California State University
Northridge

NorMAN Jr.

Northridge's Mobile Autonomous Navigator

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Total Person Hours Expended (Approximate)

- 5700 Hours (August 2008-June 2009)

Required Faculty Advisor Statement:

I certify that the engineering design of the vehicle described in this report, NorMAN Jr., has been significant, and that each team member has earned four semester hours of senior design credit for their work on this project.

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1. Introduction

California State University Northridge is proud to present Northridge's Mobile Autonomous Navigator Jr. (NorMAN Jr.). NorMAN Jr. will be competing in the 17th annual Intelligent Ground Vehicle Competition (IGVC) in June 2009. The NorMAN Jr. team is composed of multi-disciplinary students with the goal of designing a state of the art autonomous robot. NorMAN Jr. is a major modification of NorMAN which competed in the 16th annual Intelligent Ground Vehicle Competition. The team has undergone many design improvements and is now ready to compete in the IGVC with the newly designed NorMAN Jr.

1.1 Design Innovations

From the beginning of the year, one of our primary goals was to develop a vehicle with innovative algorithms, design features and technologies. The design features such as an offset top cover of 2 inches allows heat produced from the system to dissipate to the atmosphere, and easy panel removal that allows effortless access to the components of the vehicle. The power system is comprised of a hydrogen PEM fuel cell battery hybrid. The power consumption profile and remaining power reserves of hydrogen and battery of the hybrid power system are monitored in real time and is displayed to alert the user of a low power condition. The cognition system uses data fusion of several sensors to get an accurate robot position and heading. Local and global probabilistic obstacle maps are constructed from the Laser Range Finder (LRF) and line image data. Our cubic spline algorithm uses this mapping to generate a smooth path for both the autonomous and navigation challenges. An Inertial Measurement Unit (IMU) is used to decrease the GPS localization standard deviation by more than a factor of 20 when compared with the raw GPS information. The vision system uses light sensing, fuzzy logic algorithm, Hough transformation, line probability mapping, and a line continuity algorithm in its filtering process to extract accurate line data and generate path goals. The data from each sensor is then fed to cognition hub using our LabVIEW shared variable engine to enable parallel processing and optimal sensor refresh rates. The innovative ideas, algorithms, and products that have been generated and integrated into this vehicle by the team have poised NorMAN Jr. to win the Intelligent Ground Vehicle Competition.

1.2 Team Structure

This years' team was based on a chain of command structure. The team leader helps facilitate communication with the different groups as well as keep the project as a whole in perspective and on track. An organizational chart is shown in Figure 1.

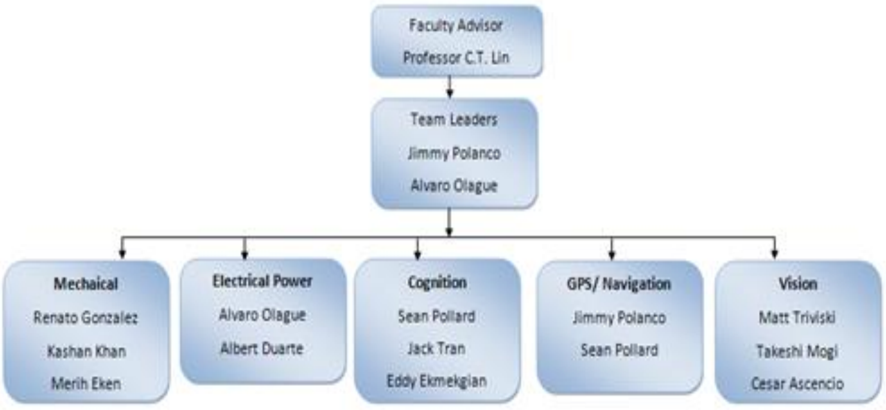


Figure 1- Team organization

2. Mechanical

2.1 Design

NorMAN Jr. is designed with the goal of major weight reduction and strategic mass distribution, as well as the ability to pass through a conventional door. This design has a safety factor of 3, which has a capability to support an evenly distributed weight up to 850lb. Care was taken to place the weight of the drive train and the computer on the rear of the vehicle close to the wheel axle to aid in vehicle maneuverability. The power source is placed on the bottom compartment of the vehicle to lower the center of gravity improving stability. In order to dispense overall heat of the vehicle, the top panels were offset by 2 inches to allow ventilation and dissipate the rising heat of the vehicle. In order to increase efficient power produced from the fuel cell, the fuel cell is placed in front of the vehicle, behind the LRF, which allows cool dense air to flow into the fuel cell.

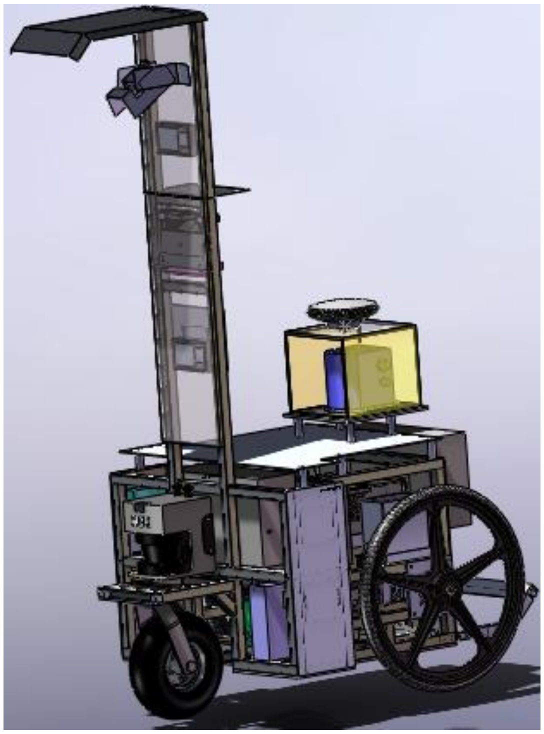


Figure 2- SolidWorks rendering of NorMAN Jr.

2.2 Chassis

The chassis of NorMAN Jr. is constructed of 1 inch square 6061 aluminum tubing, welded together and heat treated to maintain 6061 properties. 6061 aluminum was used due to its high strength to weight ratio, and its compatibility with the onboard components. The square tubing was selected for structural support, as well as the ability to mount the outer panels on the chassis with relative ease. The ability of NorMAN Jr. to fit through a 32 inch door was a key issue when designing the chassis. NorMAN Jr. measures, 38 inches long, 28 inches hub to hub, and 72 inches at the top of the mast, with a ground clearance of 4.25 inches. In comparison to NorMAN's chassis, NorMAN Jr. is 29.5% smaller and 39.2% lighter.

2.3 Wheel Configuration

The wheel configuration is partly influenced by our goal of size reduction. A differential-drive three-wheel design was chosen due to the ease of controlling the vehicle direction and stability. This design has two 20 inch utility wheels with built in keyway hubs as drive wheels in the rear and one 10 inch pneumatic castor wheel in the front.

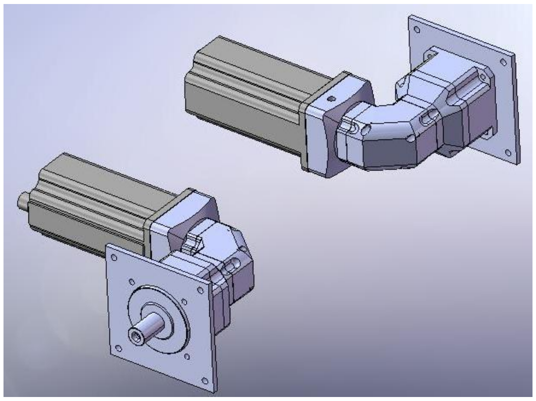


Figure 3-SolidWorks rendering of motor/gearbox configuration

2.4 Drive Train

NorMAN Jr. is driven by two Quick Silver QCI-A34HC-2 motors connected to right angle Apex Dynamics gearbox ABR090 with special NEMA 34 flange mount with a 30:1 gear ratio. NorMAN Jr.'s drive train is redesigned with goals to reduce weight and the width of the vehicle. The former NorMAN drive train consisted of shafts, brackets, and bearings which added significant weight to the vehicle. However, NorMAN Jr.'s drive train is reconstructed with the removal of these extra components which allow the weight of the vehicle to be reduced by 25lb and the width by 5 inches. As seen in Figure 4; in NorMAN Jr. the motors are mounted to the chassis, and the wheels are mounted directly to the gearbox.

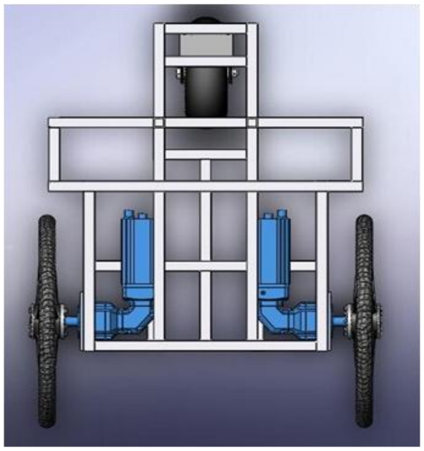


Figure 4- SolidWorks representation of the removal of brackets, bearings, and shafts

The space obtained in NorMAN Jr. allows efficient cooling of the internal components of the vehicle. Due to the mounting of the wheels directly to the gearboxes, new hubs were designed. The original wheel hubs had a 15mm shaft hole; however, for the gearbox, a 22 mm shaft hole was required. Due to time constraints, the shaft hole was modified and bore to 22mm.

2.5 Shell

The chassis was purposely designed to have an easily removable shell. The shell is constructed of polycarbonate sheets (panels), all of which are mounted to the chassis by removable thumb screws. This will allow easy access to our inner components of the vehicle. The outside panels are left clear whereas the panel on the tower mount is painted black in order to reduce glare to the camera. The top panel is left clear in order to allow the internal components of the vehicle to be observed by a judge or students.

3. Electrical

The Electrical Power system is comprised of several subsystems: The DC power distribution system, two interchangeable power sources, and the power monitoring system. The integration of all three of these subsystems is innovative and has not been offered on previous robots. The power distribution is implemented with a professional, reliable printed circuit board (PCB) designed for high power, individualized subsystem power paths, and quick disconnect capability. The power source is comprised of a hydrogen fuel cell battery hybrid system with a lithium polymer (Li-Po) or lead acid battery system. The power monitoring system monitors current and voltage from the whole vehicle and is also used to inform the user when the power resources are low.

3.1 Power Distribution

NorMAN Jr. features a PCB power distribution system shown in Figure 5. The equipment and sensors used on the robot utilize both 24V and 12V power. The 24V power is supplied by the Fuel Cell – Battery

Hybrid source or the battery pack. The 12V power is supplied with an on-board DC-DC converter that is routed back into the PCB for centralized distribution. This PCB distribution panel is a multi-layered board that was designed for high power use. It utilizes high current capable Anderson connectors for ease of assembly and quick disconnecting capability. Each subsystem is separately fused and has a dedicated switch. This provides for localized troubleshooting and maintenance of the power systems and reduces unnecessary power consumption during subsystem testing.

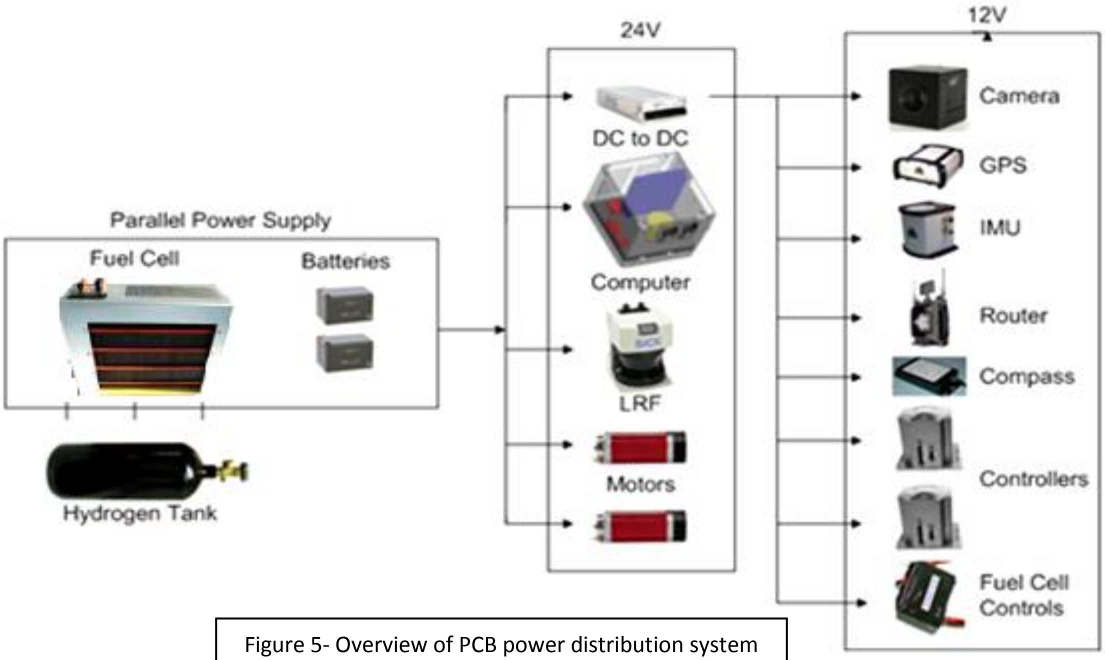


Figure 5- Overview of PCB power distribution system

3.2 Fuel Cell Battery Hybrid Power System

Two modular interchangeable power systems were designed for NorMAN Jr. The first is three 14.8V 40Ahr Li-Po batteries in series. The second and primary power system is a parallel Fuel Cell – Battery Hybrid system. The vehicle power analysis diagram is shown by component in Figure 6. One Horizon H-1000 hydrogen fuel cell is connected in parallel with two 14.8V 40Ahr lithium polymer batteries. The fuel cell can provide a maximum of 30A, 36 V and be used for the constant load of the 12V sources. This is ideal since the vehicle's 12 V sources do not provide a transient load on the power source. The battery pack handles the surge of transient power that is drawn from the motors. The worst case scenario base load is 919W. The worst case scenario Load and power analysis is shown in Figure 7.

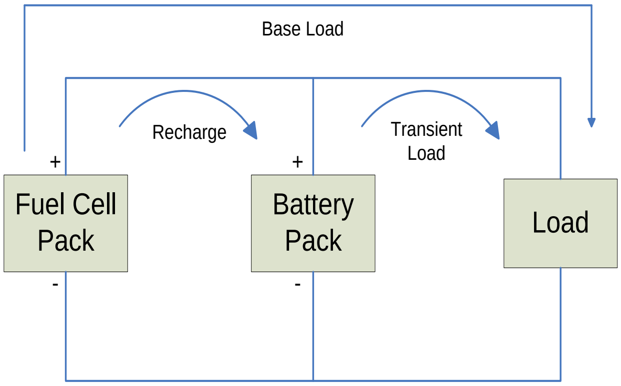
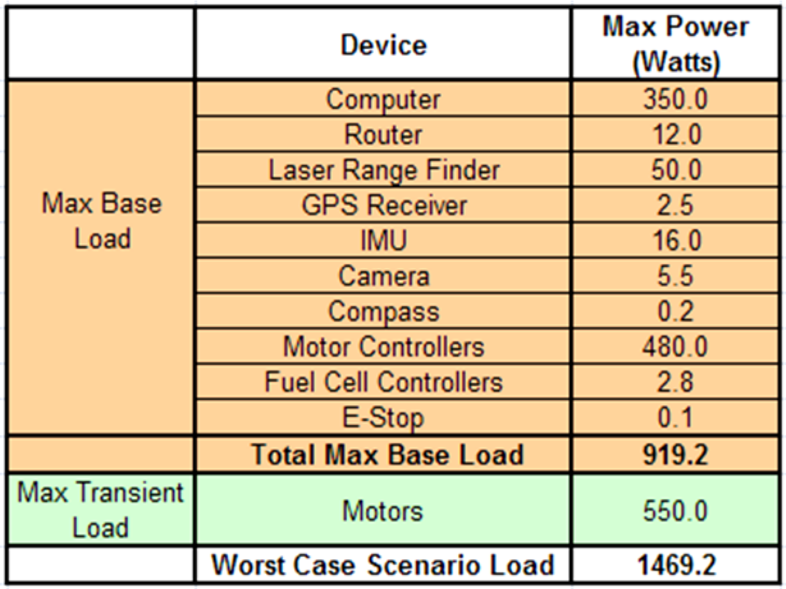


Figure 6- Fuel Cell Battery Hybrid system

3.3 Power Monitoring

NorMAN Jr. is equipped with a powerful, easy to use power monitoring system. The current and voltage of the battery pack and fuel cell are measured using a USB DAQ (Data Acquisition Box). The current sensor output and voltage of the vehicle through a voltage divider is inputed into individual channels on the DAQ board for analysis. This information is used to approximate the total run time of the vehicles hybrid-battery and battery only systems.



	Device	Max Power (Watts)
Max Base Load	Computer	350.0
	Router	12.0
	Laser Range Finder	50.0
	GPS Receiver	2.5
	IMU	16.0
	Camera	5.5
	Compass	0.2
	Motor Controllers	480.0
	Fuel Cell Controllers	2.8
	E-Stop	0.1
	Total Max Base Load	**919.2**
Max Transient Load	Motors	550.0
	Worst Case Scenario Load	**1469.2**

Figure 7 - Worst-case power consumption calculations

4. Computer & Sensors

4.1 Computer and System Integration

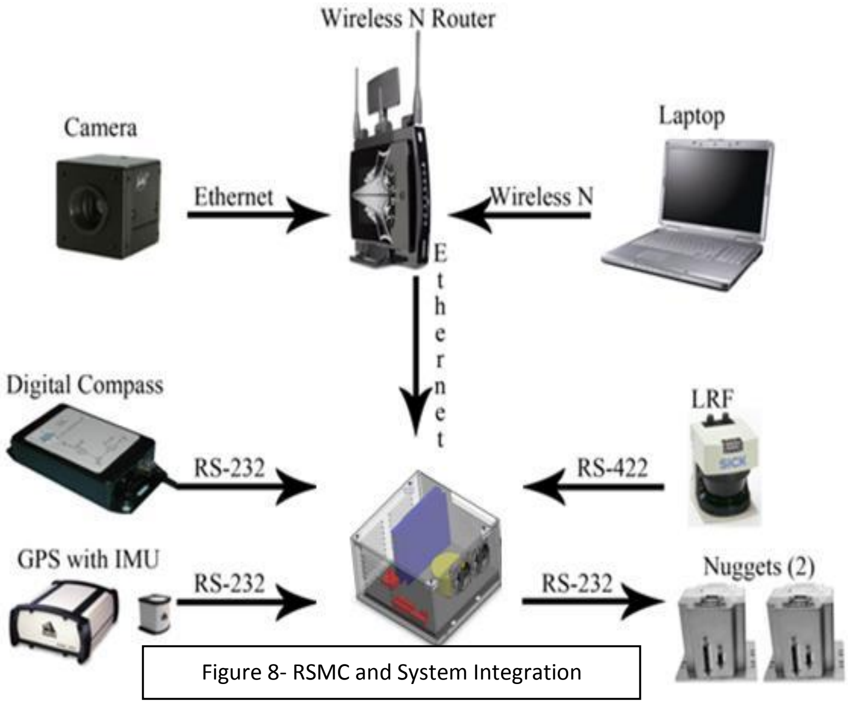


Figure 8- RSMC and System Integration

The Robotic Systems Mission Computer (RSMC) is the new mission computer onboard NorMAN Jr. It is fully designed to meet all specifications to handle the computational tasks and communication requirements with the NorMAN Jr. sensors. The parts are cheaper and faster to be replaced than the previous year’s proprietary NI PXI parts because they are widely available off the shelf. Although the internal components of the RSMC were kept the same from the former NorMAN; the outer case was redesign in order to obtain more space and reduce the overall weight of the computer. The computer case in NorMAN had dimensions of 17.25 x 11.00 x 8.75 inches, and weighed 30 lb. NorMAN Jr. computer case is designed to have dimensions of 10.8 x 10.5 x 5.6 inches and weighs 15 lb. The computer case for NorMAN Jr. is constructed with a nonconductive, static dissipative and translucent polycarbonate material. The three properties were considered due to safety factors such as avoidance of short, protection against electric discharges and for visual inspection of internal components during critical times in competition and testing. Figure 8 represents the current system integration of the NorMAN Jr. sensors communicating with the RSMC. In addition, RSMC runs an Intel Quad Core 2.4GHz processor with 4GB of 800MHz DDR2 memory which computes many more tasks than a conventional single core processor. To handle all the sensors onboard the NorMAN Jr., the RSMC is equipped with a special serial card which contains 8 customizable ports at customizable speeds. Each port can be set to RS-232, RS-422, and/or RS-485 with any baud rate ranging from 50bps up to 1.8432Mbps depending on the serial communication used, in addition to its 6 USB ports, a FireWire port, and an Ethernet port for all the other sensors. RSMC incorporates a DC power supply which eliminates the need for an AC to DC converter onboard the NorMAN Jr. The end result is a robotics systems mission computer enclosed in a mini case that conserves space, weight, and handles the required computations with minimal effort.

4.2 Laser Range Finder

NorMAN Jr.'s main source of obstacle detection is a SICK LMS291-SO4 laser rangefinder. This device is capable of scanning a range of 180º in 0.25º increments, measuring distances up to 80m away. The settings used for NorMAN Jr. makes the device scan a range of 180º in 1º increments, measuring distances up to 8m away and returning values in mm. Any distance further than 8m will not be considered by the obstacle avoidance algorithm, and 1º increments are sufficient at this distance. An RS-422 serial interface was used in order to obtain a data transfer rate of 500kbaud.

Figure 9- Laser range finder

4.3 GPS/IMU

NorMAN Jr. is incorporating the Novatel SPAN System which consists of the ProPak-V3 GPS Receiver along with an LN200 Inertial Measurement Unit (IMU). Using a serial communication of RS-232 with the RSMC, a baud rate of 57,600 and log data rate at a maximum of 20Hz is achieved. The Log BESTPOSA gives the best possible computed solution using both the GPS and the IMU. The data received from the SPAN System consists of latitude, longitude, and azimuth and is converted from latitude and longitude to x and y in Cartesian coordinates.

Figure 10- GPS receiver (left) and IMU (right)

4.4 Camera

The camera used is a JAI A70GE. The JAI camera is selected due to features such as selectable 8-bit or 10-bit color output, a ½" color CCD, Gigabit Ethernet output, 4-12mm Tamron lens with Auto-Iris functionality, and an angle of view greater than 90 degrees horizontal. Maximum resolution is 766x572 at a frame rate of 60 FPS. Figure 11 shows the JAI camera (camera lens detached)

4.5 Digital Compass

The compass that is being used for NorMAN Jr. is the 2X Revolution by True North. This device has an accuracy of 0.3 degrees and can be updated at a frequency of 12Hz. It communicates using an RS-232 serial communication interface for data transmission. Figure 12 shows the digital compass which is being used with NorMAN Jr.

Figure 12- True North 2X Revolution compass

4.6 Motor Controller

The Silver Nugget N3 M-Grade controller/driver has a 10-bit ADC for single input from a signal range of 0 to +5 VDC. The controllers have a RS-232 serial interface and baud rate of 57.6k with a variety of preset commands for controlling and interfacing. The controller communicates with the encoder by pulse width modulation at a TTL logic level of +5VDC. The encoder provides 16000 counts/rev with a maximum rotational speed of 4000RPM.

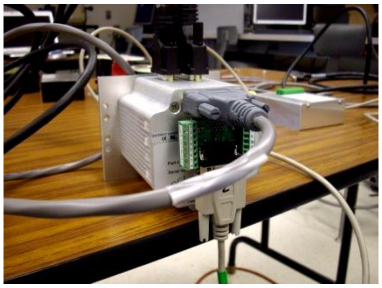


Figure 13- Silver Nugget N3 M-Grade controller/driver

5. System Software

5.1 System Communication

The software used to program NorMAN Jr. was written entirely in LabVIEW 8.2. This GUI application was user friendly when interfacing and integrating all our sensors together. By using the embedded functions provided with LabVIEW, sending and receiving commands from our outside sources became quite simple. Figure 14 shows the overview how LabVIEW is used to communicate with NorMAN Jr.

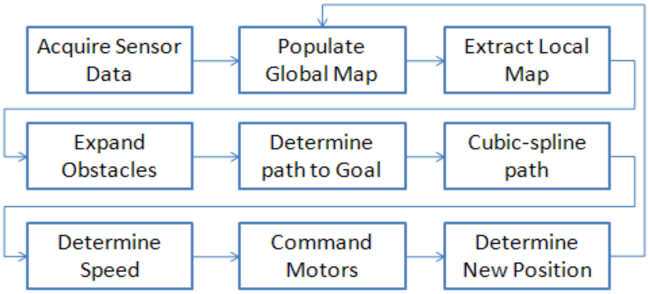


Figure 14- Software system

5.2 Vision

The goal of vision is to provide cognition with locations of white lines and a general heading for the robot to move towards. This is accomplished by a continuous sequence: Acquiring vision data from a camera, filtering to accent white lines, analyzing the image to remove noise and extract white lines, and examining line data to determine goal heading.

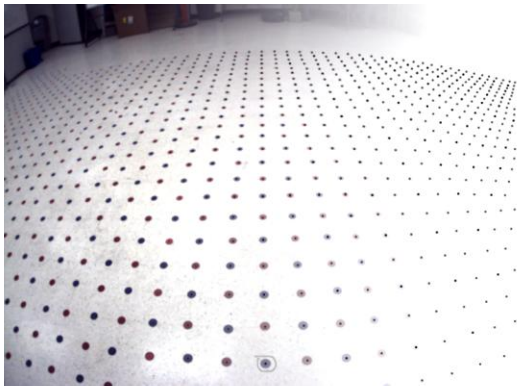


Figure 15- Camera calibration. Image fades from camera photo to digitally edited image for calibration.

Because cognition needs a birds-eye view of the corrected for both perspective and lens distortion. A grid of evenly spaced markers is laid in front of the camera, as shown in Figure 15, which illustrates the extent of the perspective and lens distortion.

Corrective parameters from this image are extracted and saved as a specific camera profile to be applied back in the vision process. The Vision system for NorMAN Jr. has been develop with one key factor in mind; dynamic lighting conditions. Before any image processing takes place, NorMAN Jr.'s Vision system ensures that the image acquired by the camera be first exposed properly in order to more easily extract important features from the image. This is done by an exposure control system that has been developed by 2008-2009 CSUN IGV Vision group. The new Vision system (including the exposure control system), is presented below in Figure 16.

In order for the Vision system to have control of the exposure, the appropriate camera had to be selected. The ideal camera would allow control of the shutter speed and camera gain via software control signals. The camera used for this purpose is the JAI camera which is a progressive scan type camera that has a high speed and resolution. The operation of the new CSUN IGV Vision System is as follows. There are two digital ambient light sensors mounted by the camera that determine the ambient lighting conditions at every instant in time.

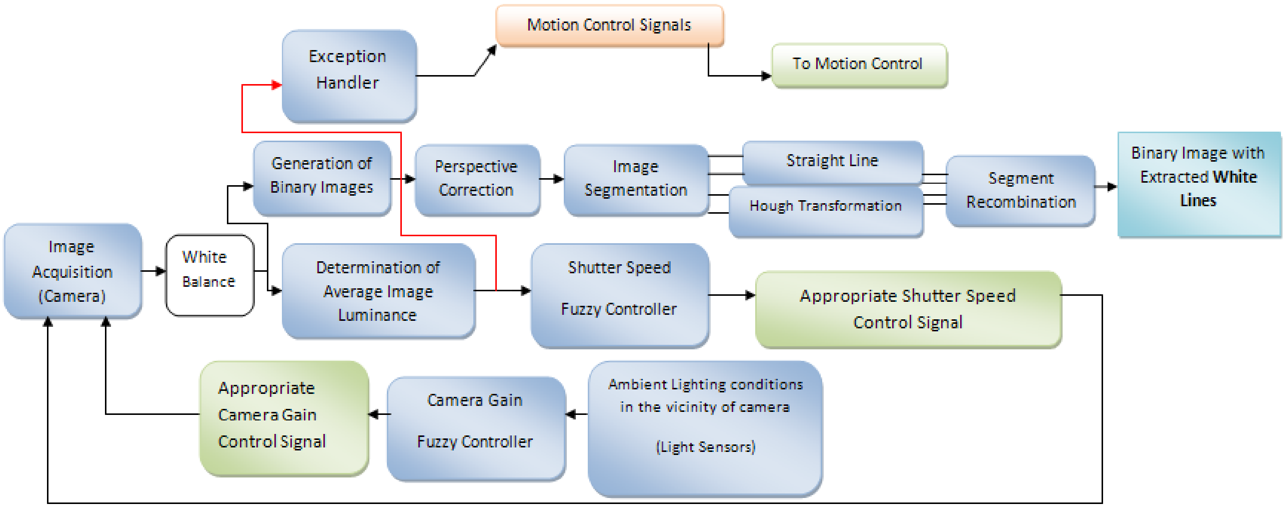


Figure 16- Vision System

The developed LabVIEW Vision code determines the optimum camera gain and adjusts this gain accordingly via software signals outputted by a fuzzy controller. The decision making for the optimum camera gain is done by this camera gain fuzzy controller. Simultaneously, the average image luminance of the white balanced version of the original image is determined and this average luminance is used as an input to a second fuzzy controller. This fuzzy controller determines the optimum shutter speed of the camera for the current average image luminance.

After a properly exposed image is acquired, the image is applied to the average luminance fuzzy controller and is converted to gray scale using the Channel Mix method. Because the camera is not pointed perpendicular to ground, some perspective correction is done to the gray scale image and the usable portion of the image is extracted and split into left and right. The extracted portion of the image is then transformed into a binary image using the brightest pixel thresh holding technique. Each segment is then segmented again into top and bottom sub images and the Hough line transform is done concurrently on all sub images before they are recombined. Thus, for each image segment, a straight line that best approximates the line in each segment is generated. These segments are then recombined and the result is, in essence, the linear approximation of the two white curved lines on the field. An example of such an approximation is shown in Figure 17 below.

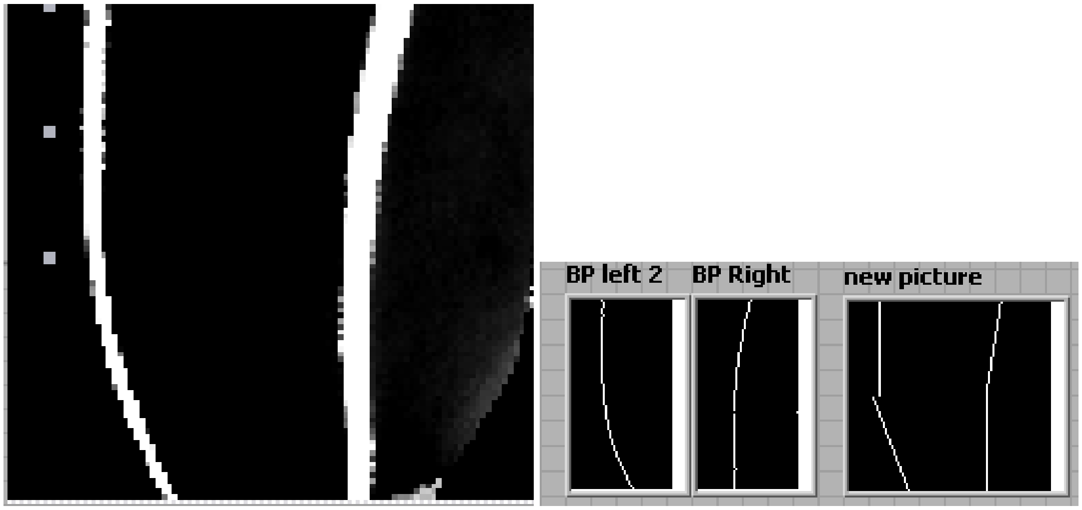


Figure 17- Curved Lines and Linear Approximation of Curved Lines Using Hough

5.3 Obstacle Avoidance, Mapping, and Path Planning (Cognition)

NorMAN Jr. uses a laser range finder to build a Cartesian style occupancy grid map around itself. The laser range finder outputs a customizable array of range points to update our software continuously. The points are converted into XY coordinates and are used to populate a grid map. There are two different style maps that NorMAN Jr. uses. A local map and a global occupancy map, shown in Figure 18 below.

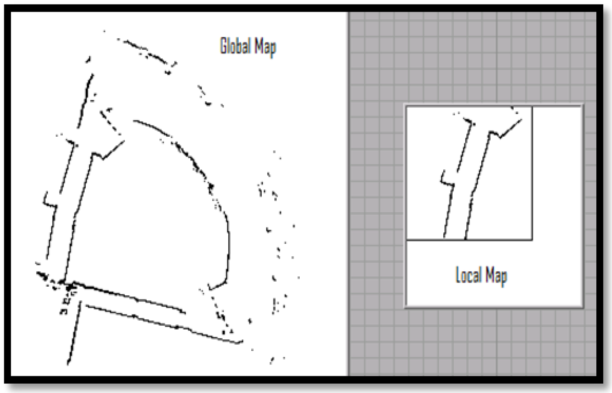


Figure 18- Two maps used for localization.

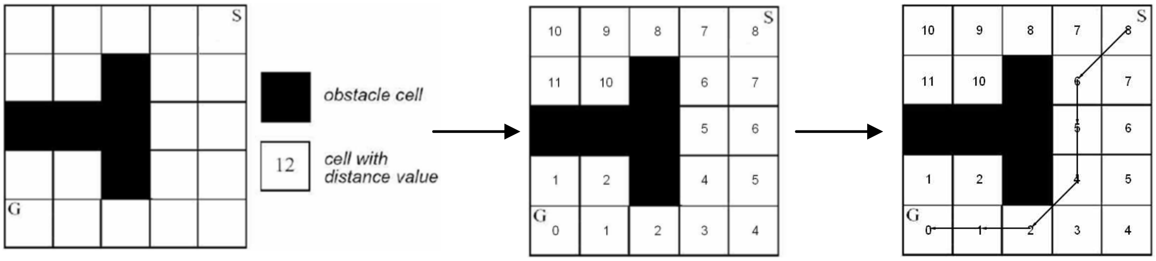


Figure 19- Grassfire process

The global map is fixed at a coarse scale to fit the entire map in an N x M array. This array is large enough to fit the entire map but coarse enough to not waste system memory. Once the immediate area around the robot is mapped and saved in the global map, a 16 m x 16 m area is extracted and used in a local reference. This map is what is used to plan paths around immediate surroundings. The obstacles and white line points from Laser ranging and Vision are expanded by an offset equal to the radius of the robot. This is done because the robot sees itself on the map as a dimensionless point. This new array is then fed back to the path-planning program.

Filled cells are recognized as obstacles and unfilled cells are recognized as clear space. This map is used to determine incremental steps towards the desired occupancy grid goals. With the use of parallel processing, we can designate one process to solely build the global map and another process to extract the local map and using a path planning algorithm called Grassfire. Occupancy grid goal point cells are located on the edge of the map, pointing to the next waypoint defined by GPS in the navigation challenge or the goal point found by the vision system during the autonomous challenge, with NorMAN Jr. being at the center. The grassfire algorithm fills in empty cells with numbers representing the distance to the goal until all of the cells around NorMAN Jr. are filled. Then a path finding algorithm outputs a cell to cell path based on the information provided in the grassfire algorithm as shown above in Figure 19.

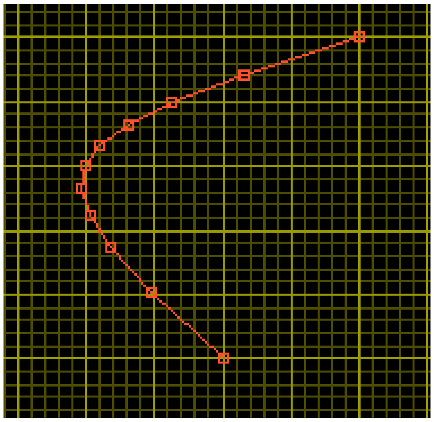


Figure 20- Cubic spline of a Grassfire path.

The output cell array is then converted to discrete x and y coordinates. These discrete coordinates represent the incremental steps towards the desired occupancy grid goals. Since there are parallel processers computing the path and extracting data, NorMAN Jr. will continuously create new paths. With the new found path to the goal, a filter needs to be implemented to smooth the trajectory. To do so, a cubic-spline algorithm is implemented as seen in Figure 20.

Another feature integrated into NorMAN Jr.'s mapping is a Local Map expansion capability. The purpose of the local map is to ease the computation of the vehicles' path since a large global map would be more difficult to process. Yet a local map has limitations such as an inability to generate a path during a long- wall obstacle situation. When a path cannot be generated by the grassfire algorithm, the local map expansion capability dynamically increments the size of the local map until a path can be generated. Once the path has been generated and the vehicle moves around the obstacle, the local map is then reduced back to the default size for faster computation of further path planning. This allows the vehicle to determine a path around large obstacles in order to avoid backtracking or wasting time locating a path.

This capability also provides an acceptable tradeoff between accuracy and speed of computation for navigating through these situations.

5.4 Autonomous

The Autonomous Challenge and Navigation Challenge both use the same core cognition algorithm with a few modifications. To accomplish this, NorMAN Jr. must first gather all information from each sensor. This is done with parallel processing, which ensures that the data is received from each sensor at their maximum rate. The key sensors used in the Autonomous Challenge are the LRF and the digital camera. Both of these sets of data are fused into one local map and placed in a larger, coarser global map. Our local referenced goal is generated by the vision algorithm's analysis of the line data.

NorMAN Jr. computes its immediate position using odometry but will deviate substantially over long distances due to losses of contact between the wheels and the ground among other factors. To correct this, a calibrated systematic error is used to compensate for the odometry position. Integrated with the GPS / IMU system this corrects the inaccuracy of the long distances while maintaining the accuracy at short ones. NorMAN Jr. also computes heading using the same odometry, yet again it distorts over long distances. The same process is applied using the digital compass and the IMU for this correction.

5.5 Navigation

Motion control for the Navigation challenge was coded similar to the Autonomous Challenge in efforts to make the algorithm compatible with both challenges. Instead of using the goal from vision, GPS will run in a parallel process to compute the global goal in reference with the lat / long position represented in Cartesian coordinates. The Cartesian coordinates are fed into motion control to plan its path to the next navigation point while avoiding obstacles. Due to an average standard deviation of 7 meters using just the GPS solution, minimization of error is required to perform well during the navigation challenge. Therefore, OmniSTAR HP is used to decrease the position error down to an average standard deviation of 0.7 meters using just the GPS coordinates. We can improve this even better while the IMU is in conjunction with the GPS to generate an average standard deviation of 0.3 meters.

Azimuth is supplied from the GPS receiver and compared to the digital compass data to give a more precise heading. This helps reduce the error in the digital compass caused by magnetic interference. Since the global goal is outside of the local map, a new goal is generated with the same heading as the global goal until the global goal is inside of the local map. At that point, the same procedure occurs as mentioned before.

6. Predicted Vehicle Performance

6.1 Reaction Time

With parallel processing and shared variables, NorMAN Jr. now computes each process separately without the need to wait for any other

Reaction Time	
Process	Time (ms)
Sensor Input	110
Grassfire	440
Map Building	140

Figure 21- Reaction time of sensors and cognition algorithms

process to finish. This allows it to process each sensor input and execute path planning and motion control VIs at its maximum potential.

6.2 Speed

NorMAN Jr.'s speed is based off an equation that involves the distance from its current position to its immediate goal. The speed is bounded with a maximum speed of 3 mph and minimum of 0.5 mph for safe traveling and course navigation.

6.3 Ramp Climbing Ability

The difference of the average robot speed on a 15 degree slope to the average speed on flat ground is about 0.001 MPH. A slope has little effect on the robot when it is traveling at a constant speed over a ramp. Furthermore, NorMAN Jr. was tested on a 30 degree slope and successfully completed the slope.

6.4 Run Time and Battery Life

Assuming that the motors are running 20% of the time and all of the equipment experiences their worst case scenario power consumption, the fuel cell battery hybrid system is calculated to provide 79 minutes of run time with one 29 standard cubic-foot tank of hydrogen instead of the 52 minutes of run time that the 28Ahr batteries alone would provide under the same conditions. This hybrid power system achieves a 52% longer run time over the previous year's system.

6.5 Sensor Range

The LRF has a 180-degree sweep with a maximum range of eight meters. With the Vision code and the JAI camera, the most accurate range that can be seen is about five feet ahead. The GPS and the compass operate best outdoors.

6.6 Complex Obstacles

If the robot finds its self heading towards a dead end, a local goal will be placed on the other side of it. Grassfire will find the shortest path to that goal point which is back from where it came from. Once the robot turns around, a new goal will be drawn in front of it and now be heading away from the dead end. Center islands are viewed as any other obstacle. Depending on the robot's current position, a trajectory will be computed around the center island. If the island happens to be perfectly centered in front of the robot so that both paths are equidistant, they are equally likely to be chosen.

6.7 Accuracy of Arrival to Navigation Waypoints

The accuracy of the robot's arrival to navigation waypoints is limited by the standard deviation of the GPS, which ranges from 7m (free service), 0.6m (OmniSTAR), to 0.3m (IMU integration).

7. Safety

When creating any autonomous vehicle it is very important to take safety into account. A careful safety analysis is essential to ensure that no one will be harmed while operating, observing, or working on the vehicle and has been incorporated into NorMAN Jr.

7.1 E-Stop

NorMAN Jr.'s Emergency Stop system has two methods of immediately stopping the vehicle: wireless and hard-stop. If either system is activated, it will send a direct 5 volt source into the breakout modules of the motion controllers to safely shut down the motors. The wireless portion includes keyless entry with a handheld transmitter and receiver with a whip antenna that sends a signal within a range of 80 feet. The wired portion uses a large red 120V 10A regulated switch that controls the on/off states of the 5 volt regulator. The on/off states are indicated by logic light emitting diodes on the E-Stop enclosure mounted on the vehicle mast.

7.2 Hydrogen Safety

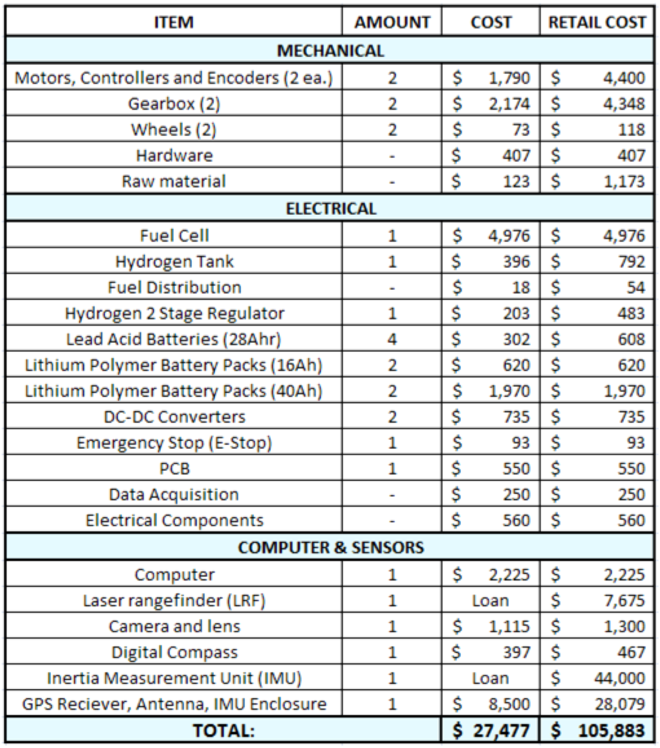
Several layers of safety were designed into the hydrogen fuel distribution system on NorMAN Jr. The first layer of safety is Containment. This consists of the hydrogen tank, 2 stage regulator, fuel distribution manifold, connectors, and tubing. These components form the primary system of containment to prevent a hydrogen leak. The second safety layer consists of several design features in NorMAN Jr. that will each reduce the probability of a catastrophic accident in the unlikely event of a hydrogen leak. This includes proper ventilation, and heat isolation of the chassis. There are 2-inch spacers added on top of the chassis of the vehicle to raise the top panel, which creates a wide-open vent for heat dissipation, and cooler air flow. If there is a leak, hydrogen which is lighter than air will rise to the top of the compartment and be vented outside, preventing a buildup of hydrogen inside the vehicle. The hydrogen tank is isolated from heat producing systems such as the computer, electronics, and fuel cell. By keeping the hydrogen tank cool, the internal tank pressure is maintained safely. The last safety design feature is the insulation of the compartments where hydrogen is used. The inside of the fuel cell and tank compartments were coated with several layers of clear, rubberized paint to reduce the probability of sparks or arcing near the hydrogen equipment.

7.3 Chassis Ground

Due to the aluminum frame and shell, it was very important to properly ground the chassis of NorMAN Jr. This will protect users from electric shock in the case of a hot wire coming into contact with the chassis. If this were to happen, the energy discharge would be routed safely to battery ground instead of through the user to ground. The chassis was grounded at the power distribution PCB using 6 AWG wire to ensure a low resistance path to the ground.

8. Cost

Although NorMAN Jr. is classified as an R&D vehicle, every effort was made to reduce costs through sponsorship agreements with material and component suppliers. This was done within the constraints of time and the effort to provide an innovative product. Figure 22 shows the team costs and retail costs associated with NorMAN Jr.



ITEM	AMOUNT	COST	RETAIL COST
MECHANICAL			
Motors, Controllers and Encoders (2 ea.)	2	$ 1,790	$ 4,400
Gearbox (2)	2	$ 2,174	$ 4,348
Wheels (2)	2	$ 73	$ 118
Hardware	-	$ 407	$ 407
Raw material	-	$ 123	$ 1,173
ELECTRICAL			
Fuel Cell	1	$ 4,976	$ 4,976
Hydrogen Tank	1	$ 396	$ 792
Fuel Distribution	-	$ 18	$ 54
Hydrogen 2 Stage Regulator	1	$ 203	$ 483
Lead Acid Batteries (28Ahr)	4	$ 302	$ 608
Lithium Polymer Battery Packs (16Ah)	2	$ 620	$ 620
Lithium Polymer Battery Packs (40Ah)	2	$ 1,970	$ 1,970
DC-DC Converters	2	$ 735	$ 735
Emergency Stop (E-Stop)	1	$ 93	$ 93
PCB	1	$ 550	$ 550
Data Acquisition	-	$ 250	$ 250
Electrical Components	-	$ 560	$ 560
COMPUTER & SENSORS			
Computer	1	$ 2,225	$ 2,225
Laser rangefinder (LRF)	1	Loan	$ 7,675
Camera and lens	1	$ 1,115	$ 1,300
Digital Compass	1	$ 397	$ 467
Inertia Measurement Unit (IMU)	1	Loan	$ 44,000
GPS Reciever, Antenna, IMU Enclosure	1	$ 8,500	$ 28,079
TOTAL:		**$ 27,477**	**$ 105,883**

Figure 22- Team costs and retail costs of NorMAN Jr.

9. Conclusion

NorMAN Jr. is an autonomous ground vehicle that is designed, built, and tested by the students of the CSUN IGV Team and integrates innovative algorithms, features, and technologies into one vehicle. The fuel cell hybrid power source, the use of positional data fusion, probabilistic obstacle mapping, vision curved line segmentation algorithm, and shared variable engine set us apart from the competition and will help establish new standards in the field of autonomous robotics.