The Virginia Tech Autonomous Vehicle Team presents:

Johnny-5

Required Faculty Advisor Statement

I certify that the engineering design of the updated 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

In the 2004 International Ground Vehicle Competition (IGVC), an earlier version Johnny-5 won the grand prize, placing first in the autonomous challenge, second in both the design competition and the navigation challenge. Virginia Tech is proud to enter a refined version of Johnny-5 in the 13th annual Intelligent Ground Vehicle Competition. Johnny-5 will compete in the Autonomous Challenge, Navigation Challenge, and Design Competitions. Improvements to Johnny-5 include a major electrical system redesign, better system integration, and refined software. These improvements promise to make Johnny-5 more reliable, more functional, and easier to operate. 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

Each member of the design team participated in the 12th annual IGVC competition so they had first-hand knowledge of the requirements of competition and areas where Johnny-5 could be enhanced to improve the safety, reliability, performance, and usability of an already exceptional vehicle platform. Using this knowledge and experience a detailed list of improvements was created which would increase the safety, reliability, performance, and usability of Johnny-5 during the 13th annual IGVC competition. The overriding goal of the design team was to create a safe 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 Target Customers

The following primary customers were identified by the design team: (1) IGVC judges and sponsors who will evaluate vehicle performance, (2) the team faculty advisor who will evaluate overall vehicle design, (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 13th annual IGVC rules and the need to provide a reliable test platform for ongoing unmanned systems research at Virginia Tech.

2.2 Design Planning Process

A methodical design process is essential for the successful development of complex systems such as Johnny-5. The team used the Kano design method described in *Attractive Quality and Must-Be Quality Method* (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996) to guide the design process. Figure 2.1 illustrates this simple common sense approach to the design process. For example, for acustomer to be fully satisfied a product must first meet the basic "must have" needs. On Johnny-5 these needs include having a sensor suite capable of providing the necessary perception providing a reliable system for testing and evaluation of software, meeting all safety requirements, and complying with the 5 mph maximum speed limit. The Kano model predicts that customer satisfaction will increase linearly with improvements in performance parameters such as the maximum reliable navigation speed of the vehicle and the continuous run time for testing. Finally, the Kano model suggests that customer satisfaction is strongly enhanced by unexpected features that are not found in competing products, Kano refers to these features as delighters

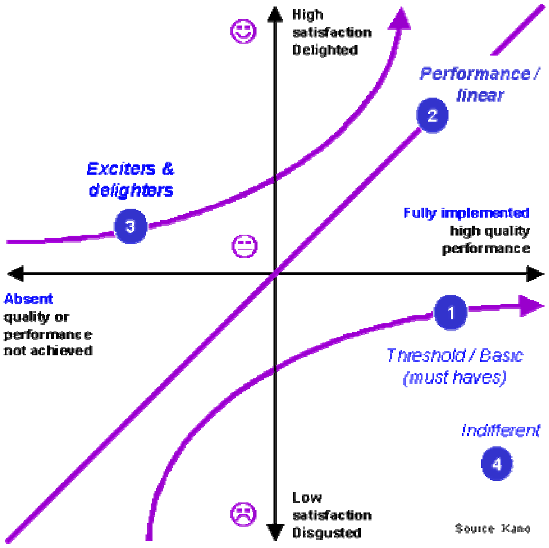


Figure 2.1 Kano design methodology

Kano's method allowed the design team to focus on the improvements necessary for increased customer satisfaction while continuing where the previous design team left off. We believe that the use of the Kano model provided a simple and efficient approach to the redesign of Johnny-5.

2.3 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 performance of the 2004 IGVC entries from Virginia Tech were evaluated. Based on this review, the following desired improvements were identified: (1) improved performance in the navigation challenge, (2) increased reliability from a system integration standpoint, (3) a more reliable electrical system, and (4) additional delighters to increase customer satisfaction were needed. Improvements to the IGVC simulator software was also cited as a desirable support tool. With Johnny-5 winning the grand prize and Virginia Tech's Gemini placing third overall at the 2004 IGVC competition, the design team focused on refining waypoint navigation, safety, mobility, maintainability, and user interface features of Johnny-5.

2.4 Design Improvements

Although Johnny-5 finished second in the Navigation challenge in 2004, there were clear opportunities for improvement. The team decided that a full redesign of the navigation and obstacle avoidance software was necessary. This will be further detailed in the software section of the report. The system integration on Johnny-5 for the 2004 IGVC was not completely reliable so the team decided to reassess the system integration components. This was evidenced by multiple sensor drop-outs and failures. Finally, the electrical system on Johnny-5 was far to large and used components that were difficult to obtain off the shelf. The design team found it necessary to completely redesign the electrical system using commercial off-the-shelf (COTS) components.

After the plan was developed to improve Johnny-5, the team set out to implement the changes while attempting to reduce down time. The team continually tested and analyzed the improvements during fabrication to ensure a quality product.

2.5 Team Organization

The design team is made up of graduate mechanical engineering students Brett Gombar and Andrew Bacha. Using the knowledge from the 2004 IGVC competition, both students were responsible for the improvements made to the electrical system, software, and vehicle frame. Both students also worked as graduate advisors for Virginia Tech's newest vehicle Polaris Overall, a total of 300 student hours were spent on design, fabrication, and implementation of Johnny-5.

3 DESIGN INNOVATIONS

Several design innovations, or Kano delighters, are incorporated into Johnny-5. Standard on Johnny-5 is the jack stand which continues to facilitate safe testing of vehicle motor controls. The success of this feature has motivated all three Virginia Tech teams to incorporate a jack stand into their vehicle designs. This innovation was motivated by the observation that team members sometimes carried concrete blocks to the test field to serve as jacks.

A second innovation is the on-board gas-electric hybrid power system that gives a 10 hour full load run time before refueling of the generator is necessary. This system will be described in detail in Section 5.1.

New for competition this year is a colapsable mast. This feature was implemented to allow the vehicle to be easily transported in a van or similar cargo vehicle. In previous years, vehicle masts were one solid piece and had to be removed in

Figure 3.1 Collapsable mast in transport position

order to transport the vehicle. This involved a time consuming and tedious process of disconnecting sensors, removing the mast, and reassembly of the components once a test site was reached. A collapsable mast elminates all of these problems and reduces downtime.

4 MECHANICAL SYSTEM

The mechanical system of Johnny-5 proved to be reliable and functional during competition and throughout extensive testing. Vehicle testing prior to the 2004 IGVC competition, performance during competition, and testing since competition has turned up no mechanical problems in the base vehicle and drive train of Johnny-5. Therefore, the mechanical systems of Johnny-5 received very minor modifications.

4.1 Vehicle Chassis

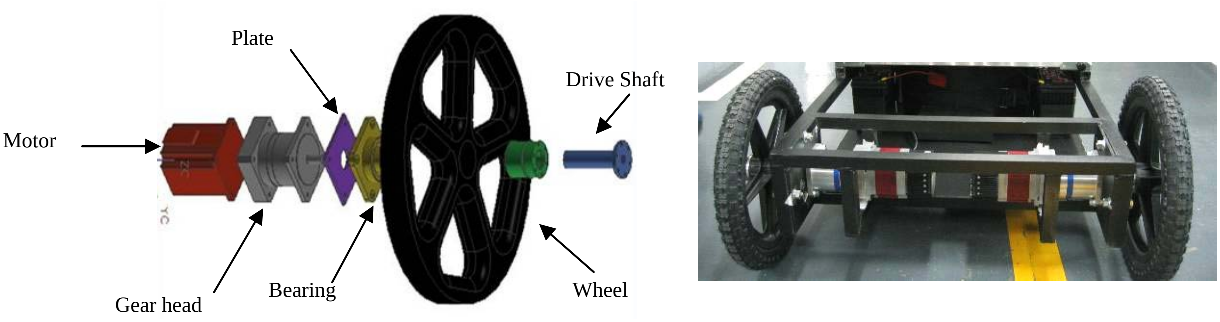
Johnny-5's chassis underwent no major revisions during the design process. The final chassis measures 25 by 35 by 8 inches. With two 16 inch rear drive wheels and a 10 inch front caster wheel, the vehicle has a ground clearance of 3.75 inches. A 1/16 inch 6063 aluminum plate covers the bottom of the frame and plastic panels cover the sides. All components can be easily removed from the chassis for maintenance. The chassis is constructed from welded 1" 6063 aluminum tubing chosen for its lightweight and nonferrous characteristics which reduce magnetic interference with the digital compass and signal lines. Finally, an aluminum cover protects the onboard equipment from weather elements.

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 drive design and weight distribution aids in traction as 60% of the weight is in the rear of the vehicle. Care was taken to mount heavy components such as the generator and batteries lower in the vehicle to lower the center of gravity, improving Johnny-5 maneuverability.

Figure 4.1 Vehicle Chassis

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 the right 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 features an eccentric locking collar that constrains 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

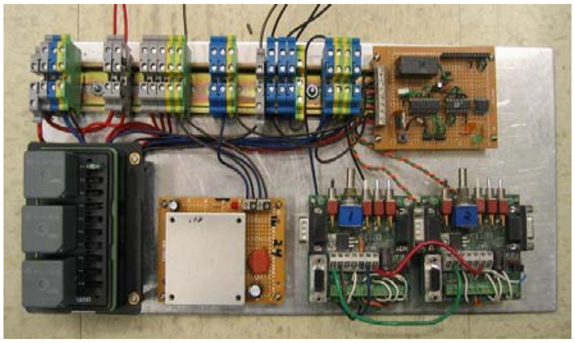


Figure 5.1 E-box Component Layout

Safety, reliability, COTS parts, and compactness are the principal goals of the electrical system. The electrical system provides communication between the computer, sensors, and motors as well as power to all on-board devices. Safety was addressed by creating a detailed electrical schematic in CAD, using COTS automotive components, and implementing two emergency stop systems. Each wire is color coded according to voltage with red wires carrying 12 Volts, blue wires carrying 24 Volts, and black wires being ground wires. The use of COTS automotive components was motivated by the need to purchase replacement parts at any local automotive repair shop. Additionally, automotive components can better withstand the dynamic conditions experienced on the vehicle. Compactness was also aided by the use of automotive components and the new electronics plate is contained in a volume of 768 in^3 while the previous electronics box was contained in a volume of 1632 in^3. Finally, rugged mil-spec environmentally sealed connectors are used to connect communication and power lines to the electronics plate.

5.1 Power System

Johnny-5's power system, shown in Figure 5.2, 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.

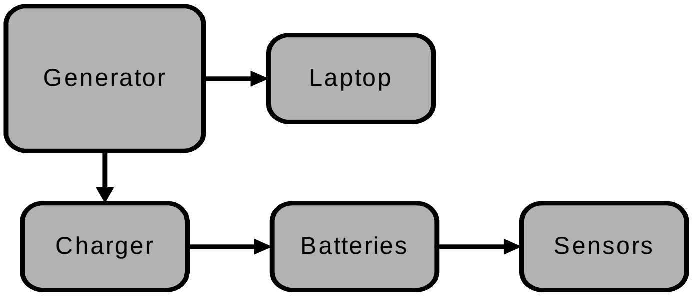


Figure 5.2 Block Diagram of Hybrid Electrical System on Johnny-5

The generator has a dry weight of 27 lbs and will produce 900 watts of power. As shown in Figure 5.2, 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. Care was taken to select sensors which could withstand a wide voltage range which eliminates the need for multiple voltage regulators. Johnny-5 only contains one voltage regulator to power the laser range finder due to its sensitive input voltage requirements.

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 10 hours before refueling is necessary. With onboard components consuming 42% (at maximum power consumption) 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. The Yamaha EF1000iS generator independently adjusts engine speed to match power load demand, resulting in greater fuel efficiency and reduced noise.

Table 5.1 Power Consumption of Johnny-5

Instrument	Voltage (volts)	Current Draw (amps)	Power (watts)
Motors	24	4	96 (x2)
Laptop	20	6	120
Laser Range Finder	24	2.5	60
DGPS	12	0.1	1.2
Digital Compass	12	0.02	0.24
Camera	12	0.075	0.9
Total Power Consumption			374

5.3 Motion Control System

The control system of Johnny-5 was simplified by using the integrated Quicksilver drive system. The motor interface is handled through a single RS-232 communications line. Each 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.

6 SENSORS and SYSTEM INTEGRATION

Electronic sensors and a laptop computer are used to gather course information, process the data, and decide the vehicle's path. 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.

- **Sick LMS 221 -** Laser Range Finder (LRF) scans for obstacles in a 180˚ planar sweep in 1˚ increments. The sensor is accurate out to 80 meters but is limited to a 2.5 meter range durring competition with a 15 Hz update rate. 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. Used in the Navigation Challenge to determine vehicle position and in the Autonomous challenge to determine if a reversal of course has occurred. It has a horizontal accuracy of 15 cm 99% of the time.

- **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. It is accurate from 0.5 to 1 degree depending on tilt.

- **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.

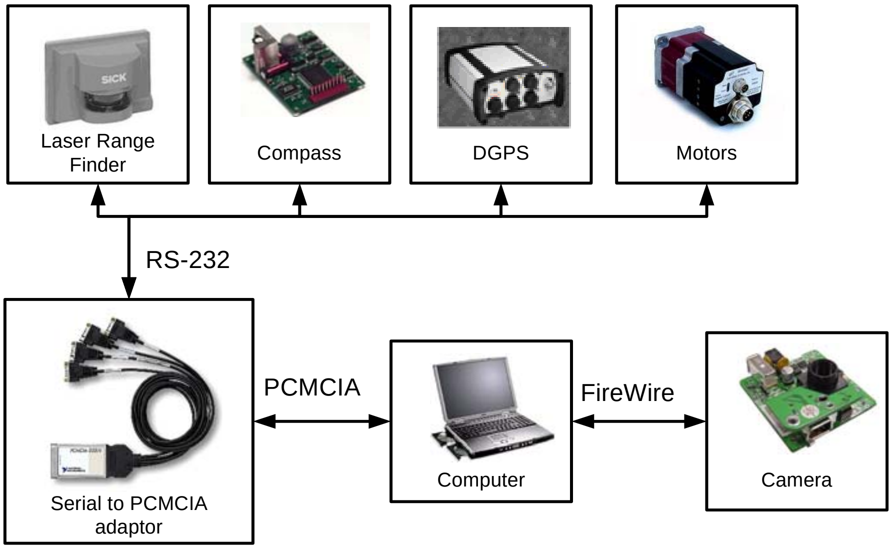


Figure 6.1 System architecture and communications protocols on Johnny-5

Figure 6.1 shows the native communication standard (RS-232 FireWire) and a serial to PCMCIA adapter used to interface the RS-232 devices to the computer. In the original design a serial (RS-232) tu USB converter was used to interface the serial devices to the computer. During testing, this converter was found to malfunction unexpectedly. Due to the difficulty in adequately resolving the issue, the design team decided to replace the converter with National Instrument’s PCMCIA-232/4 serial to PCMCIA 4 port adaptor. Testing the current system has shown the serial to PCMCIA adapter to be reliable.

6.1 Sensor Communications and Signal Processing

As described above, each sensor has an independent line of communications to the computer. However, care must be taken to analyze the data coming from each sensor correctly. Each sensor interface is designed to output the most recent complete data frame. This prevents the problem of a partial message corrupting navigation algorithms and aids in error checking. Also, data from each sensor is taken independently and analyzed according to the specific sensor. The laser range finder, differential GPS, digital compass, and motors on Johnny-5 have signal processing built into their hardware. It is therefore unnecessary to do any further processing to correctly interpret the data coming from the sensors.

7 SOFTWARE

All software running on Johnny-5 was developed using National Instruments LabVIEW 7.1. Last year, the Autonomous Vehicle Team of Virginia Tech experienced great success with LabVIEW and has decided to standardize on this language for all programming needs. 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.

7.1 Simulator Software

Software debugging and quantifying software performance are difficult tasks that have challenged developers of autonomous systems. To address these issues, Virginia Tech continues to make extensive use of a custom-developed simulator for software validation, benchmarking, and optimization. New features have been added to this simulator to make it more realistic and to ease the migration to the actual vehicle. The AVT Simulator is a software library that allows the user to construct a virtual world with simulated lines, obstacles, waypoints, and vehicle dynamics mimicking previous IGVC challenges. Figure 7.1 illustrates the basic structure of the simulator software.

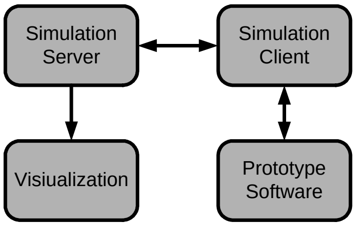


Figure 7.1 Simulation software structure

Included in the new simulator library are added features such as a vehicle creator, which allows the user to create an Ackerman or differential drive vehicle with sensors placed at user-defined locations on the vehicle. Visualization, sensor configuration, vehicle configuration and recording options are handled by the simulation server. The simulator client interfaces with the simulation server and provides virtual sensor outputs for prototype software. The prototype software, created by the software designer, interacts with the virtual sensor interface from the simulation client and allows the designer to test programs in an idealized virtual world. A global map of a simulated environment with obstacles, waypoints, and the vehicle path (in purple) is shown in Figure

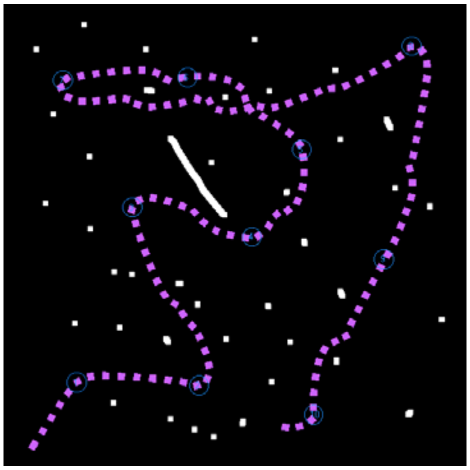


Figure 7.2 Vehicle path (purple), waypoints (blue), obstacles (white) in a simulated IGVC navigation challenge

7.2. The simulator eliminates downtime due to vehicle maintenance, poor weather conditions, and multiple software designers vying for vehicle testing time. Once the prototype software has been proven and debugged on the simulator it can then be transported to the vehicle for testing.

7.2 Software Structure

To simplify software development, the programming structure shown in Figure 7.3 was implemented in both the Autonomous and Navigation Challenges. Sensor data is collected simultaneously through individual communication channels and 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 subsumption architecture 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.

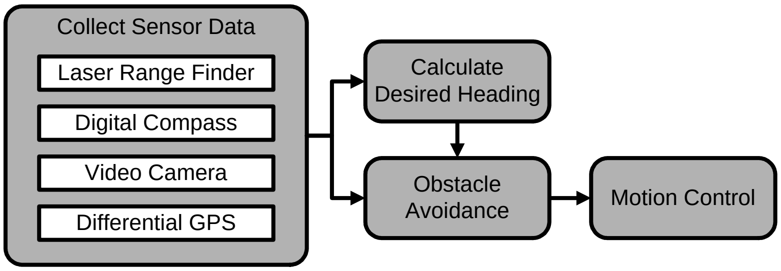


Figure 7.3 Software architecture for autonomous and navigation challenges

7.3 Autonomous Challenge

The software programming specific to the autonomous challenge is contained in the routine to calculate the desired heading of the vehicle. A flowchart of this algorithm is shown in Figure 7.4. The goal of the autonomous challenge software is to set the desired vehicle heading between the course boundary lines. This larger task can be broken down to the tasks of detecting the lines, analyzing the lines, and setting the desired direction.

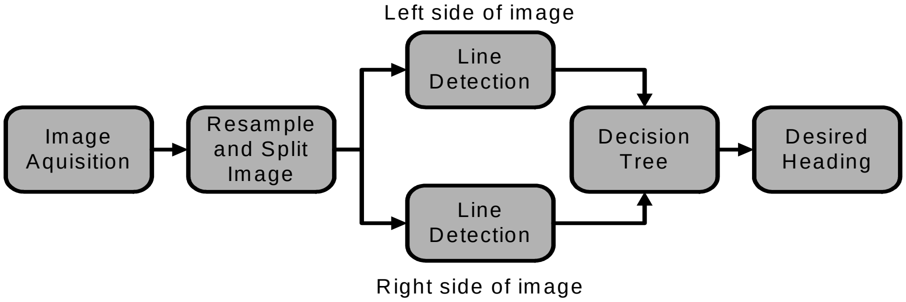


Figure 7.4 Autonomous challenge software diagram for calculating the desired heading

Once the image has been acquired it is resampled, taken through a threshold operation, and split into a left and right half. These three steps are intended to reduce processing time, eliminate noise, and facilitate a structure for the line detection algorithm respectively. Lines are detected using an algorithm known as the Hough Transform. Figure 7.5 shows the result of the Hough Transform used on an image of a line on grass after a threshold operation. Notice, that the Hough Transform is not affected or skewed by the noise to left of the line in Figure 7.5. 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. This information is then passed to a decision tree which determines the best direction for the vehicle to move towards.

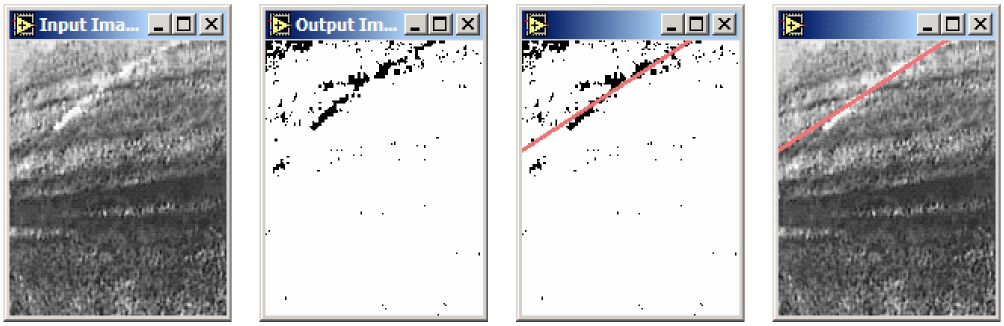


Figure 7.5 Original Image (a), After Threshold (b), Detected Line (c), and Original Image with Detected line (d)

After the line detection process, the results are fed to a decision tree. This step takes into account the line score and line orientation. A low line score may indicate that the image identified noise as the line, while a high line score indicates a prominent line in the image. Orientation of the line will help determine the desired direction of the vehicle. 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.

The success of the autonomous challenge software was apparent in the 2004 IGVC competition. Modifications to the software focused on making the code easier to read and edit and on making the code run more efficiently.

7.4 Obstacle Avoidance

The obstacle avoidance process starts by mapping detected obstacles into 3x3 inch squares in an occupancy grid. During the Autonomous Challenge, the equations of lines generated by the Hough Transform are considered obstacles. We also consider distinct regions containing more than 80 white pixels as potholes. Since the camera can only detect lines 8 ft away from the vehicle, the laser range finder range 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.

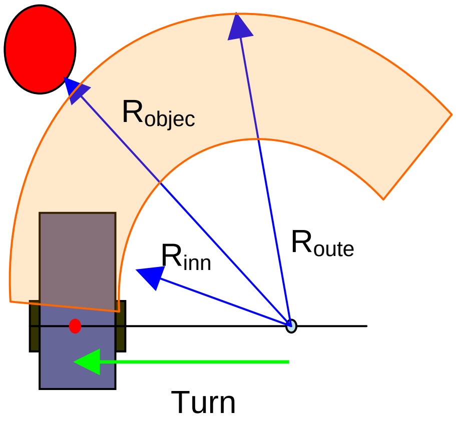


Figure 7.6 Distances used during obstacle

Our software examines potential 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 7.6. The obstacle avoidance program analyzes 36 different paths each cycle. Each path is checked for obstacles and 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.

7.5 Navigation Challenge

Johnny-5 placed second in the 2004 IGVC Navigation challenge. However, the performance of the vehicle was hindered by software bugs. To improve performance, the design team decided to take a different approach for competition this year.

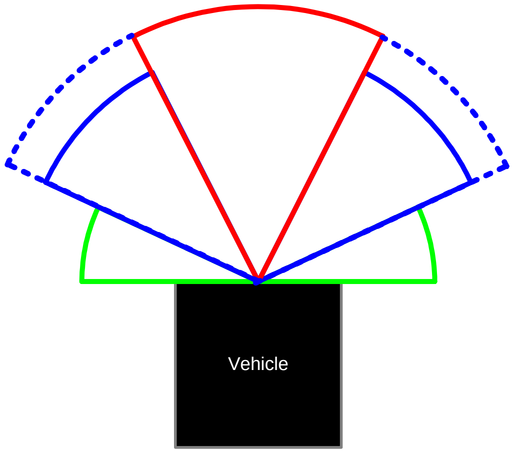


Figure 7.7 Obstacle avoidance regions for the navigation challenge

The previous method of obstacle avoidance used a local map approach. The design team has developed a novel behavior based obstacle avoidance approach for competition this year. A diagram of this approach is shown in Figure 7.7. The algorithm operates using a subsumption architecture. First, a desired direction is computed using the vehicle's current location and the location of the goal waypoint. Using this information, the vehicle will then travel to the waypoint. If an obstacle is encountered while traveling to the waypoint the obstacle avoidance software then takes over motion control.

Obstacle avoidance is controlled by a novel behavior based approach. Using predefined regions in front of the vehicle, shown in Figure 7.7, the vehicle will decide which direction to turn based on which region contains an obstacle and the direction to the goal waypoint. The first priority is to avoid obstacles in the center (red) region, followed by the middle (blue) and side (green) regions respectively. The dashed blue lines indicate what happens if an obstacle is detected in the center region. Testing in the simulator indicated a tendency for the vehicle to oscillate away from then back into an obstacle that was detected in the center region. To fix this the two middle regions were grown out to the length of the center region and an obstacle that was avoided in the center region would then transition into a middle region and no longer turn back towards an obstacle.

Testing on both the simulator and on the real vehicle has shown this algorithm to be robust and simple to implement. The emergent behavior from this algorithm is a tendency for the vehicle to round obstacles or follow along a wall of obstacles until a clear path to the goal is reached. We are confident that Johnny-5's performance in the navigation challenge will be more reliable than last year.

8 PREDICTED PERFORMANCE AND TESTING

8.1 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 was able to reach speeds of 5 MPH on level ground.

8.2 Ramp Climbing Ability

The Silvermax motors have a stall torque of 422 in-lb after the 10:1 gear reduction. 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.

8.4 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. 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.

9 SAFETY CONSIDERATIONS

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 both a remote controlled E-stop and vehicle mounted E-stop push 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.

9.1 Costs

Table 9.1 shows the cost to fabricate Johnny-5.

Table 9.1 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	Serial to PCMCIA converter	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

10 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 system. 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.