

# The College of New Jersey

2008 Intelligent Ground Vehicle Competition Entry

Saturday May 31<sup>st</sup>, 2008

**Team Members:**

Jerry Wallace

Brian Fay

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## Chapter 1 - Mechanical Systems (Brian Fay)

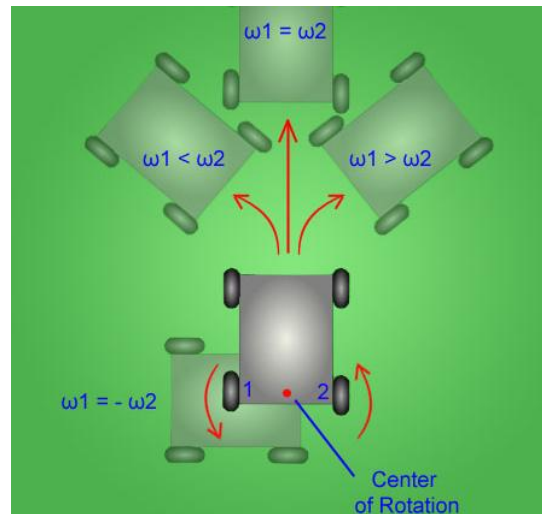
### *1.1 – Mechanical System Problems of 2007 NJAV*

This year's iteration of the NJAV project features a complete redesign of both the steering and drive systems to address issues discovered by last year's team at the 2007 IGVC competition. It was determined that there were two main problems with the mechanical systems onboard the vehicle. The previous motor used to rotate the drive-wheels could not provide enough torque to drive the vehicle up a steep 25% grade hills to necessary waypoints. Problems with the previous steering system were addressed where based on the inherent design of a rack and pinion system, the vehicle needed to be moving forward or backward to change its orientation. The rack and pinion system also meant a finite limit on how tight a turning circle the vehicle could maneuver, necessitating an algorithm where the vehicle moves in reverse to complete certain turns. Not only did this waste time at competition during the timed runs, but also introduced a greater possibility of disqualification and penalties: the vehicle has no sensors behind it, and could much more easily knock into an obstacle or move outside the course boundaries while backing up.

### *1.2 – Mechanical System Improvements for 2008 NJAV*

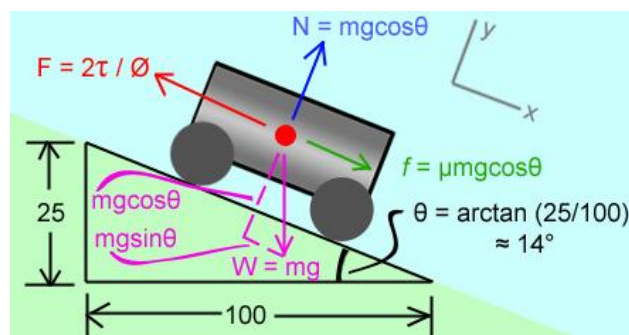
This year's vehicle accounts for both the aforementioned torque and steering problems with the implementation of one new system: a zero turning radius system. In a zero turning radius system, the drive wheels are controlled independently of one another as opposed to a typical setup of being linked mechanically to one drive shaft. This means the drive wheels may be operated at different velocities concurrently, allowing them to control not only the speed of the vehicle, but also the orientation. When the velocities of both wheels are equal, the vehicle moves straight ahead. When the velocity of the right wheel is greater than that of the left, the vehicle will rotate left in addition to moving forward, and vice versa. As the difference between these two velocities becomes greater, the turning radius will become smaller. Because of this principle, when the velocity of one drive wheel is equal in magnitude but opposite in direction to the opposing wheel, the vehicle will rotate about the center point of the two wheels. While this rotation is not truly a zero radius turn unless the drive wheel axis is located in the center plane of the vehicle, the system is nevertheless called a zero turning radius system, and typically provides a much higher degree of maneuverability than rack and pinion steering systems. Figure 3.1 summarizes this concept. Proper control systems such as an encoder feedback loop with a motor controller must be utilized to ensure the wheels are operating at the programmed velocities despite any

changes in terrain. Without this, small differences between the desired and actual velocities may slightly alter the path of the vehicle, resulting in possible obstacle avoidance failure.



**Figure 1-1 - Independent drive wheel maneuvering**

This new method of maneuvering greatly increases the turning capabilities of the vehicle, and requires the replacement of the previous single drive motor and shaft with two DC reversible motors instead. The remaining problem of too little torque is corrected through the selection of new motors that are in combination more powerful than last year’s drive system. A static force balance was done to determine the minimal torque required by the motors to counteract the gravitational forces that would occur on the vehicle resting on a 25% grade hill. Figure 1-2 illustrates the setup.



**Figure 1-2 - 25% grade force balance free body diagram**

Possible motors considered included robotics hobby motors and motorized wheelchair motors. After researching different options, two NPC Robotics 41250 gear motors were selected. The model features a 90° output shaft, allowing the two motors to fit into the narrow frame. A no load shaft speed less than 200 RPM or so was a desirable characteristic in order to achieve a reasonable vehicle speed

through voltage control as opposed to designing additional gear trains. An added reason for the selection of these motors was the availability of dynamometer test data online, including stall torque data indicating a stall torque well above our expected range. Dimensioned technical drawings for the motors were also available, where as wheelchair motors were not.

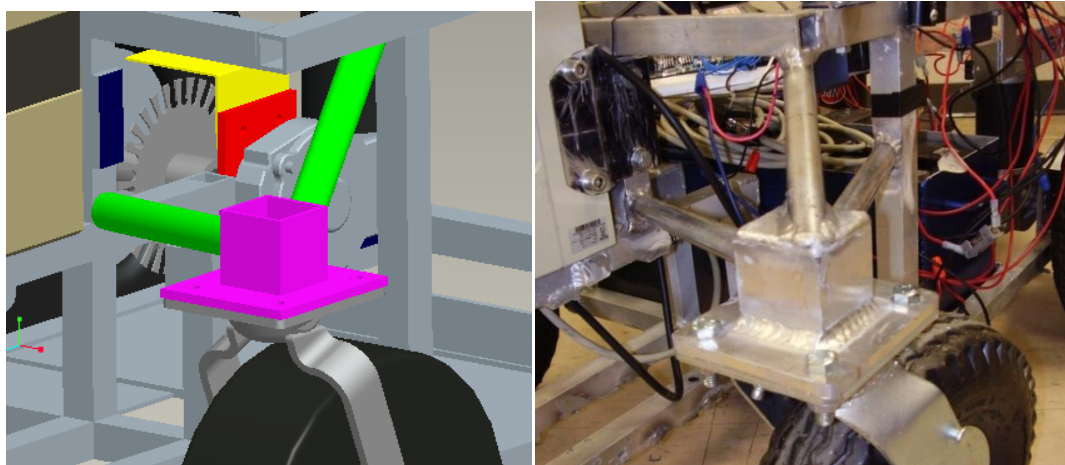
As previously mentioned, the front wheels that were connected to the rack and pinion steering system have been replaced with 10" pneumatic (air-filled) swivel casters. Rack and pinion wheel systems are designed to fix the steering wheels at a certain angle for the duration of a turn, and then return the wheels to a straight orientation for forward motion. In a zero turning radius system all wheels other than the drive wheels must be able to pivot 360° freely to be able to roll in the direction of motion, so that there is minimal resistance to the rotation of the vehicle. The large diameter of the casters ensures minimal disturbance on the vehicle from hazards such as potholes and other uneven terrain that may be present in the course. Pneumatic type casters were chosen over solid types for several reasons. Not only do the wide, rubber treaded tires provide better traction over outdoor surfaces like grass and sand, but air filled wheels serve to better dampen vibrations in the system than other caster types. This is an important point considering that one of the few regrettable drawbacks of the removal of the rack and pinion system is the loss of the suspension system as well. Given the added height, and awkward positioning required for the addition of casters, a shock absorber in the new system does not appear practical at this time.

### *1.3 – Design and Fabrication of the Improved Mechanical Systems*

The current optical encoder on the drive shaft has been both reused and duplicated so that both drive wheels may provide the motor controller with feedback. Since, as previously detailed, both the steering and drive are controlled by one set of motors, the old steering controller board as well as drive motor controller were replaced with a new controller capable of handling 2 channel output at high amperage. Custom brackets had to be designed to attach the motors to the frame as well as the casters. The casters needed to be positioned not only so that the vehicle was still level with the new smaller diameter front wheels, but also so that there was sufficient clearance for the casters to maintain a full 360° range of motion without mechanically interfering with the frame or sending false detection signals to the SICK laser range finder, given their close proximity.

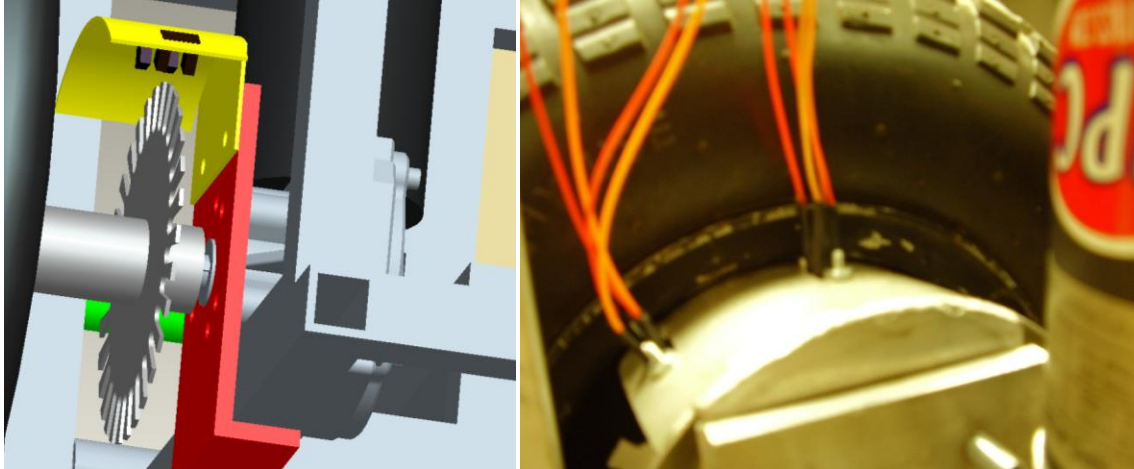
Given these sensitive placement issues, Pro/ENGINEER Wildfire was used for the component design, where the frame and relevant components were measured, modeled, and assembled. Using this

accurate model, the brackets could be designed to provide the proper positioning. The casters bolt onto a flange welded onto a piece of 2" x 2" square aluminum tubing, which is in turn welded onto the rest of the frame by 3/4" cylindrical tubing cut at angles on its ends to mount flush. To provide greater strength against loading in multiple directions, it was originally proposed to have two members aligned along different axis, one supporting the vehicle primarily in the length and height axis, and one mostly supporting any possible loading in the width axis. Figure 1-3a illustrates the proposed design. During fabrication, however, it was found that a third tube could be added to the top surface without interfering with the SICK LMS detection. This allowed the other tube in the length and height planes to be shifted, so that each of the three tubes are providing support principally in one axis at 90° away from the others, seen in Figure 1-3b. This achieves a greater strength in all possible loading orientations.



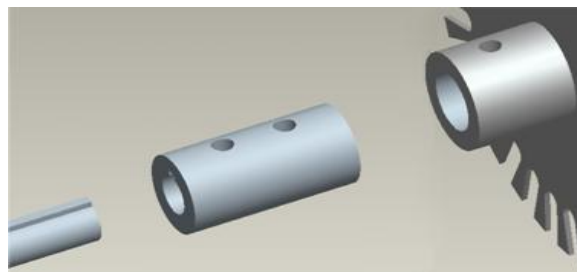
**Figure 1-3 (a & b) - Caster bracket Model & Implementation**

In the previous year's design, a single opto-switch was sufficient to give the controller a value for the wheel's rotational velocity. However, the new motor controller board utilized this year requires a quadrature encoder input, which consists of signals from two opto-switches mounted 90° out of phase electrically. This allows the board to determine the direction of rotation as well as the magnitude. To achieve this difference in signals, the sensors had to be mounted so that there was half a tooth of difference between the two, plus any number of complete tooth/window pairs. The necessary angle and radius of curvature were determined based on the number of window pairs of the encoder as well as the geometry of the setup.. Using trigonometry with the known angle and radius, the necessary location could be found for drilling the mounting holes into the flat plate before being rolled to the proper curvature. The curved piece was then welded to a flat section for securing to the motor mount. The design is shown in Figure 1-4.



**Figure 1-4 - Encoder Bracket Design**

The remaining mechanical design required for this iteration of the vehicle was coupling the output shafts of the motor with the shafts of the drive wheels. The motors use a  $\frac{1}{2}$ " inch diameter ANSI keyway equipped output shaft, where as the bore of the drive wheel shaft is  $\frac{3}{4}$ ". It was decided the most effective way to connect the two components together would be using an off the shelf  $\frac{1}{2}$ " bore keyed coupler with set screws. The bore of the hole in the drive wheel shaft was increased until the coupler could slide in, and was then welded in place, concentrically. While the keyed motor shaft could transfer power to the coupler with no problems, research into shaft couplers indicated that use of a set screw alone to join the shafts would slip under the expected amount of torque. This explains the necessity of welding the coupler within the drive wheel shaft, as opposed to simply set screwing it in place. Figure 1-5 illustrates the design.



**Figure 1-5 - Motor to drive shaft connection**

With the aforementioned improvements to the mechanical systems design, the team is confident in the vehicle's ability to perform more competitively in this year's IGVC.

## Chapter 2 – Electrical Systems (Michael Ziller)

### 2.1 – Electrical Systems Overview

The 2008 New Jersey Autonomous Vehicle team uses five major components for the electrical systems of their robot, Spinster. These components consist of a laser range finder, GPS unit, digital compass, a video camera, and a drive and steering motor controller. The software uses the four inputs (sensor, video camera, GPS unit, and digital compass) and produces an output to the controller board which powers the drive and steering system of the robot.

The sensor that was selected was a SICK LMS 291-S05 laser range finder. This scanning laser range finder offers a field of view of  $180^{\circ}$  with  $1^{\circ}$  increments and has a range of up to 250 feet. It is easily interfaced using a serial to USB connection. The SICK LMS proves to be advantageous and performed optimally.



**Figure 2-1 - Sick LMS laser range finder showing field of view**

The GPS unit that was selected was a Furuno GP37. This specific unit was ordered because it is WAAS enabled as well as DGPS enabled. Because the competition is doubled covered, which is explained below, this unit should have the necessary accuracy for the Navigation Challenge at the IGVC. Also, it is easily interfaced with our vehicle through serial RS232.

The difference between WAAS and Differential Global Positioning (DGPS) is that WAAS retains the same accuracy at any location. DGPS acquires better correctional service as it becomes closer to any of the beacon receivers which provide the correctional service. If the GPS unit is within 115 miles of a

beacon receiver the accuracy of the unit is increased to one meter. Rochester, MI, where the competition is being held is doubled covered. There is a beacon receiver in Detroit 25 miles away and there is one in Saginow Bay 90 miles away. Also, testing can be done here in Trenton using DGPS because there are two beacon receivers in this area as well; one in Sandy Hook 55 miles away and one in Reedy Point, DE 80 miles away.



**Figure 2-2 - Furuno GP37**

It was decided that the Furuno GP37's built-in digital compass was too slow and inaccurate. To supply the heading data instead is a Silicon Laboratories (model: C8051F 350) digital compass. This also interfaces to the computer through a USB connection. The combination of this discrete digital compass and the Furuno GP37 provides the position/angle data used for the "Navigation Challenge".

The video camera that the 2008 NJAV team implements is a Basler 302fc video camera. This camera replaced the previous year's camera which only captured still-pictures. The Basler camera produces RGB images at a resolution of 640 X 480 pixels. This eliminates the need to down sample while still providing adequate detail.

Because this year's NJAV robot will be implementing a zero-turning radius system, the steering will be controlled via the drive motor. Data from the computer will be sent to the controller. Then, the controller will activate the two drive motors. Each drive motor should receive a distinct voltage. This will allow for the zero-turning radius, which means the robot will be able to change direction without having to go in the reverse direction.

60 amps of current is more than enough to produce the required torque on the motors, therefore a Roboteq AX3550, a 60 Amp dual-channel motor controller, was chosen. This digital motor speed controller includes an optical encoder, which allows a negative feedback in a closed loop system,

and fits into the budget. The two output channels will be connected to the two drive motors, and with the software written and the closed loop feedback system, this controller will run our vehicle.

The closed loop system computes the error, current output vs. desired speed. If the computer were to implement the closed loop, the speed would need to be read very often from the encoder. Industrial controllers with optical encoders can do this every sixteen milliseconds. This is too fast for the DAQ, which was used last year, to perform. This is because the DAQ has too many operations to perform (wait for a trigger, start the analog-to-digital converter, look up the time, wait for the analog-to-digital converter to finish, move value to RAM, switch multiplexor, get TTL input, let the digital-to-analog converter proceed with the voltage ramp) to send continuous signals at that speed.

The AX3550 can communicate with the computer via serial cable RS232. This eliminates the need for the Data Acquisition board (DAQ), which needs a C-Stamp to implement the necessary speed required for information transmission. The board is also able to communicate with the computer implementing C++ source code. This is necessary because our code is written in C++.



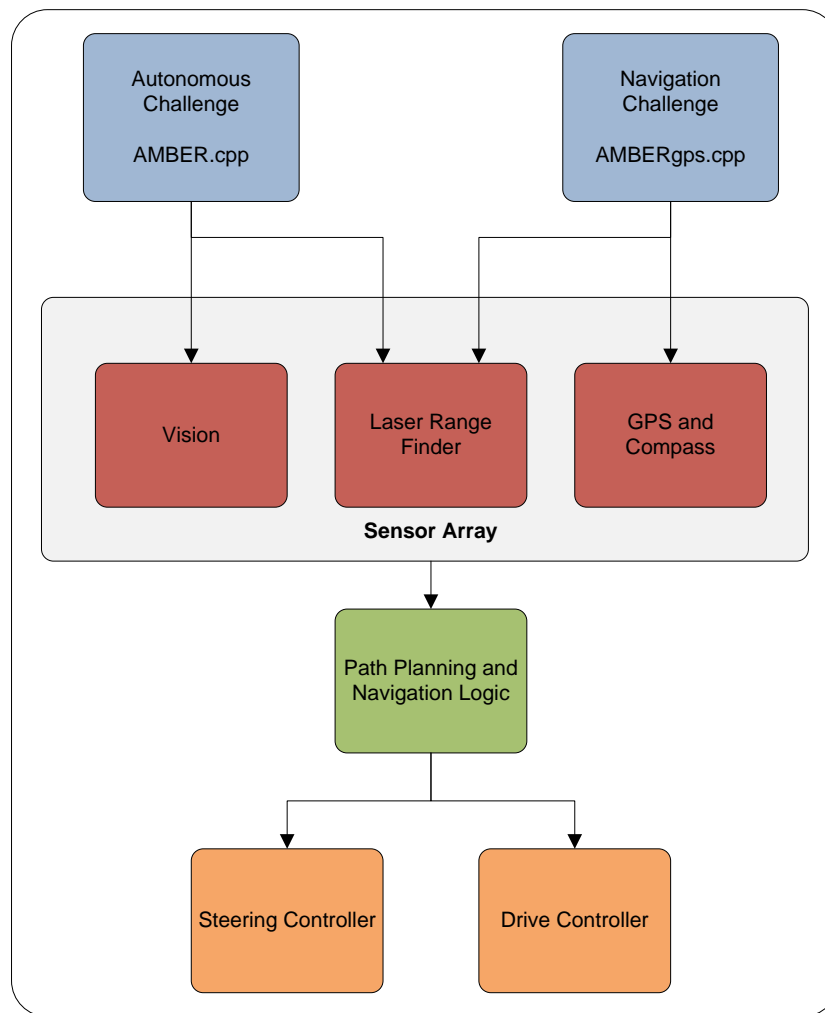
**Figure 2-3 - Roboteq AX3550**

Using these five components for the electrical systems of the 2008 New Jersey Autonomous Vehicle, Spinster is ready for competition at the Intelligent Ground Vehicle Competition. The four sensors (laser range finder, GPS unit, digital compass, video camera) and the controller have been interfaced with the computer. Also, the systems were tested and fine-tuned to ensure safety and reliability for competition.

## Chapter 3 - Software Systems (Jerry Wallace)

### 3.1 - Software System Overview

The software controlling the autonomous vehicle was completely rewritten in C++ in 2007 for reasons of processing speed and sensor interfacing. The software system consists of two major programs: one for operation in the Autonomous Challenge mode, and another for operation in the Navigation Challenge mode. Each program is further broken down into several components, some of which are shared between the main programs as shown in Figure 3.1 below.



**Figure 3-1 - Overall software system architecture**

An arc selection process is used for path planning and navigation, shown in green in Figure 3.1. An “arc” is a potential curve that the vehicle can follow based on the Ackerman steering geometry of the

rack and pinion steering of last years vehicle. All possible arcs are pre-generated and tested to see if they intersect any obstacles based on information from the sensor array. The arcs are then scored based on the number of obstacles intersected as well as the destination point. The new zero turn radius system was designed to provide the ability to follow the same arcs as a rack and pinion system. Additionally, smaller radius arcs can be added to the set, as well as the ability to rotate in place as a replacement for reversing.

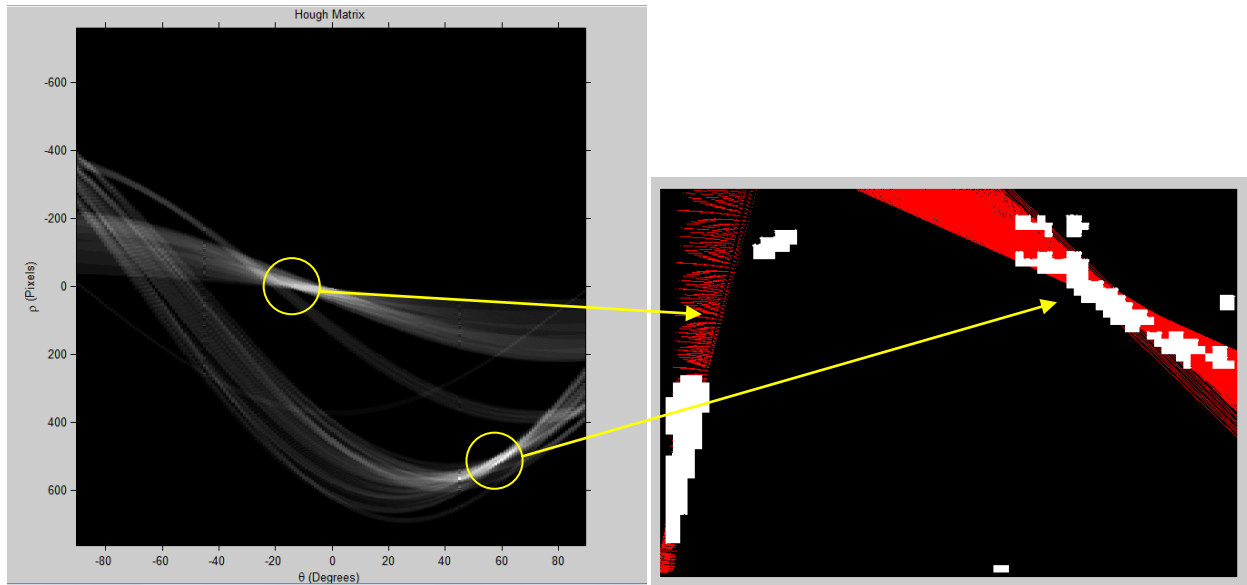
Of the sensor components shown in red in Figure 3.1, the laser range finder, GPS, and compass interfaces all operated as intended last year. The vision component performed with impressive results; however, it still possessed some room for improvement. The vision system uses a five-step process to analyze images from the camera. It begins by down-sampling the received image to decrease processing time. The next step converts the image to grayscale, while removing grassy areas and highlighting painted areas. The next step is to median filter the image to reduce the amount of noise. Finally, a Sobel edge operation is performed on the resulting image to show only the edges of the painted lines. This process proved effective, except under certain conditions. The problems were most apparent when the vehicle encountered one of the courses ramps or sand pits. In either of these cases, the vehicle erroneously avoided the surface and left the boundaries of the course. It was therefore obvious that some changes needed to be made to the vision system. These changes are discussed thoroughly in the next section.

The final pieces of the software system are the steering and drive controllers shown in orange in Figure 3.1. These components communicate with the steering and drive controller boards through an external data acquisition card. The steering controller software selects the desired wheel orientation. The drive controller software controls the speed of the drive motor by adjusting a digital potentiometer. Due to various reasons, the steering and drive hardware components were replaced this year. Therefore, significant changes were needed within the steering and drive controller software components.

### *3.2 - Software System Updates*

The main software component in need of revision was the image analysis process. The first issue deals with processing broken lines. Last year's software correctly detected all pieces of the broken lines, but left an unmarked gap between sections. Research of image processing algorithms lead to the decision to use a Hough Transform to identify lines within the captured image, regardless of their

completeness. The Hough Transform allows lines in an image to be converted to points in slope-intercept space. When all lines in an image are processed, curves are plotted in the Hough Transform matrix and the intersections are the best fit lines in the captured image as shown in Figure 3.2. The Hough Transform was first prototyped in MATLAB, then recoded in C++ to efficiently integrate with the rest of the software components.



**Figure 3-2 - Hough Transform**

Besides the line detection issue, another factor that seriously hindered NJAV's performance in the 2007 competition was its avoidance of ramps and sand pits. These obstacles reflected too much light, and appeared as white lines to the image processing system. To correct this, a new image processing algorithm was developed that removes glare by subtracting a blurred grayscale version of the image from the original image before processing. The algorithm is summarized below in Figure 3.3.

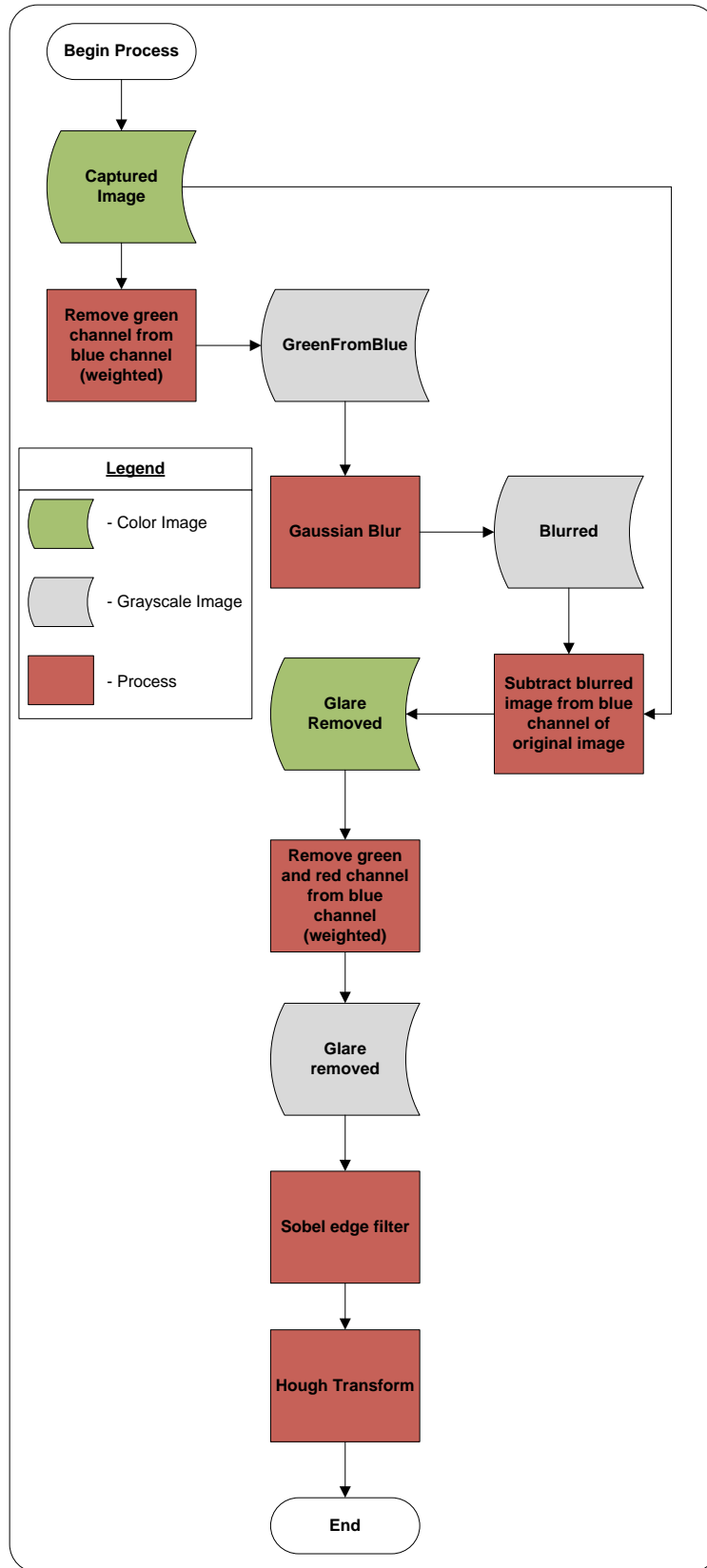


Figure 3-3 – Improved image analysis process

In addition to optimizing the image processing, the software had to be updated to work with and take full advantage of the new zero turn radius system. A new C++ object was created that accepts an arc selected by the path planning and navigation logic and communicates with the new Roboteq motor controller to implement the desired path. Using the new zero-turn system, arcs of much smaller radii were added to avoid close obstacles. Another improvement to the drive control system is the elimination of reversing. Any situation that previously required the vehicle to back up, is instead resolved by rotating the vehicle in place, saving valuable time.

The motor controller was set to operate in mixed-mode. In this mode, one channel is used to control the average speed of both motors. Another channel is used to control the difference in speed between the two motors. This approach is optimal for a zero-turn radius design. Commands are sent via RS232 serial communication in a two-byte hexadecimal string containing the desired command and magnitude. As an added safety feature, the RoboteQ AX3550 motor controller also includes a Watch-Dog feature which cuts power to the motors if no commands are received within a one second interval. If the program was to crash for any reason, the safety command would not be sent and the vehicle would come to a complete stop.

The final major update required for the software system was communication with the new Furuno GPS. The original Garmin unit used a proprietary "Text Out" format, while the new Furuno uses the NMEA standard. An NMEA parser was designed and written in C++ by viewing RS232 transmissions from the GPS. Other information besides location can also be obtained if desired, such as satellite links and date/time information.

## Chapter 4 – Project Resources

The cost to duplicate this project from start to finish is estimated below.

<b>Component</b>	<b>Cost (\$)</b>
Motors	300
Casters	75
Frame	150
Motor Controller	400
GPS	600
Laptop	1000
Basler Camera	2000
Laser Range Finder	2500
Digital Compass	75
Wireless E-Stop	50
Misc Electrical	100
Batteries	300
Misc Mechanical	50
<b>Total</b>	<b>7600</b>

It is estimated that each team member spent an average of five hours per week on this project throughout the 36 week school year. This comes to a total of 540 person-hours expended on the project this year alone.

## Biographies

### *Brian Fay*



Brian Fay is a senior mechanical engineer from Rockaway, New Jersey. He has completed internships in the electronics and chemical industries focused on mechanical design and computer modeling work. After graduation, he would like to start a career with AE Polysilicon, with the possibility of pursuing further degrees. Brian is responsible for the implementation of the zero turning radius drive system, as well as various miscellaneous mechanical systems. He is also the webmaster for this year's site.

### *Michael Ziller*



Mike Ziller is a senior electrical engineer from Millville, New Jersey. After graduation Mike plans on pursuing a career in the field of electrical engineering with Sargent and Lundy. He would also like to obtain a master's degree in engineering and intends to take classes while working. Mike worked on the GPS navigation system of the autonomous vehicle, and also the steering controller board.

### *Jerry Wallace*



Jerry Wallace is a senior electrical engineer from Coatesville, Pennsylvania. After graduation, he plans to start his career in electrical engineering with Lockheed Martin while working towards his Master's Degree. A recipient of the TCNJ Full Merit Scholarship and Fred O. Armstrong Scholars Award, he also heads the TCNJ chapter of the IEEE. Jerry served as the project manager this year, as well as worked on the image recognition and software systems.