Presents:

Reagle II

Team Members

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Advisors

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Faculty Advisor Statement

I certify that the engineering design of the vehicle described in this report, Reagle II, has been significant, and that the student effort is equivalent to a senior design capstone project.

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Charles F. Reinholtz, Mechanical Engineering, Embry-Riddle Aeronautical University

1.0 Introduction

The Autonomous Vehicle Team of Embry-Riddle Aeronautical University is proud to introduce Reagle II, a modified vehicle platform, configured from the previous Reagle model and designed to compete in the 2009 Intelligent Ground Vehicle Competition (IGVC). Embry-Riddle last competed in the 2008 IGVC, finishing 5th in the Autonomous Challenge, 5th in the Navigation Challenge, and 2nd in Design.

Reagle II incorporates many of last year's innovations, while improving performance through an innovative expandable-run-time Lithium Ion Nanophosphate battery pack and a lighter, safer overall design. An additional focus of this year's team was to develop a more environmentally and user-friendly vehicle system and supporting documentation. Reagle II's underlying software, which is an evolutionary improvement of previous code, has been tested and refined throughout the year. It has been developed to be safe, adaptable to changing conditions and effective in both the Navigation Challenge and the Autonomous Challenge. The team has also worked to ensure that the system will meet the JAUS interoperability requirements.

1.1 Vehicle Overview

Reagle II is a three-wheel, differentially driven vehicle. The drive wheels are located in the rear and a passive caster wheel is mounted in the front. The overall vehicle specifications are provided in table 1.1:

Table 1.1: Vehicle Specifications

Overall weight:	160 lbs (not including 20 lb payload)
Overall length and width:	Length: 36 inches; Width: 28 inches
Weight distribution:	65% rear, 35% front
Wheelbase:	27 inches
Wheel sizes:	14 inch rear, 10 inch front caster
Height:	14 inches (without sensor mast and payload box)

Reagle II uses two Quicksilver brushless DC drive servomotors with integrated 10:1 reduction planetary gear heads. All system power is provided by custom A123 lithium-ion nanophosphate battery packs that provide almost one hour of run time in typical use. All system electronics, including a custom power regulation and distribution board, a TORC Technologies emergency SafeStop™ system, and a radio control receiver, are mounted in a waterproof, quick-disconnect model 1520 Pelican case. Figure 1.2 shows the final vehicle and the optional hybrid electric power trailer.

Figure 1.2: Reagle II with Safety Bumper (in orange) and Hybrid Power Trailer

1.2 Innovations

In developing Reagle II, the team attempted to incorporate the strengths of previous designs while improving on identified weaknesses. Whenever possible, the team made use of commercial, off-the-shelf (COTS) components to expedite development and to ensure reliability. Reagle II includes many innovative features in both software and mechanical design. This section will highlight three key innovations that the team developed to improve safety and utility and to reduce the overall impact of our product on the environment. These innovations, which will be discussed in detail in the subsequent sections, are the expandable, hot-swappable A123 LiFePo4 battery packs, the improved SoftRide2.0© chassis featuring a SuperSafe© foam bumper, and an extensive use of recyclable materials and instructions to facilitate environmental responsibility.

1.2.1 Innovation #1: A123 LiFePo4 Battery Pack

The previous version of Reagle used sealed lead-acid batteries, which weigh approximately 60 lbs, take an hour to charge and are relatively harmful to the environment. The team chose to use A123 lithium ion nanophosphate batteries for their efficiency, environmental impact, and charge time. Table 1.3 shows various properties of lithium ion batteries as compared to the previously used lead-acid batteries.

Table 1.3: Lithium-Ion versus Lead-Acid Batteries

	Lithium Ion	Lead-Acid
Energy Efficiency	90%	82.50%
Assembly & Recycling Environmental Impact	189.4	240
Total Environmental Impact	278	503
Charge Time	.25 hours	1 hour
Weight of Standard Pack	2.5 lbs	60 lbs

Environmental impact ratings in the table are based on studies published in the paper, "Comparison of the Environmental Impact of Five Electric Vehicle Battery Technologies Using LCA," *International Journal of Sustainable Manufacturing 2009, Vol.1, No.3.* According to this study, lithium ion batteries have about half the negative environmental impact of lead acid, nickel metal hydride and nickel cadmium batteries.

A power system analysis was used to predict the required performance of the battery pack. This analysis, which is discussed in section 4.2, showed that sixteen A123 lithium ion battery cells with a total energy capacity of 121 watt-hours would be needed to achieve the desired competition run time of 45 minutes. The 3.3 volt cells are custom wired into packs of eight batteries in series to produce 26.4 volt packs. The average charge time for these packs is ten minutes. The previously used lead acid batteries required an hour to charge. The A123 cells each weigh 0.15 lbs; therefore the standard sixteen battery cluster weighs 2.4 lbs. This compares to an overall battery weight of 60 lbs for the lead-acid battery pack used in last year's vehicle. This weight reduction makes the vehicle safer in the event of a collision, more maneuverable and easier to transport. Figure 1.4 shows two battery packs mounted on the fold down storage compartment on the back of Reagle II.

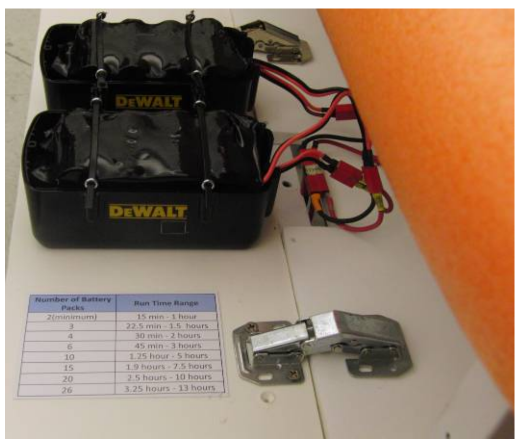

Figure 1.4: Battery Compartment with Hot-swappable Packs

The standard battery cluster provides fifteen minutes of run time with all systems, including the motors, at maximum power draw. Based on typical motor power consumption of 96 watts, the vehicle will run for 45 minutes. This is enough run time for both dynamic IGVC events.   To accommodate longer practice sessions and applications requiring extended run times, Reagle II has been developed to accept additional battery packs that operate in parallel with the standard pack. Reagle II has the capability to carry 4 battery packs in the regular battery compartment and an additional 22 battery packs in the payload compartment. This arrangement provides the extended run times listed in Table 1.5. In keeping with the theme of maximizing utility and convenience for the user, this table is also included on a label posted in the battery compartment. The compartment also includes an LED battery-life indicator to that indicates the remaining charge state.

Table 1.5: Run Time Chart

Number of Battery Packs	Run Time Range (peak draw – typical operation)
2 (minimum)	15 min - 1 hour
4	30 min - 2 hours
6	45 min - 3 hours
10	1.25 hour - 5 hours
20	2.5 hours - 10 hours
26	3.25 hours - 13 hours

1.2.2 Innovation #2: Modified SoftRide2.0 © Chassis and SuperSafe© Bumper System

The SoftRide2.0 SuperSafe© Chassis is an improved system based on the SoftRide© Chassis used in the earlier version of Reagle. The SoftRide© Chassis provides passive suspension and vibration damping. The chassis is a combination of a rigid aluminum rear drive box frame and a high-density polyethylene (HDPE) front deck. The aluminum box frame provides the rigidity and strength needed to support the high-torque motor assembly, while the HDPE material provides a passive suspension and inherent damping. The new design also provides additional payload space and a lower profile. The HDPE front deck has an upper and lower tier spaced ten inches apart. This arrangement increases the area moment of the section, which provides better resistance cold-flow deformations inherent in polyethylene that caused last year's vehicle to sag under extended static loading. The effectiveness of the SoftRide© chassis in damping vibrations of the sensor mast compared to a rigid aluminum frame vehicle of similar size and layout is illustrated in Figure 1.6.

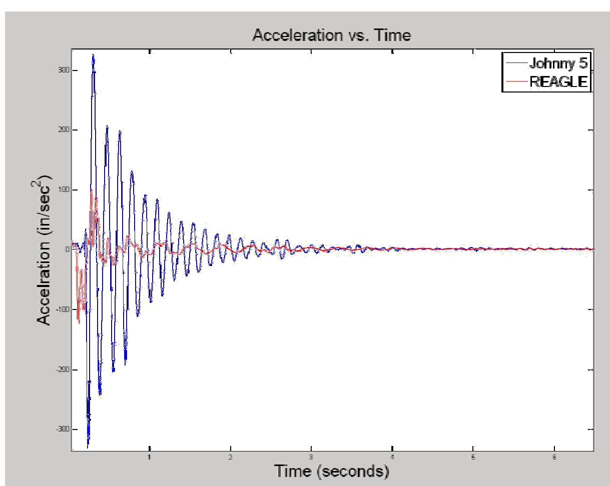

Figure 1.6: Sensor Mast Acceleration Comparison

The chassis also has a built-in SuperSafe© rounded bumper system custom shaped for Reagle II that improves safety for users and pedestrians in case of impact. The orange foam bumpers, which can be seen in the cover photograph and in Figure 1.2, cushion the outermost perimeter of the vehicle. The bumper system is placed at a height of 14 inches based on the experiences of past IGVC participants who observed IGVC vehicles colliding with people's legs at previous competitions.

1.2.3 Innovation #3: Life-Cycle-Based Design and Recycling Instructions

An important goal of our team was to realize sustainable product life cycle systems. Such systems reduce environmental impacts, resource consumption, and waste generation. At the same time, we made every effort to increase system utility and, ultimately, corporate profits. Reagle II is designed for durability and a long life. However, at the end of its product life cycle, Reagle II is designed to be recycled. The vehicle system includes six different groups of materials that can be recycled, namely, high-density polyethylene (HDPE), aluminum, steel, rubber, electronics, and batteries. The HDPE is a #1 recyclable plastic that can be cut into pieces and recycled in a standard plastic recycle bin. Reagle II uses HDPE manufactured by King Plastics Corporation and sold under the brand name Starboard®. The company buys back used Starboard® material and recycles it directly into new products. Aluminum can also be cut into manageable pieces and placed in a recycle bin. The rubber tires, plastic and steel wheel hubs, electronics, and batteries should be taken to the nearest recyclable center (refer to the web site www.therecyclingcenter.info for locations). The A123 LiFePo4 batteries are rated safe for regular disposal because they do not contain metal lithium (they contain only ionic lithium). We designed Reagle II to be environmentally friendly. To assist the user, we have also provided recycling instruction labels on the vehicle.

2.0 Design Process

The 2008-09 Embry Riddle IGVC team is an ambitious group of mostly freshman and sophomore engineering students. The team split their effort between a totally new vehicle design that we intend to debut at the 2010 competition, and a sharply focused redesign of the original Reagle vehicle developed for the 2008 competition. We believe we were able to improve upon the previous design by incrementally improving overall performance in all areas and by introducing critical innovations designed to substantially increase customer satisfaction. This approach is in keeping with the Kano design methodology, where customer satisfaction is linearly proportional to improvements in performance features, such as lighter weight and efficiency, and exponentially proportional to the number of innovative delighter features, such as the SoftRide2.0© Chassis, the SuperSafe© bumper, the range-expanding battery system and the environmentally conscious design. The team used feedback from previous competitions and input from faculty advisors to gauge the value of proposed improvements.

2.1 Team Organization

Members of the Reagle II team are listed in table 2.1. Each team member contributed to the design process. There were three focus areas for the team: software and electronics, mechanical design, and documentation.

Table 2.1: Student Team Members

Member	**Academic major and Year**	**Team Function**
Aaron Brookshire	Mechanical Engineering, Sophomore	Software & Electronics
Jerson Mezquita	Mechanical Engineering, Freshman	Mechanical Design
William Nobles	Computer Engineering, Freshman	Software & Electronics
Ashley Nelson	Mechanical Engineering, Freshman	Documentation
Christopher Kennedy	Aerospace Engineering, Freshman	Mechanical Design & CAD
Christopher Sammet	Aerospace Engineering, Sophomore	Mechanical Design
Derek Osterloh	Mechanical Engineering, Senior	Mechanical Design
Christopher Hockley	Graduate Advisor	Mechanical Design

3.0 Mechanical Design

Reagle II was designed to meet and exceed the requirements of the 2009 Intelligent Ground Vehicle Competitions and to serve as a base platform for University research and development. The new mechanical design emphasizes enhanced performance along with safety for users, pedestrians and the environment.

3.1 Vehicle Chassis

As stated in the innovations section, Reagle II's chassis is a combination of an aluminum frame for the motors and batteries, and a two-tier deck made of high-density polyethylene (HDPE) sheets. The top tier is fabricated from a single sheet of HDPE and supports the electronics case. The lower tier is made of eight pieces of HDPE and is designed to support the payload and laser scanner, as shown in figure 3.1. The HDPE SoftRide2.0© decks serve as main structural members, but they also provide compliance and damping to reduce peak accelerations and forces in the sensor mast and electronics.

3.2 Vehicle Drive Train

Two Quicksilver SilverMax 34HC-1 brushless DC servomotors drive Reagle II. The motors provide a maximum 384 watts of power at 2.47 N-m of torque with a continuous stall torque of 4.77 N-m. Integral with the motors are 10:1 reduction NEMA 34 single stage planetary gear heads. When joined with eccentric locking bearing and a custom-machined steel hub, the motor and gear head provide a simple and reliable drive train, as shown in Figure 3.2.

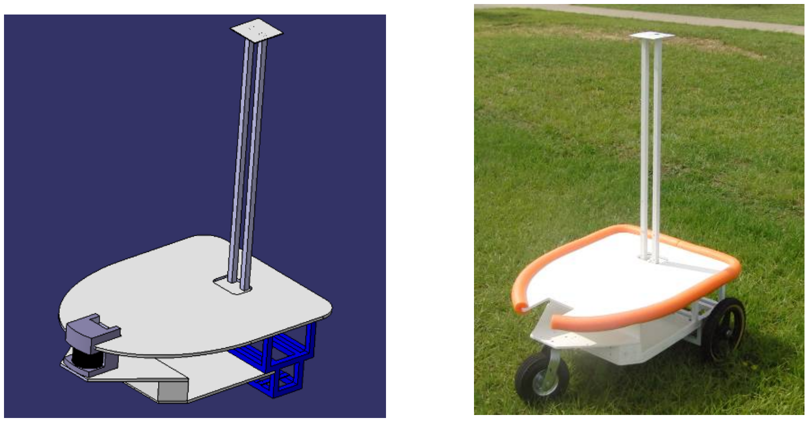

Figure 3.1: CATIA Model and Final Chassis

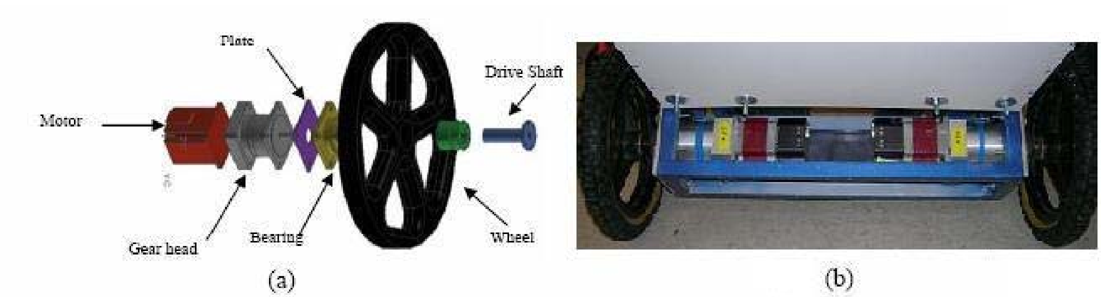

Figure 3.2: (a) CATIA Exploded View of Drive Assembly, (b) Vehicle Drive Train

4.0 Electronics

The electrical systems on Reagle II have been adapted from the original Reagle with the exception of the power supply system and the control computer. While the systems on the original Regal were reliable and effective, changes were motivated by our desire to make the vehicle lighter, to give the user the option of extended run times and to be better stewards of the environment.

4.1 Power System

Reagle II implements a flexible power system in its use of hot-swappable lithium ion nanophosphate battery packs. This safe and reliable power source allows Reagle II to operate for 13 hours in typical running mode and for nearly two days in a sensor-only stationary surveillance mode. This battery system is lighter, more compact, and better for the environment than the lead acid batteries used in the past. An optional auxiliary hybrid-electric power trailer, shown on the cover photo, provides at least eight hours of continuous run time without the use of batteries.

Central to the electrical system is the power board, which regulates voltage to each component. The power schematic including the auxiliary power trailer is shown in Figure 4.1. The physical layout of the weatherproof Pelican case electronics box is shown in figure 4.2.

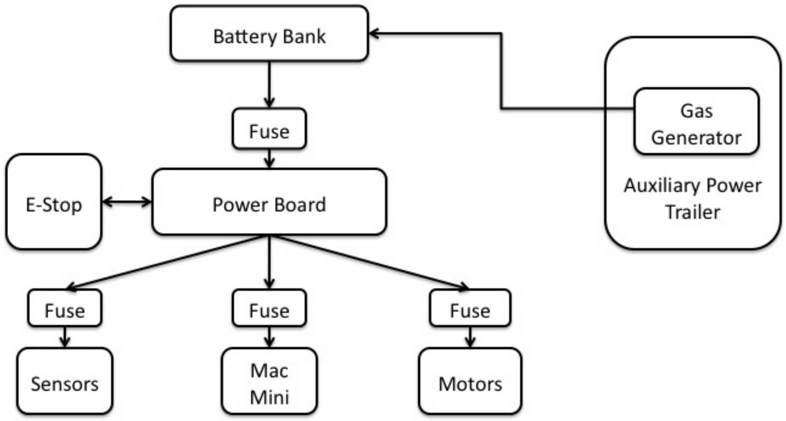

Figure 4.1: Power System

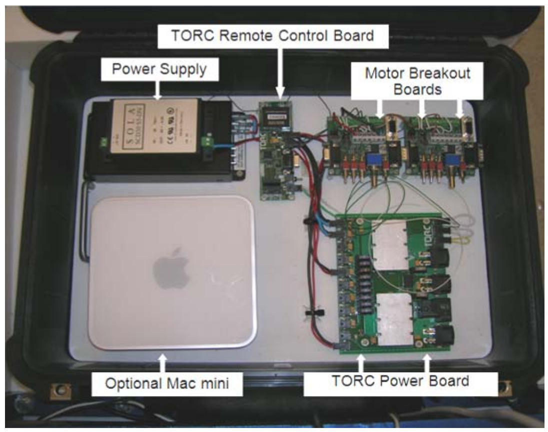

Figure 4.2: Pelican Case and Electronics Layout

4.2 Power Distribution

Power distribution for Reagle II is accomplished through a TORC Technologies power board shown in Figure 4.2. This board is mounted inside a weather resistant 1520 Pelican case with the other electronic components. The main power input sends a nominal 24 volts from the battery through two DC to DC Voltage regulators; one 24 Volt regulator and one 12 Volt regulator, which regulate voltage to the sensors and Mac Mini Computer. The power to the motors is unregulated 24 Volts. A remote emergency stop or a hardwired button can interrupt power. The vehicle uses one main power switch to control the entire electrical system.

The distribution section of the power board receives regulated 12 and 24 volts and is responsible for power distribution and monitoring. The regulated 24 volts is distributed to the Laser Range Finder (LRF) and to an auxiliary connector. The regulated 12 volts is sent to the compass, GPS, camera, and to two auxiliary 12 volt connectors. Each of these connectors has an individual fuse to avoid damage from a power surge. Table 4.3 shows the power requirements of each component in the electrical system.

Table 4.3: Power Requirements

Equipment	Volts	Amps	Watts
Motors & Encoders	24	16	384
Laser Scanner	24	1.1	26.4
GPS	12	0.35	4.2
Compass	12	0.02	0.24
Camera	12	0.05	0.6
Mac Mini Computer	18	2	36
Total			**451.44**

4.3 Emergency Stop System and Safety Strobe Light

Reagle II incorporates the SafeStop emergency stop system from TORC Technologies shown in Figure 4.4. The SafeStop transmitter uses spread spectrum frequency hopping for decreased interference and reliable transmission of up to 6 miles. The battery lasts 30 hours on a single charge.

Figure 4.4: TORC Technologies SafeStop Transmitter and Receiver.

As implemented, the SafeStop system provides both a pause mode, which rapidly brings the vehicle to a controlled stop without cutting power, and a "hard" emergency stop that opens a relay, disengaging all electrical power. A separate radio controlled transmitter is used to drive the vehicle in non-autonomous mode. Reagle II is also equipped with a strobe light that indicates to bystanders when Reagle II is under autonomous control.

5.0 System Integration

Reagle II is a system of systems. While there are a number of components on the vehicle, each must be able to function individually and in conjunction with the other systems on the vehicle. The same is true of the team members working on each system. The members working on the mechanical components must be aware of the visual requirements of the sensors in order to build a functional vehicle. The main systems on Reagle II are: the electrical system, the hardware (sensors) and software system, and the mechanical system. The electrical and mechanical systems were discussed previously.

Each of the different systems has a central point of integration; for example, the central point of integration for electrical system is the power board. The central point of integration in the mechanical system is the chassis and the hard mounting points for the attached components. For the sensors and flow of information, the central point of integration is the Mac Mini computer with a 320GB hard drive and 1GB of RAM. The LabVIEW programming environment is installed on the Mac Mini and is the central point of software integration. LabVIEW is a critical tool used to receive and organize data from the sensors, and then make the necessary decisions. Standard JAUS messaging is the final central point of integration. It provides a standard framework for communication between the various subsystems.

5.1 Sensor Communications and Data Integration

There are four commercial off-the-shelf (COTS) sensors used on Reagle II: a SICK LMS-291 laser rangefinder, a Pacific Navigation Instruments TCM2-20 3-axis digital compass, a Novatel Propack GPS and a Unibrain Fire-I board digital color CCD IEEE 1394 Firewire camera. Figure 5.1 shows the flow of data from each sensor. As stated previously, the team uses LabVIEW to interpret the data from the sensors, which then sends commands to the motors. However, the sensors are at different locations on Reagle II and therefore their data must be translated to a common coordinate system. This is done in LabVIEW on the Mac Mini.

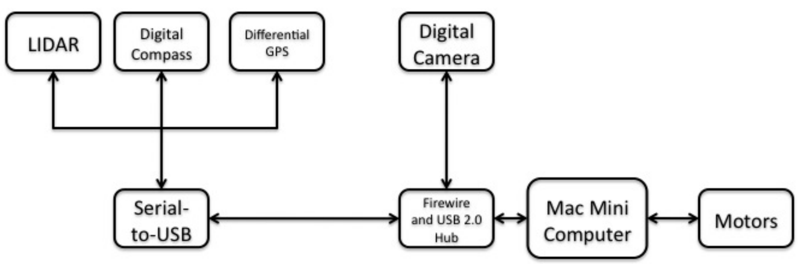

Figure 5.1: Flow of Sensor and Control Information

6.0 Software and Navigation Strategies

The National Instruments LabVIEW environment is used to develop all software. This virtual-instrument-based programming approach naturally compliments the modular system architecture of Reagle II.

6.1 Software Structure

The intelligent navigation software is preloaded on the onboard Mac Mini computer prior to deployment. The user simply opens the program for the specific IGVC challenge. The software provides feedback through an easy-to-understand visual display verifying that all systems are operational and optimal for navigation. Once all systems are online, the user or judge presses "Start" and the vehicle begins autonomous operation after a brief delay to allow personnel to clear the area.

6.2 Autonomous Challenge Algorithm

The software developed for the Autonomous Challenge uses a digital Firewire camera for lane detection and a SICK laser rangefinder for obstacle avoidance. The general approach for the autonomous challenge is detailed in Figure 6.1. The process cycles continuously at approximately 8 hertz during navigation, adjusting the vehicle heading and speed to effectively navigate the course.

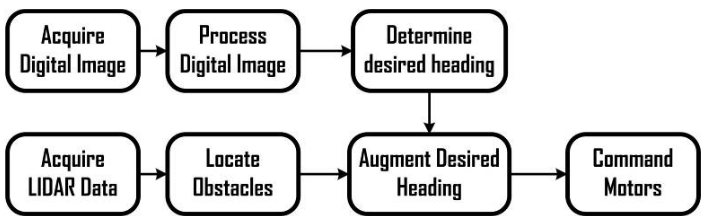

Figure 6.1: Autonomous Challenge Algorithm

The image-processing algorithm is described in Figure 6.2. The acquired image is pre-processed by extracting specific image values from the composite RGB color image. To reduce processing time, the image is down sampled from the 640 by 480 pixel native camera resolution to 160 by 120 pixels and converted to grayscale. The image is then split in two, representing the view to the left and to the right of the vehicle. To determine the strongest course boundary line in the images, a Hough transform is used and the dominant line occurring in each half of the image is identified. This method works equally well for solid or dashed lines. A decision tree is implemented to determine a vehicle heading based upon situational line detection cases. The obstacle avoidance capability subsumes the vision derived heading. The final vehicle heading, being the composite of the vision and obstacle avoidance data, is then used to command the motors.

The final commanded path is a circular arc, which yields a fluid motion as the vehicle navigates the course. The circular arc path accounts for the dynamic response of the vehicle to the commanded wheel speeds and more accurately renders the actual motion of the differentially steered vehicle.

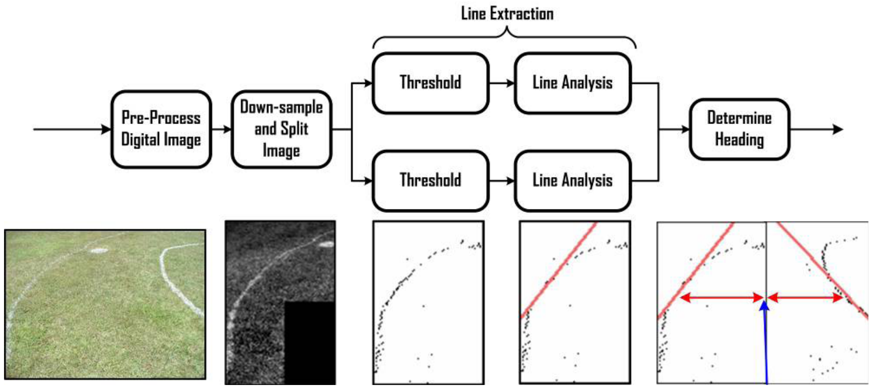

Figure 6.2: Image Processing Algorithm for Boundary Line Extraction

6.3 Autonomous Navigation Algorithm

The Navigation Challenge algorithm uses sensory input from a Novatel differential GPS with Ominstar corrections, Pacific Navigation Instruments TCM2-20 3-axis digital compass, and a SICK LMS-291 scanning laser rangefinder. A block diagram overview of this algorithm is provided in Figure 6.3.

Path generation is derived from the known position and orientation of the vehicle and the next target waypoint. A polynomial curve fit is used to plan a suitable path between waypoints. A subsumption approach has been adopted, so that the laser-rangefinder-based obstacle avoidance subsumes the GPS-based heading whenever an obstacle is perceived to be blocking the desired path. When Reagle II reaches the last target waypoint, it returns to the initial starting position and ceases motion indicating that the mission has been accomplished.

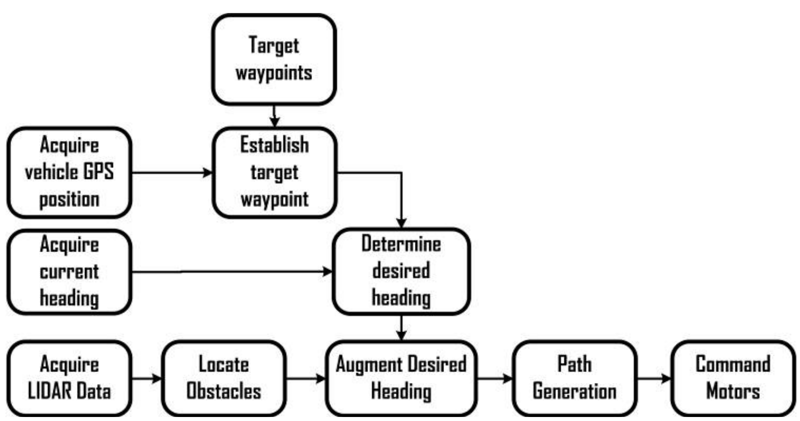

Figure 6.3: Overview of the Navigation Challenge Algorithm

7.0 Predicted Performance

We expect Reagle II to meet and surpass all competition requirements based on its performance in the 2008 competition and based on the improvements and refinements made this year. Throughout the report, we have attempted to document the predicted performance of the vehicle and its subsystems. For example, predicted battery performance was discussed in the innovations section and autonomous navigation update rates were discussed in the Software Structure section.

Reagle II is limited to a maximum speed of 5mph, which it should be able to maintain even on a 15% grade ramp. The accuracy of the GPS system is 0.2 meters Circular Error Probable (CEP) using Oministar corrections. Circular Error Probable refers to the radius of the circle, centered about the true position, that contains 50% of the GPS position estimates. The range of the laser rangefinder is well over 30 meters, but we typically only look ahead 4 meters. The camera has essentially unlimited range, but its accuracy diminishes with distance. The camera and laser rangefinder are accurate to a 0.02 meter, or better, in the ranges we are using them.

8.0 Problems and Solutions

Creating Reagle II was an exercise in improving safety and performance. Many difficulties arose that produced opportunities to learn and improve. To gain access to drive system components and for the transport of Reagle II, the vehicle had to be lifted. This was an unwieldy process as there were no safe lift points in easy-to-access locations. To solve this problem, we mounted lifting handles on the upper chassis. Run times during testing varied due to the amount of components drawing off the power, so we added the hot-swappable battery component in order to increase run time in extended practice runs. We also have the auxiliary power trailer for this reason.

This year the team approached safety and operation from the viewpoint of a customer who has never interacted with the system. This led us to create safety labels and critical instructions that are displayed on the vehicle in strategic locations. For example, we have included a run time chart for the number of batteries and labels to distinguish the recyclable components of Reagle II.

9.0 Vehicle Cost

Many of the components on Reagle II have been adapted from previous entries in IGVC and other AUVSI student competitions. New components acquired this year include the lithium ion batteries (donated by DeWalt), Mac Mini computer, and additional high-density polyethylene sheet material. The team made a concerted effort to minimize the actual cost of the vehicle through component re-use and through pursuit of industry donations and support. This goal was largely achieved, and the majority of the vehicle development cost was eliminated or reduced due to generous sponsor donations. Table 9.1 provides the retail cost of each component and actual costs incurred by the design team.

Table 9.1: Summary of Vehicle Component Cost

Components	**Retail Cost**	**Team Cost**
Mac Mini Computer	$249	$0
(2) Quicksilver DC Brushless Motors	$2,450	$2,450
(16) A123 Lithium Ion Nanophosphate Battery Cells	$120	Donated
Novatel GPS System	$5,000	$1,500
Sick LMS-221 Scanning Laser Range Finder	$5,930	$2,000
Unibrain Firewire Digital Camera	$82	$82
PNI TCM2-20 Digital Compass	$700	$0
National Instruments RS-232 Serial to USB Converters	$200	$200
TORC Power Distribution Board		Donated
TORC Remote Control Board		Donated
Aluminum frame and High-Density Polyethylene	$350	$350
Caster wheel	$25	$25
(2) Low Rolling Resistance Composite Nylon Wheels	$75	$75
Total	$15,281	$6, 682

10.0 JAUS Challenge

We intend to compete in the JAUS Challenge. Our approach has been to implement JAUS using a commercially available JAUS Toolkit marketed by TORC Technologies and specifically developed to integrate with LabVIEW.

11.0 Conclusion

Reagle II is a fully autonomous vehicle system designed by a team of students from Embry-Riddle Aeronautical University. It has been designed to comply with the 2009 Intelligent Ground Vehicle Competition rules. Reagle II has been tested and refined to compete successfully in both the Autonomous Challenge and the Navigation Challenge. In addition, it incorporates innovative safety and performance features that should position it well in a competitive market of small, unmanned ground vehicles. We believe our focus on minimizing the environmental impact of the system will prove to be a popular and important consideration for consumers.