IONO

Cal State University, Fullerton

Team members:
Francisco Zabala EE, Senior; Aurelio Garcia EE, B.S.

Project Collaborators:
David Parsons, CS, Machinist; Burhan Nashawati, EE, Senior; Dustin Morrison, ME, Senior

Faculty Advisor Statement

I certify that the engineering design of the vehicle described in this report –IONO, has been significant, and that the amount of work that each team member has devoted to this extra-curricular project is equivalent to what is required in the Senior Design course (EGEE-485).

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1. INTRODUCTION

The Institute of Navigation at Cal State Fullerton proudly presents IONO, an Intelligent Ground Vehicle (IGV) developed to compete in this year's edition of the IGV Competition (IGVC). The name IONO follows our student organization acronym (ION), and it was chosen based on our commitment to advance the art and science of navigation through promoting student projects and research in the field of navigation.

Following the 2005 DARPA Grand Challenge, our motivation in the field of Autonomous Vehicles grew exponentially, driving our research interest towards the development of a team entry for the 2006 IGV Competition. In previous editions of the IGVC, a vast majority of the teams have used differential steering mechanisms, which allowed the vehicles to pivot around obstacles, thus easing some of the difficulties of path planning and obstacle avoidance. In spite of this, our goal is to showcase a successful navigation and path planning algorithm that will allow any real-life vehicle (i.e. using rack-pinion steering) to operate autonomously. For this matter, the chosen platform for the project is a small-scale, custom, electric All-Terrain Vehicle (ATV).

The effectiveness of the path planning algorithm is crucial to the performance of the vehicle, thus the main focus of the IONO team is to process efficiently the information provided by the different sensors, allowing the vehicle to make optimal decisions during operation.

IONO exemplifies the current demands of the Engineering field, where inter-disciplinary (i.e. Computer, Mechanical, and Electrical) knowledge is vital to the success of the project.

2. DESIGN METHOD

Inspired by the "Great Robot Race" (i.e. the 2005 DARPA Grand Challenge), and eager to partake in a student Research and Design competition, two Electrical Engineering students, members of the Institute of Navigation at Cal State Fullerton, started the design of an Autonomous Ground Vehicle capable of participating in the 2006 Intelligent Ground Vehicle Competition. The strategy was designed to produce an autonomous system that could compete in all three challenges at the IGVC, in an effective and safe manner. Careful planning, structured design methods, and a high-level of organization and cooperation, constituted key components in the pursuit of that goal.

2.1. Design Strategy

The 2006 IGVC is the first entry of the IONO team in a student Research and Design competition. Therefore, intuition and common sense were powerful weapons at the beginning of the process. However, our design strategy was methodically planned. The theoretical knowledge of Control and Dynamical Systems constituted a great asset for its development. Figure 1.1 shows a Top-Level view of the stages of production of a project; this was our founding block in the development of IONO.

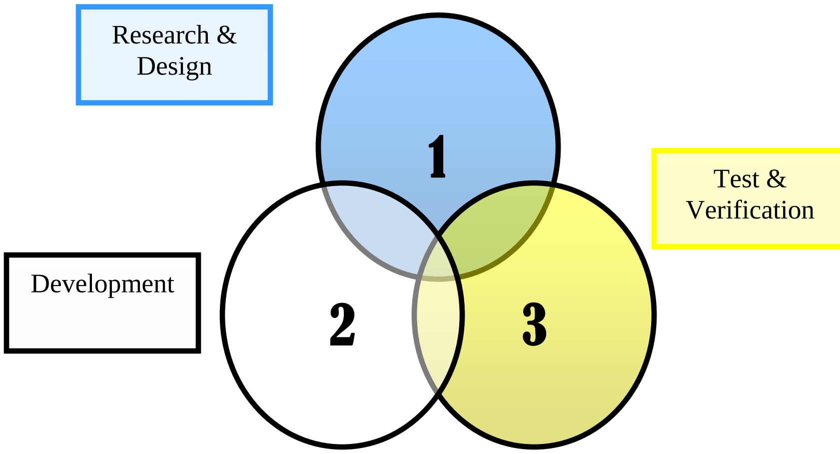

Figure 1.1 - General Design Strategy

Each stage overlaps with the other two, implying that the design process is iterative. This model allows developers to conduct more research and possibly redesign certain aspects of the project to enhance it. The model also allows the developers to analyze the flaws and errors found after conducting initial testing, in order to correct them and improve the reliability and safety of the project. Furthermore, the model follows a forward path 1) Research & Design, 2) Development, and 3) Test & Verification. Each stage requires defining criteria (i.e. goals), so developers know when to move on to the next stage. The issue of going back to a previous stage promoted our implementation of a Cost-Benefit Analysis, which is explained in Part 2.3 of this report.

2.2. Design Stages

Research & Design – Stage 1

In this stage, the main objective of the team was to identify the customers for the product, and to establish the project specifications. Research of the Rules and Regulations of the IGVC, and an overview of the different design reports were our first steps. Two primary customers were identified: (1) The IGVC organizers, (2) the university, the college of Engineering and Computer Science, and our student organization (ION-CSUF). Additionally, secondary customers like the team's sponsors, and future vehicle developers were also considered.

Each customer has needs that the project should satisfy; we outlined these needs and determined most of the specifications that the vehicle had to obey in order to ensure customer satisfaction.

Finally, an initial design model was established based on our research findings. The essential equipment for autonomous operation was determined, and progress towards development of the vehicle was achieved.

Development – Stage 2

This was the main stage of the project, where the developer's assembled the vehicle, interfaced the instruments, programmed the software, and produced an Autonomous Vehicle. Often times, problems in the development required one of the team members to go back to the previous stage to conduct further research and/or redesign certain areas of the vehicle, to facilitate the resolution of the difficulties.

Test & Verification – Stage 3

In this final stage of the Design Strategy, the IONO team verified the operation, robustness, safety, autonomy, and many other features of the vehicle. Often times, the team members had to return to the Development Stage, or the Research & Design Stage, to improve the performance of the vehicle.

2.3. Cost-Benefit Analysis

The success of any development project relies heavily in the adaptability of the designers' strategy to any unforeseen circumstances throughout the whole process. With this in mind, our team adopted a cost-benefit analysis to facilitate and optimize the decision-making and problem-solving processes.

The cost-benefit analysis is a simple, but effective tool that enhanced our design strategy. Our particular implementation consisted in a 1 to 10 (low to high) scale indicating the **cost:benefit** ratio presented by a solution to any given problem. A low **cost:benefit** ratio is desirable when making a decision in our daily life (e.g. which road has less traffic? Which product is on-sale?); hence, for the different parameters that were considered when making a decision in any stage of the development of IONO, the solution that offered the lowest score was adopted and implemented. A low scoring ratio means that the benefit outweighs the cost; the lowest possible ratio (i.e. 1:10; 1/10) means that the benefit of a decision is 10 times greater than the cost of making it. Different examples that illustrate the implementation of this analysis are included in later parts of this report (Parts 4, and 6).

Although the inclusion of novel features was emphasized in the design of IONO, the cost to implement most of the ideas outweighed the benefits. Thus, we focused on our unique steering mechanism as the distinguishing characteristic of our design. We trusted that this remarkable capability would differentiate our design from the competition.

3. TEAM ORGANIZATION

The IONO team consists in two Electrical Engineering undergraduate students (Mr. Francisco Zabala, and Mr. Aurelio Garcia); however, several people contributed in the development of the project. The school's machinist (Mr. Dave Parsons), one Mechanical Engineering undergraduate student (Mr. Dustin Morrison), and one Electrical Engineering undergraduate student (Mr. Burhan Nashawati), provided additional help during the Development Stage of IONO. The two project designers cooperated in the development of the Design Strategy. In addition, the initial steps in the Research & Design Stage were also a collaborative effort. After determining the vehicle specifications, and the customers' needs, the different development areas of the vehicle were divided among the two team members, according to our level of expertise (Table 2).

Assigned Task	**Member**	**Major**	**Class Standing**
Mechanical Assembly (Platform)	Aurelio Garcia	Electrical Engineering	Senior
Electrical System	Aurelio Garcia	Electrical Engineering	Senior
Sensors	Francisco Zabala	Electrical Engineering	Senior
Navigation (Motors, Steering)	Francisco Zabala	Electrical Engineering	Senior
Interfaces	Francisco Zabala	Electrical Engineering	Senior
Control Software	Francisco Zabala	Electrical Engineering	Senior
Design Report	Francisco Zabala	Electrical Engineering	Senior

Table 2 – Team Organization

4. IONO – MECHANICAL ASSEMBLY

Our biggest design challenges did not come from the hardware/software point-of-view; during the Research & Design Stage, the team identified the necessary instruments for autonomous operation, which represented approximately 75% of our $10,000 estimated budget. The initial allocated funds for the IONO team covered only 25% of the expenses. We focused on minimizing the cost of the Mechanical Assembly, and at the same time, we directed our efforts towards finding several sponsors that would support our project.

Given our lack of familiarity with mechanical engineering design, our original strategy of assembling the vehicle was quickly re-evaluated; a Commercially Off-The-Shelf (COTS) electric ATV was purchased (Figure 4.1), following the corresponding Cost-Benefit Analysis (Table 4). Even though the purchase of a vehicle solved some of the mechanical difficulties that we faced; help was sought from the school's machinist and some of the Mechanical Engineers, who gracefully helped us in the design and development of some necessary parts for the vehicle.

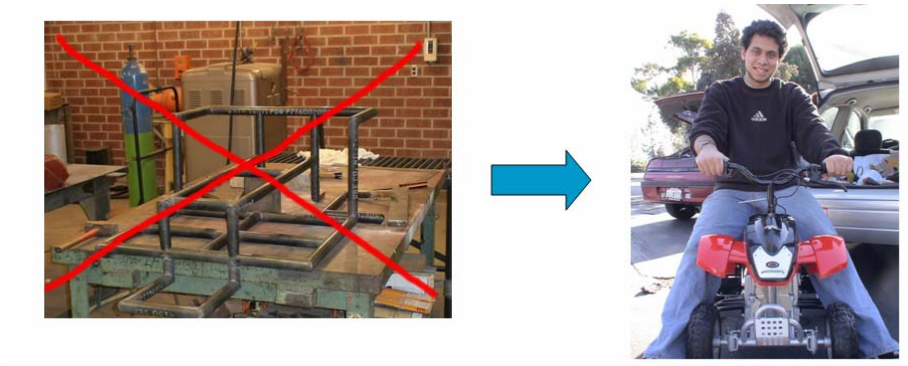

Figure 4.1 – Original frame; COTS Electric ATV

	Parameters 1; (best) to 10 (worst) scale					
Decision	**Cost**	**Time**	**Efficiency**	**Safety**	**Originality**	**Score**
Custom Assembly	3.0	8.0	5.0	6.0	1.0	*4.6*
COTS Electric ATV	7.0	2.0	3.0	3.0	5.0	***4.0***

Table 4 – Cost-Benefit Analysis; Mechanical Assembly

The results of the Cost-Benefit Analysis (Table 4) are based on forecasted parameters. It clearly shows the benefits of the decision of purchasing (bold) versus assembling (underlined) the vehicle.

After the ATV was purchased, the team quickly developed a safe and reliable platform on which the necessary instruments to perform the "sensing" and "thinking" could be integrated. This initial platform was used to demonstrate (partially) the vehicle's capabilities, to different interested parties to obtain funding to acquire the necessary instruments.

4.1. Chassis

The Chassis of the vehicle consists of a steel tubing frame, covered with a fiberglass shell. The original design underwent several modifications for the following reasons (Figure 3.3):

Increased turning radii Camera Pole Laptop Tray LADAR Mount

Figure 3.3 – Chassis Modifications

4.2. Drive System

The Drive System is a combination of a 36VDC Motor, and a 27 ft.lb servo. Both are controlled, by the Laptop serial commands via a Roboteq AX3500 Speed Controller (Figure 3.4). The inclusion of the servo allowed the vehicle to steer autonomously. The steering column was coupled to a servo using a gear and belt drive system (Figure 3.5).

Figure 3.5 – Drive System

The Roboteq AX3500 Speed Controller uses Pulse-Width Modulation to control electric motors. The duty cycle percentage is directly proportional to the speed of the motor (see Figure 3.6).

5. ELECTRICAL SYSTEM

IONO's electrical system was developed to meet two specific requirements, (1) Efficient power distribution to the different on-board devices (i.e. sensors and Laptop); (2) Safe and reliable operation for a considerable period of time.

5.1. Power Distribution System

The original power system of the vehicle included one 36V 12Ah Sealed Lead Acid (SLA) battery, it was enhanced by adding a second battery in parallel; implementation of linear voltage regulation, all the devices were integrated to a single Power Distribution System. However, after some performance testing, we determined that our power-hungry steering servo required the inclusion of an additional 12VDC battery, which served as a dedicated power supply. The Laptop computer was also powered by a dedicated power supply (24VDC Laptop Battery). The power requirements for the vehicle are shown on Table 5.

Component	Current (A)	Power (W)
36VDC 1/3 Hp Motor	6.90	248.50
27 ft.lb Servo	4.90	108.00
Speed Controller	0.50	18.00
Camera	0.08	0.96
DGPS	0.25	4.00
Digital Compass	0.02	0.24
LADAR	2.50	60.00
Laptop	6.00	70.00
Total Power Requirement		509.70

Table 5 – Power Requirement for IONO

The overall efficiency of the system is approximately 68.1%. Power consumption was addressed during the development of the Electrical Box; we applied several power dissipation methods to maintain a suitable efficiency.

5.2. Electrical Box

The Power Distribution System was designed using Linear Voltage Regulator ICs. Thus, it was necessary to dissipate the heat produced by voltage the regulation. Customized heat-sinks and three cooling fans were used for this purpose.

The Electrical Box includes fuses to avoid any damage in case of electrical malfunction. Two separate switches control the flow of the current into the Electrical Box. A Master Switch is used to turn the vehicle ON, and a secondary switch is used to control the charging of the batteries.

6. MOTOR CONTROL

Our initial goal was to design most of the electronic circuits and interfaces of the different components in the vehicle. However our design strategy steered us into purchasing a commercially available PWM Speed Controller. The Cost-Benefit Analysis aided us in the decision of purchasing the Roboteq AX3500 Speed Controller; this speed controller is capable of controlling two separate channels, and providing standard R/C outputs.

	Parameters; 1 (best) to 10 (worst) scale				
Decision	**Cost**	**Time**	**2+ Channels?**	**R/C outputs?**	**Avg. Score**
Vantec RDFR21 Dual Controller	3.0	6.0	1.0	1.0	*2.8*
Roboteq AX2850	4.0	3.0	1.0	5.0	*3.3*
Roboteq AX3500	6.0	2.0	1.0	1.0	***2.5***
Custom Speed Controller	2.0	9.0	1.0	1.0	*3.3*

Table 6 – Cost-Benefit Analysis; Speed Control

The features of the Roboteq AX3500 matched our design ideas; furthermore, the adaptability of this controller to our design was a determining factor in our decision.

The Roboteq AX3500 default operating mode is Remote Control. To begin autonomous operation, the computer transmits a password via the RS-232 Serial Port interface. The different commands sent by the computer, control the number of pulses that are sent to the motors; and thus, control the speed and direction of the vehicle.

7. SENSOR INTEGRATION

IONO perceives its surroundings through a series of sensors, a LADAR, a forward-looking camera, a digital compass, and a differential GPS receiver; the data is processed by a Laptop computer, which actuates the motors via the speed controller. The interfaces of the sensors to the computer are depicted on Figure 7.1.

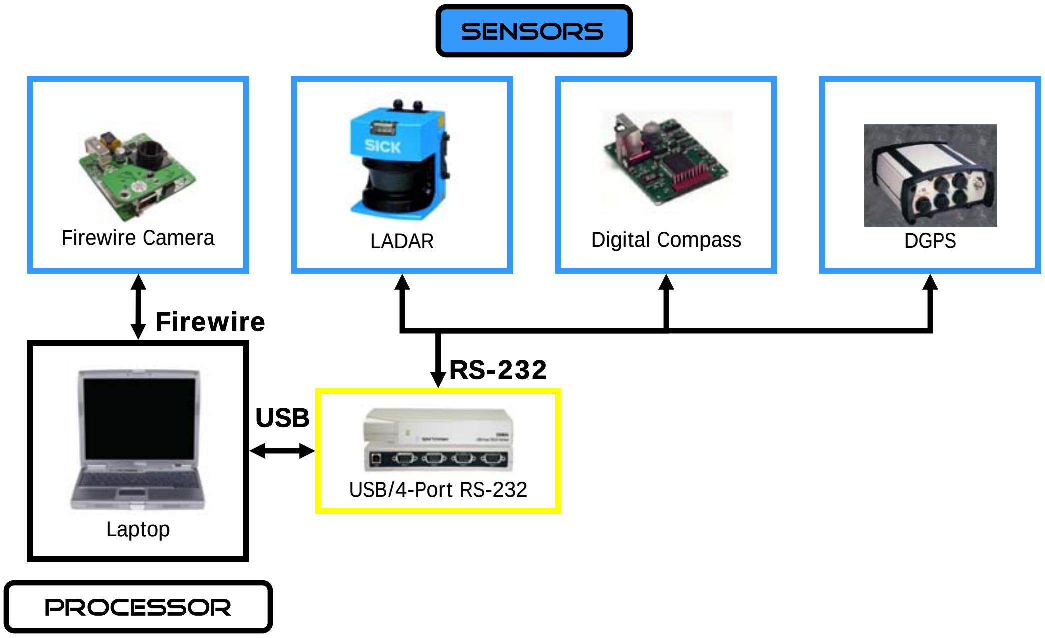

Figure 7.1 – IONO Sensor Integration

7.1. Sensor Description

Unibrain Fire-i Board Camera – forward-looking, wide-angle (94 degree diagonal field of view) camera used to acquire image data for the Line Detection algorithm. Additionally, it allows the detection of "negative obstacles" (i.e. potholes) that cannot be spotted by the Laser Measurement System. (Retail price: $170; Team price: $170)

Sick LMS 291 - S05 – time-of flight based sensor used to scan 180° in 1° increments. Also known as a Laser Range Finder (LRF), the LADAR provides accurate data to for the Obstacle Avoidance algorithm. (Retail price: $7,100; Team price: $4,100)

Digital Compass – combination of a three-axis magnetometer with a high-performance two-axis tilt sensor that allows IONO to determine its orientation with respect to the magnetic north (tilt compensated). (Retail price: $700; Team price: $0)

DGPS - Novatel's ProPak-LB DGPS uses the OmniSTAR HP correctional service to enhance the accuracy of the Global Positioning System (GPS). This instrument provides the GPS coordinate reference used in the Navigation Challenge to determine the position of the vehicle in respect to the given waypoints. (Retail price: $5,400; Team price: $2,700)

7.2. System Integration

Safety of both equipment and bystanders, during operation, was our highest priority when integrating the different systems in IONO. The only concern at the time of this writing, is the fact that we have a "six-thousand dollar bumper", however, the overall robustness of the system meets our expectations.

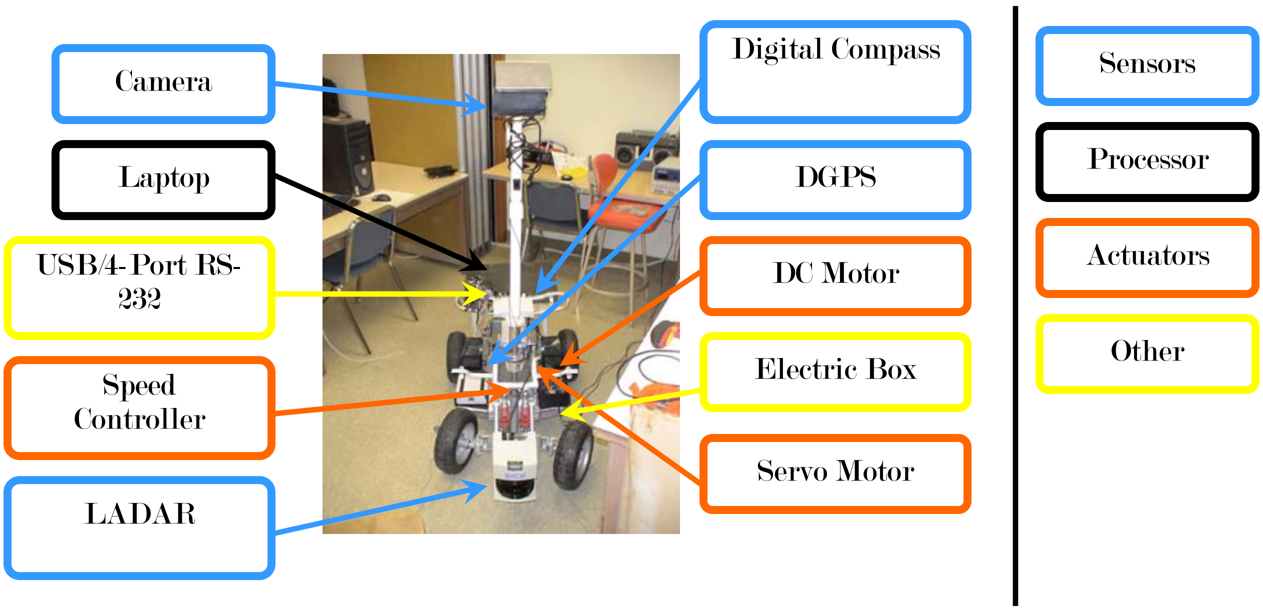

Figure 7.2 – IONO System Integration

8. CONTROL SOFTWARE

The control software allows IONO to acquire data from the sensors, process the information, and send output commands to the actuators via the speed controller (Figure 8.1). It is performed by the onboard computer, a Dell Precision M20, with a processor Intel Pentium M 3.0GHz. The language chosen for programming was MATLAB. Familiarity with the language was crucial for the development of the Control Software.   In addition, MATLAB includes a set of toolboxes and libraries that facilitate the interfacing with the different sensors.

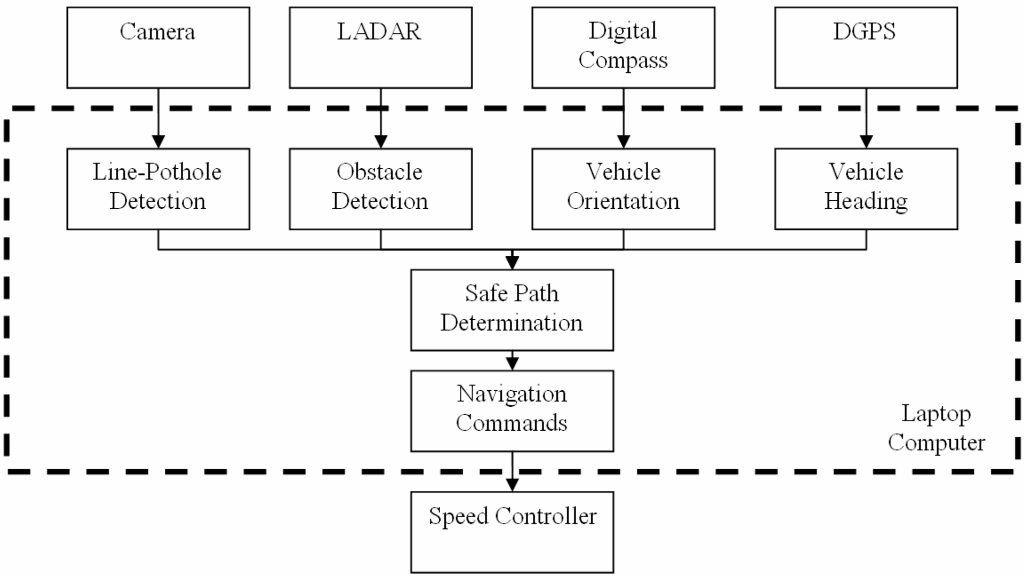

Figure 8.1 – Software Architecture

8.1. ACCS - Autonomous Challenge Control Software

During the development stage of the project, the control software for the Autonomous Challenge represented our top priority. The IONO team focused in developing software that would not only control the vehicle during the Autonomous Challenge, but that it would easily adapt to meet the requirements of the Navigation Challenge (given the similarity of the two contests). As it is shown in Figure 8.1 (above), the software acquires data from the LADAR, camera, digital compass, and differential GPS receiver, processes the information, determines a safe path for the vehicle to navigate, and commands the motors (via the speed controller) accordingly.

Successful path planning in the Autonomous Challenge requires the vehicle to be able to stay within the boundary lines and avoid all obstacles. Therefore, a Line Detection and an Obstacle Avoidance module were developed.

Line Detection

The ability to detect the boundary lines is an extremely important requirement for the vehicle, crossing them would represent the end of the run. Knowing that the results of Digital Image Processing algorithms vary with different lighting conditions, the image stream from the camera was thoroughly analyzed and processed. An RGB colorspace analysis (Figure 8.2) allowed us to determine that the Blue colorspace offers the best contrast for this particular application (i.e. greatest difference between the intensity level of a green and a white pixel). Some of the parameters will be modified during the competition to adjust our vision system to the particular lighting conditions.

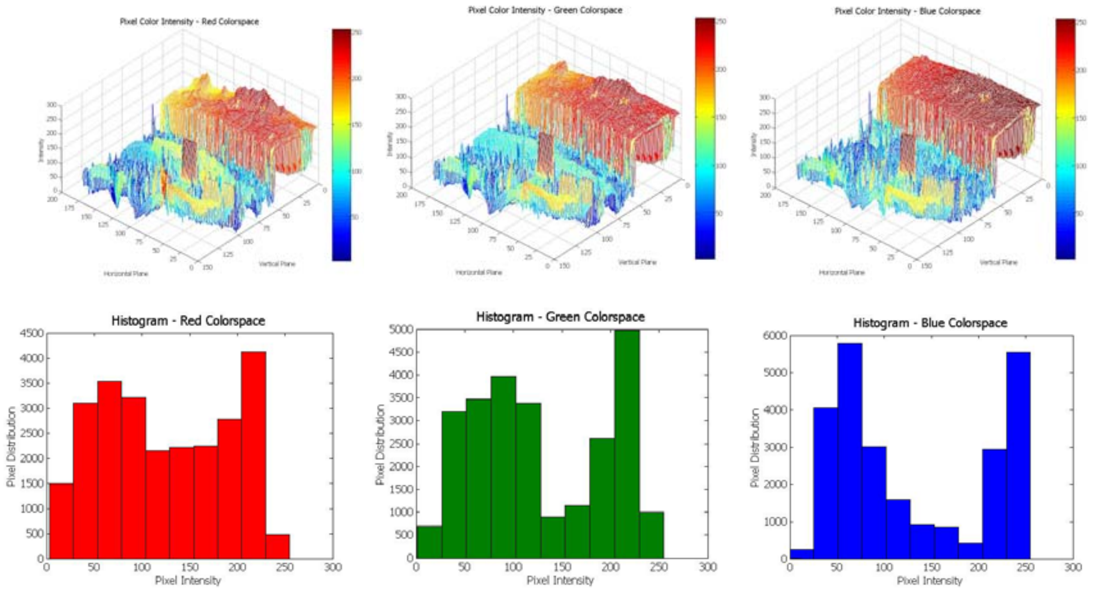

Figure 8.2 – RGB colorspace analysis of a sample image (featuring different levels of green and white pixels)

Processing time was a concern for this algorithm, so the first step was to downsample the acquired images by 75% (i.e. ignoring 3 out of every 4 pixels). Secondly, we decided to divide the image into two symmetrical halves (given that during autonomous operation it is possible that there will be only one line available); in case that one of the lines is not present in the image, IONO can mirror the other line and estimate the location of the missing one. Once the lines are detected, a threshold is applied to each half of the image to determine which pixels are part of a boundary line, and which are not (i.e. implementing color segmentation). The resulting binary data is linearized using the Hough Transform method; thus determining the most dominant set of collinear points in the image. The results of the Hough Transform are used to determine the angle and distance of the boundary lines with respect to IONO. (Figure 8.3).

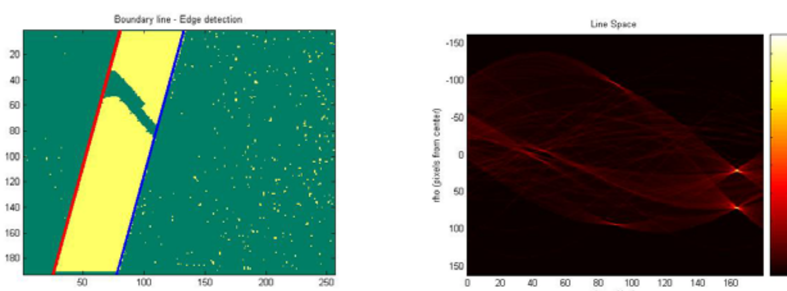

Figure 8.3 – Line Detection Process (Hough Transform)

<u>Obstacle Avoidance</u>

Obstacle detection is also crucial for safety of IONO's operation. The output from the LADAR is carefully analyzed and combined with the Line Detection information. The LADAR provides a data array consisting of distances to detected objects up to 4 meters away from the vehicle. Each value in this array corresponds to 1° increment of the scan angle (0° - 180°). The LADAR data is combined with the lines detected by our Line Detection algorithm; the information is mapped in a path-finding matrix (Figure 8.5). When an obstacle is detected in the path of the vehicle, the Obstacle Avoidance algorithm searches the matrix for an "optimal opening." It also determines the navigation angle (i.e. heading) of the vehicle and commands the steering servo accordingly.

Figure 8.5 – Mapping of obstacles

Angular Range	Measured Distance (mm)
0°	8191
1°	8191
…	…
75°	4251
76°	4238
…	…
179°	8191
180°	8191

Negative obstacles such as potholes are also included in the obstacle array, these obstacles are detected by the camera through a template matching process, and they are either placed in the matrix or discarded in the case of template mismatch (e.g. erratic data in the image).

8.2. NCCS - Navigation Challenge Control Software

The Navigation Challenge Control Software is a modified version of the ACCS, as it was planned during the designing stage. The only major modification was the exclusion of the Line Detection algorithm. The addition of data from the DGPS receiver and the Digital Compass, allows IONO to determine the path to the lat/long waypoints through which the vehicle must navigate. IONO's Vision System is currently being enhanced as a method of cross-checking that the vehicle passes through the waypoint. The differential corrections to the receiver are provided by OmniSTAR, the horizontal accuracy of the receiver using these corrections is on the centimeter level (14-15 cm). The TCM2-20 digital compass has an accuracy of 0.5 to 1 degree depending on tilt. Different state estimation methods are being developed to improve the reliability and integrity of the navigation software.

9. VEHICLE PERFORMANCE (PREDICTED AND EXPERIMENTAL)

9.1. Maximum Speed

IONO is capable of reaching speeds of 14 mph, we have limited the power of our 1/3 hp motor to comply with the customer requirement of 5 mph.

9.2. Ramp climbing ability

IONO has the capability of climbing surfaces up to 53-degree incline, however, we have limited the power of the motor to meet the IGVC regulations (5 mph maximum speed), which allows the vehicle to climb surfaces of a maximum of 32-degree incline.

9.3. Reaction Times

The software developed for the IGVC Challenges was efficiently designed to minimize the computational time during autonomous operation. IONO's navigation algorithm is able to produce a navigation command in 230ms; if it determines that no path is available (i.e. dead end), it stops, returns to the point where the last obstacle was avoided, and tries to navigate through a different path. All navigation commands are executed with a latency of 23ms (computing time of the speed controller). We estimated that IONO's reaction time would be of 253ms; actual results have proven that IONO's reaction time is on average 262.5ms. The Reaction Time to the activation of either of the Emergency Stops (wireless and mechanical) is less than 500ms. The time to come to a full stop when traveling at maximum speed (on grass) is –on average, 700 ms, which translates in a maximum distance of 4.8ft.

9.4. Battery Life

The Battery Life for the vehicle has not been tested at the time of this writing. However, based on a thorough analysis of the vehicle's power consumption, we predict that it can safely operate for 6.5 hours.

9.5. Costs

2,200 hours have been spent on the design, development, and testing of IONO. Capital costs are in the order of $10,000. Several sources have provided funds for the developments of IONO.

10. CONCLUSION

IONO constitutes a very challenging project developed by Electrical Engineering students, to advance the field of Robotics and Autonomous Navigation within the student body of the California State University, Fullerton. The inter-disciplinary knowledge that the Intelligent Ground Vehicle provides to its developers is remarkable; furthermore, the team members learn the different stages of the Design Process, and improve their teamwork ability. Much room is left for improvement of this project, along with proper documentation of the system. It is hoped that the Intelligent Ground Vehicle Competition becomes a tradition for Cal State Fullerton students and faculty members.