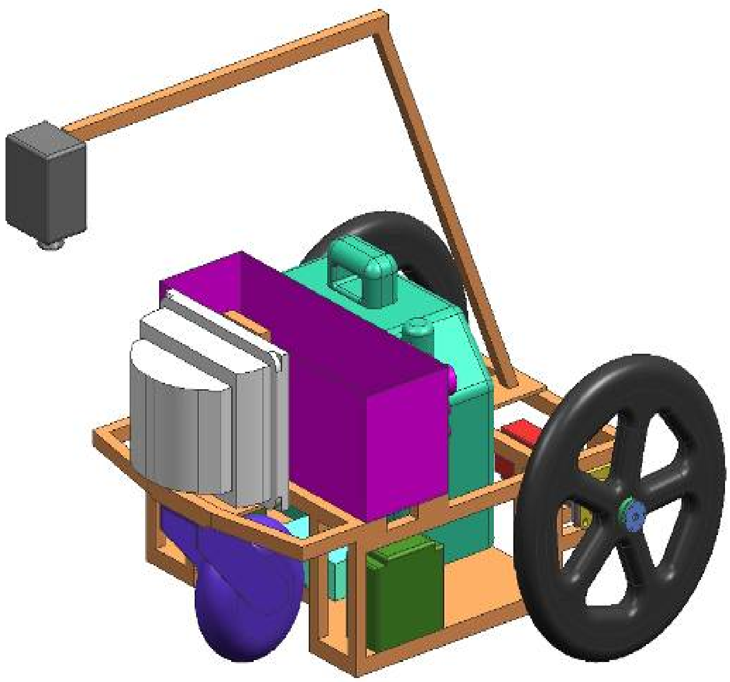
The Virginia Tech Autonomous Vehicle Team presents:

Johnny-5



Required Faculty Advisor Statement

I certify that the engineering design of the new vehicle described in this report, Johnny-5, has been significant, and that each team member has earned six semester hours of senior design credit for their work on this project.

Charles F. Reinholtz
Department of Mechanical Engineering
Virginia Tech

1 INTRODUCTION

The 2003-2004 Virginia Tech Autonomous Vehicle Team proudly presents Johnny-5, a new standard in innovation and design of autonomous vehicles. Johnny-5 will compete in the Autonomous Challenge, Navigation Challenge, and Design Competitions at the 12th annual Intelligent Ground Vehicle Competition (IGVC). The vehicle's name originates from the popular 1986 cinema, *Short Circuit*, which depicts a robot imbued with amazing humanistic decision making and control capabilities. Throughout the design process, the name Johnny-5 served as a constant reminder to design an autonomous system that could more closely mimic human intelligence and behavior.

Figure 1.1: The Original Cinema Version of Johnny-5

2 DESIGN PROCESS

In Fall 2003 the design team began developing Johnny-5 by establishing the vehicle's primary design objectives. These objectives focus on creating a safe autonomous system that competes favorably in all three IGVC events, promotes awareness of unmanned systems, and provides a reliable platform for future testing and research. To accomplish these goals, the team implemented a design strategy that held customer needs paramount, provided a clear path for project completion, and focused on innovations.

2.1 Design Planning Process

A methodical design process is essential for the successful development of complex systems such as Johnny-5. The team used the six-step design method shown in Figure 2.1 to help guide the design process. Details of this method are described in *Product Design and Development* (Ulrich and Eppinger, 2000). Although the figure indicates sequential steps, the designer is encouraged to return to earlier steps as problems are encountered and as new information becomes available.

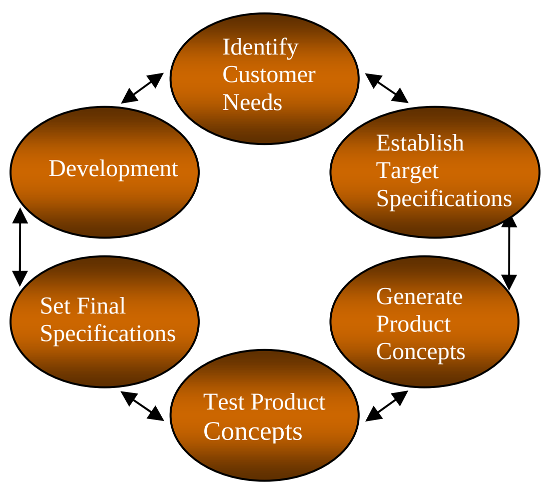


Figure 2.1: Ulrich and Eppinger's Design Methodology

While Ulrich and Eppinger's method has been successful for past teams, it does not explicitly represent the importance of innovation in the conceptual phase of product development. To help insure an innovative design, the team adopted the Kano Model as described in *Attractive Quality and Must-Be*

Quality Method (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996). The Kano model predicts that, to achieve a high degree of customer satisfaction, a product must incorporate innovative, or unexpected, features in the design. Kano refers to these features as "delighters." We believe that features such as nine-hour continuous run time and an on-board jack stand for field testing are "Kano delighters" that will help distinguish Johnny-5 from the competition.

2.1.1 Identifying Customer Needs

The following primary customers were identified: (1) IGVC judges and sponsors, (2) the team faculty advisor, (3) current and future vehicle users. Secondary customers include team sponsors and the autonomous vehicle community. Many of the primary customer needs were expressed in the 12th annual IGVC rules, and in the syllabus for our senior design course, which include the faculty advisor's expectations and the course educational objectives.

2.1.2 Establish Target Specifications

Target specifications were established by determining vehicle performance requirements that fulfill customer needs. To assist in this step, the IGVC rules were reviewed and the 2003 IGVC Virginia Tech vehicles Optimus and Zieg were evaluated. Based on this review, the following desired improvements were identified: (1) longer run times without changing or charging batteries, (2) improved electronic design and layout, and (3) autonomous navigation at higher speeds. The development of simulation software for more efficient software debugging was also cited as a desirable support tool. With Optimus and Zieg placing 1st and 2nd in the 2003 Autonomous Challenge, the design team focused on retaining the strengths of these vehicles by adapting safety, mobility, maintainability, and user interface concepts to the new vehicle.

2.1.3 Final Design Stages

Three conceptual designs were generated based on the target specifications: (1) a tracked vehicle, (2) a three-wheel differential vehicle, and (3) a four-wheel Ackerman-steered vehicle. Each design was analyzed and compared to the target specifications. In addition, sketches, computer drawings, and cardboard mockups of these designs aided in the visualization of these vehicle configurations. The three-wheeled differential vehicle was selected based, in part, on the concept matrix as shown in Table 2.1.

Table 2.1: Excerpt of Concept Matrix

	Tracked Vehicle	Three-wheel differential vehicle	Four-wheel Ackerman-steered vehicle
Turning Radius	Good	Good	Poor
Control System Complexity	Low	Low	Low
Mechanical Complexity	High	Fair	High
Cost	High	Fair	Fair
Rank	2nd	1st	3rd

After a conceptual design was selected, the team continued modifying the final specifications and testing the design. The team continually tested and analyzed the planned specifications during fabrication to ensure a quality product. Force and stress analysis were performed on mechanical components, electrical specifications were revised, and software was tested in custom developed software simulator (to be discussed in software section).

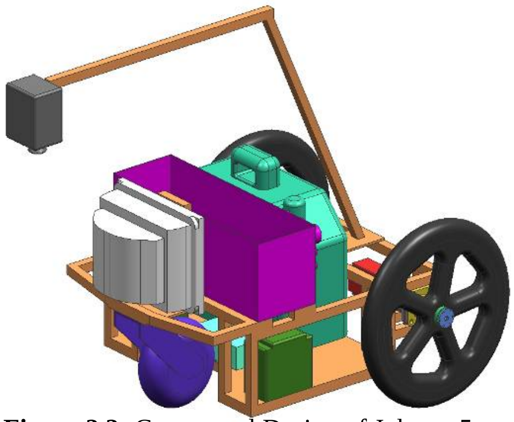


Figure 2.2: Conceptual Design of Johnny-5

2.2 Team Organization

The team worked as a group during the initial stages of the design process. After a final concept was chosen and initial specifications were set, the team divided into mechanical, electrical, and software sub teams as shown in Table 2.2. During the final phases of the design process, the design team met twice per week to maintain communication and collaboration between each sub team. Overall, a total of 3,200 student hours were spent on design, fabrication, and implementation of Johnny-5.

Table 2.2: Team Members Information

Member Name	Contribution	Major	Year
Curtis Hall	**Mechanical Deign and Fabrication**	**ME**	**Senior**
Neal Buchanan	**Mechanical Design and Fabrication**	**ME**	**Senior**
Ryan Limpin	**Mechanical Fabrication**	**ME**	**Senior**
Patrick Hall	**Electrical Design & Fabrication**	**ME**	**Senior**
Jared Cooper	**Mechanical & Electrical Fabrication, Programmer**	**ME**	**Senior**
Brett Gombar	**Electrical Design, Programmer, Project Leader**	**ME**	**Senior**
Andrew Bacha	**Programmer, Project Consultant**	**ME**	**Masters**
Ankur Naik	**Programmer, Project Consultant**	**ME**	**Masters**

3 DESIGN INNOVATIONS

Several design innovations, or Kano delighters, were incorporated into Johnny-5. An on-board jack stand was added to facilitate stationary testing and to enhance safety. Figure 3.1 shows Johnny-5 raised on the jack stand for testing. This stand enables the user to raise the drive wheels off the ground to test motor control function, for example. This innovation was motivated by the observation that team members sometimes carried concrete blocks to the test field to serve as jacks.

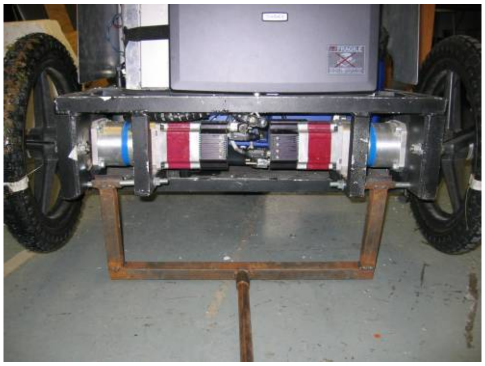


Figure 3.1: Johnny-5 with Jack Stand

A second innovation is the on-board gas-electric hybrid power system that gives a 9 hour run time before refueling of the generator is necessary. A schematic of this system is shown in Figure 3.2. The integrated system uses a Yamaha EF1000iS generator, Soneil 2416RSF battery charger, and two 12 VDC Hawker Odyssey PC535 batteries.

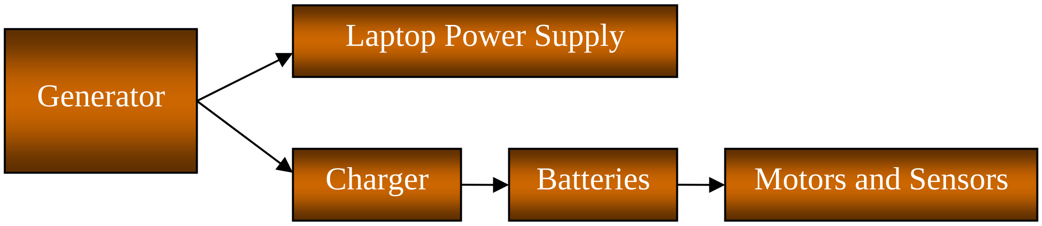


Figure 3.2: Block Diagram of Electrical System

Two independently driven QuickSilver Contol Silvermax 34HC-1 drive systems power Johnny-5. These drive systems, shown in Figure 3.3, integrate the motor, encoder, amplifier, and controller in one compact package. In prior years, vehicles from Virginia Tech employed an independent motor controller board, an amplifier and accompanying software to adjust control loop gains and control the motors. The QuickSilver motors reduce the size and weight of the vehicle, simplify electrical and software systems, and allow vehicle speeds of 5 MPH with a 100lb payload.

Figure 3.3: Silvermax 34HC-1 Drive System

4 MECHANICAL SYSTEM

The mechanical subsystems on Johnny-5 were developed to support the customer needs and the resulting detailed specifications developed during the design process. For example, the drive system was required to produce zero-radius turns, and the chassis was required to support a long-run-time hybrid gas-electric power system. Mechanical design to support these and other requirements are addressed in the sections below.

4.1 Vehicle Chassis

Johnny-5's chassis underwent multiple revisions during the design process as improved packaging schemes were developed. The final chassis measures 25 by 35 by 8 inches. With two 16 inch rear drive wheels and a 10 inch front caster wheel, the vehicle has a ground clearance of 3.75 inches. A 1/16 inch aluminum plate covers the bottom of the frame and plastic panels cover the sides. The chassis carries a removable electrical box, generator, and all sensor mounts. The chassis is constructed from welded one inch aluminum tubing. Aluminum is lightweight and its nonferrous characteristics reduce magnetic interference with digital compasses. Finally, an aluminum cover protects the onboard equipment from weather elements.

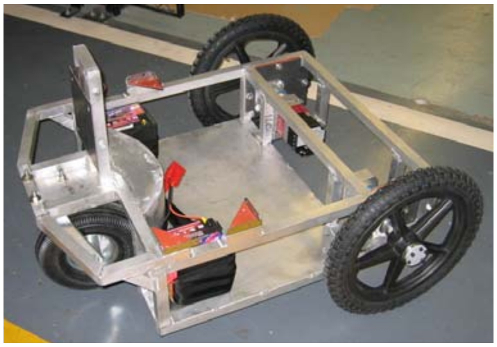
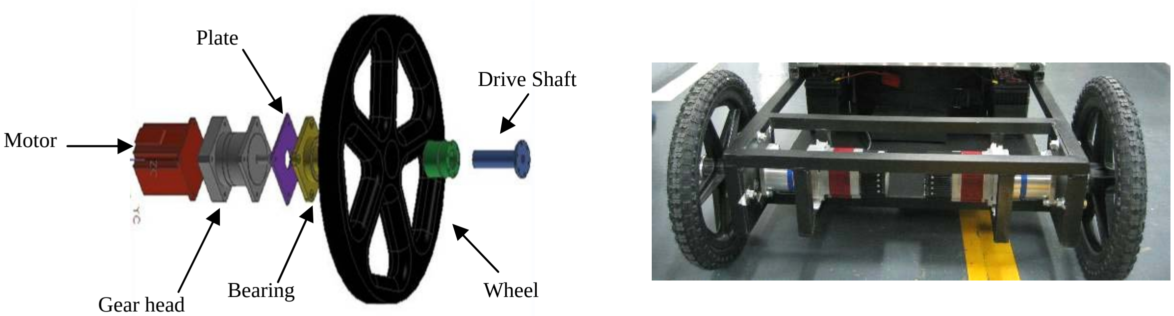


Figure 4.1: Vehicle Chassis

A front caster allows Johnny-5 to perform zero-radius turns without concern of the vehicle rear "swinging out" and colliding with an obstacle. The rear wheel design and weight distribution aids in traction as 60% of the weight is in the rear of the vehicle. Components mounted below the drive axis lowers the center of gravity, improving Johnny-5's maneuverability.

4.2 Drive System

Johnny-5 is driven by two QuickSilver Control Silvermax 34HC-1 drive systems. Figure 4.1 shows an exploded view of one wheel of the drive train (a) and the assembled rear drive (b). The components of each drive system include a 16 inch composite drive wheel, a 10:1 NEMA 34 gear head, a 1/8 inch steel mounting plate, a Torrington PT Survivor bearing, and a custom drive shaft for each wheel. The mounting plate connects the motor/gear head assembly and the bearing to the frame. The bearing locks the wheels in the axial direction, while L-shaped brackets (not shown in exploded view) support the motor and assist in alignment. Finally, the drive shaft connects all these components.



(a) Drive System Design (b) Fabricated Drive System

Figure 4.2: Vehicle Drive System

5 ELECTRICAL SYSTEM

The electrical system provides communication between the computer, sensors, and motors as well as power to all on-board devices. Safety, efficiency, and compactness are the principal goals of the electrical system. Multiple switches, color coded wiring, and emergency stops (E-stop) were employed to increase safety and maintainability. A compact and removable electrical box (E-box) was designed and fabricated to house all the electronics. The E-box measures 8 by 24 by 8.5 inches and uses two levels of DIN rail. Figure 5.1 shows the E-box. Quick release, environmentally sealed connectors are used to connect communication and power lines to the E-box.

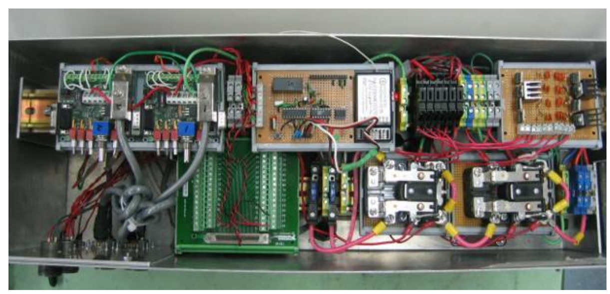


Figure 5.1: E-box Component Layout

5.1 Power System

Johnny-5's power system consists of two Hawker Odyssey PC535 dry cell batteries, a Soneil 24V, 8 Amp battery charger, and a Yamaha EF1000iS generator. The Odyssey PC535 is a sealed dry cell battery that recycles its internal gas during operation and charging. This increases safety while providing a long lasting power source. An insulative coating was applied to the battery terminals to prevent accidental shorting. A strap and industrial strength Velcro are used to secure the batteries to the chassis.

The Yamaha EF1000iS generator has a dry weight of 27 lbs and will produce 900 Watts of power. The generator powers the charger which in turn continuously charges the batteries. The batteries provide power to all the sensors and motors through an arrangement of switches, fuses, and voltage regulators. The voltage regulators provide +24, +12, and +5 VDC for the various sensors.

5.2 Efficient Use of Power

The insight and recommendations of previous Virginia Tech IGVC team members contributed to the design and development of an effective and efficient vehicle power system. By incorporating a Yamaha EF1000iS generator, a Soneil 2416SRF battery charger, and two Odyssey PC535 batteries, Johnny-5 can sustain run times of up to 9 hours before refueling is necessary. With onboard components consuming 63% of Johnny-5's 900 Watt power capacity, powering of additional components is supported for system expansion. Table 5.1 shows the power consumed by each major component.

Table 5.1: Power Consumption of Johnny-5

Instrument	Voltage (V)	Current (A)	Power (W)
Motors	24	4	96 (x2)
Laptop	20	6	120
DGPS	12	0.1	1.2
Digital Compass	12	0.02	0.24
Charger	24	6	192
Camera	12	0.075	0.9
Laser Range Finder	24	2.5	60
Total Power Consumption			566.34

The Yamaha EF1000iS generator independently adjusts engine speed to match power load demand, resulting in greater fuel efficiency and noise reduction.

5.3 Control System

The control system of Johnny-5 was simplified by using the integrated Quicksilver drive system. The drive system uses an internal servo loop algorithm called Position, Velocity, Feedback/Feedforward, Integral, and Acceleration Feedback/Feedforward (PVIA). There are 7 gain parameters and 3 filter parameters that can be varied in this control algorithm. Testing revealed that Johnny-5 performed well with the default gain settings.

5.4 Sensors and System Integration

Electronic sensors and a laptop computer are used to mimic human senses and behavior. The sensors gather physical data, which is sent to the laptop. Based on this data, the laptop determines the best course of action for the vehicle. Four sensors are used to obtain peripheral data. The following list briefly explains the primary function of each component and how it is used in the Autonomous Challenge or Navigation Competition.

- **Unibrain Fire-i Board Camera —** This firewire camera captures images used for line detection algorithms in the Autonomous Challenge. It has a native resolution of 640x480 and 94 degree diagonal field of view. A weatherproof housing was constructed to enclose the camera.

- **LRF** — Sick's LMS 221- Laser Range Finder (LRF) scans for obstacles in a 180˚ planar sweep in 1˚ increments. Time-of-flight technology is used to calculate the distance to an object from the vehicle. This sensor scans in front of the vehicle and is used for obstacle detection and avoidance algorithms.

- **DGPS —** Novatel's ProPak-LB DGPS combines global positioning satellites with the OmniSTAR HP correctional service. The DGPS is used in the Navigation Challenge to determine vehicle position.

- **Digital Compass** — Pacific Navigation Instrument's TCM2-20 digital compass detects the earth's magnetic field and determines the vehicle's heading relative to magnetic north. The compass is a three-axis, tilt compensated instrument and is used in the Navigation Challenge to determine vehicle heading.

- **Laptop** — A Sager NP8890 laptop reads data from each sensor and determines the best course for the vehicle to take. The laptop uses a 3.2GHz Pentium 4 processor with Hyperthreading and 1 gigabyte of 400mhz DDR ram. All navigational software is executed on this machine.

Figure 5.2 outlines the native communication standard for each sensor and corresponding interface with the computer. To connect to the computer using the USB standard, devices with native serial communications were run through converters. National Instrument's USB-232 4-Port interface and EasySync's RS-422 to USB converter were used to interface the digital compass, DGPS, and laser range finder.

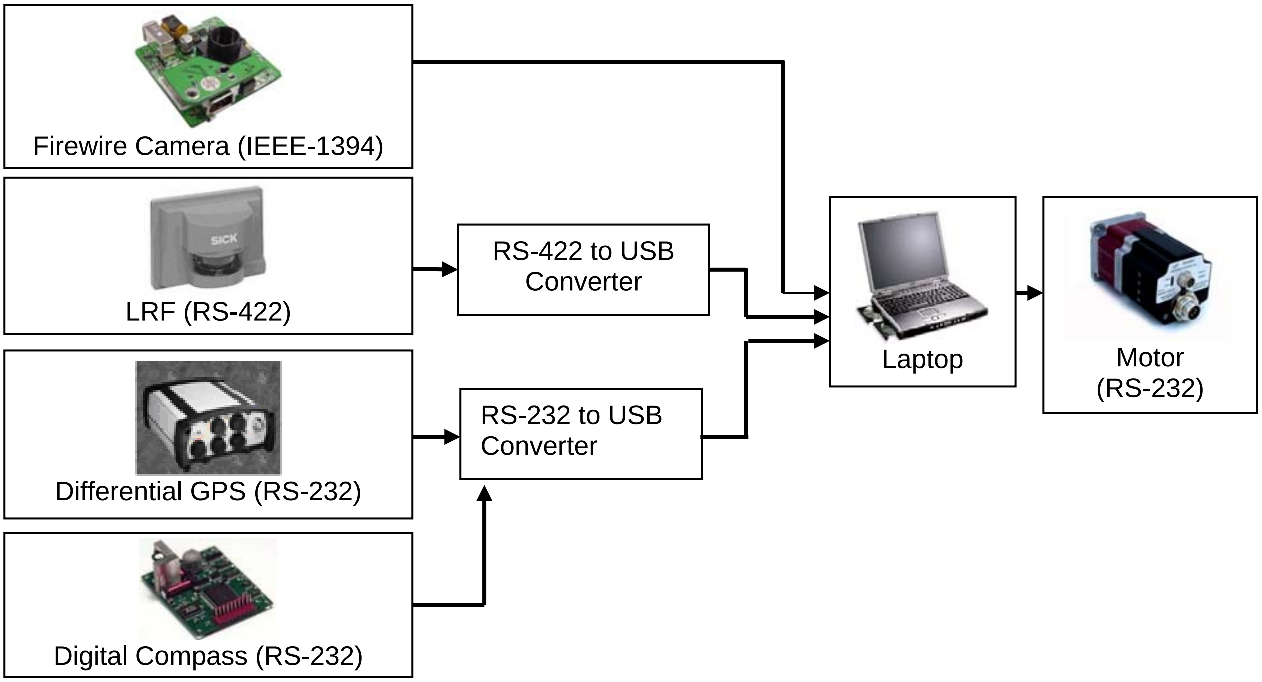


Figure 5.2: Component Communication Diagram

6 – SOFTWARE

6.1—LabVIEW Development Platform

All software running on Johnny-5 was developed using National Instruments LabVIEW 7.0. Last year, The Autonomous Vehicle Team of Virginia Tech switched from visual C++ to LabVIEW for all software development. The use of LabVIEW simplifies coding and expedites system integration. The graphical nature of this programming environment allows new team members to begin developing code with less formal training and experience.

6.2—Simulator Software

Software debugging and quantification of software performance are difficult tasks that have challenged developers of autonomous systems. To address this, we have developed the Autonomous Vehicle Team (AVT) Simulator. The AVT Simulator is a library of software that constructs a virtual world with simulated lines, obstacles, and waypoints mimicking previous IGVC Autonomous and Navigation Challenge courses. The Johnny-5 team has utilized the AVT Simulator by implementing different navigational algorithms with various settings for benchmarking and optimization. Within the simulation software, users can monitor simulated sensor data, vehicle response, and a global map of the constructed virtual world. The global map of a simulated environment with course lines, physical obstacles, and the vehicle (in red) is shown in Figure 6.1. The AVT Simulator allows immediate evaluation of developed software without the use of a vehicle which is often under development or repair.

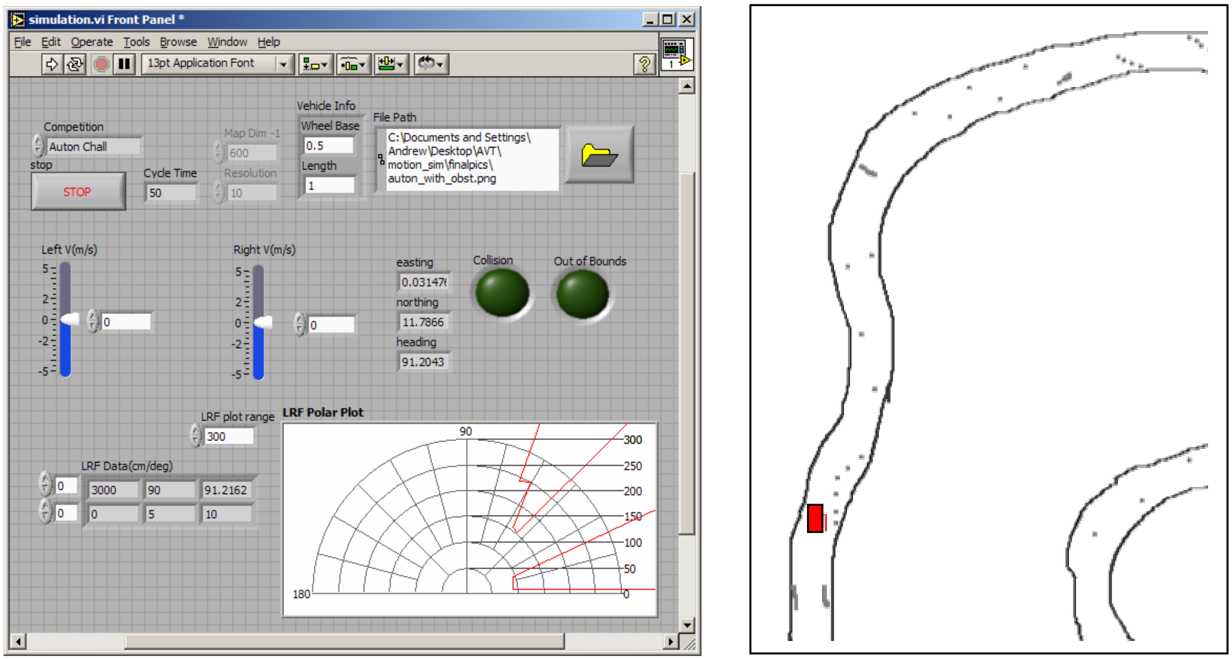


Figure 6.1: AVT Simulator interface and output

6.3 – Software Structure

To simplify software development, the programming structure shown in Figure 6.2 was implemented in both the Autonomous and Navigation Challenges. Sensor data is collected simultaneously through individual communication channels. Sensor data is processed by the navigational algorithm to determine a desired vehicle heading. Once a desired heading is computed, the navigational software plans a path for the vehicle around any detected obstacles. This obstacle avoidance algorithm is implemented in both the Autonomous and Navigation Challenges. Once the desired vehicle path has been determined, the motor control software executes the corresponding velocities for each wheel.

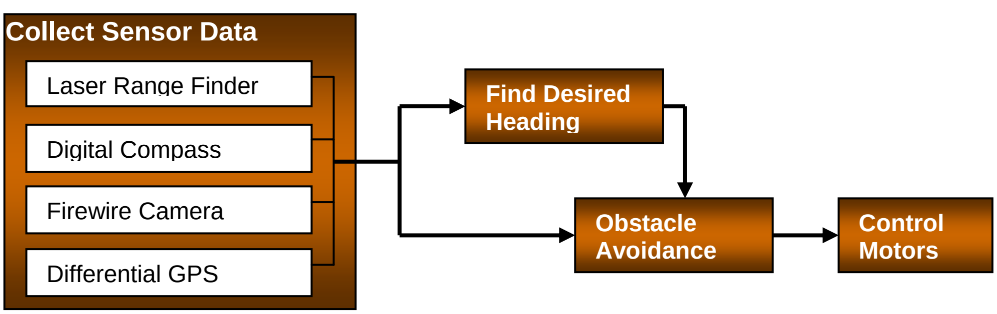


Figure 6.2: Software Structure for Both the Autonomous and Navigation Challenge

6.4 – Autonomous Challenge

The software programming specific to the autonomous challenge is contained in the routine to find the desired heading of the vehicle. This algorithm is outlined in Figure 6.3. The goal of the autonomous challenge software is to set the desired vehicle heading between both painted lines. This can be broken down to the tasks of detecting the lines, analyzing the lines, and setting the desired direction.

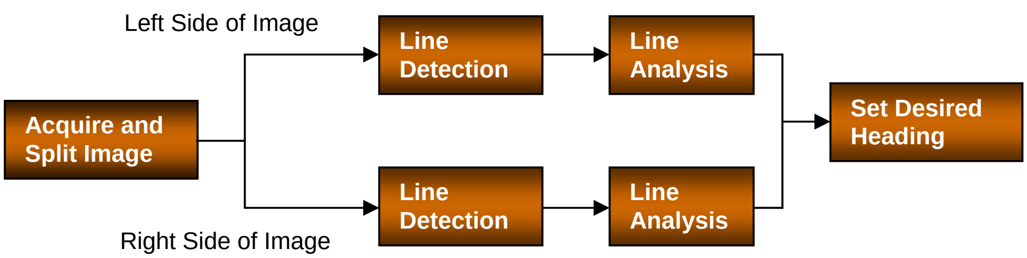


Figure 6.3: Flow Diagram of Autonomous Challenge Software

First, a threshold operation is applied to the image. Next the image is split into a left and right section, which are processed separately. Lines are detected using an algorithm known as the Hough Transform. The Hough Transform is able to find the dominant lines by finding the largest number of collinear points Figure 6.4 shows the result of the Hough Transform used on an image of a line on grass after a threshold operation. The Hough Transform is not affected or skewed by the noise to left of the line in Figure 6.4. The result of the Hough transform is a score indicating how many points are on the line and an equation, giving both the location, and direction of the line.

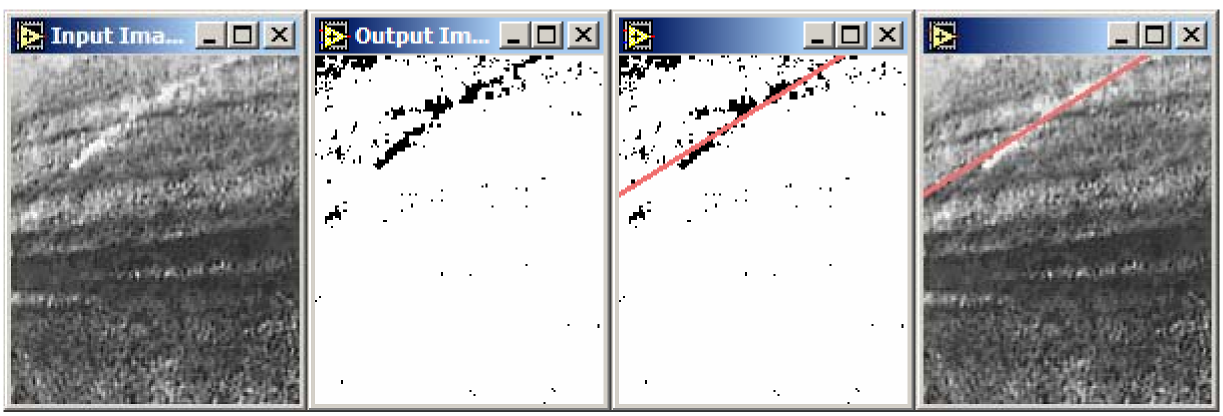


Figure 6.4: Original Image, After Threshold, Detected Line, and Original Image with Detected line

After the initial line detection process, the results are processed to check if the detected object is truly a line, if the lines have become dashed or if one or both of the lines has left the camera field of view. The line quality score generated by the Hough Transform is used to check if a line was detected rather than noise. If no line is detected, the software will decide if the line has become dashed or if the line has left the camera view depending on the last position of the line.

To set the desired direction of the vehicle, the detected lines are first corrected for perspective distortion. If the image contains both lines, the desired direction is set so the vehicle will head to center of the lines. If only one line is present, the software assumes the lines are 8 feet apart and sets the direction based on the position of the known line. The desired heading, as well as the location of the lines is then passed to the obstacle avoidance software.

6.5 – Obstacle Avoidance

The obstacle avoidance process starts by mapping detected obstacles into a single occupancy grid. Obstacles detected by the laser range finder are mapped into a 3x3 inch square Cartesian style occupancy grid. During the Autonomous Challenge, the equations of lines generated by the Hough Transform are considered obstacles. We also consider distinct regions with more than 80 pixels as potholes. Since the camera can only detect lines 8 ft away from the vehicle, the laser range finder was also limited to 8 ft. 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.

Our software examines arc shaped paths. An obstacle will lie in the vehicle path if the distance from the obstacle to the arc's center is between the turning radii of each wheel. This is represented in Figure 6.5. Therefore, the obstacle avoidance program analyzes possible paths from -90 degrees (directly right) to +90 degrees (directly left) in 5 degree increments. Each path is checked for obstacles, the final path of the vehicle is chosen by combining the following factors for each path: distance to closest obstacle along path, deviation from desired heading, and the deviation from the last heading chosen.

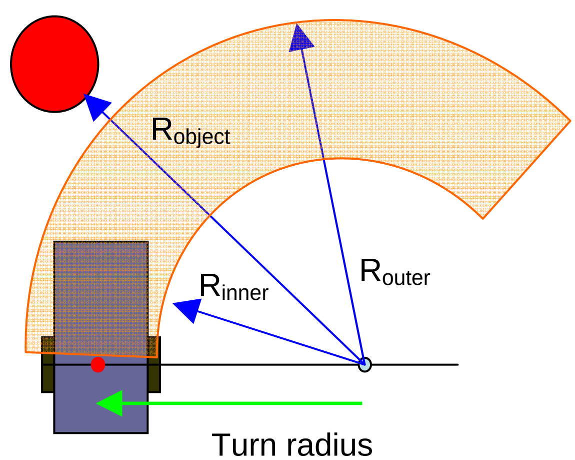


Figure 6.5: Distances used during obstacle avoidance

6.6 – Navigation Challenge

The navigation challenge uses the same obstacle avoidance software as the autonomous challenge. The DGPS is used to find the position of the vehicle, while a 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 the waypoint. The OmniSTAR HP DGPS correction service provides a horizontal accuracy of

15 cm 99% of the time, while the TCM2-20 digital compass has an accuracy of 0.5 to 1 degree depending on tilt. The high precision sensors used make sure the waypoint is reached, and reduce the heading deviation during travel.

7 – PREDICTED PERFORMANCE AND TESTING

7.1 – Speed

The two Silvermax 34HC-1 motors in conjunction with 10:1 gear heads give a maximum driveshaft speed of 300 RPM. With 16 inch drive wheels, this equates to 14.3 MPH. Johnny 5's maximum speed is regulated to 105 RPM, or 5 MPH, in accordance with IGVC regulations. In testing, the vehicle reached speeds of 10 MPH on level ground.

7.2 – Ramp Climbing Ability

The Silvermax motors have a stall torque of 422 in-lb after the 10:1 gear reduction. The motor's internal control algorithm automatically adjusts to maintain a desired speed under varying load conditions. Although, the IGVC rules specify that a vehicle should be able to transverse a 15% grade (8.5 degrees), the team specified that Johnny 5 should be able to climb a 15 degree incline. This provided a factor of safety in the case of unexpected conditions during competition. During testing, Johnny 5 was able to climb inclines of approximately 35 degrees.

7.4 – Reaction Times

From initially polling the sensors to issuing a command to the motor, the software takes 0.067 seconds to complete a cycle. The sensors are able to collect and transmit data faster than the software refresh, leaving processing as the limiting reaction factor. Depending on when the obstacle is detected by the sensor, it could take between 0.067 and 0.13 seconds from the time an obstacle is sensed to when a signal is sent to the motor for the Autonomous Challenge. The obstacle distance, and how close the obstacle is to the desired heading will determine what action the software commands. At a speed of 5 mph, the maximum 0.13 reaction time means that the vehicle will move 0.95 feet before the motors start reacting to an obstacle. This distance is well within the sensing range of Johnny-5.

8 – OTHER DESIGN FACTORS

8.1 – Safety

Safety has been, and continues to be, the most important objective in designing and operating Johnny-5. The team successfully implemented safety features in the mechanical, electrical, and software systems. An important safety feature of the mechanical system is the jack stand, which is used in start up procedures and indoor testing. Electrically, Johnny-5 has two different emergency stops: a remote controlled E-stop and an on-board E-stop button. The remote E-stop has been tested to distances of 150 feet. The on-board E-stop is located on the camera mast and is easily accessible. Both E-stops cut power to the motors and engage a fail-safe brake. Braking was a unique challenge for the team, as the Silvermax motors do not come with an integrated motor brake. The team fabricated a custom fail safe brake consisting of wheel stop held open by a servo motor. The wheel stop is normally engaged, and the servo will remove the stop only when the vehicle has power. The motors can also be stopped via software.

8.2 – Costs

Table 8.1 shows the cost to fabricate Johnny-5.

Table 8.1: Cost Analysis of Johnny-5

Vendor	Item	Quantity	List Cost (each)	Team Cost
McMaster Carr	6063 Al Swuare Tubing 1-1/4" X 1-1/4"	84 ft	$120	$120.00
Frame Materials	Electronics Box	1	$100	$50.00
Frame Materials	Aluminum Cover	1	$300	$0
Allied Electronics	Electronic Parts	1	$211.30	$211.00
Sager	Laptop	1	$2,500.00	$0
National Instruments	USB to Serial Converter (RS-232)	1	$495	$0
East Coasters Bike Shop	16" X 2.5" BW Tires	2	$18.00	$36.00
Northern Hydraulic	10" Pneumatic Swivel Caster 500 lb	1	$22.99	$22.99
Fairchild Semiconductor	PWR MOS UltraFET 80V/75A/0.010	5	$12.50	$0
Hawker Odyssey	12V sealed Lead-Acid Battery	2	$170.00	$0
Soneil	24V/8A Battery Charger	1	$160.00	$145.00
Skyway Machine, Inc	16" Tuffwheels with Disc Brake Hub	2	$42.50	$0
Quicksilver Controls	48V DC High Output Servo Motors and gearhead	2	$1,225.00	$2,450.00
Unibrain	Wide Angle 80.95 deg Firewire Camera	1	$81.75	$81.75
Novatel	Propack-LB DGPS	1	$7,995.00	$2,995.00
Sick	LMS-221 Laser Range Finder	1	$5,927.25	$5,927.25
Yamaha	EF 1000is Generator	1	$700.00	$700.00
Total Cost			$20,081	$12,738.99

9 - CONCLUSION

Johnny-5 is an autonomous ground vehicle that was designed and fabricated by students at Virginia Tech. Johnny-5 was designed using the latest design and simulation tools, resulting in a reliable, compact, and safe product. An onboard generator can power the vehicle for up to 9 hours of continuous operation. A single powerful computer running National Instrument's LabVIEW software streamlined systems integration. We believe Johnny-5 will provide an adaptable and reliable platform for this and future competitions.