physical interconnects that have the potential to degrade or fail. The power system board has built-in power conditioning, power status indicators, and fuses.

Polaris combines exceptional features from Virginia Tech's 2004 IGVC entries, Johnny-5 and Gemini. Like Johhny-5, Polaris uses an on-board generator for system power, and like Gemini, Polaris is based on an articulated twin-body design; combining the strengths of both of these earlier vehicles into one package. As a result, Polaris exhibits superior terrain mobility and a nine-hour autonomous runtime.

3 Design Process

The design process used by the Virginia Tech Autonomous Vehicle Team is illustrated in Figure 3. This process has been termed the Definition, Design and Produce, or DDP, approach to system development. It is a 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 rigorous methodical approach to design with milestones and deliverables providing checkpoints along the way.

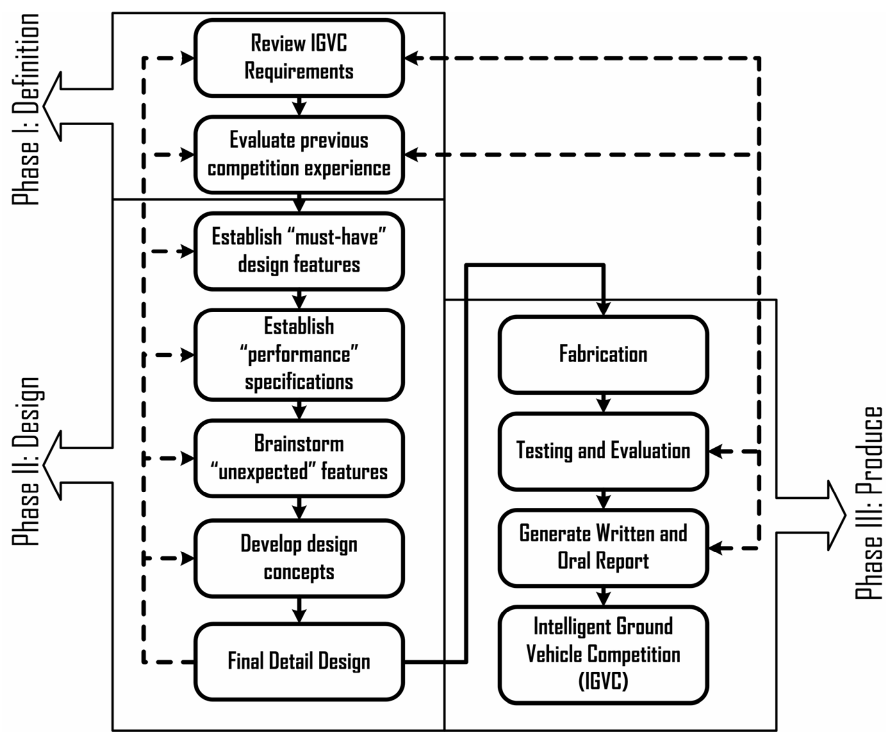


Figure 3: Detailed decomposition of the iterative steps of the DDP design process

3.1 Definition Phase

The DDP process begins with an initial *Definition* phase that includes an intensive review of the IGVC rules and requirements where the vital elements pertaining to the design of an intelligent ground vehicle are identified. This step is followed by a team review of the previous competition performance and functional dissection of previous IGVC entrants. These initial steps serve to identify the customer needs and user requirements for the vehicle. The IGVC judges are viewed as the primary customers by the design team. Secondary customers are the team project advisors and the unmanned systems research community. The result of the definition process is a collection of customer needs based upon competition requirements, previous competition experiences, and the design team's observations of the strengths and weaknesses of previous designs. Key customer needs that were identified were extended run time, better electronics packaging, improved mobility, higher reliable autonomous speeds, and an improved user interface.

3.2 Design Phase

In the *Design* phase, the team attempts to identify "must-have," "performance" and "unexpected" features that would be desirable in the finished vehicle. Must-have and performance features are identified based upon the results of the definition phase. Must-have design features are the elements of the design that are requisite for participation in the IGVC. Must-have items include the ability for autonomous lane following and inherent safety features such as an emergency stop function. Performance features are based primarily on the demands of competition events and previous competition performance. This phase is where the team focuses on performance improvement in the IGVC autonomous and navigation challenges. The team concluded that gains in performance could be achieved by using an improved machine vision camera, faster update rates and improved navigation code.

"Unexpected" design features are the most difficult to develop. These features, sometimes referred to as "delighters" in the design methodology literature, advance the state of the art by giving the consumer something useful that is beyond what they may have specified or expected in the product. These features are developed through brainstorming in the conceptual step of the Design Phase. Unexpected features on Polaris include a printed circuit board power system, a jack stand, a multi-function E-stop and OCU, and a foldable mast.

The final step in the Design Phase is the maturation of design features into concrete specifications. During each meeting, group members brainstormed and refined ideas to identify the optimal concept. Concluding the design phase is the selection of an optimal concept. The team used Unigraphics NX 3 to create a CAD model of Polaris that allowed for virtual system integration. This model provided valuable insight into component sizing, material estimates, and overall finish.

3.3 Produce Phase

The *Produce* phase of the design process is the culmination of the design effort. This is where the detailed design specifications generated by the team are transformed into a functional intelligent ground vehicle. The design team is directly responsible for all phases of vehicle fabrication.

Problems are often encountered in production. For example, the two degree-of-freedom joint bushings were initially fabricated with tolerances that allowed considerable instability of the front section of the vehicle. To address the problem, part dimension were re-analyzed, and a higher density plastic bushing material was selected. Design performance is validated through extensive field trials as comprehensive platform testing and experimentation rounds out the produce phase. The end result of this process is a competitive and intelligent ground vehicle suitable for participation in the IGVC.

3.4 Team Organization

The team was divided into three sub-teams to work on Polaris. A functional decomposition is shown in Figure 4. Team members migrated between sub-teams as needed to complete tasks and integrate systems. A total of 3,980 recorded hours of labor were expended in the development of Polaris.

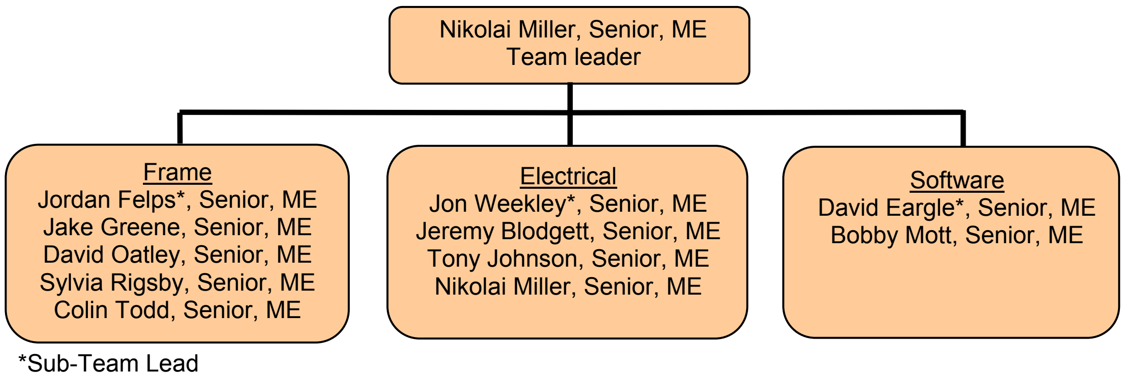


Figure 4: Team organization structure

4 Base Vehicle

A custom designed frame was fabricated for Polaris using one inch square aluminum tubing with 0.125 inch a wall thickness. Figure 5 shows the CAD model of Polaris next to the constructed vehicle.

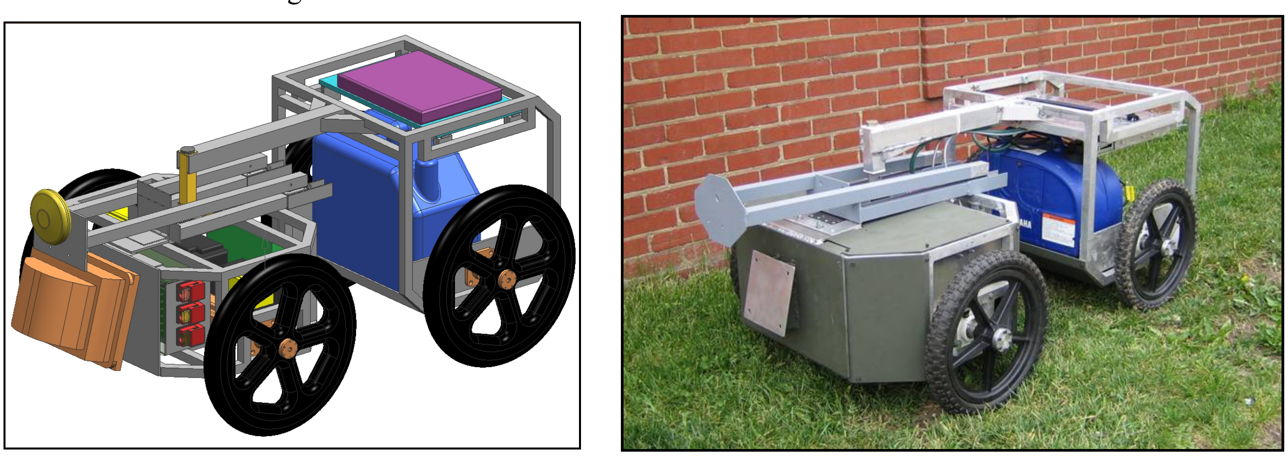


Figure 5: Polaris CAD model next to the constructed vehicle. The mast is in the folded, “transport” position

Polaris has a weight of 240 pounds without the competition payload. Weight is distributed in a ratio of 71/29 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 are mounted below the axles to achieve roll stability. As a result, the center of gravity is only 12.5 inches above the ground. In operation, Polaris is 50 inches long, 38 inches wide, and 68 inches tall.

4.1 Chassis Features

The chassis of Polaris 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 feature that does not directly affect vehicle performance, but it makes the vehicle easier to store and transport. The team developed this feature as a direct result of their experience transporting vehicles from previous competitions. Another example of a subtle but useful feature is the five-spoke composite wheels that also serve as handles for lifting and loading Polaris. Solid wheels, or wheels with many spokes, are far more difficult to grasp and control than the wheels used on Polaris.

4.2 Drivetrain

Polaris 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 gearhead. The gearheads 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 gearhead as shown in Figure 6.

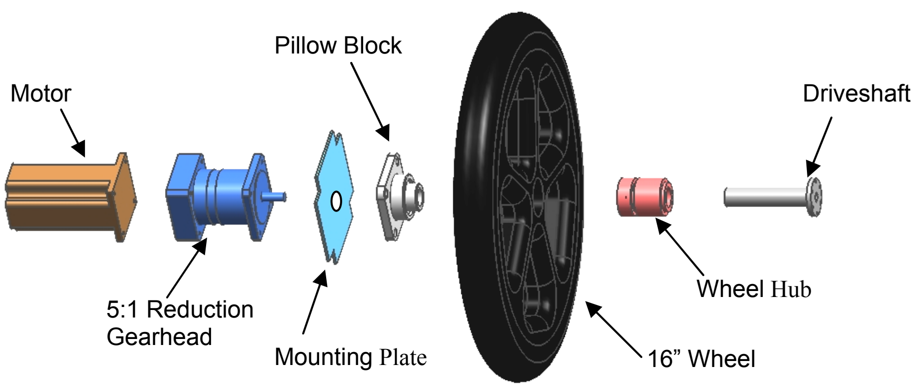


Figure 6: Assembly drawing of the Polaris drivetrain

4.3 Steering and Mobility

Excellent vehicle mobility is achieved using the twin-body articulated-joint configuration. The two degree-of-freedom joint allows the front section of the vehicle to roll relative to the rear section, as shown in Figure 7. The steer axis allows the vehicle to make turns by differentially controlling the right and left wheel velocities. In this sense, Polaris is similar to other differentially driven, zero-turn-radius vehicles. Zero radius turns are software limited to 90 degrees in either direction to prevent excessive cable wrapping. Our experience in both testing and simulation has shown that this limitation does not affect mobility or overall performance. The roll axis allows the vehicle to traverse uneven terrain as shown in Figure 7.

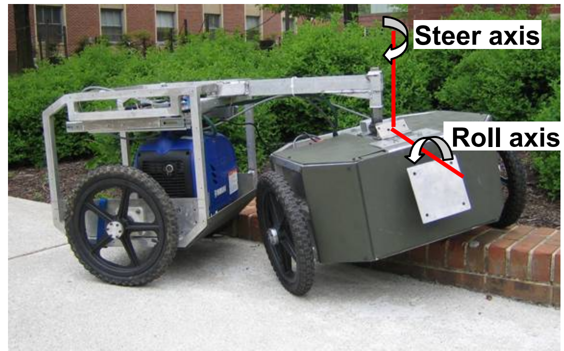


Figure 7: Polaris demonstrating a right turn over uneven terrain during mobility testing

Polaris has four 16 inch deep-tread tires that provide excellent traction, even on wet grass and sand. Additional traction is gained because 71% of the vehicle weight is on the driven wheels. During mobility testing, Polaris was able to climb a 40% grade grass hill without wheel slip. Furthermore, Polaris has five inches of ground clearance, which will help it overcome obstacles and uneven terrain.

5 Electrical System

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

5.1 Electrical Box

The electrical box is extremely compact and lightweight. The dimensions of the electrical box are 15 by 6 by 8 inches. The motor breakout boards, relays, fuses, emergency stop receiver, and power distribution board are all located in the electrical box.

The electrical box is constructed of welded 0.10 inch sheet aluminum. The front and top panels of the electrical box are fabricated from abrasion-resistant transparent acrylic. The acrylic panels allow visual inspection of the box fuses and LED indicators without opening the box. Military grade electrical connectors are used to bring logic and power into and out of the box.

5.2 Power System

The hybrid gas-electric power system is rugged and efficient. The power system consists of two Hawker Odyssey PC680MJ 16Ah dry cell batteries, a Pro Sport 20 amp dual-bank battery charger, and a 1000-watt Yamaha EF1000iS generator. Figure 8 details the basic power system architecture of Polaris.

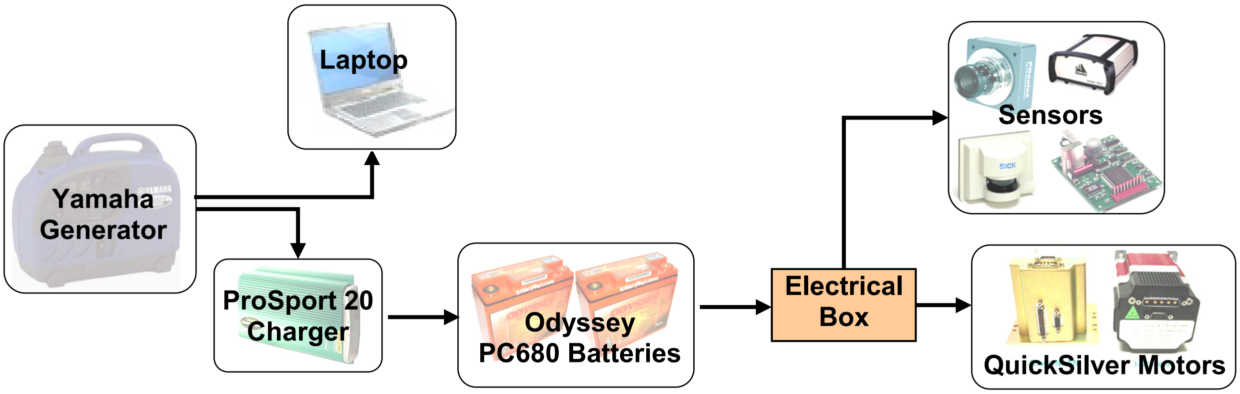


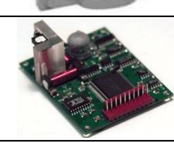
Figure 9: Power system block diagram

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. The batteries provide 12 volts and 24 volts to the motors, relays, and the power distribution board. The Yamaha generator directly powers the dual-bank charger and the AC adapter for the laptop. With a single 0.66 gallon tank of gasoline, the generator provides a nine hour vehicle run time at a fraction of the added weight of a comparable set of dry cell batteries. The hybrid power system is another example of an unexpected, but exceedingly useful feature. Run times in competition are limited to ten minutes, plus setup time. Designing with this as the specified run time would theoretically allow a vehicle to be successful in competition. This logic fails to consider the importance of extended testing, especially at the competition site where valuable calibration time can be lost while changing batteries or repositioning long extension chords.

5.3 Sensors and System Integration

Sensors are mounted on Polaris to perceive the vehicle's environment. Data from the sensors is sent to an onboard laptop computer. The laptop is a Dell 800D with a 2.0 GHz Intel Centrino processor and 512Mb of RAM. Table 1 provides information on each sensor.

Table 1: Summary of sensors used on Polaris

Sensor	Description	Picture
FOculus FO114/C Camera	The camera provides a 640x480 RGB image at a rate of 15 Hz. The camera is mounted at a height of 5'6" to allow viewing across the entire width of the course.	
SICK LMS-221 Laser Rangefinder	The laser rangefinder scans in a horizontal plane and returns the distance to any obstacle at a resolution of 1 degree.	
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 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 15cm from the true position.	

6.4 Device Communication

The method for communication between the electrical components is presented in Figure 10. The RS-232 serial output of the laser rangefinder, the differential global positioning system, and the digital compass output is passed through serial-to-USB converters before being connected to the laptop computer. The use of industry standard communication protocols provides for the use of inexpensive yet extremely reliable hardware. This sensor integration strategy has proven extremely successful at providing uninterrupted and accurate data acquisition on not only Polaris but on the legacy vehicle platforms Gemini and Johnny-5.

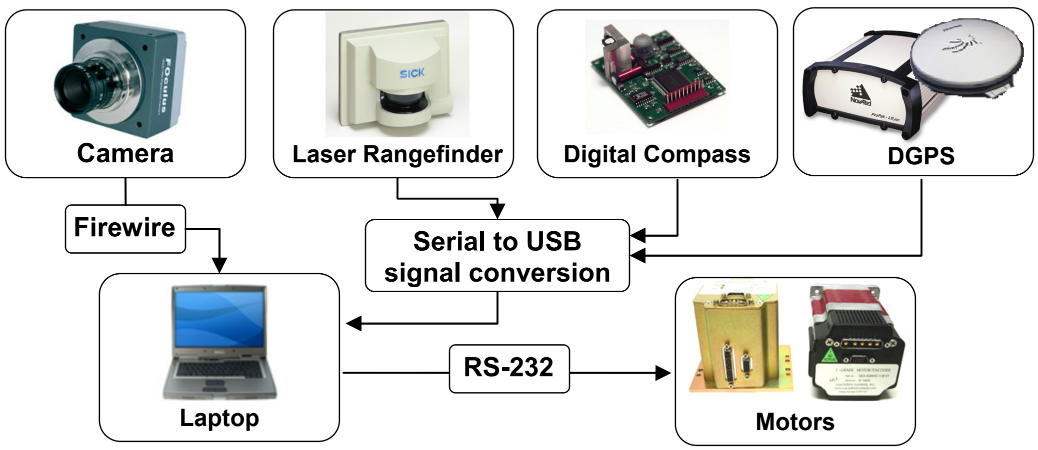


Figure 10: Sensor communication diagram

7 Software

Software for Polaris was developed using National Instruments LabView 7.1. LabView is a programming environment that simplifies communication with external devices and allows easy creation of graphical user interfaces with virtual instrument controls. The simplified programming environment allows new team members to begin developing code with minimal formal training and experience.

7.1 Autonomous Challenge

The Autonomous Challenge software is an extension and improvement of software that was successfully implemented in last year's competition. Major improvements have been made in both the user interface and in reducing the execution time. The updated user interface, with an interactive tab control and help text, allows inexperienced users to quickly learn to operate Polaris. A refined user interface was implemented to allow the user to better monitor software performance through simple diagnostic displays and controls. Also, by creating a compact display, the user can readily observe the software flow as it processes the sensor data and makes decisions without developer "clutter" crowding the interface.

The first goal of the autonomous challenge software is to set a preliminary desired vehicle heading to achieve reliable and intelligent lane following. This process can be broken down into the tasks of detecting boundary lines, analyzing acquired lines, and establishing an ideal desired vehicle direction. This process is carried out through the analysis of acquired digital images via the computer vision algorithm presented in Figure 11.

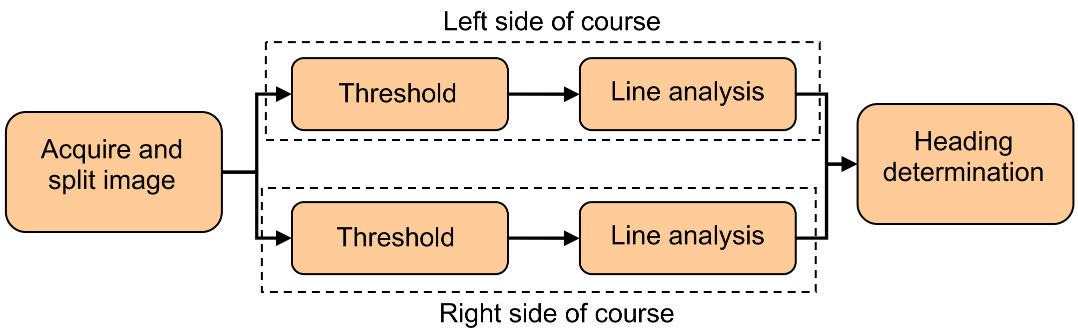


Figure 11: Flow of image processing for Autonomous Challenge Software

Following the acquisition of the forward looking digital image, the captured frame is split into left and right sections, which are processed separately. After accentuating boundary lines, linear trends are detected in the images using an algorithm known as the Hough Transform. The Hough Transform is able to identify the dominant linear trend by determining the largest number collinear points. Figure 12 shows the result of the Hough Transform applied to an image of a line on grass after a threshold operation. The results of the Hough transform are equations for the identified lines coupled with scores relating the certainty of the correlation. The line with the highest shore is typically selected as the course boundary.

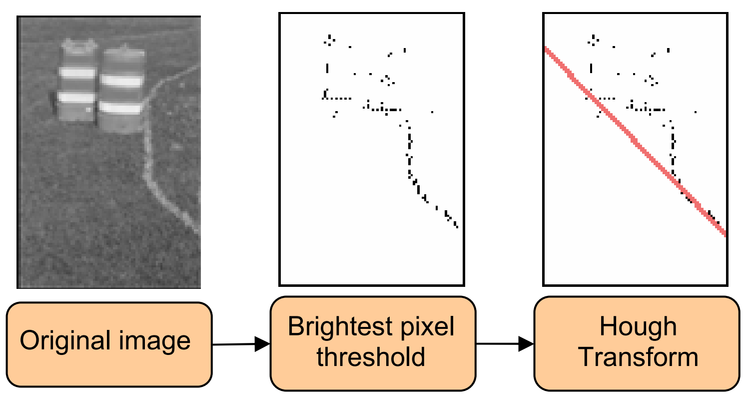


Figure 12: Original Image, After Threshold, Detected Line

To determine a forward heading from the image processing, the program enters a decision tree process, as shown in Figures 13 and 14. Prerequisite to the application of the decision tree is the use of a Hough transform threshold. This threshold determines if the correlative score generated from the Hough analysis of each image section is sufficient to label the identified linear relationship as being the resultant of the presence of a line rather than the consequence of random noise.

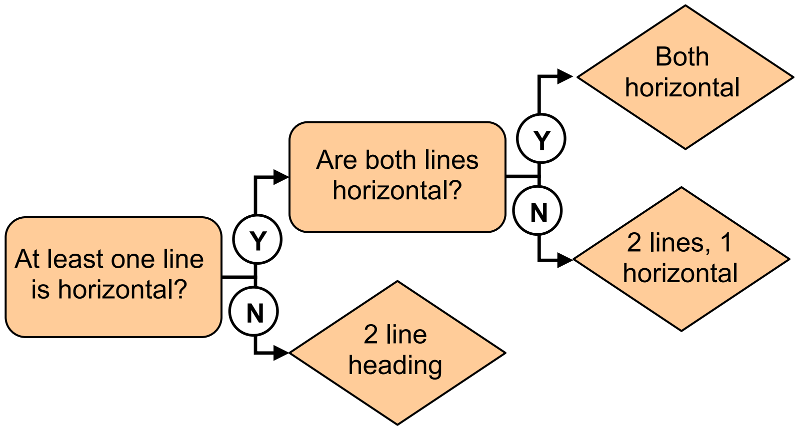


Figure 13: Decision tree executed when a line is detected on both sides of the source image

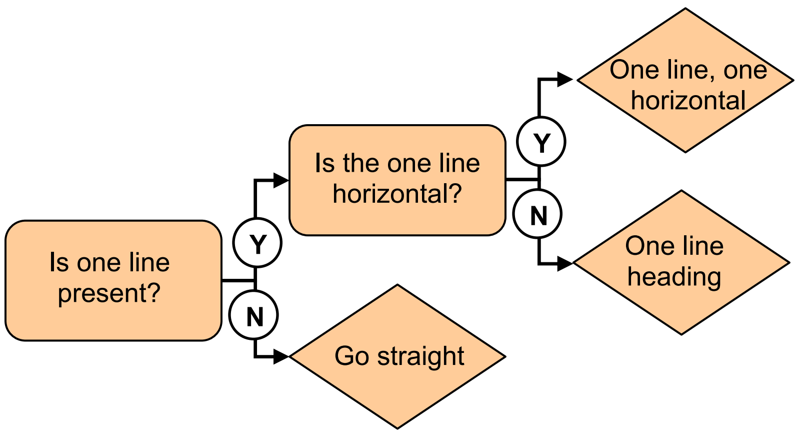


Figure 14: Decision tree executed when at least one side of the image does not have a detected line

To allow for successful reaction to the various course configurations, the software is programmed to handle several image scenarios. If a line is detected in both sections, the software determines whether the lines are part of the same line or two separate lines on the course. If it determines the lines to be separate, it chooses a desired direction toward the center of the lines. If a single line is present, the software assumes the lines are 8 feet apart and essentially mirrors the detected line onto the opposite region and determines heading as if there were two lines detected. If no line is detected, the software will decide if the line has become dashed or if the line has left the camera view. This determination is derived from the last detected line orientation and the vehicle motion. Based on the line presence, continuity, and location, the software determines the desired direction. The desired heading, as well as the location of the lines, is then passed to the obstacle avoidance software.

7.2 Obstacle Avoidance

After the desired heading is determined based upon the vision analysis, it is checked against detected obstacle locations to create an ideal vehicle heading before motion commands are issued. The obstacle avoidance process begins by mapping detected obstacles into a single Cartesian style occupancy grid. During the

Autonomous Challenge, lines and potholes are both considered as obstacles. Potholes are identified by menas of supplemental analysis of the acquired digital image. Regions of the image that contain more than 80 white pixels are labeled as potholes. The lines and potholes detected by the camera are mapped into the same occupancy grid as the laser range finder data, putting all the data into a common form. Lumping both lines and detected obstacles into the same space simplifies the obstacle avoidance process. Since the camera's field of view and mounting position can only detect lines eight feet from the vehicle, the laser range finder data used in the occupancy grid is also limited to eight feet.

Finally, the software examines possible arc-shaped paths. The obstacle avoidance program analyzes possible paths from -90 degrees (directly right) to +90 degrees (directly left) in five degree increments. Possible paths are compared against ideal vehicle heading and the occupancy grid. If the distance to the obstacle, from the arc's center, is between the turning radii of each wheel, then the obstacle is considered to be in the vehicle's path. Each path is checked for obstacles, and the final path of the vehicle is chosen by a cost function which combines the following factors for each path: distance to closest obstacle along path, deviation from the ideal vehicle heading, and the deviation from the last heading chosen. This final chosen path is converted into left and right wheel speeds and sent as a serial command to the motors.

7.3 Navigation Challenge

For the Navigation challenge the Differential GPS is used to find the position of the vehicle while the digital compass is used find the vehicle's current heading. This information is used with the location of the next waypoint to set a desired heading to that waypoint.

Once the desired heading is determined, the vehicle will continue towards the waypoint until an object enters the laser rangefinder's field of view. The laser rangefinder's field of view is broken up into the five distinct regions shown in Figure 15. The vehicle's response is dependant on which regions contain a detected obstacle.

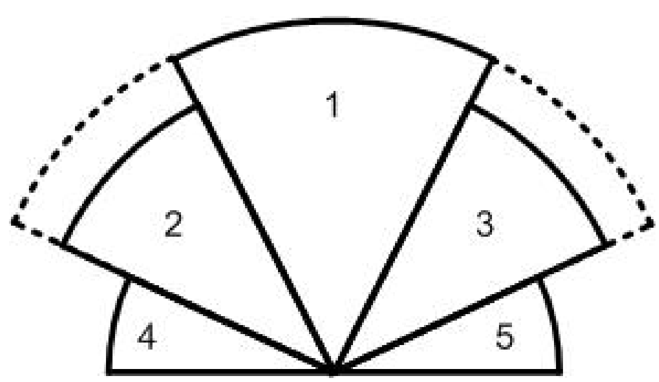


Figure 15. Laser Range Finder Regions for Obstacle Avoidance in the Navigation Challenge

Since obstacles directly in front of the vehicle are of greatest concern, laser range finder data is processed out to a distance of 16 feet in this central region, region one. Laser range finder data from regions two and three is initially truncated to 11 feet. This allows the vehicle to avoid obstacles in its direct path while ignoring obstacles to either side. Once an obstacle is detected in region 1, the look-ahead range in regions two and three is increased to 16 feet, as shown by the dashed lines in figure 15. While testing in the software simulator, the vehicle tended to oscillate around an object detected in the central region. To remedy this, regions two and three were extended to match the length of region one. Implementing this modification allowed the vehicle to circumvent obstacles without the aforementioned oscillations. Finally, regions 4 and 5 prevent the vehicle from turning back into a previously avoided obstacle. Motion commands are issued based on which region detected an obstacle and the direction to the next waypoint.

8 Predicted Performance

8.1 Speed

The Quicksilver brushless DC motors and integral 5:1 reduction gearheads generate a maximum no-load rotational speed of 2500 rpm. Operating through Polaris's 16 inch tires, this would produce a theoretical maximum speed of 23.8 mph. However, the motor speed is limited through motor-control software to ensure a maximum speed of five mph. The torque generated at this speed is 3.65 ft-lb.

8.2 Reaction Time

The reaction time of the vehicle is based on the computational time for a single software repetition during the autonomous challenge. A summary of results is shown in Table 2. These results estimate a minimum update rate of approximately 10 hertz.

Table 2: Maximum computational time for one software cycle in the autonomous challenge

Process		Time (ms)
Image Acquisition		67
Vision		
	Preproccessing	2
	Thresholding	0.4
	Hough Transform	12
	Heading Determination	<1
	Total	14
Obstacle Avoidance		24
Total		105

8.3 Runtime

Polaris is capable of runtimes exceeding nine hours on a single tank of gasoline. Longer runtimes are possible by running the generator in economy mode or applying alternative power schemes where unused sensors are switched off. Without the use of the generator and under typical conditions, Polaris can operate for approximately two hours on battery power alone. The Dell laptop with mobile Intel processor technology draws significantly less power than many earlier laptops used by Virginia Tech teams at competition and proves a significant contributor to extended runtimes exhibited by Polaris.

8.4 Obstacle Detection Distance

For the Autonomous Challenge, obstacles will be detected using both the laser rangefinder and the Firewire camera. Since the maximum range of the camera is about eight feet, the laser rangefinder detection distance is limited to eight feet. However, for the Navigation challenge, obstacles will be detected at 16 (region one), 11 (regions two and three), and five (regions four and five) feet.

8.5 Dead Ends, Traps, and Potholes

Generally, effective path planning proves to avoid dead ends and traps. However, in the event of a dead or trap situation the software is designed to slow the vehicle and execute a zero-radius turn until the vehicle is extricated. This allows the vehicle to turn away from the obstacles and find a clear path. To deal with potholes in the Autonomous Challenge, the Firewire camera is used to detect the lines large white regions designating a pothole. These lines are then combined with the laser rangefinder data and are considered obstacles, which the vehicle then avoids.

9 Vehicle Cost

In an effort to control costs, the team sought equipment, software, and monetary donations from companies. We were also able to share some equipment with other research and competition project teams at Virginia Tech, such as the DARPA Grand Challenge project team. A cost summery for Polaris is provided in Table 3.

Table 3: Polaris cost summary

Part Description	Retail cost	Cost to team
Dell D800 laptop	$2100	$2100
(2) QuickSilver 34HC-2 Servo motors and Controllers	$3000	$2700
(3) Odyssey PC AGM lead acid batteries	$210	$210
Yamaha EF 1000is gas generator	$650	$650
Electrical Components	$500	$500
IGUS flex cables	$1000	$0
PNI TCM2-20 digital compass	$700	$0
Sick LMS-221 Laser Rangefinder	$6000	$0
Novatel DGPS	$8000	$0
Foculus Firewire camera	$1200	$700
Aluminum and frame materials	$700	$700
Custom welding – Piedmont Metal Fabricators	$1000	$0
(4) 16” Skyway Tuffwheels	$250	$0
Totals	$25,310	$7,560

10 Conclusion

Polaris should be a promising contestant in the 2005 IGVC. It was designed and fabricated by a dedicated team of undergraduate students from Virginia Tech, and it features refined versions of many of the best ideas from previous vehicle designs, including durable construction, reliable electronics, and refined software. The team's drive towards innovation is evident in the many unique features of Polaris such as the custom multi-function OCU and the printed circuit board power electronics. The excellent mobility and extensive run time of the vehicle should contribute to its overall success. We believe we have developed an exceptional vehicle that should perform well in all three events at the 13th annual IGVC.