NorMAN Jr

Northridge's Mobile Autonomous Navigator

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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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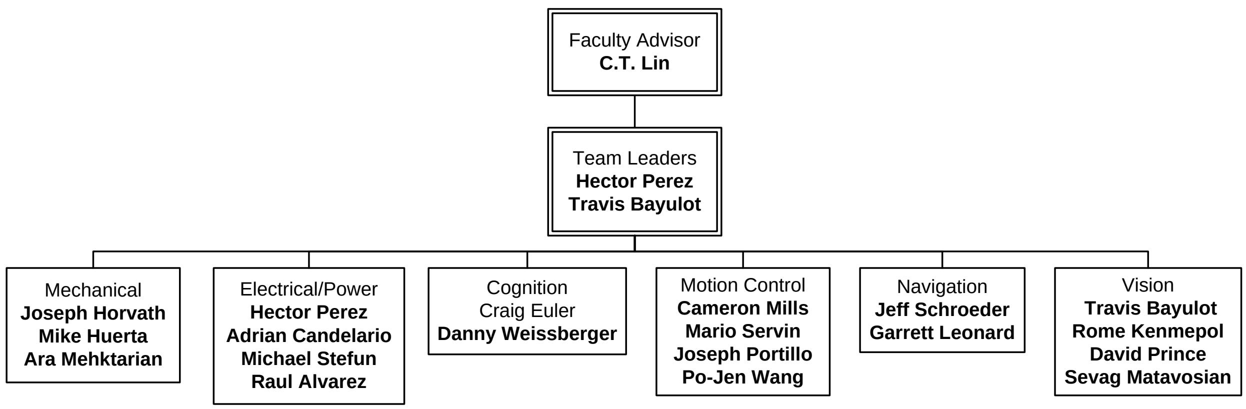
1. Introduction

The Intelligent Ground Vehicle team of the College of Engineering and Computer Science at California State University, Northridge (CSUN) is proud to present NorMAN Jr. Last year, CSUN placed 5th in the design challenge. This year, new innovations have been introduced to the original NorMAN Jr. including a fully functional hydrogen fuel cell power system and an improved cognition scheme.

1.1 Team Organization

The IGV project at CSUN is comprised of six sub groups: mechanical, power and electrical, path planning and obstacle avoidance, vision, navigation, and motion control. Each team has a team leader that structures the organization of the group and enforces open communication among the other teams so that proper integration is achieved.



2. Innovation

2.1 In Mechanical Design

An additional camera mount has been implemented to pave the way for a dual camera line detection system. Removable handles have also been integrated for easy carrying of NorMAN Jr. when unpowered. Layout changes have been made to accommodate for various hardware innovations such as a damped fuel cell mount, an isolated battery box, a capacitor/daq system plate, and an elevated shell.

2.2 In Electrical Design

One of two primary innovations implemented to the design of NorMAN Jr. is a green (clean and environmentally) friendly Hybrid Hydrogen Fuel Cell Lithium Polymer Battery system which powers the robot, whose only byproducts are heat and water vapor, as opposed to the lead acid battery configuration utilized by previous vehicles. A power source switching design is also featured, allowing for several power configurations. A fail safe e-stop system has also been achieved, in contrast to unreliable, fence destroying systems in the past.

2.3 In Software Design

The second primary innovation of NorMAN Jr. features a complete path planning overhaul. Previous designs featured “Grassfire,” a map building centric path planning algorithm. NorMAN Jr. approaches path planning and obstacle avoidance in a drastically different way with Vector Polar Histogram (VPH), a heading based algorithm. Algorithms for GPS navigation have also been improved using brute force methods to solve for shortest distance between waypoints. Motor control algorithms to control robot motion have been simplified as well.

3. Mechanical Design

NorMAN Jr’s outer dimensions are chosen with the goal of fitting through a standard doorway. Emphasis is placed on agility and maneuverability at low speeds. NorMAN Jr.’s frame was modified to accommodate the addition of several hardware innovations. Heavier components were placed on the lower locations of the chassis to keep the center of gravity low, and to prevent body roll when turning. A tower mounted in the front of the vehicle gives the camera a wide angle of view. Weatherproofing is achieved while still maintaining a transparent view of internal components by using polycarbonate sheeting as external panels.

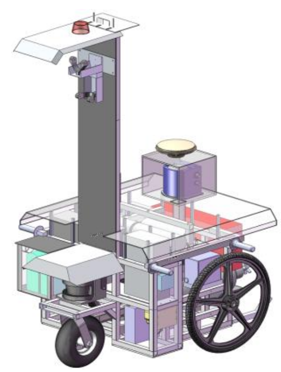


Figure 3.1 – NorMAN Jr. Solid Model

3.1 Chassis

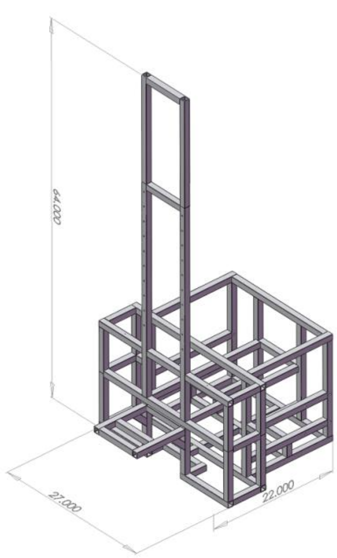


Figure 3.2 – NorMAN Jr. Chassis

NorMAN Jr.’s chassis (Figure 3.2) is constructed using 1 in. square tubing with 90 degree welds. In order to maintain lighter weight, Aluminum 6061-T6 was used as opposed to Alloy Steel. To increase strength, rigidity and to resist stress cracking, multiple heat treatments were performed on the chassis. Square tubing also allowed easy mounting of panels and internal components and simplified welding, as well as providing level surfaces.

NorMAN Jr. is a modified design originating from previous chassis’. Previous chassis’ were longer, heavier, and wider so the main goal was to optimize dimensions. Reducing overall length provided less stress when turning due to the reduction of moment on the front caster wheel. Due to NorMAN Jr’s reduction in body role mentioned above we were able to reduce the width of the chassis allowing it to navigate through obstacles efficiently. 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 previous chassis', NorMAN Jr. is 29.5% smaller and 39.2% lighter.

3.2 Wheel Configuration and Drive System

NorMAN Jr.'s differential drive was chosen for control and to eliminate the need for a differential gearbox. The wheel configuration involves two 20" lightweight driving wheels in the rear, and one free turning 8" caster wheel in the front. To optimize space, the wheels are mounted directly to the gear box shaft and the gear boxes are mounted to the frame using aluminum plates (Figure 3.3). In addition, 90º Apex Dynamics gear boxes were chosen to allow optimize space for the hydrogen tank assembly at the center of NorMAN Jr., while maintaining 173ft-lb when coupled to 2 Quick Silver QCI-A34HC-2 DC servo motors. A 30:1 gear ratio with high torque maintains agility at low speeds. NorMAN Jr.'s redesigned drive system results in a 25lb reduction.

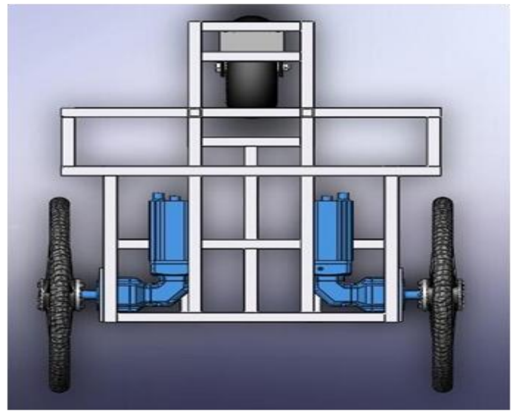


Figure 3.3 – Motors and Gear Boxes (Top)

4. Electronics Design

The Electrical Power system is comprised of several subsystems: The DC power distribution system, selectable power sources, an uninterruptible power switching module and the power monitoring system. The integration of these subsystems includes a combination of innovative systems that have not been offered previously on other robots. The power distribution is implemented with a high power printed circuit board (PCB), isolated subsystem power paths, and quick disconnect capability. The power sources are comprised of a Hydrogen Fuel Cell, Battery Hybrid Power system, standalone Battery Power systems, an AC Power supply, and a 2kW Honda gas generator. The power monitoring system monitors current and voltage from key areas of concern.

4.1 Power Distribution

NorMAN Jr. features a PCB power distribution system as shown in figure 4.1. The equipment and sensors used on the robot utilize both 24V and 12V power through high efficiency DC-DC converters. The power source provides power to both the 24V and 12V DC-DC converters, which route to a 2.5F and 1F capacitor bank, respectively, which then route to the PCB for centralized distribution. This

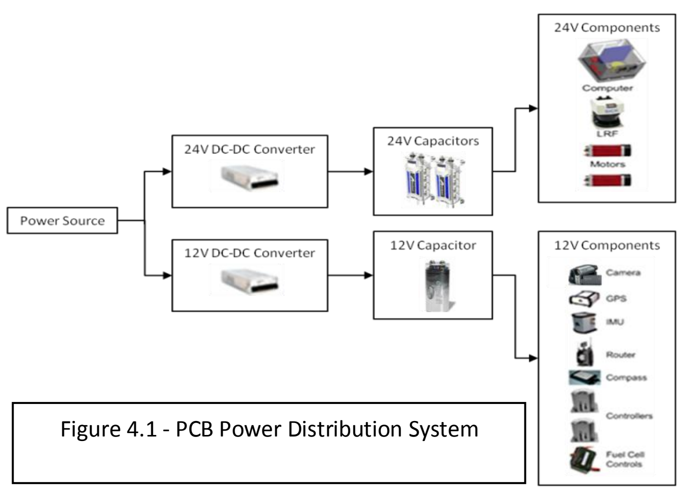


Figure 4.1 - PCB Power Distribution System

PCB distribution panel is a multi-layered board, designed for the power needs of the vehicle. 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 a safe turn-on sequence to power up the vehicle, which allows testing of individualized subsystems, simplistic troubleshooting and maintenance of the power systems.

4.1.1 Uninterruptable Power Switching Module

An uninterruptable power switching process was implemented onto the vehicles power system for ease of connectivity and to eliminate downtime between battery or hydrogen tank exchanges. The use of capacitors from the output of the 24V and 12V DC-DC converters allows for a wide range of applications independent of the power source, allowing the vehicle's respective systems to remain powered when switching between power systems through the use of a heavy duty on-on switch and high amperage Anderson connectors on the rear of the vehicle. The capacitors also assist the power source under transient vehicle operation.

4.1.2 Fuel Cell Battery Hybrid Power System

Previous efforts on NorMAN had not yielded a reliable hydrogen powered system. This became the motivation to implement a robust system that could be used for various applications, extending the runtime of NorMAN Jr. The Hybrid Power System operational diagram is shown in figure 4.2. A 1kW Horizon H-1000 PEM Hydrogen Fuel Cell is used to supply power to the user programmable Outback Power Systems FlexMAX 60 MPPT Charge Controller which then supplies a base load to the vehicle, while regulating the charge to three 14.8V 16Ah Lithium Polymer batteries in series (44.4V 16Ah battery pack), allowing the batteries to assist the fuel cell under transient conditions.

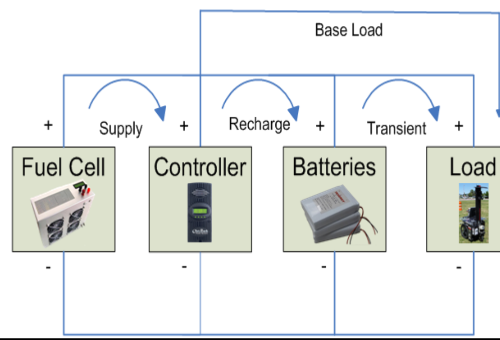


Figure 4.2 - Fuel Cell Battery Hybrid System

4.1.3 Auxiliary Power Systems

As an auxiliary power source to NorMAN Jr., a standalone battery power system is used for short to mid range operation: four 14.8V 16Ah Lithium Polymer Batteries in series to achieve a 59.2V battery pack at 16Ah. For long term operation, a Honda 2kW Gas Generator is used in conjunction with any AC Power Supply. For indoor software and static component testing an AC Power Supply connected to the electrical grid is used.

4.1.4 Power Monitoring

NorMAN Jr. is equipped with a user friendly power monitoring system. Through the use of the NI-DAQ USB6009 shown in figure 4.3, used at a sampling rate of 20Hz for long term tests, and 40Hz for short term tests, the user is able to monitor


Figure 4.3 - NI DAQ USB 6009

current, voltage, and power consumption from the vehicle at different points of interest. Voltage is measured through a high impedance voltage divider system, and current is measured through Hall Effect sensors and filters to clean the signal to the DAQ. The user is then able to view these conditions through a custom LabVIEW algorithm which can be displayed on the vehicle monitor, or externally monitored through a laptop. This information is used to approximate the total run time of the vehicle's power systems using average and peak current, voltage, and power measurements.

4.1.5 Vehicle Power Consumption Overview and Analysis

The maximum vehicle power consumption overview of NorMAN Jr. is shown in figure 4.4. Main power consumption comes from transient operation of the motors and computer under heavy processing conditions. The worst case power consumption is 1448.2 watts, and was the initial design point for our power system, to ensure robustness. Based on extreme case testing with the data acquisition system, vehicle power consumption (Figure 4.5) reached a 1112 watt peak surge, with an average power consumption maximum of 775 watts and became our new design point for the power system. Average power consumption for NorMAN Jr. was measured at 457 watts. The Hybrid Power System is able to deliver 1000 watts from the PEM Fuel Cell, and 710.4 watt-hours from the Lithium Polymer Battery Pack.

		Vehicle Power System	
		Device	Power Consumption (Watts)
Max Base Load	24 Volt	**Computer**	**350**
		Laser Range Finder	50
	12 Volt	Motor Controllers	48
		Fuel Cell Controller	42
		IMU	16
		Router	12
		Fans	9.5
		Camera	6.6
		Charge Controller	4
		GPS Receiver	2.5
		E-Stop	0.4
		Compass	0.2
	Combined	**Worst Case Base Load**	**544.5**
Max Transient Load	**24 Volt**	**Motors (Both)**	**907**
Total	**Combined**	**Worst Case Total Load**	**1448.2**

Figure 4.4 – Specified Component Power Consumption

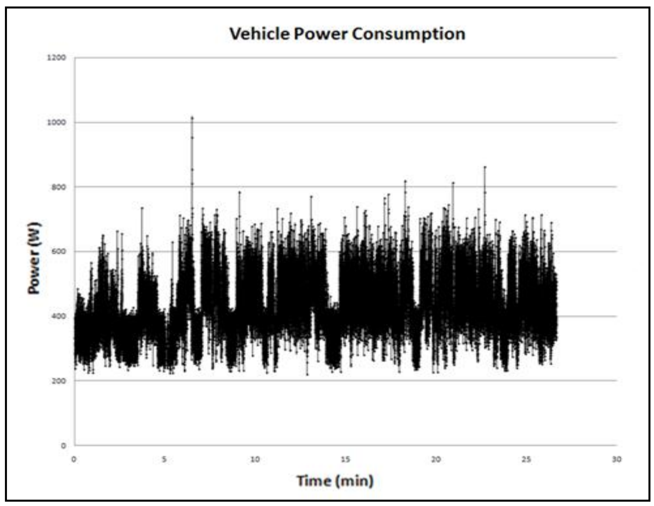


Figure 4.5– Vehicle Power Consumption

4.1.6 Vehicle Main Power Source Wiring Diagram

A wiring diagram of the vehicle's main power source is shown in figure 4.6.

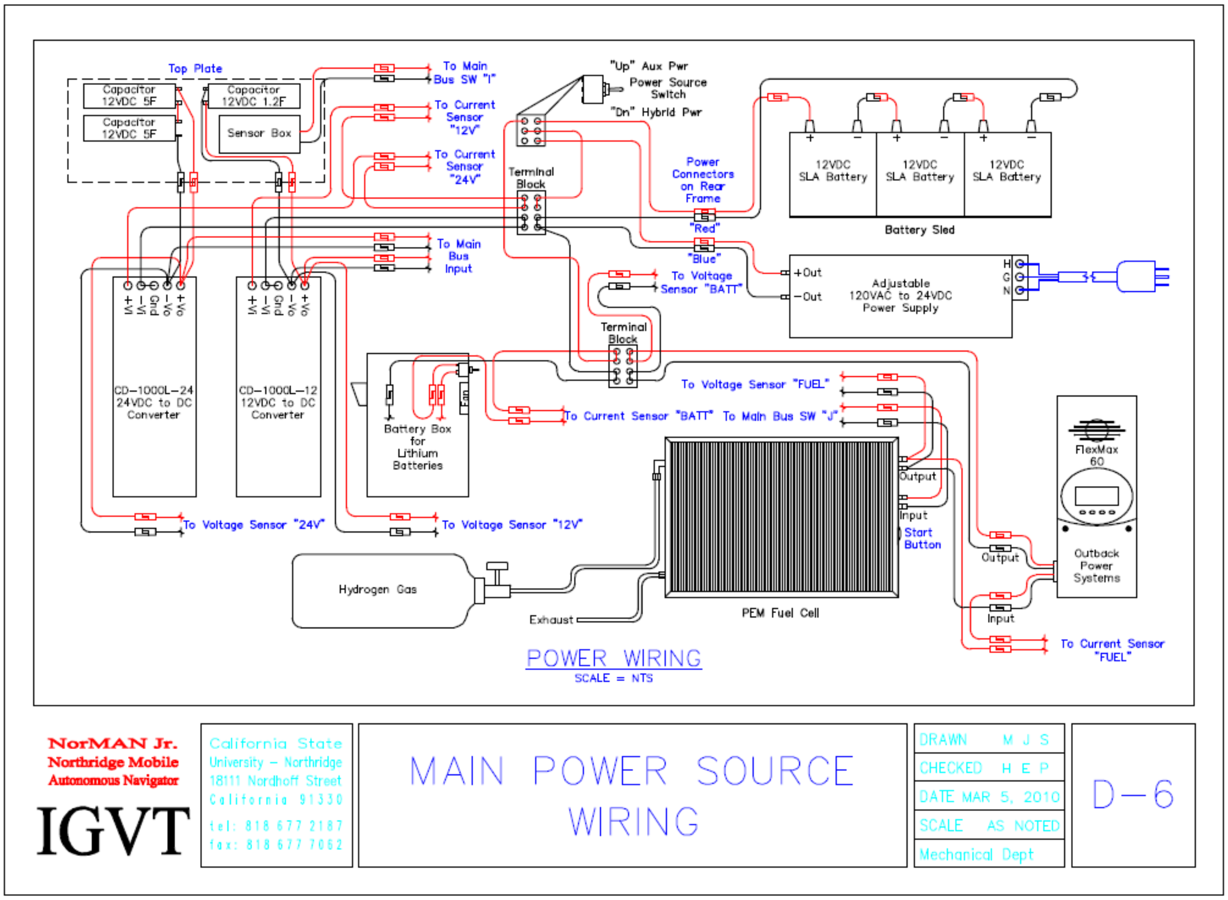


Figure 4.6 – Main Power Source Wiring Diagram

4.2 Sensors and Range

4.2.1 Cognition/Path Planning Sensor

The laser range finder used on NorMAN Jr. is the SICK LMS-291 SO4 as shown in Figure 4.7. This LRF has a scanning range of 180 degrees at a selectable scale of .25, .5, or 1 degree resolution and a range of up to 80 meters with an accuracy of 1cm. The setting selected is .5 degree resolution with an 8 meter range and a baud rate of 57.6k. An RS-422 serial interface is used for receiving data.

Figure 4.7 - SICK LMS-291 SO4

4.2.2 Navigation Sensors

NorMAN Jr. uses a NovAtel SPAN (Synchronized Position Attitude & Navigation) system for navigation. This system consists of a GPS-702L antenna (Figure 4.8) and LN200 IMU (Inertial Measurement Unit) (Figure 4.11), which feed into a ProPak-V3 receiver. Omnistar has donated their HP differential GPS service, which increases accuracy to 0.1 meters. The IMU provides position data when GPS data is unavailable, as well as increasing the refresh rate up to 200Hz. The ProPak receiver merges the GPS and IMU data and provides Latitude, Longitude and velocity to the computer. The receiver interfaces with the computer via an RS232 serial connection at 57.6k baud rate. NorMAN Jr. also uses a True North Revolution 2X digital compass to identify heading. This compass provides heading data at 27.5 Hz, with an accuracy of 0.5°. It communicates with the computer via an RS232 serial connection.

Figure 4.8 - Antenna

Figure 4.9- Receiver

Figure 4.10 - Compass

Figure 4.11 - IMU

4.2.3 Vision Sensor

The digital camera used is a Panasonic PV-GS90 (Figure 4.12). The PV-GS90 was selected for its rich features such as automatic white balancing, exposure, focus, and widescreen video capture. With a maximum aperture of F/1.9 and an optical sensor size of 1/6", it has an area of view without lens distortion at 67.38° horizontal and 53.13° vertical. It uses an IEEE-1394 interface providing data transfer of up to 800 Mb/s.

Figure 4.12 – Panasonic PV-GS90 Digital Camera

4.2.4 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 by TTL logic at +5VDC. The encoder provides 16000 counts/rev with a speed of 4000RPM.

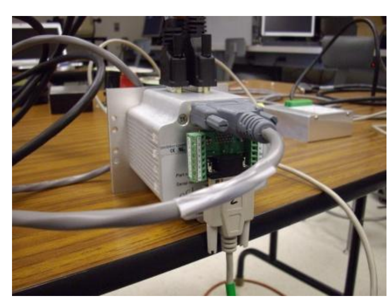


Figure 4.13. Silver Nugget N3 M-Grade Controller/Driver

5 Software Strategy

5.1 Vision (Line Detection) Software Strategy

The goal of the vision process is to provide the cognition system with the locations of white boundary lines and a general heading to move toward in the form of a polar histogram. This is accomplished by continuously capturing still images, correcting for perspective distortion, analyzing each image to extract white boundary lines, remove noise and finally, examining the line data to determine a goal heading.

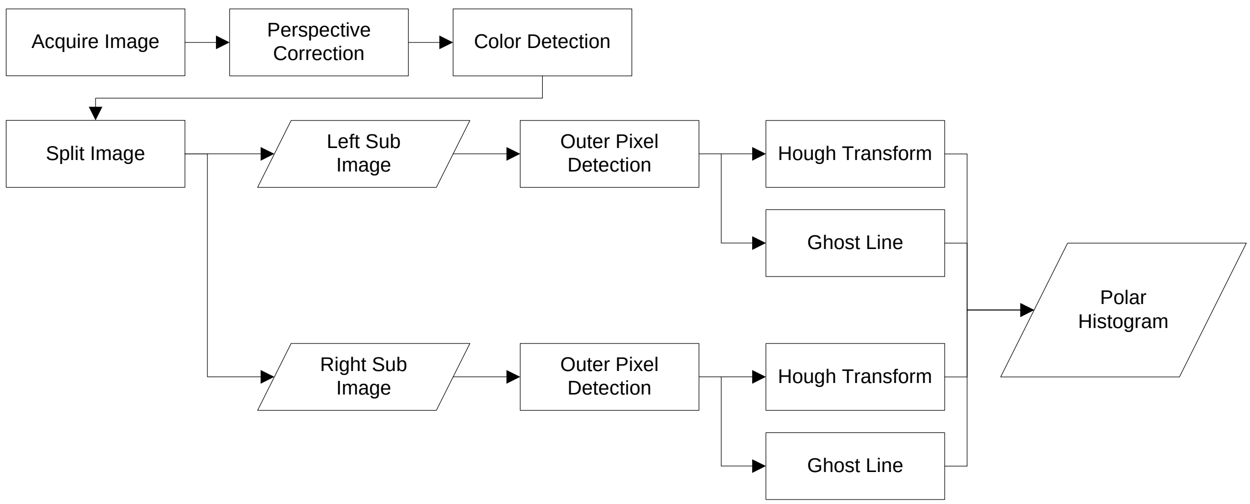
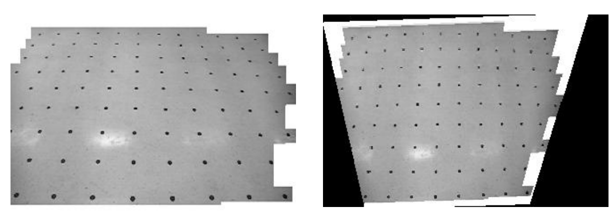


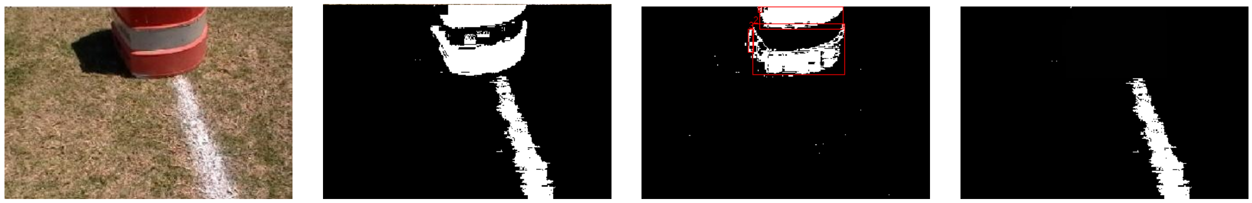
Figure 5.1 – Vision System Process

Since the camera is mounted at an angle, the perspective of the camera image must be corrected to show an overhead view. Figure 5.2 shows an example of the perspective angle calibration. Corrective parameters are extracted and saved as a specific camera profile to be applied back into the vision process. After perspective, the image is analyzed to extract white boundary lines and remove noise through the use of basic color theory. The color detection algorithm can be calibrated using one of the various color models such as RGB, and HSL/HSV/HSI. Which color model to use is based on the one that will provide an optimal filter of boundary lines and noise. The algorithm changes all shades of green (grass environment) to black and all other colors to white, extracting boundary lines and obstacles. A separate process removes obstacles by changing other colors, except white, to black; isolating the boundary line. This results in a binary image with line data that can be further analyzed. Figure 5.3 shows the color detection process.



a. b.

Figure 5.2 – Perspective Angle Calibration at 40 degrees
(a) Original image, (b) Corrected image.



a. b. c. d.

Figure 5.3 - Color detection process: (a) Original image, (b) Green extracted, (c) Obstacle detected, and (d) Line isolated.

Once the boundary lines are isolated, line data is then examined using an outer pixel detection algorithm and dominant line detection (Hough transform) algorithm is used to find and generate lines. The binary image is divided into left and right sub images, as shown in Figure 5.3, to examine the individual left and right boundary lines. Figure 5.4 also shows the outer pixels detected in the example. The line with the most pixels running through it is determined to be the dominant line. The Hough line is given at a distance and an angle from the point of origin at the center of each sub image. The Hough line is then overlaid on a polar histogram graph, as shown in Figure 5.5-a.

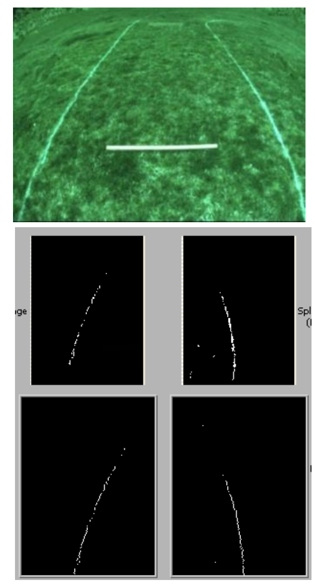
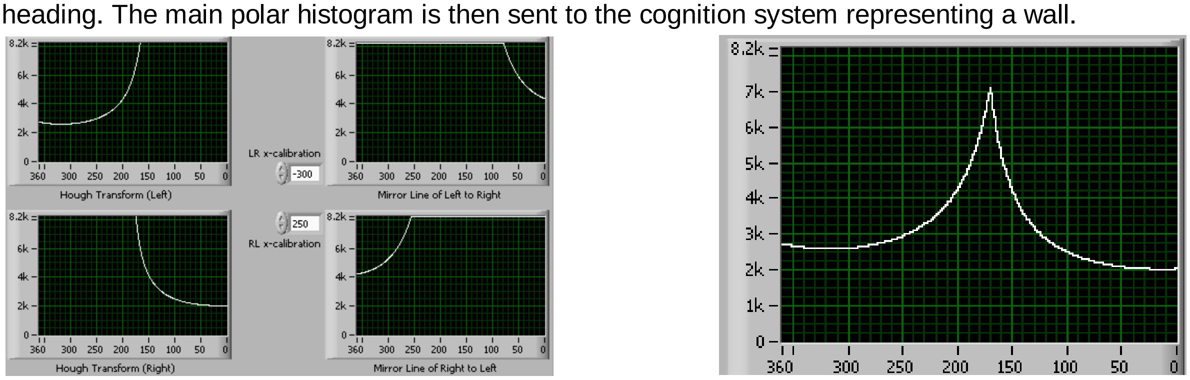


Figure 5.4 – Outer Pixel Detection

A “ghost line” system was implemented to correct for any instance where no line was detected to the right or left side, increasing accuracy of the goal heading. If no line is detected on either sub image, a mirrored Hough or “ghost line” is generated on a separate polar histogram (Figure 5.5-a), so the cognition system does not think there is an open field. It does not affect normal boundary line detection, as it is outside the boundary line.

Once the Hough lines and the ghost lines are determined for each sub image, the boundary line data of those images are combined onto a polar histogram (Figure 5.5-b), which represents the closest distance to the boundary lines for every angle. Maximum distance and corresponding angle represent the goal heading. The main polar histogram is then sent to the cognition system representing a wall.



a. b.

Figure 5.5 - (a) Hough line of the left sub image (top left), Hough line of the right sub image (bottom left), Ghost line of the left sub image (top right), Ghost line of the right sub image (bottom right), and (b) the combined, main polar histogram.

5.2 Navigation (GPS) Software Strategy

For the Navigation challenge, the software accepts a list of waypoints, in any order, and selects the sequence in which to visit the points. Navigating between waypoints in the shortest time possible is an application of the "traveling salesman" problem. For a large number of points, approximation methods must be used to efficiently find the shortest path. However, the Navigation challenge contains a relatively small number of points and can be quickly solved using a brute force algorithm. The Navigation program iterates through every possible path and chooses the one with the shortest total distance. An ordered list is created, and the vehicle uses the first point as its goal.

The Navigation program must continuously calculate the bearing and distance between the vehicle's current position and its current goal waypoint. This is done using the Haversine and Great Circle formulas. The vehicle's compass heading is compared to the bearing in order to find the relative direction to the goal, the "goal angle". This angle is provided to cognition, where it can be used for path planning. The "goal distance" is constantly monitored, and when it becomes smaller than the radius given in the IGVC rules (2 meters for the Valley and 1 meter for the Mesa), the current waypoint can be checked off. Figure 5.6 shows the optimized waypoint path as well as a test run of NorMAN Jr.'s GPS system. NorMAN Jr. arrived within 1 meter of each waypoint, and completed each one successfully.

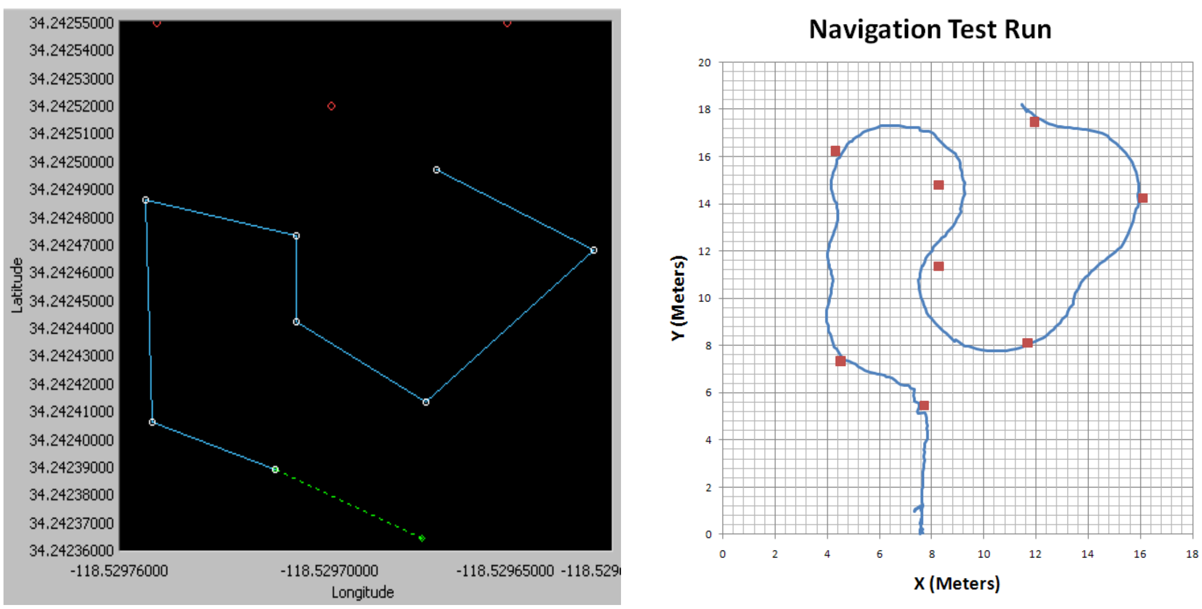


Figure 5.6 - Navigation Path Display

5.3 Cognition (Obstacle Avoidance/Path Planning) Strategy

5.3.1 Map Generation and Heading Determination

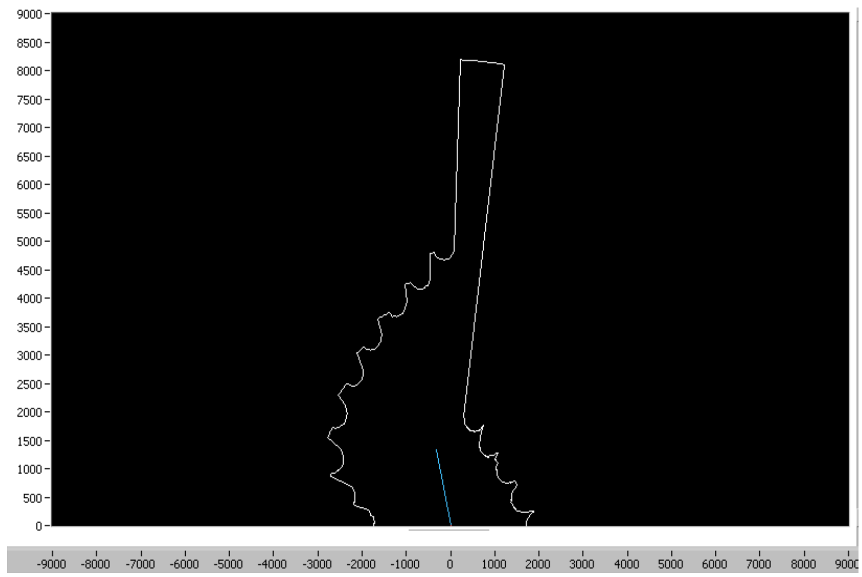


Figure 5.7- Vehicle Heading

The cognition system used on NorMAN Jr. is based primarily on heading determination. During the autonomous challenge, a polar graph (distance, angle) is input from the vision and the laser range finder sensors of the white lines and obstacles, and are combined together to create a local map in Cartesian coordinates (x,y). An ellipse is drawn from the tensor generated from this information. The primary axis of the ellipse is used to determine the heading of travel for the robot (as seen in Figure 5.7 as a blue line). During the navigation challenge the heading is determined by the GPS locations relative to the robot and the obstacle avoidance is dependent purely on the obstacle avoidance algorithm.

5.3.2 Obstacle Avoidance

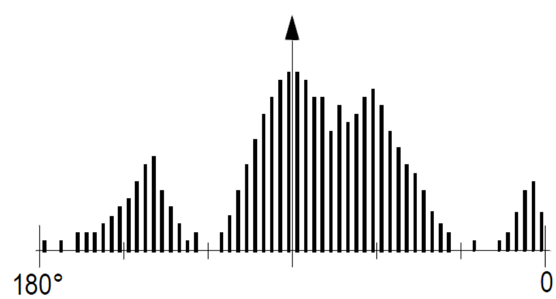


Figure 5.8 - Histogram

The obstacle avoidance algorithm used is Vector Polar Histogram (VPH): a heading based obstacle avoidance algorithm that utilizes a histogram, or polar graph such as the one in figure 5.8, and creates a cost function to each direction and selects the best direction from all the other headings. The algorithm itself is not computationally excessive, and thus can be executed as a serial process rather than a parallel. The simplicity of VPH comes from the fact that accurate sensor instruments are used, such as the laser range finder and camera, alleviating the need for filtering.

The VPH program receives data from both the LRF and the vision sensors in the form of a polar histogram. This histogram data is in the form of distance in millimeters and respective angle from 0 to 180 degrees right to left. The histogram sent to VPH represents the field of obstacles, which include white lines detected by the camera. VPH operates by first identifying individual obstacles in the robot's field of view by grouping together adjacent points within a set proximity. It then classifies each obstacle as either concave or non concave, where concavity is defined as an obstacle that is closer to the robot than its neighbors. The relative proximity of obstacle blocks is determined by an edge detection algorithm which determines the position of obstacle edges relative to each other. Any directions that are concave are excluded from directions of travel. Robot diameter is accounted for by a padding function which determines the padding necessary for sufficient maneuverability based upon distance and angle to an object.

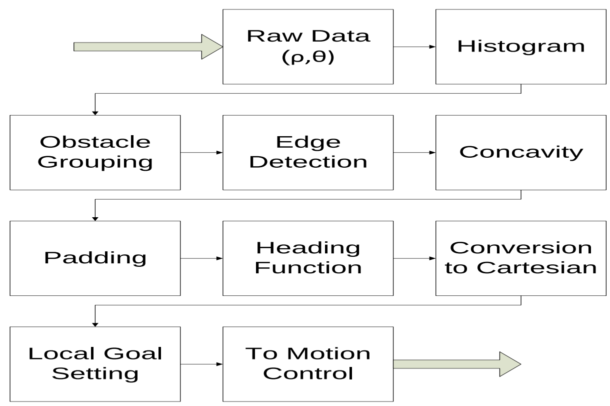


Figure 5.9 – VPH Process

The final determination of robot heading is established by the heading function which analyzes the array of all possible headings and assigns to each a value. The heading function is based upon the edges, concavity and padding functions; which are all evaluated to determine a heading. Figure 5.9 summarizes the data processing for the VPH algorithm. The heading function output is used to create a display which shows the robot's position relative to the obstacle field as well as the desired goal heading. This display is output to the function's front panel on LabVIEW where the algorithm's goal determination can easily be read and tested for accuracy.

5.4 Motion Control

The primary improvement from the previous motion algorithm is due to the change from Grassfire path planning to VPH. Grassfire was originally a map building algorithm, and required extensive odometry calculations and updates. VPH is a continuously updating heading algorithm where the goal point is continuously changing. This change demanded a modified motion control. This was an improvement, as odometry was found to be un-reliable because of slippage and un-even road conditions, causing large inaccuracies in actual distance traveled vs. desired distance. This change greatly simplified motion control and improved performance. From cognition, motion control takes in an angle and magnitude vector to the goal point. Motion control compares its current heading with its desired heading and creates an angle from the difference. That angle, along with the magnitude of the goal vector, is then used to adjust left and right motor speeds to align the robot's current heading with the desired heading. Motion Control for NorMAN Jr. is based upon a kinematic differential drive model, from which motion equations are derived. The motion of the vehicle is improved by fine tuning control gains, which are developed from parameters that govern the motion response of the vehicle. By altering these gains the vehicle's motion behavior changes. Motion control utilizes two specific gains: $K\rho$ and $K\alpha$. $K\alpha$ is a turning gain which controls the vehicle's turning rate, and $K\rho$ adjusts the speed the vehicle approaches its goal point.

6. System Integration

NorMAN Jr. begins its program loop (Figure 6.1) by gathering applicable sensor data (GPS for Navigation Challenge and Camera for Autonomous Challenge) with the LRF readings as the primary reference point. The vision algorithm analyzes white lines, determining the robot distance to each line, which VPH interprets as obstacles. Navigation uses bearing compass angle as well as longitude and latitude positions to give VPH a preferred goal heading to the desired waypoints, in the most efficient path possible. Once NorMAN Jr. has sensed its environment, this data is evaluated by the cognition program to develop a desired heading to travel in. After this desired heading is developed, polar coordinates for the angle of travel as well as the distance to goal point is passed to motion control, which determines the speed at which the left and right motors of NorMAN Jr. are required to reach the goal. The motion algorithm is also codependent on mechanical design. Without adequate hardware and sturdy frame design, the robots motion will be less stable and unpredictable. Since each algorithm is codependent to another, many factors play a part in integrating these systems. Since each sensor is located at a different part of NorMAN Jr., these distances must be accounted for by collocation of their reference points to the LRF, which is the forward most point of the vehicle and therefore chosen as the primary reference point of the vehicle. Another important factor for integration is accurate Cartesian to polar coordinate transformations, as well as latitude and longitudinal to local coordinate conversion. The effectiveness of NorMAN Jr's software system integration can be seen in Figure 6.2, which shows a total execution time is less than 300ms. Each algorithm is executing at a desirable rate. Motion control is fast, resulting in agility and accuracy. Sensor data from the camera and GPS systems are continually updated based on its surroundings and the heading algorithm quickly responds to give an optimal goal point continuously.

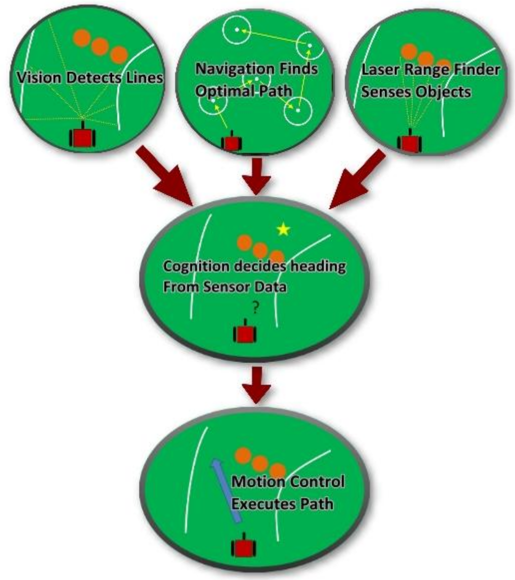


Figure 6.1 – Program Loop

Execution Time	
Program	ms
Heading/ Obstacle Avoidance	35
Laser Range Finder	130
Camera	35
Motion Control	2
Motors	20
Navigation	65
Total	287

Figure 6.2 – Execution Time

7. Performance

7.1 Speed

NorMAN Jr.'s speed is bounded with a maximum speed of 3 mph and minimum speed of 0.5 mph for safe traveling, as well as quick response time for obstacle avoidance and course navigation.

7.2 Total Reaction Time

Total reaction time is less than 300ms as addressed in section 6 (figure 6.2).

7.3 Accuracy of Arrival at Navigation Waypoints

The accuracy at arrival at navigation waypoints is less than 1m as addressed in section 5.2 (figure 5.6).

7.4 Ramp Climbing Ability

The difference of the robot speed on a 15 degree slope to the speed on flat ground is about 0.001 MPH. Due to NorMAN Jr.'s weight and high torque, it has successfully completed a 30 degree ramp.

7.5 Run Time and Battery Life

The Fuel Cell Lithium Polymer Battery Power system provides 6 hours of run time with one 29 standard cubic-foot tank of hydrogen and 3 – 16Ah Lithium Polymer batteries. A 4 -16Ah Lithium Polymer battery power system provides 1.87 hours of runtime. Runtimes are under continuous mixed modes of operation. The hybrid system provides a 4.5 hr improvement over previous lead acid battery power system designs.

7.6 Complex Obstacles

NorMAN Jr. has successfully completed simulated switchback and center island courses, mainly due to continuous updating of goal heading. Potholes are outline and avoided by detecting brightest pixels and color detection.

8. Safety

Safety was taken into consideration when designing the autonomous robot to ensure no one is harmed while operating, observing, or working on NorMAN Jr. The E-Stop system has two methods of activation to immediately stop the autonomous vehicle. There is a main E-Stop button on the back of the robot and two remote transmitters. The E-Stop circuit is designed to be failsafe, by connecting receivers in series to allow simultaneous signals from all three controls. Indication of the on-off status of the E-Stop is shown on top of the mast with an LED light that indicates when the E-stop is activated. The lithium batteries were relocated to the front of the vehicle away from the hydrogen fuel cell to eliminate hydrogen ignition through battery failure. Poly-carbonate covers effectively protect the sensitive electronic components of NorMAN Jr. from the elements, as well as the user from electric shock. Many electrical components require proper chassis grounding, accomplished at the PCB using 10 AWG wire to ensure a low resistance path to the ground.

9. Cost Analysis

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 9.1 shows the team costs and retail costs associated with NorMAN Jr.

2009-2010 EXPENSES			
ITEM	**AMOUNT**	**COST**	**RETAIL COST**
MECHANICAL			
Motors, Controllers and Encoders (2 ea.)	2	$1,790	$4,400
Gearbox	2	$2,174	$4,348
Wheels	2	$73	$118
Hardware	-	$407	$407
Raw Material	-	$123	$1,173
Trailer	1	$450	$450
ELECTRICAL			
Fuel Cell	1	$4,976	$4,976
Charge Controller	1	$559	$559
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 (16Ahr)	4	$1,240	$1,240
DC-DC Converters	2	$735	$735
Emergency Stop (E-Stop)	1	$93	$93
PCB	1	$550	$550
Data Aquisiton	-	$250	$250
Electrical Components	-	$560	$560
Gas Generator	1	$1,200	$1,200
COMPUTER & SENSORS			
Computer	1	$2,225	$2,225
Laser Rangefinder (LRF)	1	Loan	$7,675
Camera	2	$250	$500
Digital Compass	1	$397	$467
Inertia Measurement Unit (IMU)	1	Loan	$44,000
GPS Receiver, Antenna, IMU Enclosure	1	$8,500	$28,079
Electronic Components	-	$500	$500
COGNITION			
Course Obstacles	-	$900	$900
TOTAL:		**$28,871**	**$107,342**

Figure 9.1 – Cost Analysis

10. Conclusion

With new innovations including a robust and proven hybrid hydrogen fuel cell-lithium polymer smart battery power source, enhanced VPH obstacle avoidance, rugged chassis, accurate sensors, consistent and streamlined vision, navigation, and motion control algorithms, NorMAN Jr. has a new foundation with longer drive time and faster computing. Extensive system integration has transformed NorMAN Jr. into a well rounded autonomous vehicle with enhanced capabilities to overcome a variety of environmental challenges.