# N.J.A.V.

(New Jersey Autonomous Vehicle)



## 2013 Intelligent Ground Vehicle Competition

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#### **Faculty Advisor Statement**

I certify that the design and engineering of NJAV for the 2013 IGVC is equivalent to what might be awarded credit in a senior design course.



Dr. Jennifer Wang Dept. of Mechanical Engineering

The College of New Jersey

#### **Introduction**

The College of New Jersey (TCNJ) is proud to present the New Jersey Autonomous Vehicle (NJAV) as its entry in the 2013 Intelligent Ground Vehicle Competition (IGVC). The vehicle has been designed by three senior mechanical engineering students working under the supervision of a faculty advisor. These students have spent the 2012-2013 academic year designing every aspect of the vehicle including its frame, electronic systems, and autonomous navigation software as part of a senior design course. The following design report provides a detailed explanation of the vehicle's various features and components.

#### **Team Organization**

Due to the size of this year's NJAV team, it was important to ensure that each member of the team had a clear understanding of their individual responsibilities. The vehicle's design was divided into three main areas and a student was placed in charge of each one. These areas included mechanical design, electronic systems and programming. While designing the vehicle, students maintained constant communication with one another and the project's faculty advisor to determine if proposed designs were feasible. Additionally, the team placed emphasis on ensuring that all of the vehicle's components were capable of effectively integrating with one another in order to form a final cohesive design. These relationships, as well as individual team member responsibilities, are shown in Figure 1.



Figure 1. NJAV team organization

## **Mechanical Design**

#### **Design Process**

The vehicle was created using an iterative design process. The first step in designing NJAV involved identifying key features to be incorporated into the vehicle and brainstorming a series of initial designs. These designs were then used to develop CAD models that could be further refined. Once an assembled CAD model of the vehicle was finalized, all of the materials necessary for its construction were procured. The vehicle was then constructed in the TCNJ machine shop. The final assembled vehicle is shown in alongside its CAD model in Figure 2.



Figure 2. CAD model and final assembled vehicle

#### Chassis

NJAV's chassis was constructed out of 1" 80/20 T-slotted Aluminum. This material was selected for both its durability and machinability. Additionally, the material's modular design allowed for quick assembly and easy modifications when compared to standard square tubing. The vehicle's final dimensions are roughly 42" x 26" x 39" as shown in Figure 3. These dimensions allow the vehicle to remain small and maneuverable while still meeting IGVC requirements.



Figure 3. NJAV's final dimensions in inches

#### **Key Features**

NJAV has been designed with the features shown in Figure 4. The main body of the vehicle provides protection to NJAV's electronics and computer. The computer rests on a retractable tray that slides out of the vehicle to provide easy access during testing. The camera stand, located above the front of the vehicle, is detachable for easy transportation and provides mounting points for the webcam, caution light, GPS, and compass. The webcam and laser range finder can be adjusted for various fields of view. Additionally, rubber washers have been installed underneath the webcam to reduce image distortion due to vibrations.



**Figure 4. NJAV's various features** 

#### **Maneuverability**

NJAV is propelled by two high torque DC motors located in the rear of the vehicle. Each motor is capable of providing 100 lbf-in of torque. Including its 20lb payload, the vehicle weighs a total of 160 lbs. With its current motors, the vehicle is able to climb ramps with a maximum incline angle of about 30<sup>0</sup> assuming a wood-rubber coefficient of friction of 0.7 and factoring in motor inefficiencies. Additionally, a low center of gravity helps keep the vehicle stable during its ascent. Two castors mounted at the front of the vehicle allow for a turning radius of 29", resulting in a high degree of maneuverability.

## **Electronics**

#### **Sensors**

NJAV utilizes a variety of sensors to detect its surrounds while navigating autonomously. It is able to identify obstacles, determine its current location, and track its speed and heading. These functions are performed using the following sensors:

- Logitech HD Pro Webcam C920
  - o 720p video, 30 FPS, USB interface
- Sick LMS 221 Laser Range Finder (LIDAR)
  - o 30 meter range, 180° field of view, 0.5° resolution, RS232 interface
- Garmin eTrex Vista HCx GPS
  - o 8' accuracy, USB interface
- Photo Interrupter and Encoder Disk
  - o 30 pulses per revolution, outputs square wave
- SainSmart HMC5883L Digital Compass Module
  - 1° accuracy, IC2 interface

#### **Vehicle Movement and Feedback**

A Sabertooth 2x25 V2 motor controller was used to control the vehicle's two DC motors. This motor controller is capable of controlling two motors independently and can output a maximum current of 25A per motor. It requires two pulse width modulation (PWM) or analog signal inputs which are supplied by the Arduino microcontroller. Attached to each motors is an encoder disk and a photo interrupter. These discs were designed and fabricated by a previous TCNJ team and are being reused for the 2013 IGVC. The photo interrupter outputs a square wave, which is used by the Arduino to calculate the speed of each wheel so that heading adjustments can be made in real time.

#### **Computer and Microcontroller**

NJAV uses an onboard Samsung laptop to run the vehicle's autonomous navigation program. Outputs from the program are sent to an Arduino microcontroller that controls the

vehicle. The following devices are connected to the laptop: LIDAR, GPS, webcam and Arduino. The LIDAR constructs a polar plot of the vehicle's field of view and sends this information to the laptop through a 9-Pin to USB converter. The GPS is connected directly to the computer via USB and reports NJAV's global coordinates according to the NMEA 0183 standard. The webcam sends captured images to the computer through a USB connection.

The laptop sends a string of commands to the Arduino as comma separated values (CSV) in order to dictate the vehicle's desired speed and heading. The Arduino compares the vehicle's current heading, which it obtains from NJAV's onboard compass and optical encoders, with its desired heading and adjusts motor speeds accordingly. An RC controller and receiver allows for the vehicle to be controlled manually if desired. The transfer of data throughout the vehicle can be seen in Figure 5.



Figure 5. Data transfer throughout NJAV

#### **Safety Features**

NJAV has numerous safety features to ensure it does not damage itself as well as objects around it. The following devices have their own fuses to provide overcurrent protection: motors, LIDAR, caution light, and motor controller. Centered on the back of the vehicle, located 2' off the ground, is a mechanical BACO E-Stop button that, once pressed, stops the motors immediately. Additionally, a LOGISYS wireless relay, capable of be activated from over 100' away, is connected in series with the batteries and the motor controller to serve as the vehicle's wireless E-stop. On the camera stand is an LED caution light that remains solid when the vehicle is on and blinks when NJAV is operating in autonomous mode.

#### **Power Distribution**

The vehicle's electronics require a combination of 24V, 12V, and 5V. 24V is supplied by two 12V, 7Ah batteries connected in series, 12V is provided by two 17Ah batteries wired in parallel and 5V is achieved using a 5V regulator and a 12V source. A diagram of how each device is powered can be seen in Figure 6. The system is designed to have an estimated battery life of 2 hours.



Figure 6. NJAV's power distribution

#### **Software**

#### **Software Strategy**

When designing NJAV's autonomous navigation software, the team chose to focus on three key features: mapping, obstacle avoidance, and line detection. The team determined that the vehicle's path planning and navigation algorithms would be potential field based since these types of algorithms are conducive to mapping and are compatible with a variety of sensors. The vehicle's thought process is summarized by the flowchart shown in Figure 7. Upon startup, NJAV reads in a series of user supplied waypoints and determines its current position using its onboard GPS. The program places the vehicle at the center of an empty computer generated map and plots each waypoint's location. Once the map has been initialized, the vehicle assigns a target waypoint and attempts to move towards it in a straight line. During its travels, the vehicle determines obstacle and course boundary locations and avoids them using a series of repulsive forces. Once all waypoints have been found, the vehicle is programmed to complete the course by returning to its starting position. MATLAB was selected as the team's programming language due to its variety of toolboxes, inherent capabilities, and student familiarity.



Figure 7. Flowchart of vehicle's thought process

#### **Mapping**

In order to effectively implement an autonomous navigation algorithm based on potential fields, NJAV must be capable of creating a reliable map of its environment. Furthermore, it also needs to be able to keep track of important locations within the map such as its current position and the positions of waypoints. Since MATLAB is well suited to handle large matrices, it was determined that the simplest solution was to have a large matrix serve as a map of the IGVC course. However, since examining this matrix in its entirety would require significant processing time, the program was designed to only monitor cells surrounding the vehicle's immediate area. This region of cells is termed the "Active Window" (Figure 8).



Figure 8. Sample world map demonstrating the concept of an active window

The next step in designing the vehicle's mapping system was to determine how much of the IGVC course would be represented by each cell. Since the basic IGVC course is known to be approximately 200' by 100', it was determined that the length and width of each cell should be fixed at 0.5'. This value was chosen for several reasons. Cells that are 0.5'x0.5' are big enough to prevent the map matrix from becoming too large, but are also small enough to provide an acceptable amount of resolution. Additionally, this value is within the resolution of the vehicle's sensors and will therefore allow for effective obstacle detection and mapping. When determining the size of the matrix representing the world map, special care was taken to ensure that its boundaries extended beyond those of the IGVC course. This was done to reduce the risk of the program crashing. If necessary, the dimensions of each cell can be adjusted to modify the size and scaling of the map.

The vehicle keeps track of its current position within the map using the GPS installed on the vehicle. When beginning an autonomous navigation attempt, NJAV reads its current GPS location and places itself at the center of the world map. The vehicle then determines which cells correspond to waypoint locations based off supplied coordinates. As the vehicle moves, changes in its latitude and longitude are recorded and this information is used to track the vehicle's progress throughout the course. By comparing its current coordinates with those of its target, NJAV is able to determine when it has reached a waypoint. Once a waypoint has been found the vehicle selects its next target and continues to traverse the course.

#### **Obstacle Detection**

In order to detect an obstacle, the program determines which cell in the map matrix corresponds to the obstacle's location and sets the value of that cell equal to one. When a cell with a value of one enters the vehicle's active window, a repulsive force is generated and the vehicle's heading it adjusted accordingly (Figure 9). The vector components of each repulsive force are determined using Equations 1 and 2. Rx and Ry are the components of the repulsive force, Cx and Cy are the coordinates of the cell, Px and Py are coordinates of the vehicle, d is the distance between the vehicle and the cell, and Kr is a constant that may be used to adjust the strength of the repulsive forces. A similar calculation is also performed to determine the vector components of the attractive force that draws the vehicle towards its target waypoint. These forces are calculated using Equations 3 and 4 where Ax and Ay are the components of the attractive force, Wx and Wy are the coordinates of the waypoint, D is the initial distance between the vehicle's staring position and its target waypoint, and Ka is a constant that may be used to adjust the strength of the attractive force. [1]

$$Rx = \frac{-\left(Cx - Px\right) * Kr}{d^3} \tag{1}$$

$$Ry = \frac{-(Cy - Py) * Kr}{d^3}$$
(2)

$$Ax = \frac{(Wx - Px) * Ka}{D}$$
(3)

$$Ay = \frac{(Wy - Py) * Ka}{D}$$
(4)



Figure 9. Obstacle mapping and avoidance

#### **Line Detection**

NJAV's line detection is performed by capturing an image of the course using the vehicle's Logitech webcam and eliminating pixels that do not satisfy a series of preset color thresholds. MATLAB's image acquisition toolbox is used to capture the image and store its pixel information in a three dimensional matrix. The first two dimensions of the matrix are used to denote a pixel's x and y coordinates while the third is reserved for storing a pixel's red, green, and blue values which can range from 0 to 255. To detect any color, upper and lower threshold values for a pixel's red, blue, and green values have been incorporated into the program. By scanning each pixel of a captured image and removing pixel's that do not satisfy all threshold values, NJAV is able to identify objects of a particular color. This color detection system is utilized by NJAV to identify both the white boundary lines and the colored flags spread throughout the IGVC course. Figure 10 shows an image captured by NJAV before and after attempting to detect the color white.



Figure 10. NJAV configured to detect the color white

Once the vehicle was able to successfully detect specific colors, its webcam needed to be calibrated so that it would be able to correctly locate and map course boundaries (Figure 11). Colored markings were placed on the ground spaced one foot apart and an image was captured using MATLAB. The pixel locations of each marking were then used in conjunction with their relative distances from the vehicle to generate functions for converting pixel distances to absolute distances. These functions are reliable over a distance of 8' and therefore pixels outside this range are currently ignored by the software. NJAV uses these functions to identify which cells in its map correspond to course boundaries. Once identified these cells are assigned a value of one. NJAV's path following is driven by the repulsive forces these cells impart on the vehicle.



Figure 11. NJAV webcam calibration

#### **Trap Avoidance**

The IGVC course contains several traps that are specifically designed to confuse and disorient autonomous vehicles. In the past, these traps have included dead ends, center islands and switchbacks. Although NJAV should be able to successfully navigate center islands and switchbacks, dead ends pose a significant threat. If NJAV enters a dead end, the acting attractive and repulsive forces would make the vehicle want to pass through obstacles (Figure 12). To combat this issue, NJAV is being programmed to recognize that it is trapped and begin increasing the strength of the repulsive forces acting on the vehicle by adjusting the value of Kr. This will force the vehicle out of the dead end and designate the location as impassable. The feasibility of this method is currently being tested to gauge its effectiveness.



Figure 12. Dead end scenario

#### **Testing**

NJAV is currently being tested on TCNJ's campus in preparation for the IGVC. The team's testing strategy involves introducing each of the vehicle's sensors individually in an additive process. This technique will allow the team to identify which parts of the vehicle's code are functioning as intended and which areas need to be refined. The vehicle's mapping

and GPS capabilities were evaluated in the following manner. NJAV was initially supplied with a single GPS coordinate and was tested to see if it was able to successfully navigate to the desired location in a course free of obstacles. Once this task could be completed successfully, the vehicle was then given multiple waypoints and told to proceed to them in quick succession. Although the vehicle was able to successfully locate these waypoints, fluctuations in the GPS' resolution led to some position discrepancies. Currently the team is looking into purchasing a more accurate GPS. The vehicle's obstacle detection and path following algorithms are still be rigorously tested and modified to allow for optimal performance at the IGVC. All of NJAV's required safety features have been successfully tested for IGVC compliance.

### **Budget & Scheduling**

Tables 1 and 2 list the costs associated with NJAV's mechanical and electrical components. An item's effective cost was taken to be \$0 if it was already owned by the NJAV team. The vehicle's combined total cost was \$1,340.25. Additionally, the construction and testing of NJAV took roughly 250 hours to complete.

Material	Quantity	Specifications	Unit Price	<b>Total Price</b>	Effective Cost
Cotter Pins	1	10 Pieces	\$7.22	\$7.22	\$0
Ratchet Strap	1	1 Set	\$5.00	\$5.00	\$0
1/8" 6061-T6 Aluminum	1	24" x 48" Sheet	\$145.10	\$145.10	\$145.10
1/4" 6061-T6 Aluminum	1	8"x8" Sheet	\$17.37	\$17.37	\$17.37
3/8" Aluminum Rod	1	6' Rod	\$11.85	\$11.85	\$0
80/20 T-Slotted Aluminium	5	1"x1"x92"	\$44.93	\$224.65	\$224.65
Miscellaneous	N/A	N/A	N/A	\$50.00	\$50.00
			Total	\$461.19	\$437.12

#### Table 1. Cost of NJAV's mechanical components

Item	Model #	Quantity	Unit Price	Total Price	Effective Cost
Laser Range Finder	Sick LMS 220	1	\$3,411.00	\$3,411.00	\$0
GPS module	Garmin eTrex Vista Hcx	1	\$795.00	\$795.00	\$0
Digital Compass	HMC5883L	1	\$15.69	\$15.69	\$15.69
Serial-Usb Connector	Prolific PL2303HX Rev D	1	\$12.95	\$12.95	\$12.95
Wireless E-Stop	RM02	1	\$16.45	\$16.45	\$16.45
Mechanical E-Stop	Baco	1	\$20.00	\$20.00	\$0
5V and 12V Relays	Radio Shack	2	\$4.99	\$9.98	\$9.98
Switches	Various	4	\$4.52	\$18.08	\$18.08
Motor Controller	Sabertooth 2X25 V2	1	\$125.00	\$125.00	\$0
DC Motor	NPC-41250	2	\$180.00	\$360.00	\$0
Caution Light	N/A	1	\$20.00	\$20.00	\$0
Photo Interrupter	N/A	2	\$5.00	\$10.00	\$0
12V 17 Ah Battery	N/A	2	\$35.00	\$70.00	\$0
12V 7Ah Battery	N/A	2	\$22.00	\$44.00	\$0
Logitech HD Webcam	C920	1	\$79.99	\$79.99	\$79.99
Laptop	Samsung Series 3 NP350V5C-T01US	1	\$699.99	\$699.99	\$699.99
Arduino Uno	R2	1	\$21.94	\$21.94	\$0
Miscellaneous (Wires, Fuses, etc.)	N/A	1	\$50.00	\$50.00	\$50.00
			Total	\$5,780.07	\$903.13

#### Table 2. Cost of NJAV's electrical components

## **Conclusion**

NJAV is an autonomous ground vehicle that has been designed, constructed and tested by three mechanical engineering students attending The College of New Jersey. The vehicle's mechanical, electrical, and software components have been specifically designed to allow it to compete in the 2013 IGVC. Testing of the vehicle has revealed that NJAV is able to successfully locate waypoints while navigating over outdoor terrain. Based off these results, the team plans to compete at the 2013 IGVC held in Rochester, Michigan on June 7<sup>th</sup>-10<sup>th</sup>.

## **Reference**

Borenstein, J., and Y. Koren. "Real-time Obstacle Avoidance for Fast Mobile Robots." *IEEE Transactions on Systems, Man, and Cybernetics* 19.5 (1989): 1179-187. *IEEE Xplore Digital Library*. IEEE. Web. 6 Jan. 2013.