EMBRY-RIDDLE
AERONAUTICAL UNIVERSITY

Presents:

# Reagle

**Team Members**

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

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, a new vehicle platform designed to compete in the 2008 Intelligent Ground Vehicle Competition (IGVC). Embry-Riddle last competed in the 2002 IGVC, finishing 8th in the Autonomous Challenge and 2nd in the Navigation Challenge.

Reagle incorporates many of the successful features and subcomponents used by other IGVC competitors in recent years, but the design also includes several key innovations specifically developed for the 2008 competition. Our goal is to make use of the knowledge and experience gained by previous teams while attempting to address the most critical problems and provide the best overall value.

The name Reagle (pronounced ˈrē-gəl) is a contraction of the University founder's last name (aviation pioneer and barnstormer John Paul *Riddle*) and the *eagle* mascot that represents the University's aviation heritage. The word "regal" (same pronunciation) means, "Of notable excellence or magnificence." We hope to live up to the lofty expectations our vehicle name and heritage may suggest.

### *1.1 Base Vehicle Overview*

Reagle is a three wheel, differentially driven and steered vehicle. The drive/steering 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: | 185 lbs (not including 20 lb payload) |
| Overall length and width: | Length: 44 inches Width: 33 inches |
| Weight Distribution: | 80% rear, 20% front caster |
| Wheelbase: | 29 inches |
| Track width: | 31 inches |
| Wheel Sizes: | 14 inch rear, 10 inch front caster |
| Height: | 17 inches (without sensor mast and payload box)<br>67 inches (with sensor mast) |

Reagle uses two Quicksilver brushless DC drive servomotors with integrated 10:1 reduction planetary gear heads. All system power is provided by four sealed lead acid batteries that provide a run time of well over an hour. 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 quick-disconnect model 1520 Pelican case. The base vehicle system, including the chassis, drive motors, wheels, sensor mast and laser rangefinder, is shown in figure 1.1.

**Figure 1.1: Reagle Chassis and Drive System**

### *1.2 Innovations*

In developing Reagle, the team attempted to understand the strengths and weaknesses of past designs. Whenever possible, the team made use of commercial, off-the-shelf (COTS) components to expedite development and to ensure reliability. As part of the design process, five former IGVC participants, Jesse Farmer, Jon Weekley, Peter King, Patrick Currier and Michael Fleming, were invited to the Embry-Riddle campus to work with the current design team. Jesse Farmer was a member of the Bluefield State College team. All other former participants were members of teams advised by Dr. Reinholtz at Virginia Tech.

Discussions and interviews with these successful former competitors revealed a number of critical requirements and design specifications for the new vehicle. While many of the requirements were achieved by past vehicle systems, the team identified three key innovations endorsed by the former IGVC participants. These innovations, which will be discussed in detail in the subsequent sections, are the SoftRide© chassis, the Portable Electronics Case and the Hybrid-Electric Trailer for extended field testing and operations.

### *1.2.1 Innovation #1: SoftRide© Chassis*

The SoftRide© chassis was developed to provide a passive suspension and vibration damping without adding complexity or weight to the system. As qualifying and competition speeds have approached the 5 mph speed limit in recent years, and with the introduction of actual potholes, vehicle dynamic response has become a factor in both perception and control. Several recent vehicles, such as Chimera in the 2006 competition [Chimera Design Report, http://www.igvc.org], have attempted to add traditional spring-damper suspension systems to vehicles with rigid frames. The result has been larger, heavier and more complex vehicles.

Reagle takes a completely different approach to solving the suspension and vibration problem. Rather than adding a spring-damper suspension to a rigid vehicle frame, Reagle has these properties built in to the chassis of the vehicle. In figure 1.1, the blue rigid tubular box frame at the rear of the vehicle is designed to support the high torques and loads associated the drive motors. This frame section also supports the heavy lead acid batteries and the competition payload. The white front portion of the vehicle chassis is fabricated from high-density polyethylene, which provides both compliance and damping to the system. This results in a vehicle that is lighter and less complex than a comparable rigid frame vehicle with a spring-damper suspension.

To help demonstrate the effectiveness of the integrated SoftRide© suspension, the dynamic response of Reagle was compared to Johnny-5 (a retired Virginia Tech vehicle from the 2007 competition currently housed at Embry-Riddle for joint research). Johnny-5 is a rigid aluminum frame vehicle of similar size and configuration. Figure 1.2 shows the typical accelerometer response to a step input at the sensor mast for the two vehicles. Peak accelerations on Reagle are reduced by a factor of three and peak velocities are reduced by a factor of two.

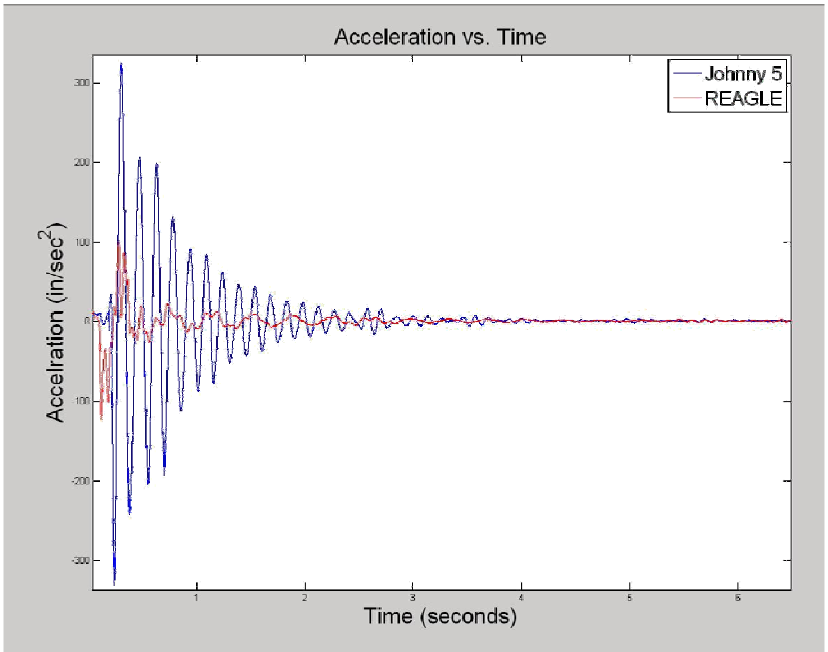

**Figure 1.2: Sensor mast acceleration comparison (SoftRide© chassis in Red)**

### *1.2.2 Innovation #2: Portable Electronics Case*

The Portable Electronics Case shown in figure 1.3 is another innovative aspect of Reagle's design. This weather-resistant enclosure allows all of the system electronics to be removed from the vehicle for quick replacement of the electronic subsystem. An additional benefit is interoperability and interchangeability. This same system can be directly integrated into another vehicle. The Embry-Riddle team has registered to participate in the 2008 AUVSI Autonomous Surface Vehicle Competition. Our goal is to use the same Pelican Case electronic subsystem and the same root software on our differentially steered surface vehicle. Although the surface vehicle uses SeaBotix thrusters rather than wheels, and it must navigate a course defined by buoys rather than lines, the electronics and controls of the two systems are remarkably similar.

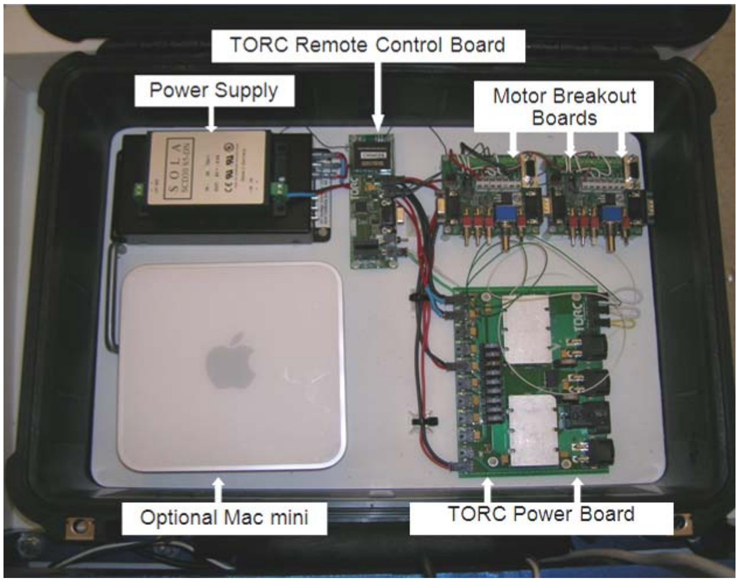

**Figure 1.3: Pelican Case 1520 Portable Electronics Enclosure and Components**

### *1.2.3 Innovation #3: Hybrid-Electric Trailer*

All of the earlier competitors who were interviewed as part of the design process agreed that long vehicle run times were critical to system testing and some field operations. They also noted that it would be highly desirable to develop a vehicle that was lighter and easier to transport than the IGVC vehicles they helped to create. The Hybrid-Electric Trailer system shown in figure 1.4 provides both of these benefits.

**Figure 1.4: Reagle without (left) and with (right) Hybrid-Electric Conversion Trailer**

Reagle is an all-electric base vehicle platform with four on-board Odyssey batteries that provide enough energy to run the vehicle in competition events for more than an hour. To substantially increase run time, a Hybrid-Electric trailer-based charging system has been developed and implemented. This trailer system includes a 1000 watt Yamaha four-stroke gasoline powered generator and a Deltran BatteryTender microcontroller-based charger. The Hybrid-Electric trailer provides extended operating times of eight hours or more. It also provides an auxiliary 120 volt AC, 12 volt DC and 24 volt DC power station. This field power station is remarkably handy for charging notebook computers, radio control units, cell phones and other common field equipment. Note that the trailer limits the vehicle’s ability to make zero-radius turns greater than 180 degrees, which must be controlled through software.

## 2.0 Design Process

The 2008 competition will be the first IGVC for all of the student members of the Embry-Riddle team. Fortunately, the team has experienced faculty advisors and significant technical support from former IGVC participants now in graduate school or working in the industry, including the people mentioned in Section 1.2 as well as Andrew Bacha, Brett Gombar and Mike Avitable, all of TORC Technologies, and Sean Baity of AAI Corporation. The experience of these previous team members has proved invaluable to the overall design and development process.

## 2.1 Team Organization

Members of the 2008 Reagle team are listed in table 2.1. The team includes two graduate students and seven undergraduate students. Every member of the team contributed to the overall design process. The graduate students, along with Alin Dobre and Aaron Brookshire focused primarily on electronics and software development, while the other members of the team focused on mechanical design, fabrication and testing. It is estimated that the team spent 1000 hours developing Reagle.

**Table 2.1: Student Team Members**

| Name | Academic Major, Year | Primary Team Functions |
|---|---|---|
| Alin Dobre | Computer Engineering, Senior | Electronics, Software, Documentation |
| Aaron Brookshire | Mechanical Engineering, Freshman | Software, Electronics, Documentation |
| Wiljariette Hernandez | Mechanical Engineering, Junior | Mechanical Design, Documentation |
| Michael Harris | Mechanical Engineering, Freshman | Mechanical Design |
| Edward Muller | Aerospace Engineering, Freshman | Mechanical Design, Testing |
| Tim Bentley | Mechanical Engineering, Freshman | Software, Testing |
| Alex Gregg | Mechanical Engineering, Freshman | Mechanical Design |
| Jason Firanski | Computer Engineering, Masters | Electronics, Software |
| Jayson Clifford | Computer Engineering, Masters | Electronics, Software |

## 2.2 Design Methodology

As can be seen in the table above, the Embry-Riddle team includes a mix of students with widely varying levels of experience and with different academic backgrounds. This made it imperative to adopt a design process that everyone on the team could quickly understand and implement. Professor Reinholtz introduced the team to two tools that met this criterion. The first tool was the six-step process described in *Product Design and Development* (Ulrich and Eppinger, 2000). This process focuses on customer needs and the iterative steps followed in design. To ensure that innovation would be effectively represented in the design, the team also adopted the Kano design method described in *Attractive Quality and Must-Be Quality Method* (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996) during the conceptual design phase. Figure 2.1 illustrates this simple, common-sense approach to design.

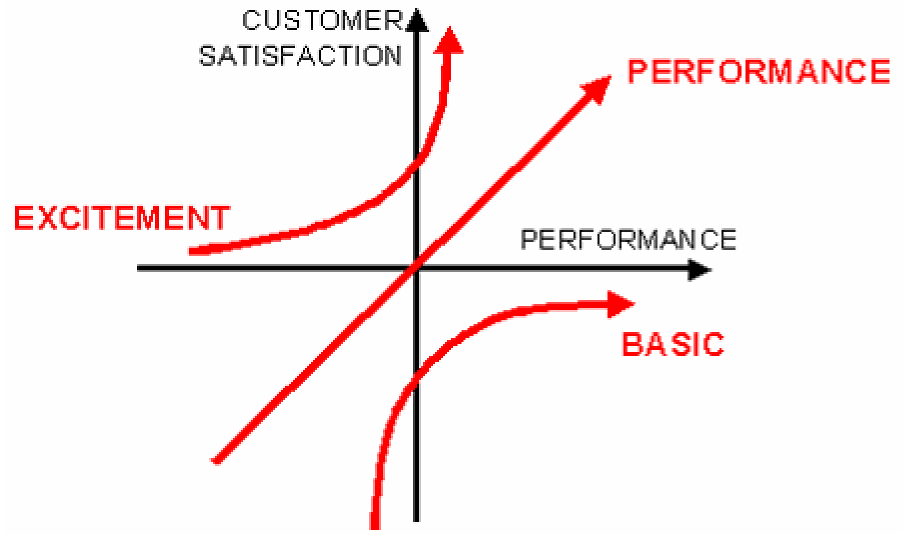

**Figure 2.1: Kano design method diagram**

For a customer to be fully satisfied, a product must first meet the basic needs such as complying with the 5 mph maximum speed limit. According to the Kano model, customer satisfaction will increase linearly with improvements in performance parameters such as battery life. Finally, the Kano model suggests that customer satisfaction is strongly enhanced by unexpected features that are not found in competing products, Kano refers to these features as "delighters". We believe that the SoftRide© chassis, the Portable Electronics Case and the Hybrid-Electric Trailer ideas generated in the brainstorming phase and later implemented in the design are delighters.

## 3.0 Mechanical Design

Reagle was developed based on the requirements specified in the 2008 IGVC rules as well as the feedback provided by experienced advisors and former competitors. Our emphasis was on simplicity of design and operation and on efficiency and value.

### *3.1 Vehicle Chassis*

As noted in the innovations section of this report, the vehicle chassis combines an aluminum frame aft section for relatively rigid support of the motors, batteries and payload, and a front component deck made of marine-grade high density polyethylene sheet. The high density polyethylene deck provides the desirable compliance and damping properties described earlier, and it has the added benefit of lightening and simplifying the overall structure. In a rigid frame vehicle, a separate deck plate would have been required for component mounting and protection. The structural polyethylene sheet deck provides both the structural and protective functions.

### *3.2 Vehicle Drive Train*

Reagle is driven by two Quicksilver SilverMax 34HC-1 brushless DC servomotors. Each motor provides a maximum 444.7 watts (0.6 hp) at 2.47 N-m (1.82 ft-lb) of torque with a continuous stall torque of 4.77 N-m (3.52 ft-lb). 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 drivetrain, as shown in figure 3.2.

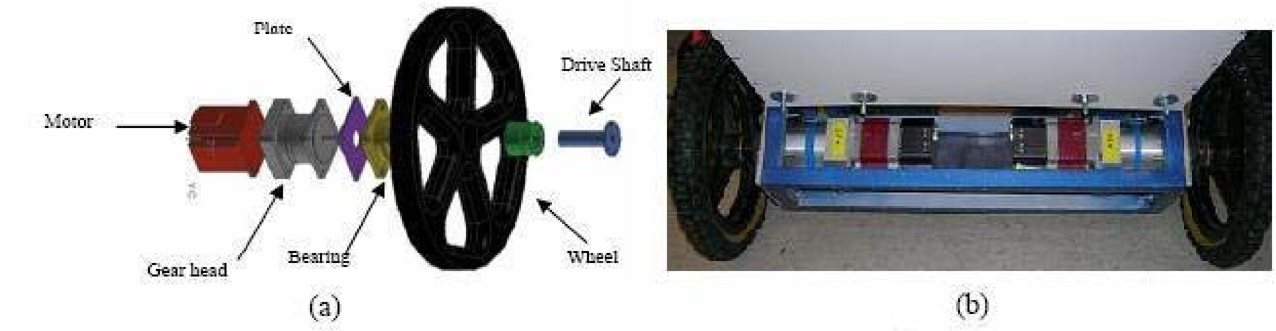

**Figure 3.2: (a) CAD exploded view of the drive shaft assembly, (b) Reagle's drive train**

## 4.0 Electronics

The electrical system on Reagle is an innovative aspect of its design. Many of the power distribution and control problems that hampered past teams have been effectively eliminated. Because of the inexperience of the team, we collaborated with former team members and TORC Technologies to develop an integrated circuit power management board that regulates and distributes power to Reagle's components.

### *4.1 Power System*

Reagle's flexible power system allows it to adapt to different mission requirements. In its base configuration (i.e. without the auxiliary power trailer), Reagle is powered by sealed lead acid batteries. This safe power source allows Reagle to operate in environments where noise and exhaust fumes would pose safety or operational concerns. When longer runtimes are needed, the auxiliary power trailer can be attached to the rear hitch, offering 8 hours or more of continuous operation. A power schematic, including the auxiliary power trailer, is shown in figure 4.1.

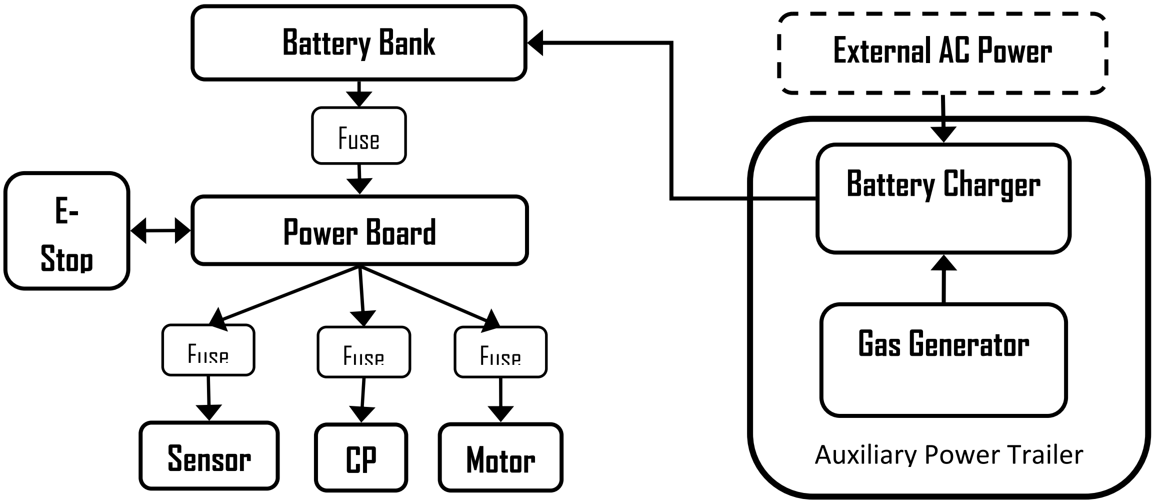

**Figure 4.1: Power system schematic**

### *4.2 Power Distribution*

Power distribution for Reagle is accomplished through the TORC Technologies power board shown in figure 1.3. This board is mounted inside a 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. 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 a separate fuse. The power to the motors is unregulated 24 Volts. Power can be interrupted by a remote emergency stop or a hardwired button. The vehicle uses one main power switch to control the entire electrical system.

### *4.3 Emergency Stop System and Safety Strobe Light*

Reagle incorporates the SafeStop™ emergency stop system from TORC Technologies shown in figure 4.2. The SafeStop™ transmitter has a 30 hour battery life and uses spread spectrum and frequency hopping for decreased interference and reliable transmission of up to 6 miles.

**Figure 4.2: TORC Technologies SafeStop™ System**

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. Further enhancing safety is the use of a flashing strobe light warning bystanders that Reagle is operating in autonomous mode.

## 5.0 Sensors and System Integration

Reagle uses the four sensors shown in table 5.1 to perceive the surrounding environment.

**Table 5.1: Sensor Suite**

| |
|---|
| Unibrain Fire-i board digital color CCD IEEE 1394 Firewire camera |
| SICK LMS-221 scanning laser rangefinder system |
| Pacific Navigation Instruments TCM2-20 3-axis digital compass |
| Novatel SMART ANTENNA™ with Omnistar Subscription Correction |

The generalized sensor system architecture is shown in figure 5.1. The selected sensors have been used by a number of past IGVC teams and have proven to be reliable and readily integrated through serial, USB and firewire busses, as shown in the figure below.

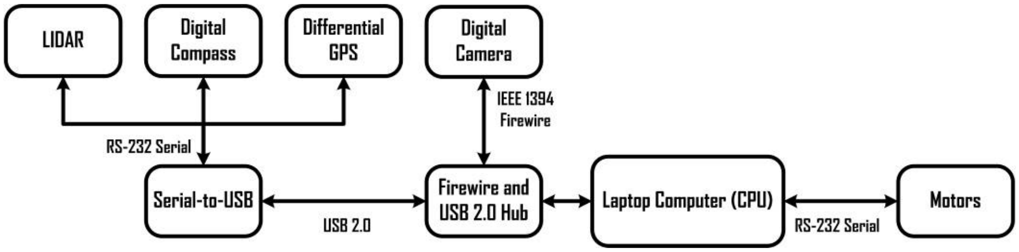

**Figure 5.1: Diagram of sensor system architecture**

### *5.1 Sensor Communication and Data Integration*

Since the sensors are at different locations on the vehicle and each has its own coordinate system, the sensor data must be converted to a common world coordinate system. Sensor data must also be checked to ensure that the messages are complete. This prevents a partial message from corrupting navigation algorithms and aids in error checking. Once the data is received, checked and translated, it is interpreted by a separate software module for each sensor. The resulting information is then overlaid on a common world map.

## 6.0 Software and Navigation Strategies

Reagle's navigation algorithms and software have been adapted from those developed under Professor Reinholtz's advisement of previous IGVC and DARPA Challenge teams. All the software has been developed using National Instruments LabView development environment, which greatly expedited the learning and development process.

### *6.1 Software Structure*

The intelligent navigation software is preloaded on the onboard laptop prior to deployment. On initiation, the software provides feedback verifying that all systems and sensors are operational. Once all systems are online, the user presses "Start" and the vehicle begins autonomous operation.

### *6.2 Autonomous Challenge Algorithm*

The software developed for the Autonomous Challenge uses a digital Firewire camera for lane detection and a SICK LIDAR unit 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.

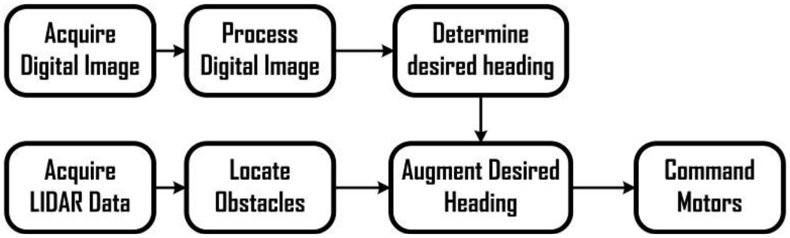

**Figure 6.1: Autonomous Challenge Algorithm.**

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 modified 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

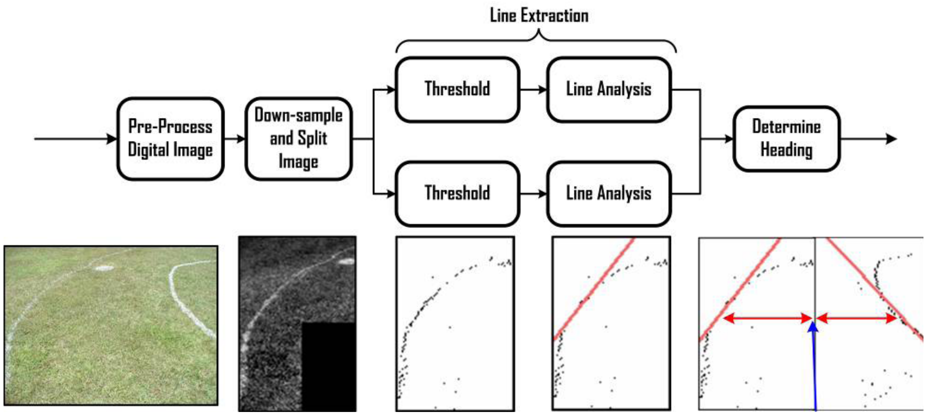

**Figure 6.2: Image processing algorithm for boundary line extraction.**

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.

### *6.3 Navigation Challenge Algorithm*

The Navigation Challenge algorithm uses sensory input from a Novatel differential GPS with Omnistar corrections, Pacific Navigation Instruments TCM2-20 3-axis digital compass, and a SICK LMS-221 scanning laser rangefinder. A block diagram overview of this algorithm is provided in figure 6.3.

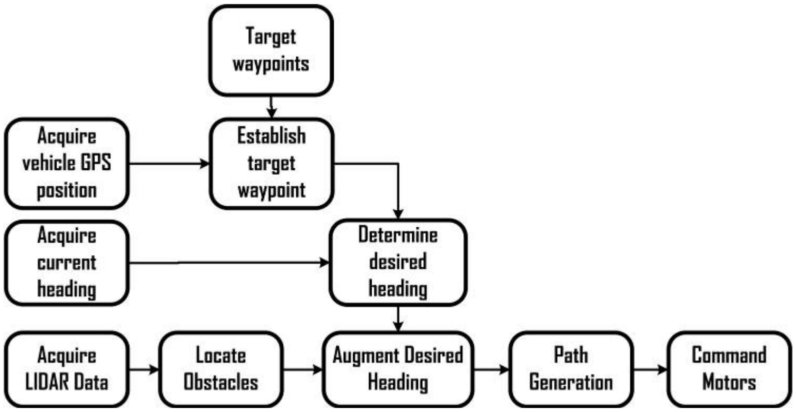

**Figure 6.3: Overview of the Navigation Challenge Algorithm.**

A desired path is determined 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 LIDAR subsumes the GPS-based heading whenever an obstacle is perceived to be blocking the desired path. When Reagle reaches the last target waypoint, it returns to the initial starting position and ceases motion indicating that the mission has been accomplished.

## 7.0 Predicted Performance

A number of aspects of Reagle's predicted performance, including software cycle times and the ability to deal with gaps in the boundary lines, have been discussed in the previous sections of the report. We generally expect Reagle to be able to deal with all aspects of the Autonomous Challenge and the Navigation Challenge. Reagle is capable of operating at the maximum 5 mph forward velocity on both the Autonomous Challenge course and the Navigation Challenge course in sections that are relatively straight and uncluttered. To account for the effects of centripetal acceleration, the maximum forward velocity is limited in proportion to the square root of the path curvature. This prevents instability when the vehicle makes near-zero-radius turns. The vehicle will also slow in proportion to the proximity of the nearest obstacle.

## 8.0 Problems and Solutions

As with any complex design project, many small problems were encountered along the way. One unexpected problem was the cold flow of the high density polyethylene (HDPE) sheet used to form the compliant front portion of the chassis. The maximum stress in this sheet occurs due to bending at the point where it attaches to the rigid aluminum frame. We calculated this stress to be:

$$\sigma = \frac{Mc}{I} = \frac{(1110\,\mathrm{in\text{-}lb})(0.25\,\mathrm{in})}{(0.25\,\mathrm{in}^4)} = 1110\,\mathrm{psi}$$

This is well below the 3.8 to 4.8 kpsi yield strength of the HDPE sheet. Unfortunately, HDPE is subject to a phenomenon known as cold flow, where the material will deform slightly over time due to low levels of persistent stress. This effect produces a slight sag in the vehicle chassis if the center is left unsupported for more than a few hours. The resulting deformation does not directly affect vehicle performance, but it does cause small changes in the angles of the camera and LIDAR unit. This effect can be compensated by adjusting the sensors, or it can be eliminated by storing the vehicle with a center support.

## 9.0 Vehicle Cost

During the design and fabrication process of Reagle, there was a concerted effort to minimize the cost of the vehicle design 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 Major Vehicle Component Cost**

| Components | Retail Cost | Team Cost |
|---|---:|---:|
| Dell Laptop | $849 | $0 |
| (2) Quicksilver DC Brushless Motors | $2,450 | $2,450 |
| (4) Hawker PC 535 AGM Dry Cell Lead Acid Batteries | $320 | $320 |
| Novatel Smart Antenna | $5,000 | $1,500 |
| Sick LMS-221 Scanning Laser Range Finder | $5,930 | $1,500 |
| 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 and Drive wheels | $150 | $150 |
| **Total** | $16,031 | $6,552 |

## 10.0 Value Engineering - Smart Antenna and Mac Mini Computer

In addressing the dynamic competition events of the 2008 IGVC, the team recognized that optimal system performance is of paramount concern. We also recognize that some customers may not require the sensor with the longest range or the greatest accuracy. Small tradeoffs in performance may produce significant cost savings. We have attempted to design our system with this value engineering construct in mind.

Two specific areas where a customer can cut cost with only a modest reduction in performance or convenience are the GPS solution and the navigation computer. A top-of-the-line Novatel Propak differential GPS system with Omnistar subscription corrections gives a 0.1m positioning accuracy at a cost of $8,000. The new Novatel Smart Antenna is a compact, lightweight and weatherproof package that gives 0.9m positioning accuracy. Since GPS accuracy is really a statistical measure that varies with conditions, we may elect to use the more accurate Propack solution in competition. However, we believe the Smart Antenna provides adequate performance for most customers, and it saves weight and space.

We have also integrated a less expensive optional computer solution into our vehicle. A Mac mini can replace the standard Dell notebook computer preferred by the team during the development process. The Mac mini is $600 less expensive the Dell notebook, and it can be completely enclosed in the Pelican case enclosure. Figure 1.3 shows the optional Mac mini inside this enclosure. The only drawback to this solution is that it does not provide a built-in keyboard and monitor. The Mac mini option is recommended for customers who prefer to interface with the vehicle through a networked developer interface, or those who operate the vehicle using a JAUS-interoperable controller.

## 11.0 JAUS Challenge

The team is in the process of developing a JAUS interface. We are familiar with the relevant sections of the JAUS Reference Architecture version 3.3, and we believe we understand the messages that are required to be interpreted, including the Resume message, the Set Discrete Devices message, the Report Global Pose message, and the Set Global Waypoint message. We are also conversant with UDP port allocation and IP address assignment.

## 12.0 Conclusion

Reagle is a fully autonomous robotic vehicle designed and manufactured by engineering students at Embry-Riddle Aeronautical University. In developing Reagle, the team maintained a customer focus, seeking to meet all base requirements while providing better-than-expected overall performance and value. In particular, the team worked to identify key innovations, including the SoftRide© system, the Auxiliary Power Trailer, and the Portable Electronics Box that would improve performance and enhance the overall experience of the customer. We believe that Reagle demonstrates exceptional systems integration, combining proven software and hardware solutions with innovative ideas and novel solutions to key problems. We expect Reagle to be a leader in competition and in the marketplace.