The University of Illinois at Chicago
Enyo
2011 Autonomous Vehicle

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The engineering design in this vehicle by the current student team has been significant and equivalent to what might be awarded in a senior design course. Faculty Advisor Certification Signature:

Miloš Žefran

1 Introduction

The Engineering Design Team of the University of Illinois at Chicago is pleased to present the new and improved Enyo. This year's entry is based on the 2009 platform of the same name. Enyo's capabilities have been extended to accommodate 2011 IGVC rule changes, general usability enhancements, and an array of functional improvements.

	Speed	Weight	Size	Sonar	IMU	Batt. Life
Enyo '09	4.3 mph	550 lbs	58275 in^3	No	No	2 hrs
Enyo '11	7.0 mph	350 lbs	46068 in^3	Yes	Yes	2 hrs

Figure 1: Summary of the differences between the 2009 version of Enyo compared with that of the 2011 version of Enyo.

Building onto the core software components of last year, the new additions support a system which is faster and more robust. With a new system of organizing the electrical systems of Enyo, the chassis has become more navigable and therefore easier to repair and modify. The drive train has been modified to be optimal for power and this year's speed requirements. The chassis' size has also been decreased to improve airflow and decrease weight. These changes are just some of the many features of Enyo which define a vehicle that has been years in the making, and continues to take its inspiration from competitors, past experiences, and new ideas from the members of our team.

2 Design Process

2.1 Team Overview

Composed of students from every field of engineering, the Engineering Design Team is a group which is rooted in years of experience with autonomous and remote controlled vehicles. With our large size and past successes we have been granted the equipment and experience which allows nearly our entire vehicle to be constructed in-house. From the circuit boards to the drive trains, components are designed and constructed in small teams led by a team captain. These captains communicate with each other in meetings every week as well as on a day-to-day basis with the IGVC leader. Since we have the manpower to make several people responsible for each component, every task is analyzed by at least two people, at least one of whom was not responsible for actually completing that task. This redundancy not only allows for a more robust vehicle, but one that can also be built much faster.

2.2 Design Process

Our team follows the Engineering Method which can be seen in Figure 1 on the next page. This method is generalized, but it is also proven and is a great tool not only for introducing students to the design process but also for standardizing the process. The central task which occurs each year is the task of brainstorming possible solutions and analyzing those solutions. We devote months of our time, months that we spend documenting, researching, and communicating our ideas. Our group concentrates on opening communication between all of our members so that problems with possible solutions can be identified early, documented, and either discarded or improved upon. In order to make this task as coherent and expedient as possible much care is taken to document everything; this means that previous ideas can be looked at for inspiration or to identify past problems that might have relevance to current ideas.

Before this task takes place, a team of officers and captains are responsible for problem identification. This includes looking at the vehicle from last year and identifying major issues that came up, looking at the changed rules and identifying any problems that might arise, and identifying scheduling issues for the coming year. By analyzing the vehicle that competed in last year's Intelligent Ground Vehicle Competition during problem identification, we eliminate issues that would otherwise come up in the next year's proposed solutions.

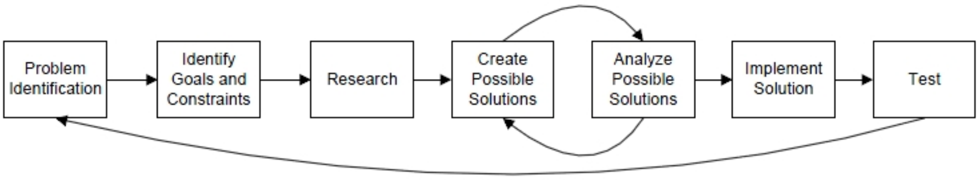


Figure 2: The Engineering Method, The Infinity Project: Engineering Our Digital Future. Upper Saddle River, NJ: Pearson, 2004.

3 Mechanical

3.1 Mechanical Design

3.1.1 Chassis

The chassis is divided into two sections: The bottom chassis and the top chassis. The bottom chassis houses the drive train and electronics. It is made of welded steel tubing in order to provide support to the drive train- which can produce significant forces during operation. The top chassis is made of aluminum T-slot. The T-slot allows for quick and efficient design, fabrication, and repair of the chassis structure. It also allows components to be added with ease.

3.1.2 Drivetrain

The drive train of Enyo is a differential drive, which allows the vehicle to turn in place. The rotation of the wheels is geared down by a factor of 1/48 multiplied by motor rotation. This keeps the vehicle at a max speed of 7 miles per hour.The gearing also results in increased torque. Each motor drives two wheels on one side of the vehicle.

3.1.3 Panelling

Panels of lacquered particle board can be found on each side of the vehicle. This lightweight solution provides protection from small impacts as well as dirt, water, and other contaminants. The panels on three sides also have windows which can be opened by actuating four small levers at the corners of each window. No tools are needed to perform this action and full access to the internal body of the vehicle is permitted.

3.2 Mechanical Innovation

- The drive train is of differential drive. Therefore the vehicle is able to turn in place without having to move forward or backwards.
- The bottom chassis is made of welded steel to provide structural strength and to hold the forces of the drive train. The top chassis is made of T-slot which allows for easy modifications or additions. Also, if any pieces of the T-slot are damaged, it can be replaced very efficiently.
- Filters and vent louvers are in place to prevent outside elements from getting in. Fans are optimized for flow through all elements.
- Since the batteries are bulky and heavy, a heavy duty drawer was designed to make replacing batteries easier.
- The panelling allows for repairs, modifications, and maintentance to be done quickly and without sacrificing the weatherproofing of the vehicle.

4 Electrical

4.1 Electrical Design

Enyo contains an innovative and robust electrical system rooted in the tenets of reliability, safety, and efficiency. These tenets are realized by designing all components to safely handle and recover from a multitude of error conditions. To increase reliability, each electrical component is packaged in a durable case with clearly labeled ports and of modular design. Furthermore, all embedded systems enter idle mode when they are not doing work, thereby reducing power consumption and increasing efficiency. The following sections highlight the electrical components of Enyo.

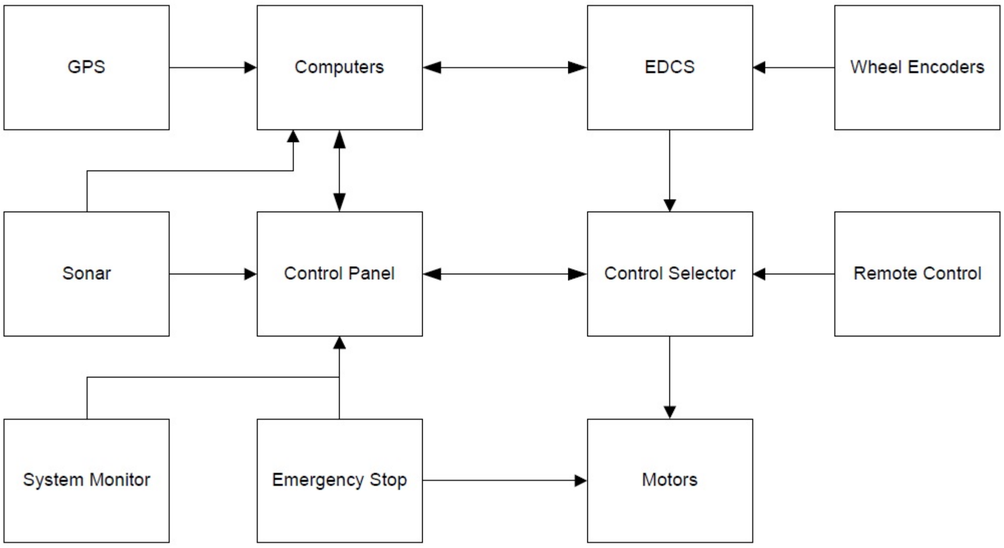


Figure 3: Electrical Systems Layout.

4.1.1 Power System

Enyo is powered with a set of six 12 volt 26 amp-hour sealed lead acid batteries. Four of them are arranged in parallel in order to form a 12 volt bank for all the electronic systems and the 1500 Watt inverter which powers the computer. The remaining two batteries are arranged in series with each other in order to provide 24 volts to the motor-controllers that control the speed of the motors. All electronic module voltages are regulated using very efficient switching regulators.

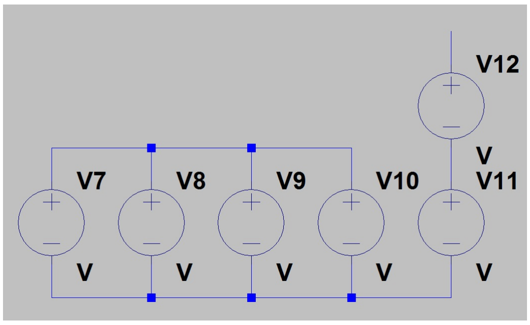


Figure 4: Power System Layout.

4.1.2 E-Stop

The emergency stop system (E-stop) is designed to disable the vehicle in emergencies. The E-Stop may be activated either by remote control or by pressing the onboard switch. The E-stop is composed of two modules: a handheld transmitter unit that wirelessly transmits a signal to the vehicle and a receiver unit that is onboard the vehicle. The transmitter unit has a highly visible red pushbutton switch that when pressed, activates the E-stop. The behavior of the E-stop is that if either the onboard switch or the wireless transmitter provides the STOP command, the vehicle will stop moving. The vehicle will resume movement only when both sources provide a GO signal. The radio module uses spread spectrum technology to ensure data encryption and prevent interference or jamming from external sources, thus improving system reliability. In addition, the radio module has a range of 5 miles in open-air line of sight.

4.1.3 Embedded Drive Train Control System (EDCS)

The EDCS is designed to interface the software controls system to the motors that drive the vehicle. The system consists of a module for each side of the vehicle. Each module is responsible for measuring the wheel speed and controlling the power level of the motor for its side. A microcontroller is the heart of each module and communicates with the software control system via RS-232 serial communication. The communications protocol between the EDCS and the computers is designed to inherently detect communication errors, leading to improved system reliability and safer operation.

4.1.4 Sensors

Enyo has several types of sensors that provide data feedback to the computer software. Two shaft wheel encoders are used to measure the exact speed of each side of the vehicle. The encoder produces two pulse trains with frequencies linearly dependent on wheel speed. The encoder sends the two pulse trains to the EDCS, which then determines the wheel speed and direction of rotation. 8 sonar units are used to measure approximate distances to objects; four sonar units are placed in the front of the vehicle, and four in the back of the vehicle. The sonar units produce a pulse train with frequencies linearly dependent on the distance to the object. The sonar units then send the pulse train to the sonar control module which measures the pulse width and sends it to the computer. An Inertial Motion Unit (IMU) is used to track the vehicle's movements in three dimensions. The IMU control board measures the readings from the IMU module and communicates the data to the computer. A stereo vision camera is used for line detection as well as object detection. The camera is interfaced to the computers via a firewire connection.

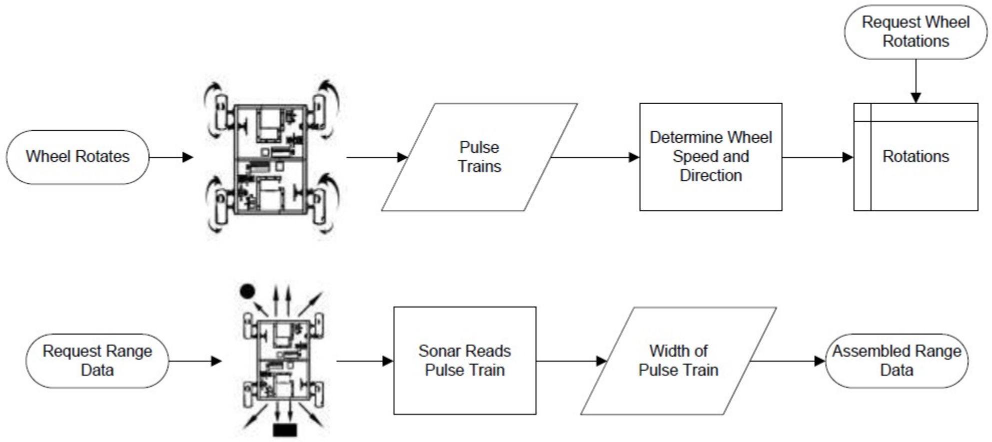


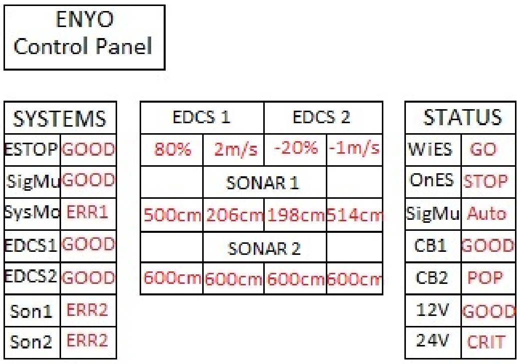
Figure 5: Data Flow for the EDCS/Wheel Encoders and Sonar devices.

4.1.5 Signal Multiplexer

The Signal Multiplexer allows the user to choose the manner in which Enyo is controlled. This system has four modes of operation that are easily controlled by the user through switches on the Control Panel. The first mode is a safety mode which causes the vehicle to remain stationary; it is also the default mode to ensure safety by not allowing the vehicle to move until a user deliberately allows it. The second mode allows the vehicle to be exclusively autonomously controlled. The third mode allows the vehicle to be exclusively controlled by remote control. The final mode allows the vehicle to switch between autonomous and radio control by the switch of a button on the remote control. In addition the system recognizes the absence of a signal from the remote control and stops the vehicle when no signal is detected.

4.1.6 Control Panel

The Control Panel interfaces with every electronic system on the vehicle through the I2C interface, allowing it to send commands and receive data. In this sense, the control panel acts as a medium between devices, as it is the only device capable of controlling others; if one device needs access to another, it must indirectly access it through the control panel. The secondary function of the control panel is to provide status information from devices and forward the information to an LCD screen, where the user can view it, and to the computers for feedback. This feedback greatly increases vehicle reliability and safety since it informs the software of possible hardware system errors. Status information includes Signal Multiplexer status, E-stop status, EDCS data, battery status, and fan status. One can adjust settings for the Signal Multiplexer and fan operation using buttons located on the Control Panel. Other features include ports for connecting monitors, keyboards, and mice to the computers, permitting quick access to the computers. Other features include ports for connecting monitors, keyboards, and mice to the computers, permitting quick access to the computers.



ENYO
Control Panel

SYSTEMS	
ESTOP	GOOD
SigMu	GOOD
SysMo	ERR1
EDCS1	GOOD
EDCS2	GOOD
Son1	ERR2
Son2	ERR2

EDCS 1		EDCS 2	
80%	2m/s	-20%	-1m/s
	SONAR 1		
500cm	206cm	198cm	514cm
	SONAR 2		
600cm	600cm	600cm	600cm

STATUS	
WiES	GO
OnES	STOP
SigMu	Auto
CB1	GOOD
CB2	POP
12V	GOOD
24V	CRIT

Figure 6: Example of the control panel display.

4.1.7 System Monitor

The System Monitor is responsible for keeping track of vehicle resources, performance, and malfunctions. If malfunctions occur, the System Monitor notifies the Control Panel, which in turn notifies the software and the user. One key task of the System Monitor is to continuously measure remaining battery life and warn if the battery capacity is becoming low. The system has two types of battery warnings for both the 12 volt and 24 volt systems, and another type of warning for each motor. Based on these warnings, the user or software can take action to correct these faults, allowing the vehicle to run in the safest manner possible.

Event	Electrical Response	Software Response
Battery Low	Msg: Change Batt. Soon	Limit Speed
Batt. Critically Low	Msg: Change Batt., Switch on E-stop	None
Motor Pwr. Lost	Msg: Motor Pwr. Lost	Wait

Figure 7: System Monitor Warning Chart

4.1.8 Computer Systems

The vehicle contains one high-performance computer to do image analysis, sensor data analysis, and control the vehicle. The computer uses an Intel Core 2 Quad Q8200 CPU, giving excellent performance due to a quad core processor that allows four different software components to run concurrently. The image processing is performed on an NVIDIA Ge-Force 9800GTX+ video card which supports CUDA. The computer uses a high performance ASUS P5E motherboard due to their resistance to overheating. The computer has an 800 watt power supply to meet the high GPU and CPU power requirements. It has 8GB of RAM to handle large amounts of data without having to rely on slow hard drive caching, letting the computer process data continuously at high speeds. An 80GB laptop hard drive is used to store data. Laptop hard drives were chosen for their resistance to vibration damage during vehicle operation.

4.2 Electrical Innovation

- The electronics are powered through switching voltage regulators that efficiently regulate the 12 volts from the batteries down to a clean 5 volts. The motor controllers receive 24 volts which is capable of supplying copious amount of current to the motors.
- The EDCS is capable of adjusting the speed of the wheels according to the commands that are issued by the computer software. The EDCS allows for two types of data to be sent, vehicle velocity and position, which allows for a flexible architecture to which the software can connect to.
- The Emergency Stop is capable of remotely triggering a relay to cut off the power to the motors at a range of up to five miles.
- Enyo has several different types of sensors that together make for an excellent source of feedback for the control software: there are two precision wheel encoders, there is an inertial motion unit (IMU), a stereo vision camera, and sonar sensors.
- The control panel is readily accessible as it is located on the side of the vehicle. It displays the state of all of the electrical components and all vital data to a Liquid Crystal Display. One can also monitor the battery level and the state of any protection circuits located in the vehicle.

5 Software

5.1 Software Design

5.1.1 Goal Planner

In order to properly navigate through the world, an agent must have a way of prioritizing certain situations over others. The obvious situations are those in which the vehicle is in contact with an obstacle or a line. Another situation can be written in first-order logic but is difficult to translate into executable code, and this situation is that of the agent going back the way it came. An easy way to handle this is to motivate the vehicle to explore areas it hasn't been before. This method works but it also places the vehicle into

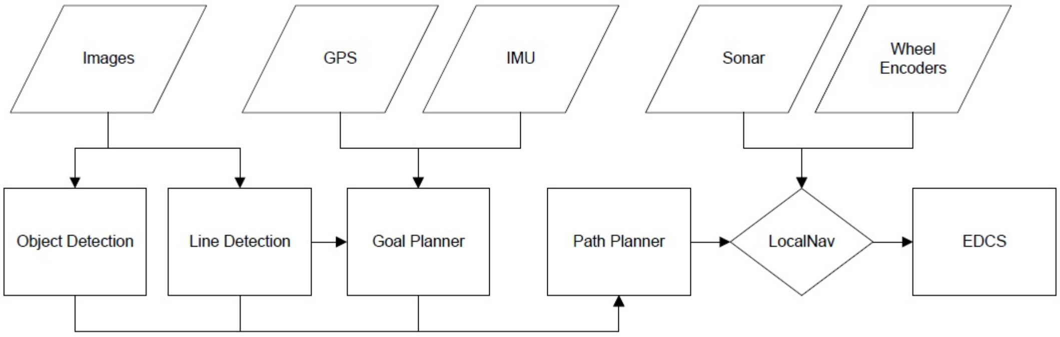


Figure 8: Software Flow Diagram.

corners where it must turn around, creating inefficient paths through the course. The better way to handle this is to motivate the vehicle to follow the lines on the sides of the course. Using the lines as a guideline, this component takes them in as input and outputs a direction which best match the lines. Since this direction has two possible rays, the ray which best matches the vehicle's recent motion vector is chosen. The next goal is chosen by finding the farthest empty location along this ray.

5.1.2 Path Planner

In order to proceed from the vehicle's position to its next goal, a set of waypoints are defined by a Path Planner component. These waypoints are defined by locating openings in the course by estimating the second derivative of the set of ranges. The second derivative will give the min and max ranges, which then define openings in the course. A waypoint is defined at each opening and then the operation is performed recursively until a straight line can be defined from a waypoint to the final goal.

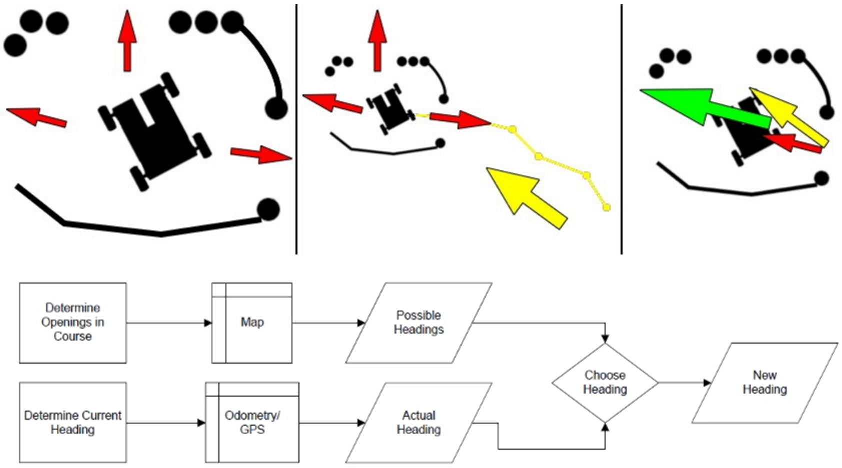


Figure 9: Path Planning Algorithm.

5.1.3 LocalNav

Once a set of waypoints to a goal has been defined, the speed commands to each motor can be defined by creating a map of vectors which defines the path of least resistance and by calculating the optimum turn radius for each waypoint. This component also receives range data from two sonar units (one on each end of the vehicle) and avoids objects that may have not been detected by the vision system or whose location was estimated incorrectly.

5.1.4 Line Detection

The lines are detected transforming the red channel of the image from the left camera by means of a threshold. The threshold used is determined by using a variable number which changes based on the average pixel intensity of the image. A Hough transform is then used to determine where the lines might be in the image and they are verified by comparing the average of the pixels on a given line with a constant which defines white in the image. These lines are then further verified by passing them to another component which maps these lines to an occupancy grid, mapping only the lines which are determined to be at ground-level.

5.1.5 Stereo Vision

Object detection is done by comparing two images from a Bumblebee stereo camera, first by calculating the disparity of the right image with respect to the left image, and then again by calculating the disparity of the left image with respect to the right image. This results in a highly accurate image where the pixel intensity represents the distance to a given point in space with respect to the center of the Bumblebee stereo camera. After transforming each pixel, the software calculates the closest object to the vehicle via ray tracing for a constant angle interval. These results are comparable to the results of a laser scan, but with higher resolution and they are delivered for a fraction of the price of a laser range scanning unit.

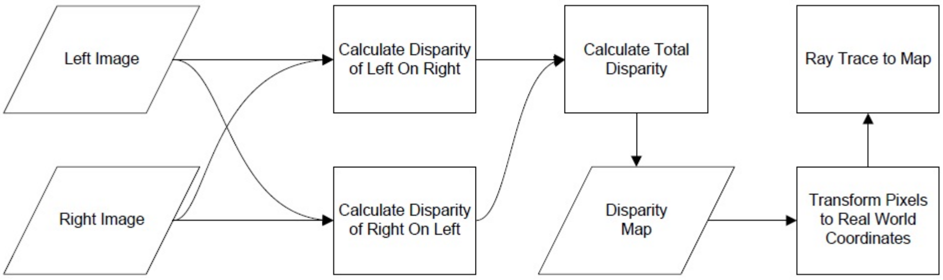


Figure 10: Disparity Mapping Algorithm.

5.2 Software Innovation

- A GPGPU (General Purpose Graphics Processing Unit) is used to perform Stereo Depth calculation. The system is extremely robust allowing for faster than real-time disparity calculation with improvements of up to 50 times over other conventional systems. The GPGPU allows us to compute disparities multiple times, in effect creating two disparity images, each with its own frame of reference, with no noticeable performance loss. The End result is a disparity image pair whose inconsistencies represent unfavorable data. Using a simple crosschecking algorithm (also running on the GPGPU) we can remove the said inconsistencies resulting in a final disparity image that is extremely accurate and free of any noise.

- A visibility roadmap-based goal planning procedure keeps the vehicle inside of the confines of the course even if the gaps in lines are not resolved by other components.

- The local histrogram plus utility uses sonar data to avoid objects that were not correctly or completely detected by the stereo vision system.

- Line detection is robust with regard to changes in lighting conditions due to an auto-thresholding algorithm, meaning that weather conditions rarely affect the detection of course lanes.

- Using a stereo imaging system for object detection is far cheaper than a laser range scanning system. Enyo's stero imaging system provides a better resolution than most laser range scanning systems with minimal cost to its computational resources since the processing is done almost entirely on the graphics card.

6 Safety

Our vehicle excels at being designed to operate safely and without incident. During the design process, special consideration is given to vehicle functionality regarding safe operation. Each system is double-checked by several members during the design process to ensure that interaction with any other system does not cause any safety concerns for vehicle operation. Also these safety features are tested multiple times upon completion.

- The E-Stop provides a way of disabling the vehicle with the press of a button from up to five miles away. If signal is lost from the E-Stop, the vehicle ceases to function until a signal is re-established.

- The speed of the vehicle is limited mechanically to around 7 miles per hour. Additionally the software limits the acceleration of the vehicle during operation.

- Feedback from the control panel allows the operator to know through text and through lights which mode is currently selected and whether the E-Stop is enabled or not.

7 Performance Summary

	Speed	Battery Life	Max Max Incline	Avg. Obstacle Detection	Waypoint Accuracy	E-Stop Range
Predicted Performance	9 mph	2 hrs	22°	15 ft	± 3 ft	5 mi
Actual Performance	7.0 mph	2 hrs	<10°	25 ft	± 2.5 ft	<3 mi

Figure 11: Performance Chart.

8 Testing

8.1 Testing Process

The testing process for our vehicle begins in the design phase of our vehicle wherein the constraints of each subsystem are tested in simulation; the total output of our drivetrain under the estimated weight of the final vehicle under different conditions is tabulated, the different electronic components can be simulated virtually, and the navigation subsystems can be tested with fake sensory information. Unit testing is done periodically when each component is finished by using stubs for software testing, computer interfacing with electronic components, and running the drivetrain under controlled conditions. Subsystem testing is then used when many components are finished via simulating different conditions by creating fake sensory information for the other subsystems; for software subsystems that means using archived data from previous years' competitions, for electronic subsystems that means interfacing with incomplete subsystems and slowly increasing the functionality of each subsystem, and for mechanical subsystems that means testing the vehicle with its full weight and in different conditions. Integration testing follows and is the last remaining step before the vehicle is ready to compete.

8.2 Testing Results

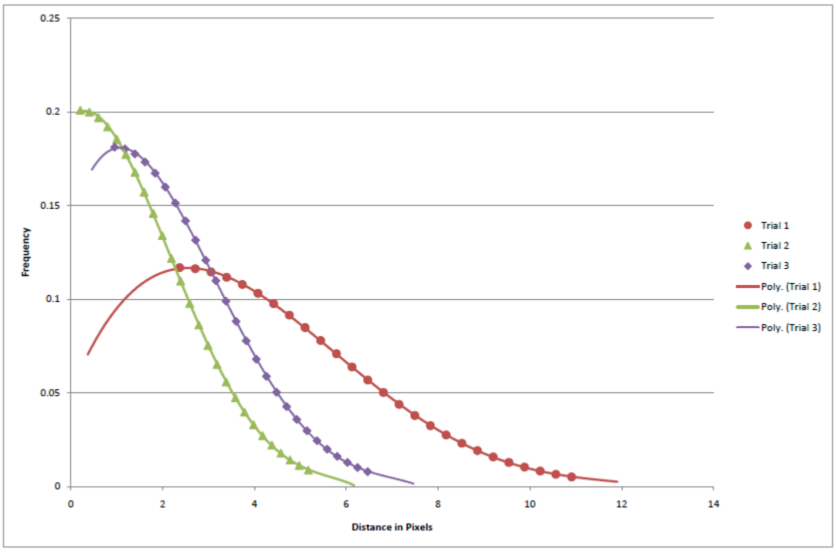


Figure 12: This graph which shows three different trials while using our line detection algorithm. Displayed is the frequencies of distances in pixels that each detected line was set apart from an actual line in the image. Our line detection algorithm consistently detects lines with only an error of a few pixels.

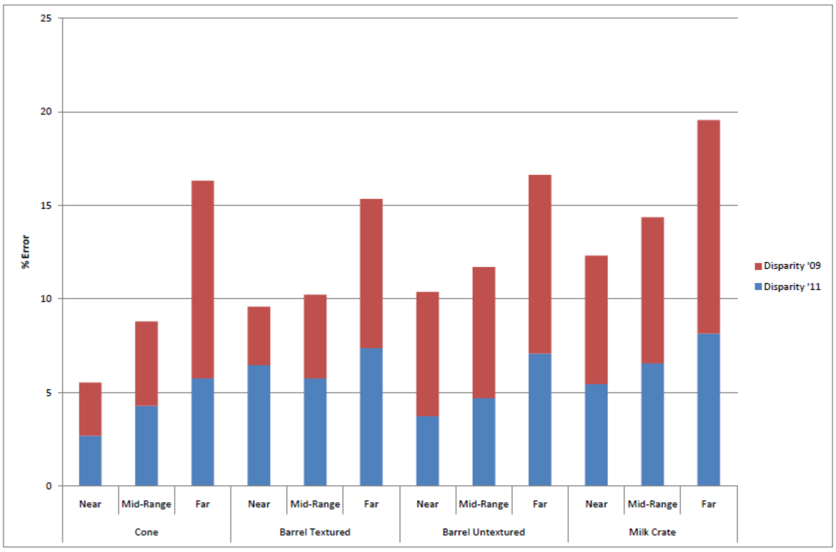


Figure 13: Testing results from object detection at distances of near (0.2-1 meters), mid-range (1-1.75 meters) and far (1.75-2.5 meters).

9 Cost

Component	Type	Retail Cost
Batteries	Lead-Acid	$500
GPS	Hemisphere	$1600
Camera	Bumblebee	$2000
Gears, Sprockets, Wheels, and Chains		$700
Raw Materials (Aluminum, Steel, and Plastic)		$800
Electronic Components and Wire		$1150
Motors		$1100
Remote Control		$350
Wheel Encoders	Shaft	$750
Computer Parts		$1320
Total		$10270

Figure 14: Cost Summary

10 Conclusion

Enyo is an exceptional vehicle not only because of its functionality and durability, but because it is a vehicle who's design is continually being updated. The design of Enyo this year reflects the mistakes that our team has fixed from past designs. Competing at IGVC allows our team to learn about the engineering method and its application to real-world problems, how to problem solve, and has been a positive reinforcement of lessons learned in the classroom. Each year lessons from past years are handed down to a new generation of engineers and because Enyo is built on such a robust and variable chassis, elements of past designs can be changed or replaced without requiring a complete re-design of the entire vehicle. The modular properties of our electronic systems allow new members to suggest modifications to particular components without having to change the functional design of the whole system. With the software framework that is the basis of most of our code, components can remain in-place and can be swapped out without any extra work. Enyo is a well-engineered vehicle and we hope that this report has been helpful in understanding its design and construction.