UIC UNIVERSITY OF ILLINOIS AT CHICAGO

ENYO

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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.

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1 Introduction

Enyo is a fully autonomous robot designed and built by the Engineering Design Team at the University of Illinois at Chicago for the Intelligent Ground Vehicle Competition. Enyo is named after an ancient Greek goddess of war. This report details the design process, predicted performance, mechanical, electrical, and software components of Enyo.

2 Design Process

An elaborate design procedure was used during Enyo's development that emphasized teamwork and communication. There were three main teams that worked together to build Enyo; a mechanical engineering team, an electrical engineering team, and a software team. All of these teams were in constant communication to ensure that all systems integrated with the robot without problems. The development team followed a waterfall design process consisting of four steps to minimize problems during construction. The first step consisted of all team members creating a document listing all of the requirements for each of Enyo's systems. Secondly, the team wrote a series of design documents that described how each of Enyo's components and systems would be built. These first two steps of the design process provided the team with a holistic understanding of the functions of the robots and the components required for full robot operation. The design documentation allowed others to review designs and identify mistakes before buying parts and committing to a design. The third step involved the actual construction of the robot and the fourth step was testing and debugging. Malfunctioning systems discovered during testing are then corrected and integrated into the robot.

3 Innovation

Enyo contains many innovations designed to increase reliability, efficiency, and user convenience. One innovation was to efficiently use battery power. To accomplish this, we utilized switching voltage regulators to power the electronics. The entire robot is also weather proof and can operate reliably in rain, snow, and high winds. Portions of the chassis are constructed out of aluminum T-slot for rapid assembly and modification. Additionally, Enyo has a centralized control panel that displays status and function information about the robot to the user and aids in troubleshooting during robot operation. These innovations are discussed in further detail in their respective sections.

4 Mechanical Design

The mechanical aspects of Enyo are designed to be rugged, reliable, and efficient. This is achieved by designing and building to high tolerances and giving attention to detail. All parts have been machined within a few thousandths of an inch using a milling machine. This ensures that the entire assembly fits together nicely and does not compromise structural strength. A detailed description of the mechanical design concepts is provided within this section.

4.1 Chassis

Enyo’s custom built chassis consists of two distinct sections; one lower section for the drivetrain and one upper section to store the computers, batteries, and payload. The drivetrain section is composed of steel tubing welded together making it strong enough to carry the full weight of the robot without itself being very heavy (Figure 1). The chassis has a ground clearance of 9.75 inches, allowing it to clear small obstacles and go over inclines of up to 30 degrees. The payload chassis section is made from aluminum T-slot to reduce weight while still maintaining a significant amount of structural strength. The T- slot also allows for a flexible design since the top chassis can be disassembled, modified, and reassembled quickly without welding or drilling. The main advantage to having separated sections is to allow the robot to accommodate future design changes. This dual section design significantly reduces the amount of effort and resources needed to change a design and is the most economical choice for our robot.

4.2 Component Mounting

Component mounting is simple due to the use of aluminum T-slot for the upper chassis. The computer case, generator, and batteries all have mounts attached to the T-slot frame. These mounts slide along their T-slot tracks and allow for the component to be easily secured (Figure 1). This is more ergonomic for users since the mounts can be slid to a location in order to create space for easy component mounting and then slid back into place to secure the component. This allows for efficient mounting and removal of components by minimizing user strain. Additionally, the positions of the heavy components were carefully selected to ensure that the robot's center of gravity is in the middle of the robot, dimensionally, and as close to the ground as possible. This improves vehicle handling and prevents the robot from tipping over while traversing inclines.

4.3 Drivetrain

The drivetrain consists of a four wheel differential setup chosen for easy control by the software. One motor provides power to two wheels on the left side of the robot and the other motor powers the other two wheels on the right (Figure 1). This setup, designed specifically for IGVC, allows better stability and a zero turn radius, while also reducing the mechanical complexity. This system is easy to control since Enyo does not have to move forward to turn, nor is there any need to control a steering system. The reduced mechanical complexity and ease of control contribute to higher reliability since there are fewer components that can fail or need monitoring. The drivetrain is geared to allow a maximum speed of 4.8 miles per hour, which is under the 5 mile per hour limit as required in the competition rules. All of the chains are lubricated with oil to reduce friction and inhibit corrosion, giving reliable and efficient operation of the drivetrain.

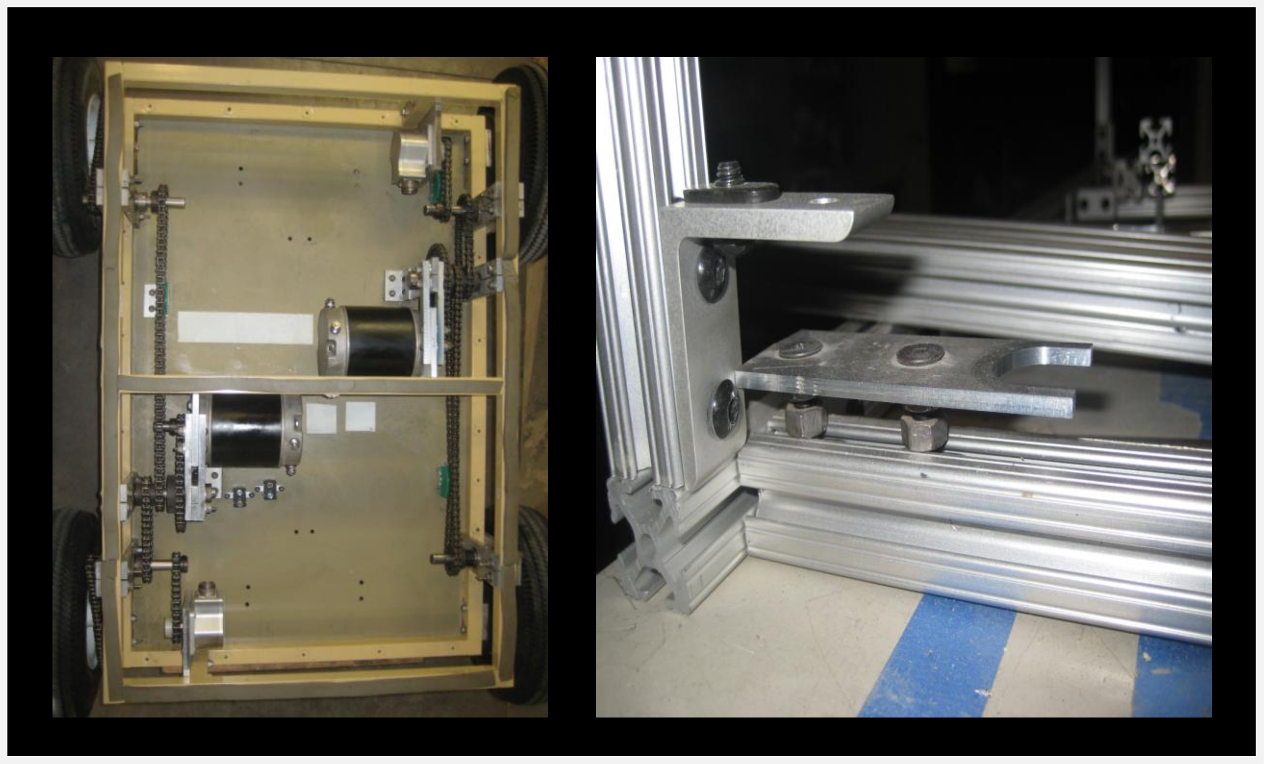


Figure 1: Selected Components of the Mechanical Design. *Left* - Image of the drivetrain section of the chassis depicting differential drive. *Right* - Mount point on the Aluminum T-Slot used for component mounting.

4.4 Vibration Resistance

Enyo contains many features to reduce the impact of vibrations on performance. It uses rubber air filled tires to absorb a significant amount of vibrations that occur as the robot drives on uneven surfaces. A layer of shock absorbing foam lies between the two sections of the chassis to prevent the spread of harmful vibrations throughout the robot. The onboard generator produces a substantial amount of vibration and these vibrations are reduced by placing rubber contacts between the generator and the chassis. These vibration reduction techniques increase reliability by attenuating the negative effects of vibrations.

4.5 Cooling

The cooling system is designed to efficiently remove the large amount of heat produced by the computers, generator, and electronics. Enyo is primarily air-cooled and cooling fans are positioned throughout the robot to direct airflow over the heat producing systems. The system has a negative airflow design, where the outtake fans expel more air than the intake fans bring in. This prevents hot air from remaining inside the robot and compromising system operation.

4.6 Exterior Casing

An elaborate system protects Enyo from the elements while still allowing airflow through the robot. One-fourth inch thick polycarbonate encases the entire robot and protects it from external impacts, dust, and water. Polycarbonate was chosen for its light weight, very high strength, and low cost. Cork lines the side edges around Enyo to prevent water from seeping in. The exterior casing is easy to open as the side and rear panels open vertically in a motion most similar to the trunk of a minivan. This allows quick, unrestricted access to the internal robot in cases where repair or modification is needed. Air vents are utilized by slanting them downwards to stop rain from entering the chassis. Furthermore, all of the air vents contain filters to stop dust and objects from entering the robot without impeding airflow needed for robot cooling. These mechanisms, collectively, allow Enyo to operate reliably in harsh environments without risking damage to the robot. The exterior is painted with a pixilated camouflage pattern for both appearance and to block sunlight to keep the robot from unnecessary heating.

5 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 modular design. Furthermore, all microcontroller systems enter into an idle mode when they are not being used, thereby reducing power consumption and increasing efficiency. A workflow diagram is presented in Figure 2 that summarizes the electrical system organization for the robot. The following sections highlight the electrical components of Enyo and how they uphold these tenets.

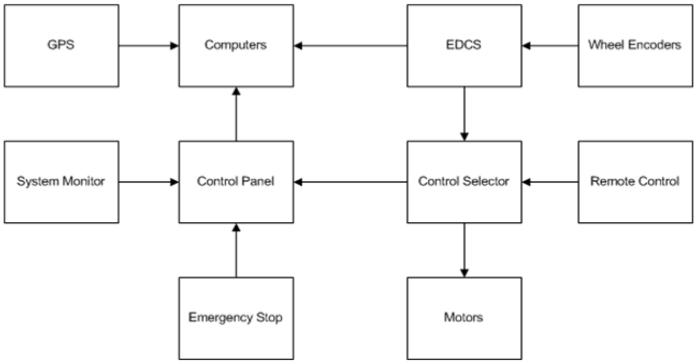


Figure 2: Condensed Electrical Organization.

5.1 Power System

A diverse and innovative system consisting of two main components powers Enyo. The first component is a set of eight 12 Volt, 26 Amp-hour, sealed lead acid batteries that are used to power the motors and embedded electronics; both which require DC power. Two of the batteries are arranged in parallel to form a 12V system and power the electronic systems. The remaining six batteries are arranged in a 2x3 array, configured in series, to provide a 24V system to the motors (Figure 3). By having many batteries, current is divided between them and the current in each individual battery is reduced. This reduces stress on each battery and results in substantially longer running time. The second power component is a 2000 Watt gasoline generator that powers the computers and non-critical electronics. The generator can power Enyo for a minimum of four hours under full load and is capable of powering external components such as monitors and power tools. In addition, to operate Enyo indoors,

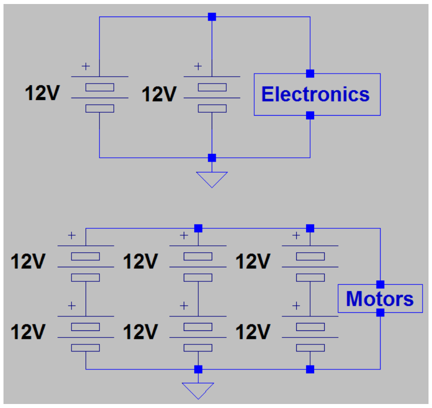


Figure 3: Battery Configuration

the robot may be plugged into a wall outlet and all systems powered by the generator will instead be automatically powered with mains electrical system.

5.2 Power Control and Distribution

All the electrical components on Enyo are powered by different methods according to their power needs. Electronics consume the least amount of power and require a supply voltage of 5V or lower. This voltage is provided by the 12V battery system through an array of 5V switching voltage regulators with each electronic system having its own dedicated regulator. Switching regulators were chosen instead of the more conventional linear regulators due to their higher efficiency. Switching regulators are approximately twice as efficient as linear regulators, translating into lower power consumption and longer battery life. Fans and headlights belong to the medium power category and are powered through switching DC power supplies, again used for their efficiency. The DC power supplies convert 110V AC, from either the generator or the wall, to 5V for the headlights, and 12V for the fans. AC power is used to avoid draining the batteries when using the medium power devices. The two 3 horsepower drive motors are the highest power consuming devices and are connected to the 24V battery system through Victor 883 motor controllers. The motor controllers control the amount of power sent to each motor based on signals from the electronic systems. Furthermore, circuit breakers are placed in series with each of the motors to prevent excessive current flow and ensure safe operation. The circuit breakers are of the auto-reset variety, allowing them to reset within a few seconds after they are tripped without any human intervention. The wiring system is also designed to reduce electrical losses and promote efficiency by using appropriate sized wires. The robot uses AWG 10 gauge copper wire for high current applications to reduce the voltage drop within the wire. All power cables are organized with terminal blocks for easy handling and routing. For better organization, wires that travel between the same components are bundled together with wire braiding.

5.3 Emergency Stop

The emergency stop system (E-stop) is a system designed to stop the robot quickly in the case of emergencies. The user may activate the E-stop in two ways, either by a wireless remote control or by pressing an onboard switch. The E-stop is composed of two modules: a handheld transmitter unit that wirelessly transmits a signal to the robot (Figure 4) and a receiver unit onboard the robot that receives the signal from the transmitter and

Figure 4: Wireless E-Stop Transmitter

is responsible for cutting power to the motors. The receiver unit also monitors the onboard switch to determine whether to activate the E-stop. The transmitter unit has a red push-button switch that when pressed, activates the E-stop. The E-stop functions if either the onboard switch or the wireless transmitter sends the STOP command, in which case the robot will stop moving. The robot will resume movement only when both sources, the onboard switch and wireless transmitter, provide a GO signal. The main components of both units are a microcontroller and a radio module. 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, which is substantially greater than the range of 50 feet required by the official rules. The E-stop transmitter operates by continuously sending a signal to the receiver module through the radio module. The receiver radio module gets the signal and, based on the received signal and the state of the onboard switch, decides whether to cut power to the motors and stop the robot. The E-stop cuts the power by deactivating a relay that is in series with the motors. Additionally, the E-stop can recognize a lost connection between the transmitter and receiver, in which case, it stops the robot as a safety precaution until the connection is restored. The E-stop is able to stop the robot in less than half a second from activation.

5.4 Embedded Drive Train Control System (EDCS)

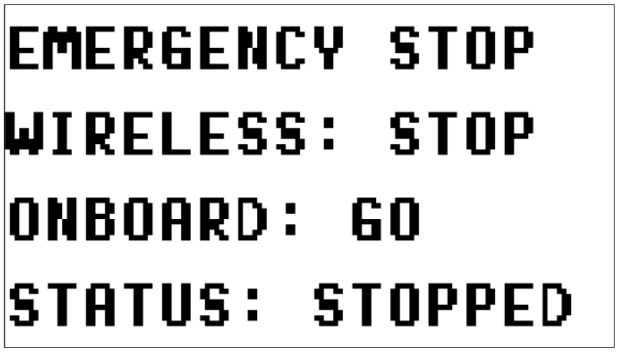
The EDCS is a system designed to interface the software controls system to the motors that drive the robot. The system consists of a module for each side of the robot. Each module is responsible for measuring the wheel speed and controlling the power level of the motor for its side. A microcontroller 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 detect communication errors inherently, leading to improved system reliability and safer operation. Each module measures the wheel speed of its respective side with a shaft encoder. The encoder produces two pulse trains with frequencies linearly dependent on wheel speed. The encoder sends the two pulse trains to the microcontroller, which then determines the wheel speed and direction of rotation. The microcontroller sends this data to the software control system through the serial communication interface. Each module also continuously listens for commands from the computers to change the amount of power supplied to the motor and sends this data to the Control Selector.

5.5 Control Selector

The Control Selector allows the user to choose how Enyo is controlled. This system has four modes of operation that are selectable by the user. The default mode is a safety mode that keeps the robot stationary. This ensures safety since Enyo will not move unless the user intentionally allows it. The second mode has the robot autonomously controlled. The third mode places the robot under remote control. The final mode allows the robot to switch between autonomous and radio control by pressing a button on the remote control. This feature is important since it can restore control to a human if the robot malfunctions and act as a backup E-stop. In addition, if the signal from the remote control is lost and the robot is not under autonomous control, the robot enters safety mode to prevent unsafe operation.

5.6 Control Panel

Enyo's Control Panel monitors and manages all of the electronic systems on the robot and acts as the liaison between the software and hardware on the robot. The Control Panel interfaces with every electronic system on the robot through the I^2C interface, allowing it to send commands and receive data. The secondary function of the Control Panel is to gather status information from the other electronic systems and forward the information to both the user and the computers (Figure 5). This greatly increases robot reliability and safety since the software is notified of errors and can correct them. The user can adjust settings for the Control Selector, cooling fans, and headlights by using buttons located on the Control Panel. The Control Panel also includes four power outlets directly from the generator and can power external devices such as computer monitors and lights. There is an AC power receptacle on the Control Panel that can draw power from the wall outlet, allowing robot operation without the generator. Other features include ports for connecting monitors, keyboards, and mice to the internal computers.



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EMERGENCY STOP
WIRELESS: STOP
ONBOARD: GO
STATUS: STOPPED
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Figure 5: Sample Control Panel Display

5.7 System Monitor

The System Monitor is responsible for monitoring the systems of the robot and detecting malfunctions. If malfunctions occur, the System Monitor notifies the Control Panel, which in turn notifies the software and the user. With knowledge of the malfunction, corrective action can be taken, enabling safer operation of the robot. 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 12V and 24V systems. The first warning is issued when the battery levels are starting to run low and it is recommended to change the batteries soon. The second warning occurs when the battery levels are critically low and it is no longer safe to operate the vehicle. Another warning is presented whenever a motor loses power, allowing the software to pause shortly until power is restored and prevent erratic and dangerous operation. With these warnings, the user or software can correct faults so that the robot can run in the safest manner possible.

5.8 Accessories

Enyo has several accessory items including cooling fans, headlights, and internal lighting. These devices are not necessary for the general operation of the robot but increase functionality and ease of use. The fans increase air circulation inside the chassis to better cool the computers, allowing Enyo to run reliably in a relatively hot environment. The headlights are composed of efficient high intensity LED's and is evenly projected in front of the robot, permitting the robot to operate at night or in low light environments. Enyo’s internal lighting consists of the same LED’s used for the headlights but directed inwards to allow crews to see inside the robot while conducting repairs. The headlights and cooling fans are powered by the generator since they are only needed while the computers are on and the internal lighting is battery powered to allow illumination whenever needed.

5.9 Computer Systems

The robot contains two computers to allow parallel execution of the software and increase performance (Figure 6). The different components of the software are spread out evenly between the two computers in order to use the available hardware efficiently. Each computer uses the Intel Core 2 Quad Q8200 CPU, giving excellent performance because a quad core processor allows four different software components to run concurrently on each computer. The computer running the vision system uses an ATI Radeon HD 4870 X2 video card. The other computer has a NVIDIA Ge-Force 9800GTX+ video card to run the disparity map algorithm. Each computer has an 800 watt power supply to meet the high GPU and CPU power requirements. Both computers have 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. Each computer has an 80 GB laptop hard drive to store data. Laptop hard drives were chosen for their resistance to vibration damage during robot operation. Each computer uses the Ubuntu Linux operating system to run the robotics software.

Figure 6: Enyo Computer Systems

6 Software

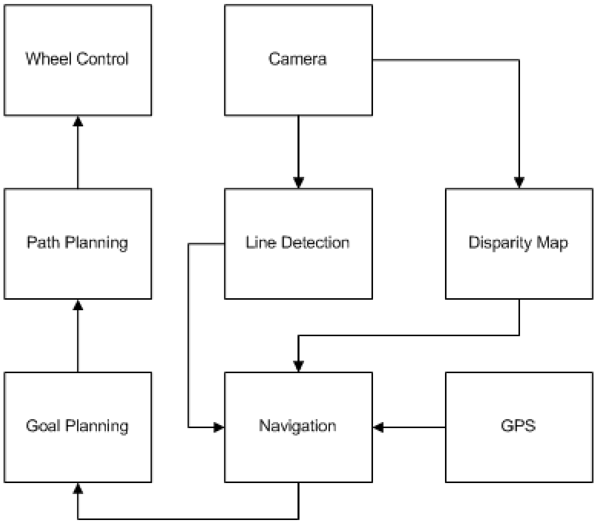

Figure 7: Condensed Software Organization

The software running within Enyo controls the robot's every move. With the large amount of computing power in Enyo, the software can be much more accurate compared to other robots. The power of two high-end desktop computers allows Enyo to implement complicated localization and path planning algorithms that provide better accuracy. Enyo's software architecture takes the form of multiple components that run independently in parallel, allowing the most amount of processing to take place in a given period (Figure 7). This advantage lets Enyo react faster and accurately determine its surroundings to travel along the optimal path to its destination. The various software components communicate with each other using the Orca Robotics framework and are written in C++ to efficiently use the computer resources. The software components run on the Ubuntu Linux operating system and are distributed between the two computers to achieve maximum data execution speed.

6.1 Line Detection

The Line Detection component identifies lines on the course by exploiting the small range of colors that constitute the lines. The component analyzes every pixel in the camera image and determines the likelihood that the pixel is reflective of a line. In essence, the algorithm calculates how close the pixel is to being gray, and discards pixels that have too much color or are too dark. This leaves only pixels that are close to being white. The result of this process is a grayscale image that represents the lines of the course which the Line Detection component then sends to the navigation component (Figure 8 - *Left*). This algorithm has two main benefits compared to other approaches. First, due to its simplicity, this algorithm runs very quickly, allowing the robot to respond swiftly to the external environment. Secondly, this algorithm is extremely consistent in its behavior and is not easily confused by noisy camera images, thus increasing robot reliability.

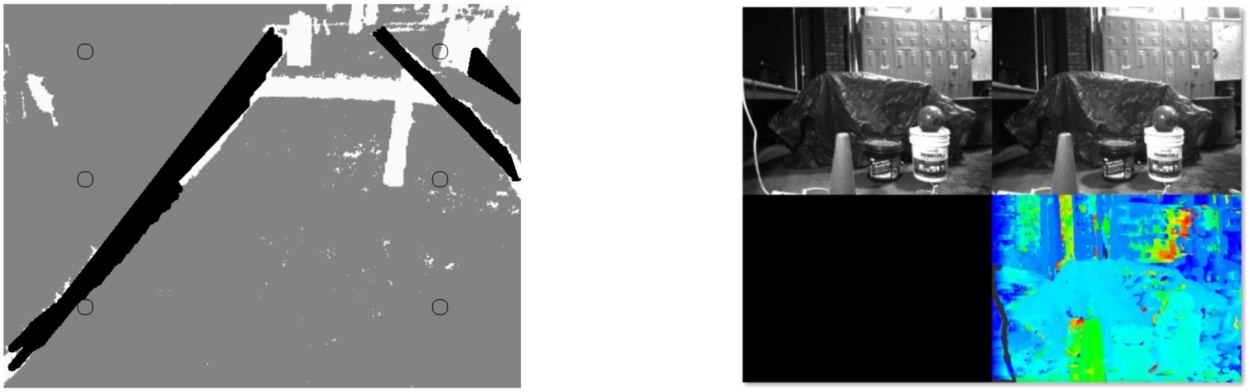

Figure 8: Image processing using Line Detection and Disparity Map. *Left* - Line Detection output. *Right* - Disparity Map input and output.

6.2 Disparity Map

The Disparity Map component forms the heart of Enyo's image processing system and determines the location of objects in the robot's field of view. Conventional disparity algorithms are very processor intensive and do not allow the processor sufficient time to perform other needed tasks. To relieve the CPU from this intensive task, the Disparity Map runs on the video card's GPU, thereby freeing the processor to perform other tasks. Two cameras, placed next to each other, each take a picture of the environment and send them to the Disparity Map. The two images are slightly different from each other since they are from two different positions and the Disparity Map identifies differences between the images. These differences are then used with parallax to find the locations of objects (Figure 8 - *Right*). The locations of these objects are sent to the navigation component. Conceptually, a GPU implementation is similar to one that would utilize the CPU, but the GPU is better for such a task because it has a large amount of stream processors designed to process many pixels simultaneously. Rather than computing the disparity of each pixel one at a time (as with a CPU implementation), the GPU can compute the disparity of the whole image at once, speeding up image processing and increasing the computational throughput of the robot.

6.3 Navigation

Enyo's navigation component utilizes the simultaneous localization and mapping (SLAM) algorithm to determine the location, orientation, and environment of the robot. SLAM is a probabilistic algorithm that allows data from multiple sources to be integrated and provides very accurate results. Enyo's implementation of SLAM takes in data from the GPS unit, Line Detection, Disparity Map, and the wheel encoders. Navigation receives the data from Line Detection and Disparity Map in the form of an occupancy grid, which contains the locations of the lines and obstacles on the course. Three possible robot positions are calculated with each position being determined by only one data source. First, Enyo's position is calculated based only on the wheel encoder data. Similarly, the component forms a second possible robot position with data from the GPS unit. A third possible robot location is found by first generating a list of landmarks from the occupancy grid and using the vision software to determine the robot's position relative to the landmarks. The SLAM algorithm then determines the center point between the three possible positions and records it as Enyo's most likely position. The component finds the orientation of the robot in a similar fashion and the orientation and position values are sent to the Goal Planning and Path Planning components for further processing.

6.4 Goal Planning

The Goal Planner component decides the next location the robot should move towards and is based on the robots current position and whether the robot is in the autonomous challenge, navigation challenge, or simply qualifying. To navigate through the course, the software sets many objectives that are close to each other so that the robot can move to these goals in succession to reach its final destination. Goal Planner looks at two main factors while determining the next short-term goal for the robot. One factor is the direction that the robot is facing and Goal Planner tries to set a goal that is in front of the robot. This encourages the robot to move forward through the course while also preventing the robot from driving blindly. The other factor utilized by Goal Planner to determine a goal is the position and layout of the lines on the course, since the lines indicate which direction the robot must go to progress through the course. Based on these two determining factors, Goal Planner calculates the best place for the robot to go and passes this data to the Path Planner component.

6.5 Path Planning

The Path Planner component generates a path for the robot to follow in order to get to its next destination based on its current goal and surrounding environment. This is accomplished by employing the Visibility Roadmap algorithm. Goal Planner sends Path Planner a destination and Path Planner calculates a path to the destination based on the robot's current position and surrounding environment.

The surrounding environment is modeled as an occupancy grid in which the Disparity Map and Line Detection components have indicated the location of lines and objects. If a path to the target location cannot be found, Path Planner will instead calculate a path that leads the robot as close to the target as possible. The path to the goal is determined by recursively considering possible paths through openings between obstacles and lines that the robot can pass through. The software first identifies openings close to the robot. It then looks for more openings on the other side of these openings, continuing this process until it finds a path to the target. In addition, the software discards longer paths when a shorter one has been found to further reduce the number of paths to consider, lowering the total time required to plan a path. Overall, the algorithm is faster than most other methods because the component does not analyze every point on the occupancy grid as a possible location for the next waypoint and only analyzes each opening once. Path Planner then sends the calculated path to the Wheel Control component, which in turn moves the robot.

6.6 Wheel Control

Wheel Control is a low-level component responsible for generating the commands that move the robot. High-level components send Wheel Control a series of waypoints that Enyo must travel to. Wheel Control then calculates the amount of power each motor should receive in order to drive to each waypoint. The component then instructs the robot to move by communicating directly with the EDCS and specifying the amount of power to provide each motor. In addition, Wheel Control uses wheel encoder data from the EDCS to correct any deviations in Enyo's path and forwards the wheel encoder data to the Navigation component to better gauge the robot's position.

7 Predicted Performance

Rigorous calculations have provided the following performance predictions though empirical observation.

Robot Characteristic	Predicted Performance
Maximum Speed	4.8 miles per hour
Maximum Hill Climbing Angle	22°
Reaction Time	300 milliseconds
Battery Life	4 hours
Object Detection Distance	20 feet
Waypoint Arrival Accuracy	Within 60 cm

8 Cost Analysis

A list consisting of Enyo's components and their respective parts. The parts that belong to a single component are grouped together for brevity.

Component	Cost
Computer parts	$2000
Generator	$1000
Batteries	$500
Camera	$2000
Gears, Sprockets, Wheels, and Chains	$700
Electronic Components and Wire	$900
Raw Materials (Aluminum, Steel, and Plastic)	$800
Motors	$1100
GPS System	$1600
E-stop Radio	$250
Remote Control System	$350
Wheel Encoders	$750
Total	**$11,950**