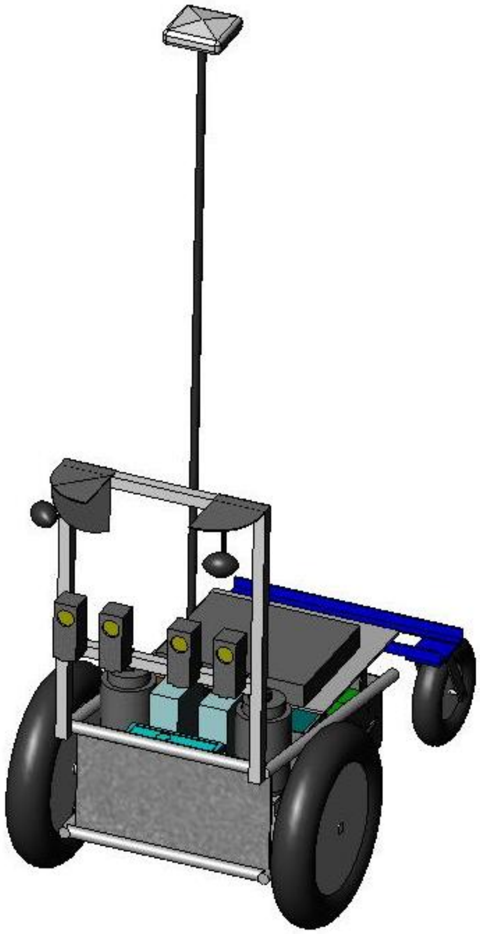
Q

2007 IGVC DESIGN REPORT



Team Members
Saroj Aryal, Susmita Bhandari, Adam Fine, Nabil Imam, Anant Raut,
Neil Robertson, Eli Roxby

Advisor
Dr. David Ahlgren

Trinity College
HARTFORD CONNECTICUT

Contents

Faculty Statement

This is to certify that Q has undergone significant redesign in both hardware and software from last year's IGVC entry. The Q team members worked on the robot as an Independent Study project and received 1.0 credit (3 credit hours) per semester. This project is significant and has led to many senior design projects in both Computer Science and Engineering.

Dr. David J. Ahlgren,
Karl W. Hallden Professor of Engineering, Trinity College

1. Introduction

The Trinity College Robot Study Team presents Q, a new autonomous vehicle for the Intelligent Ground Vehicle Competition (IGVC). Q is named for the omnipotent entity found in Star Trek and for the gadget guy in the James Bond series. A new design approach was used to develop Q. There is a focus on a simplified control system, rather than the highly modular systems of previous years. Based on a modified wheel chair chassis, Q is a stable and reliable platform. The team continues its tradition of exploring innovative technologies by employing a modern high density battery system.

2. Innovation

The 2007 IGVC competition is the debut of a new autonomous robotics platform from the Trinity College Team. An extensive analysis of performance during previous years resulted in the decision to design a new robot for the 2007 competition. Q uses new control algorithms and a new physical platform, only the sensor hardware has been carried over from previous designs.

Q features JAUS level 2 compliance and a centralized control system. Additionally, closed loop speed control and image processing obstacle detection will significantly improve the performance of Q over its predecessors. A modern power system increases efficiency by using reduced state of the art high energy density batteries.

The base platform is a modified PerMobil Trax off road wheel chair frame. This is a significant improvement in reliability and stability of the platform compared to the custom built platforms of previous entries.

A Dell Inspiron D820 with an Intel T7400 Core 2 Duo processor and 2GB of ram running NI LabVIEW 8.21 acts as the central control for Q. A Roboteq AX3500 dedicated motor controller and a pair of domestically manufactured US Digital E5S optical encoders act the platform for the closed loop speed control. A NI Compact FieldPoint (cFP-2020) is used as dedicated I/O. Rather than separating processes between three computers as in the past; all processing will be performed on the laptop, this allows for a simplified communication structure between components.

Q also features new control algorithms; a dynamic waypoint algorithm is used for the navigation challenge; this is an improvement over the static waypoint order of previous years. A modified Vector Field Histogram (VFH) algorithm has been implemented this year; this is a significant improvement over the state table based navigation of previous robots. Rather than reacting to obstacles within the field of vision of the robot, a path will be planned based on all known obstacles on the course. Obstacle detection via image processing will increase data available to the new algorithm.

Q uses cutting edge battery technology by employing a pair of Nilar 24 Volt 9Ah NiMH batteries and an UltraLife 30V 6Ah battery. These batteries provide high energy densities and are ideal for autonomous robotics.

3. Design Process

3.1 Team Organization

The team was organized into five main groups based on the various task families within the scope of Q. Most members of the team were in more than one group. This year sees the addition of the systems, management and testing groups to the software and mechanical groups. The systems group was created in order to facilitate communication between team members and requires collaboration across specialties. This new format enables more efficient communication between team members since most necessary communication happens within groups rather than across groups.

Traditional project management techniques were implemented throughout the project. This includes a clear definition of the scope before design began as well as a group dedicated to managing risk throughout the design process.

3.1.2 Group Definitions

The following is a definition of the responsibilities of each group.

Management

This group defines the scope of the project and designates team members and tasks to each group. The group is also responsible for identifying risk throughout the project. Risk includes falling behind schedule, changing the scope of the project or not documenting a task. This group is also responsible for recording weekly progress and updating the Gantt chart accordingly.

Documentation and Testing

This group is in charge of creating testing procedures and identifying the required documentation for each task. The group also makes sure that Q complies with all IGVC design regulations.

Systems

The Systems group works with the mechanical and software groups to implement an optimized design. The group is responsible for connections between components as well as power, sensors and communications.

Mechanical

This group is responsible for the design, mounting, and documentation of all hardware.

Software

The software group follows standard software design protocol to meet the scope of the project.

3.2 Design Methodology

The design process for Q began with the definition of a project scope based on the analysis of customer requirements as determined by IGVC rules, innovation goals and an evaluation of previous performances. An iterative process of reverse scope creep was used to design Q. In this process, the initial goals were scaled back until the design became feasibly based on the time and resources available.

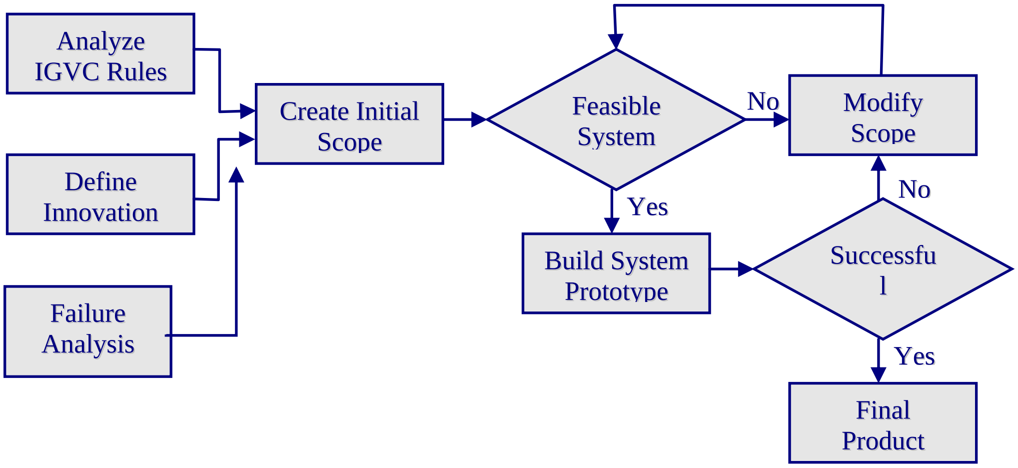


Figure 3.1: Iterative Design Cycle

4. Mechanical System

4.1 System Layout

The physical platform of Q is a modified Permobil Trax off road wheelchair. It is a steel frame with designated compartments for each component. The frame can support a payload of over 250 lbs and has a small footprint of 40” by 26”. Component placement was carefully designed in order to isolate the power and control systems and to minimize wire lengths. A slider assembly was designed for the laptop platform to allow easy access to components underneath. The sensor frame was constructed of 80/20 extruded aluminum channel, which allowed for quick changes to component layout, the sensor frame folds down onto the body for easy transportation. Figure 4.1 shows the modified chassis.

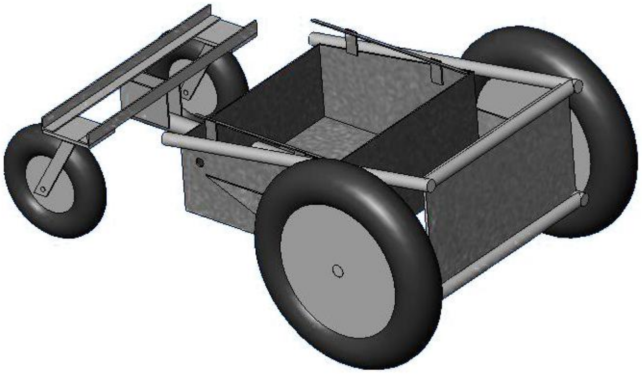


Figure 4.1: Q Chassis

4.2 Drivetrain

Q is powered by a pair of 500W Leroy Somer MBT1141 motors geared with a 26:1 ratio. The low voltage continuous DC current motors provide high torque and allow for simplified control compared to DC stepper motors. The Roboteq AX3500 motor controller provides an extended 40A per channel with 250A peak. There is a theoretical maximum speed of 9.5 mph although the speed is limited to 5 mph in order to comply with IGVC regulations.

4.3 Mobility

Q has a differential drive system with a pair of rear mounted casters. The casters are mounted on a pipe that pivots to keep the casters in contact with the ground on any level terrain. This configuration significantly improves mobility by enabling Q to turn around in place if confronted with a dead end. This configuration also allows a greater range of motion as there is no restriction on the heading of Q due to turning radius. The caster system is mounted on a pipe that pivots in order to keep the casters in contact with the ground at all times.

4.4 Reliability

Q is based on a professionally manufactured platform. The customer base of the Permobil Trax off-road wheel chair demands a reliable and safe platform. The modifications performed by the team kept this ideal in mind. There is a front suspension system that limits vibration to the components. The caster system is designed to adapt to uneven terrain. This guarantees that the main platform of the robot will always be level with the ground, with the two wheels and two casters on the ground at all times. This design provides greater accuracy for each sensor system, since stability is maximized and vibration is minimized.

The 80/20 extrusion forming Q’s sensor frame is designed for industrial environments and is resistant to dirt, moisture, and vibration. The extrusion’s profile is tapered to allow all hardware attached to it to be self-locking, simplifying the choice of hardware and further reducing weight. All critical electrical connections utilize positive locking connectors that are immune to shock and vibration and provide tactile feedback to confirm proper connection. Wiring is carefully dressed with strain reliefs to prevent fatigue failure. All components are mounted using multiple points and protected by durable acrylic panels that are resistant to the environment and to impact, for all-weather operability. The wheels and casters are loaded at a fraction of their rated design loads, giving a large margin of safety in the mechanicals.

5. Electrical System

The onboard electronics and power distribution system have been dramatically improved in Q to ensure reliability and robustness during operation. A custom power distribution circuit with redundant safety features supplies three voltage levels from one battery source to accommodate the various power requirements of the electronics. A separate power source is used for the drive system; this isolation reduces the effect of noise caused by the motors on the rest of the system.

5.1 System Integration

The Dell Inspiron D820 laptop acts as the central control of Q. All image processing and navigation algorithms are performed on the laptop. The IEEE1394 cameras connect directly to the laptop. The Compact FieldPoint (cFP) is responsible for I/O and performs low level data collection. The digital compass, DGPS and sonar array are connected to the cFP. This data is sent over ethernet to the laptop, where it is processed and an updated speed is sent to the motor controller. The motor controller uses a PID algorithm in order to determine to correct amount of power to send to each motor. The optical encoders provide feedback for this algorithm. An RF remote control is used to control Q and perform a remote emergency stop if required.

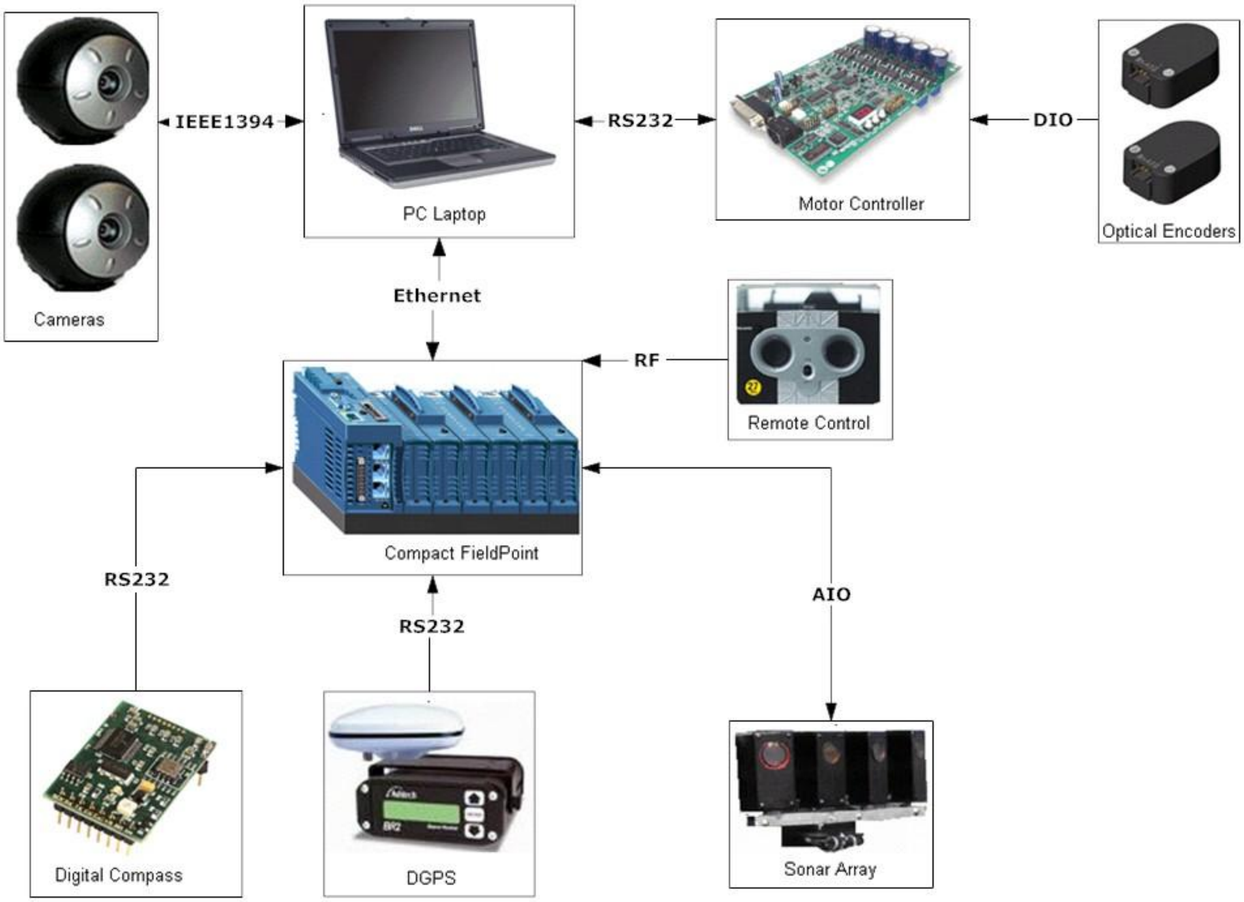


Figure 5.1: Control and Sensor System

5.2 Power Supply

Q’s power supply comes from two different battery sources. The two DC motors are powered using a pair of Nilar nickel metal hydride (NiMH) 24 VDC 9Ah batteries. This battery has a relatively horizontal discharge curve that enables it to provide a steady power over a range of voltages. It is highly compact and lightweight with dimensions of 278 x 129 x 57 mm and weight of 4.3 kg. Its features such as deep cycle capacity and high energy density together with its robustness makes this battery ideal for powering motors in an autonomous robotics setting.

The Nilar batteries are connected through the motor controller to each of the motors. A 100A circuit breaker is installed between the batteries and motor controller in order to safely limit the current drawn by the system.

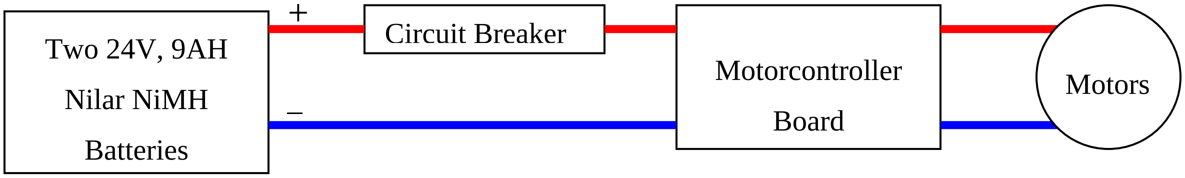


Figure 5.2: Drive Power System

The entire sensor and control system, except for the laptop, is powered using one UltraLife Lithium Ion battery. The battery provides 6 Ah continuous at 30 VDC, resulting in a run time of approximately one hour. It is lightweight and compact, weighing in at 1,440 grams. The state of the art design of the UltraLife battery allows it to have a high energy density and provide a total of 173 WH of continuous power.

The power from the UltraLife battery is converted to +5, +12 and +24 Volt regulated potentials by DC-to-DC converters that are mounted on a custom printed circuit board. The board accepts input voltages in the range of 18-21 VDC. For safety, several circuit breakers and heat sinks are put in place to limit the current and dissipate heat respectively. A regulated clean supply of voltage is important for onboard equipment, and bypass capacitors between each voltage line and ground achieve this purpose. Figure 5.3 illustrates the power distribution of onboard components.

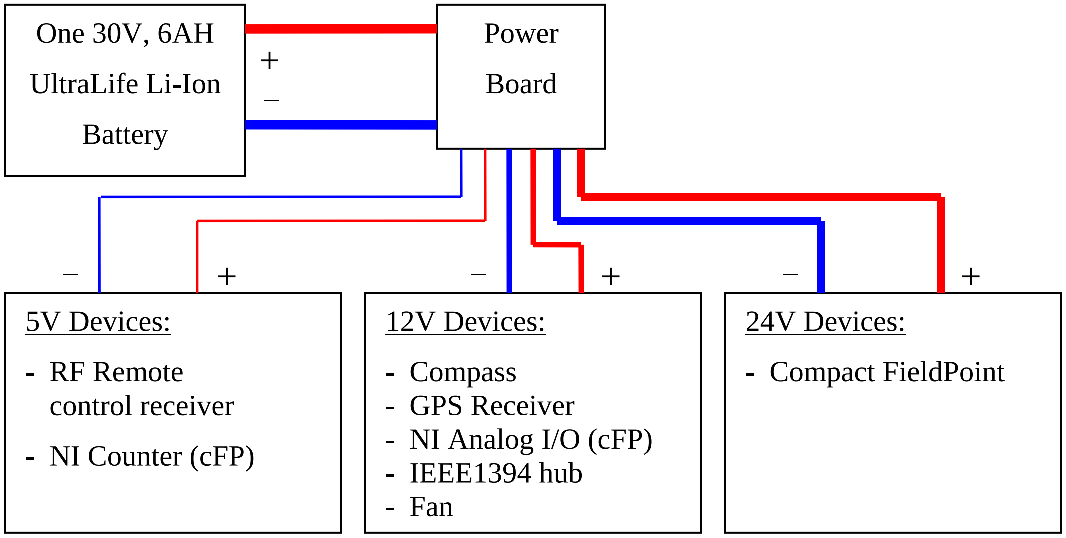


Figure 5.3: Control and Sensor Power System

5.3 User Interface

User initialization of Q occurs via the user control panel located next to the laptop. The control panel features an on-off switch for the main system along with a switch to select either navigation or autonomous challenge mode. The panel also features an analog display for the current voltage level of the system battery as well as the 5 V, 12 V, and 24 V lines on the power supply. Q can also be operated using a remote control that directly controls the motors and the E-Stop as a safety precaution. Q can be programmed over Wi-Fi or directly from the onboard laptop.

6. Sensors

The advancement of commercially available sensor systems has made intelligent and efficient obstacle avoidance a simplified process in mobile robotics. Q utilizes four sonar sensors, two digital cameras, a compass and a differential GPS to perceive its environment and support intelligent operation.

6.1 Digital Cameras

Q uses two ADS Tech Pyro cameras for its vision system. Both cameras use a 640 by 480 pixel resolution with an update rate of 15 frames per second (fps) and a 52° viewing angle. They are interfaced to the laptop through an IEEE1394 hub. The cameras are mounted with custom built devices that allow for 90° of freedom in both the vertical and horizontal direction

6.2 Sonar Sensors

Obstacle avoidance is carried out by a bank of four sonar sensors that are interfaced with the NI counter module (cFP CTR-502). Each SensComp/Polaroid 6500 ranging module is capable of detecting objects between 6 inches and 35 feet to an accuracy of 1%. The sensors are contained in custom built housings that are mounted using a frame of 80/20 extruded aluminum channel.

6.3 Digital Compass

Vehicle orientation on Q is obtained using a Honeywell HMR-3300 digital compass that is interfaced to the cFP over RS232. The compass provides precise readings for the azimuth angle and has a range of ±60° for pitch and roll data with an accuracy of ±1°.

6.4 Differential Global Positioning System (DGPS)

Vehicle localization is achieved by means of an Ashtech BR2G-S GPS receiver. The receiver combines dual channel beacon receiver technology with industry standard Ashtech 12-channel precision GPS for reliable readings. The receiver is interfaced with the NI cFP module through 232. The antenna is mounted on a carbon fiber rod at six feet, which is the highest allowed by the IGVC competition.

7. Software

This year there was a focus on efficient software design; source control was implemented and the NI LabVIEW programming environment was used. LabVIEW enables efficient and effective software design by providing integrated source control and project management. LabVIEW provides a graphic programming interface which allows complicated algorithms to be represented with simple graphic controls.

7.1 Obstacle Avoidance

Obstacle avoidance represents one of most substantial innovations over previous years. The obstacle avoidance algorithm is a modified Vector Field Histogram (VFH) algorithm. This algorithm takes a polar histogram representation of obstacles and plans a path accordingly. Data from the sonars is by its very nature a polar histogram. Camera data is represented as a binary bitmap. This bitmap is converted into a grid and placed into a localized occupancy grid in the correct location based on camera orientation. This occupancy grid is converted into a polar histogram. The sonar and camera histograms are combined and the resulting histogram is analyzed for openings between obstacles. Openings are categorized as wide or small. Q will navigate through the middle of a small opening and to the side closest to the target direction for a large opening.

The algorithm utilizes a cost function which considers the target direction, wheel orientation and previous direction. When there is more than one opening between obstacles, this cost function is used in order to select the best candidate direction. The opening with the lowest cost is chosen. The result is a heading which represents the best path.

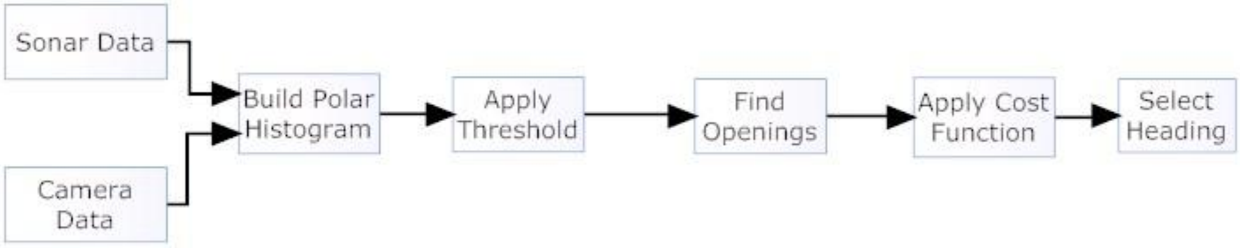


Figure 7.1: Modified VFH Algorithm

7.2 Navigation

Navigation is performed by applying the A* search algorithm on top of the obstacle avoidance algorithm. The combination of these algorithms allows for look ahead verification and ensures that a candidate direction of the obstacle avoidance algorithm actually guides Q around an obstacle. This is mostly important in the navigation challenge, where there is no clearly defined path. The navigation algorithm performs several iterations of the obstacle avoidance algorithm in order to determine the best path up to a defined distance in front of Q. For each candidate direction, a new polar histogram is created based on the projected location of Q, the obstacle avoidance algorithm is performed and another set of candidate directions is calculated. This results in a tree of candidate directions. The A* search method is used in order to selected the candidate direction with the lowest cost.

7.3 Image Processing

Images are extracted from two IEEE1394 digital web cameras in a real-time environment. The raw images are passed over to the laptop and processed by an algorithm which detects lines and obstacles. The image processing algorithm was developed using National Instruments IMAQ Vision Builder and utilizes hue, saturation, and luminance of an input image. In addition, the image is sent through a number of low pass and particle filters to reliably identify lines, potholes and any other obstacle. The thresholds for filtering are determined through statistical analysis, which makes the algorithm effective in a variety of outdoor lighting conditions. First a color analysis is performed in order to detect any non-white obstacle. A mask is created from this analysis and added to the original image. A threshold which identifies lines and white obstacles is applied to the masked image. The result is a binary bitmap which clearly defines obstacles. This bitmap is used by the obstacle avoidance algorithm.

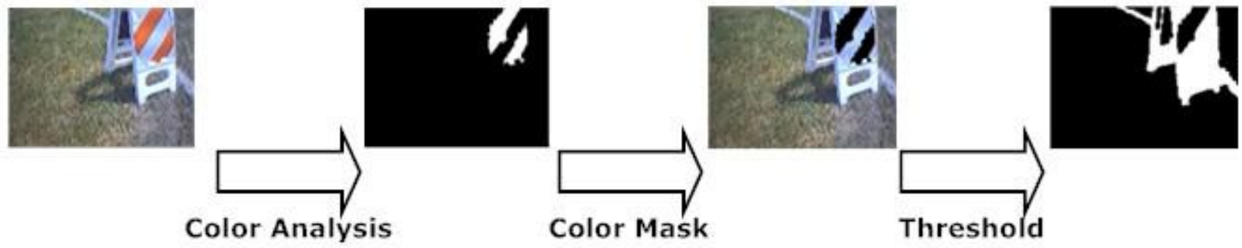


Figure 7.2: Image Processing Algorithm

7.4 Autonomous Challenge

An improvement over previous years is that the same algorithm is used for both the autonomous and navigation challenges. For the autonomous challenge the strategy is to set the target for the obstacle avoidance algorithm to a fixed distance in front of Q along the planned path. In cases where Q is approaching a turn, the target will be appropriately placed along the turn and within the boundaries of the lane. In case no obstacles or lines are present; Q assumes a lane width of ten feet and sets a target down the middle of the path.

7.5 Navigation Challenge

The navigation challenge strategy represents another improvement over previous years. The waypoint target will dynamically change based on information the robot leans about its environment. As more information is learned about the course, Q decides which waypoint is closest to its current location.

The first step in the path planning strategy determines the drive order of the waypoints. Since only the coordinates of the waypoints are given, and not the obstacle coordinates, the order is initially determined assuming that no obstacles are present. This is done by a fairly simple program that was written using knowledge of graph theory and discrete mathematics with ideas being borrowed from Dijkstra's algorithm. The program calculates the shortest path between all waypoints from a starting position. The procedure is illustrated in the following diagram.

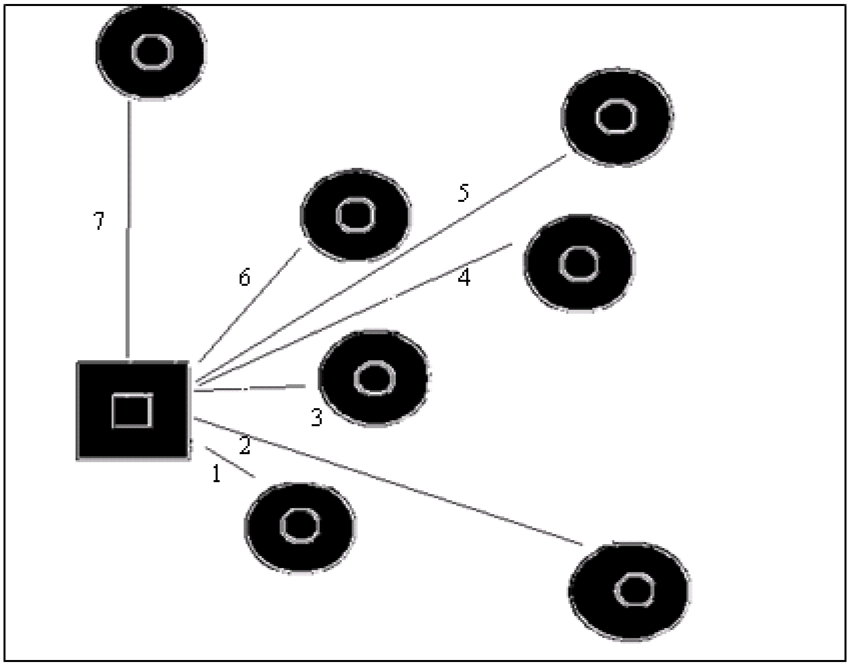


Figure 7.3: Navigation Algorithm

Distances of straight line segments from the starting location to each of the waypoints are calculated by the program. As Q gains knowledge of obstacles on the course, new waypoint orders are calculated based on the most efficient path to waypoints with obstacles in the way. After each waypoint is reached, the program is run again, with the most recently reached waypoint as the source, and all previous waypoints ignored. As more information is obtained about course obstacles, a more efficient waypoint order is determined.

7.7 Motor Control

The motor control is a closed loop system utilizing PID control. A lookup table is used in order to convert the speed and heading generated by the VFH algorithm to motor controller commands.

8. Safety

Safety has been given the utmost priority in Q. Care has been taken to properly wire all components with strain relief. The power supply also ensures safety of the electronic components by its use of circuit breakers to limit the current from exceeding two amps for each voltage line. In addition, the control panel serves as a safe interface to operate the vehicle.

The high current draw throughout the motor power system necessitate proper handling and care to ensure safety of the vehicle and team members during operation. The Nilar battery is equipped with a nylon-insulated, AWG 6 copper wire and quick connectors, rated at 50 Amperes, for easy and efficient connections to the vehicle's onboard circuitry. An industrial grade 100A circuit breaker interfaces the batteries and motor controller for additional safety.

The stopping of the vehicle is another safety consideration. Q can be stopped in three ways, each of which can bring the robot to a complete stop within two feet distance. One way is to use the red e-stop push button on the top rear end of the vehicle. Another method is to use the remote control to wirelessly stop the vehicle during its run. The effective distance for this method is 50 feet. The last method is the use of the on/off switch on the control panel. The multiple circuit breakers and fuses throughout the power system ensure that power will be cut to the motors in the event of a power failure.

9. JAUS

The team builds on the successful JAUS implementation of last year by implementing Level 2 JAUS compliance. Level 2 is specified as a demonstration that the vehicle only accept messages intended for it and to provide the Navigation Challenge waypoints upon request.

The laptop's built in 802.11g Wi-FI is used to send and receive JAUS commands. The LabVIEW programming environment includes code that is designed to enable communication using UDP packets. Each UDP packet is decomposed; the JAUS message header is checked in order to insure that Q is the target vehicle. Next, a look up table associates each JAUS message with an appropriate response from Q.

10. Predicted Performance

Extensive testing of all system was performed in order to ensure that Q is able to successfully complete each of the IGVC challenges.

10.1 Mobility

Q is driven by a pair of 500W motors at 3000rpm with a 26:1 gear head and 16" diameter wheels. This corresponds to a theoretical maximum speed of 9.5 mph on level surfaces. However, in compliance with IGVC speed regulations, the motor controller is configured to limit speeds to 5 mph.

10.2 Battery life

There are three battery systems; the laptop battery, Nilar batteries for the motor system and UltraLife battery for the remaining subsystems. The laptop battery has been tested at 2.5 hours runtime at full CPU load. The pair of Nilar batteries has been tested to a half hour of continuous runtime at maximum motor speed. With one lightweight UltraLife battery running aboard the vehicle during operation, the system is capable of 70 minutes of continuous runtime before the battery must be replaced

10.3 Complex Obstacles

The best way to handle obstacles such as dead ends is to avoid them by following a well planned path. If Q finds itself in a dead end, the VFH algorithm will cause Q to turn around until it finds a clear path. Potholes are detected using image processing and are consider in the same manner as all other obstacles.

10.4 GPS Waypoint Accuracy

The GPS receiver is accurate to within 1 meter of a waypoint and is unaffected by cloudy or overcast weather conditions. In testing, Q reached a variety of waypoints within an accuracy of about 1 meter.

Readings given by the GPS hardware were tested on a one-dimensional 50m space. Readings were taken at 1 or 2m intervals. 31m corresponded to 1 sec according to the Global Geodetic System. Thus, 1m corresponded to 1/31m, which equals 0.032 seconds or 0.0005 minutes. Hence a 0.0005 minutes change was expected in every 1m interval, and a 0.0011 minutes change was expected in every 2m interval. The average error for this test was 1.26m. With this accuracy, it is reasonable to assume that the GPS position is the absolute position of Q. This level of accuracy is sufficient for Q to cross the diameter of the waypoint circle.

11. Vehicle Cost

Throughout the design and fabrication process of Q a concerted effort was placed on minimizing the cost by actively pursuing industry donations and support as well as reusing components from previous robots. The table below shows each component used in Q along with retail cost and cost to the team. The NI hardware represents a majority of the cost of the system; it is possible to replace this hardware with inexpensive microcontrollers. Improved navigation algorithms also allow for a less accurate and less expensive DGPS system. The team also uses inexpensive sensors such as a standard webcam and ranging modules.

COMPONENTS	**RETAIL COST ($)**	**COST INCURRED ($)**
ADS Tech Pyro Cameras(2)	180	180
Ashtech BR2G-S DGPS	3350	0
Caster Assembly	150	150
Chassis	650	0
Encoders	100	100
Honeywell Compass (HMR-3300)	750	0
IEEE1394 Hub	50	50
Motors	1000	0
NI cFP	3188	0
Nilar Membrane NiMH 24V 9Ah Battery (2)	550	0
Polaroid 6500 Ranging Modules(4)	180	180
Power Supply Board	150	0
Remote Control	50	50
Roboteq AX3500 Motor Controller	400	300
UltraLife 30V Lithium Ion Battery	385	0
Wiring	50	50
Total	11183	1060

Table 11.1: Cost Itemization

12. Conclusion

Q is an autonomous vehicle designed by the Robotics Study Team (RST) at Trinity College. The vehicle features a reliable and sturdy frame which enables it to be used on many different types of terrain. Substantial innovation in the areas of control algorithms and the mechanical platform add to Q's ability to perform in any situation. Q provides a solid research foundation for a military autonomous vehicle. Its payload capacity and small footprint makes Q ideal for transportation of equipment in hostile environments. By the process of iterative design along with the help of the latest software tools and cutting edge battery technology, the RST has Q, which is an example of an efficient and effective autonomous vehicle that should perform well at the 15th annual IGVC competition.

13. Sponsors

- Connecticut NASA Space Grant Consortium
- Enterprise Rent-A-Car
- Honeywell International Inc.
- National Instruments
- Trinity College
- Travelers Insurance
- Teknicircuits Inc.
- UltraLife Batteries
- Nilar, Inc.
- PCB Express
- PerMobil Corporation
- Thales Navigation