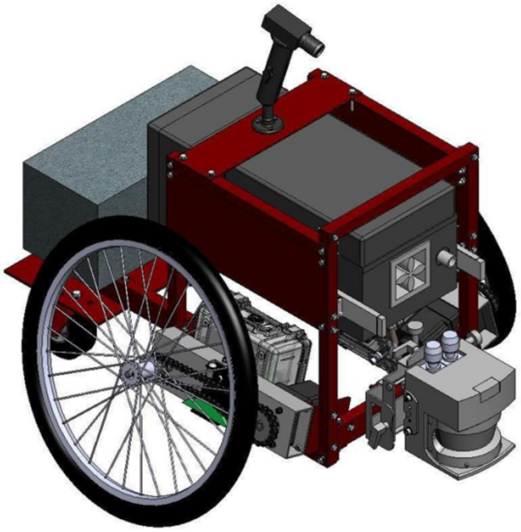
Cornell University
Cornell MineSweeper
Vehicle Design Report



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Amphenol

Faculty Advisor Statement
I certify that the engineering design of the robot Nero, described in this report has been significant and equivalent to what might be awarded credit in a senior design course.

E.G.

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Department of Mechanical and Aerospace Engineering, Cornell University

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1 Introduction

Cornell Minesweeper (CMS) project was founded in 2006 to develop an autonomous vehicle that can accurately detect land mines and facilitate their clearance. To validate the design of the autonomous platform on which the mine detection sensors will be mounted, we present Nero, Cornell University's first entry at the International Ground Vehicle Competition (IGVC).

Cornell Minesweeper follows a revolutionary student team structure in that it is completely flat, featuring no sub team leaders for each division. This leads to greater responsibility and participation from all team members, regardless of experience. The team consists of 32 undergraduate and 3 graduate students, split into three main divisions during Phase I: production, finance and marketing, and the support division. As production of Nero wraps up, the team transitions to Phase II, breaking up into Competition Staff, Next Gen Division and the Support Staff.

Nero is IP65 rated, lightweight and modular in design and features a zero-point turn capability. It was designed and built entirely in-house by Cornell engineering undergraduates.

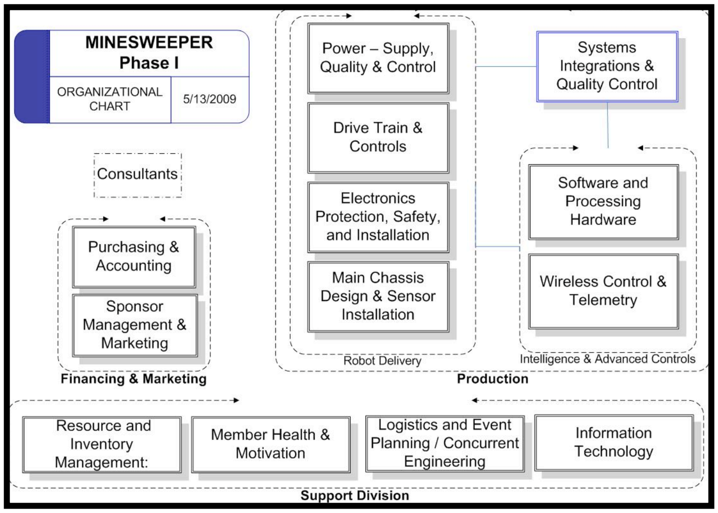

MINESWEEPER Phase I
ORGANIZATIONAL CHART
5/13/2009
Consultants
Purchasing & Accounting
Sponsor Management & Marketing
Financing & Marketing
Power – Supply, Quality & Control
Drive Train & Controls
Electronics Protection, Safety, and Installation
Main Chassis Design & Sensor Installation
Robot Delivery
Systems Integrations & Quality Control
Software and Processing Hardware
Wireless Control & Telemetry
Intelligence & Advanced Controls
Production
Resource and Inventory Management:
Member Health & Motivation
Logistics and Event Planning / Concurrent Engineering
Information Technology
Support Division

Figure 1: Phase I Organizational Chart

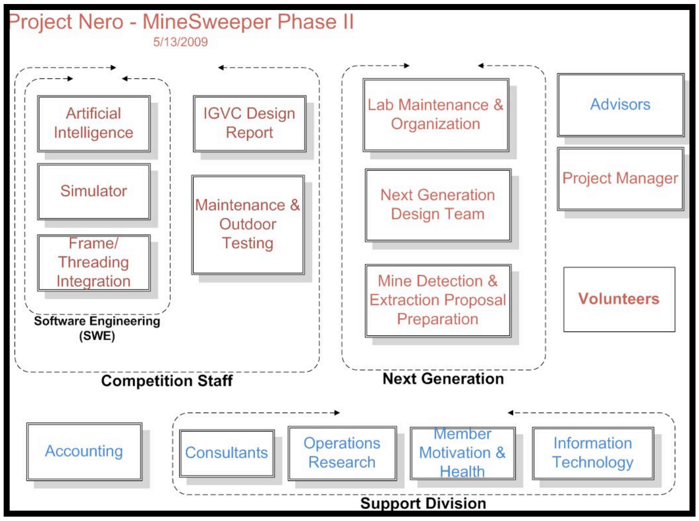

Project Nero - MineSweeper Phase II
5/13/2009
Artificial Intelligence
Simulator
Frame/ Threading Integration
Software Engineering (SWE)
IGVC Design Report
Maintenance & Outdoor Testing
Competition Staff
Lab Maintenance & Organization
Next Generation Design Team
Mine Detection & Extraction Proposal Preparation
Next Generation
Advisors
Project Manager
Volunteers
Accounting
Consultants
Operations Research
Member Motivation & Health
Information Technology
Support Division

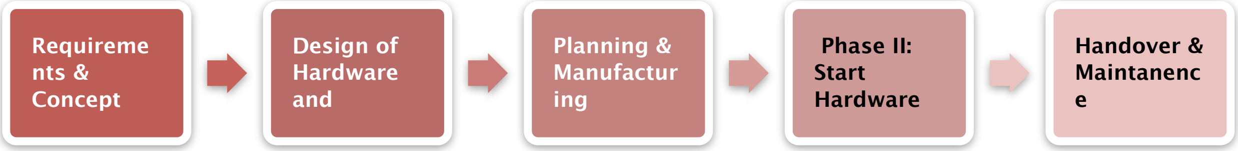
Figure 2: Phase II Organizational Chart

2 Design Process

The philosophy of the applied Systems Engineering (SE) process is "Design for Quality, Reliability and Manufacturing," each of which are capabilities. Quality is internally measured by meeting the requirements, reliability by having no hardware failures, and manufacturing by reduced manufacturing time and labor intensity. Each of these resulted in defining modularity, establishing a highly Commercial Off-the-Shelf (COTS) and lean engineering approach in systems design, and applying very simple reliability engineering techniques. The project is divided into two phases: the platform delivery (Phase I) and the software delivery (Phase II). Phase II for hardware manufacturing can be thought of as a subset of Phase I.

Figure 3: Phase I Waterfall Model Applied with Control Documents. Refer to Phase I Organization

Each phase possesses a process model, a timeline or calendar, control documents and an associated organization.



Control is exerted by following the calendar, monitoring the information system weekly, project reporting, and applying the control documents as constraints.

Top level requirements were defined by Software Engineering (SWE) and derived requirements were developed by each of the subgroups (which included the project staff i.e. support). Once we reached hardware testing & unplanned events stage, we redefined the Interface Control Document (ICD), and as new requirements were developed, they were implemented in the Verification Cross-Reference Matrix (VCRM). A testing method (as the VCRM implies) was assigned and applied for each of the requirements based on the SE philosophy of "testing tests the requirements."

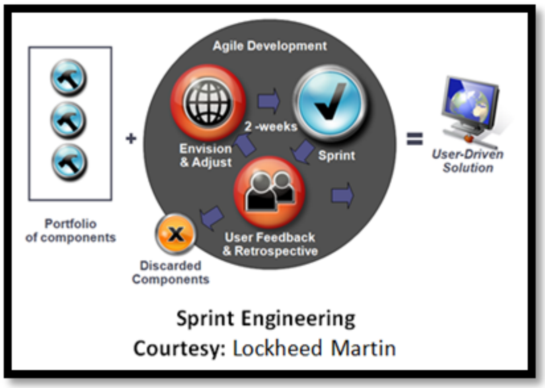


Figure 4: Phase II Sprint/Agile Engineering for Unplanned Testing & Software Engineering

2.1 Design Objective & Requirements Development

Concept Selection and Requirements Development was the primary step in our process, and was given extensive attention to develop effective design objectives:

1. Turnover Cycle of 1 year
2. Modular in design
3. Comply with IGVC qualification requirements
4. Support a 20 lb payload
5. Apply COTS approach to software design
6. Zero point turn capability
7. Traverse 15% incline from static position.
8. Weigh Less than 60 kg
9. Battery Life of at least an hour
10. System IP65 Rated
11. Maximize Hardware Reliability via COTS, Risk Assessment, and reduced parts.
12. Compile consistent documentation
13. Design Hardware for Software requirements
14. Design Software Framework for continued improvement & changing requirements

These design objectives were established with our entire team staff after reviewing the IGVC rulebook, past videos and reports, and the recommendations of professors. Objectives 1,2,5 and 11 were objectives established by the systems engineer to ensure project success. Objectives 3,4,6,7 and 9 were required by the software engineers (customer) to ensure mission success and software design competency. Objectives 8, 10, 12, 13 and 14 were established by the systems engineer and Professors to ensure hardware design competency, which is demonstrated.

Requirements were developed by each subgroup according to the following categories for their respective subsystems and were frozen during design freeze prior to production:

1. Overall System Requirements
2. Functional Requirements
3. Performance Requirements
4. Design Requirements
5. Derived Requirements
6. Interface Requirements
7. Verification Requirements
8. Environmental Requirements
9. Non-behavioral Requirements
10. Component Requirements

Additional requirements after the design freeze were constrained by IGVC compliance requirements, software requirements and subsystem hardware interfacing requirements. Since requirements development is the backbone of SE thinking, strict "shall" grammar was enforced. An example of an interfacing requirement: "Power shall supply 24 V at 200 W each in 2 black and 2 red 20 AWG Teflon coated wires over an Amphenol D-Sub circular connector with 4 pins". This would be supplemented by other requirements. For a requirement to be valid, it must be unambiguous, isolated, concise, measurable, unique and consistent with respect to all other requirements.

3 Hardware

As highlighted before by the organizational chart, the production division of Minesweeper was broken up into 5 main groups: Chassis, Drive Train and Controls, Power and Quality Control, Electronics Protection and Safety, and Software and Hardware Processing. The goal of these subgroups was to be cross-disciplinary, drawing expertise from different fields to create the best design. While the different subsystems were developed independently, communication and integration between sub-teams was a top priority, ensuring an effective overall design.

Table 1: Summary of Costs

Item	**Value**	**Cost to Team**
Microbotics MIDG-II INS	$7060.00	$0.00
Sick LMS291 LIDAR	$5137.00	$5137.00
MC-433 Camera	$350.00	$350.00
Drive Train	$1109.48	$1109.48
Chassis	$818.66	$818.66
Mini ITX	$529.93	$529.93
Wireless E-Stop	$85.00	$85.00
Mechanical E-Stop	$50.00	$50.00
Amphenol Connectors	$962.00	$0.00
Waterproof Connectors	$75.00	$75.00
Waterproof Cases	$140.00	$140.00
Battery	$869.95	$869.95
Power System Hardware	$560.00	$560.00
Total:	**$17,747.02**	**$9,725.02**

Beyond the fundamental requirements, the design emphasizes endurance, safety and reliability, organization, and modularity that separates Nero from other robots.

Throughout the design process, extensive use of the *SolidWorks*™ Computer Aided Drafting and Design tool was utilized in product visualization and troubleshooting. Every component from design to fabrication was drafted: aiding in fabrication, assembly and redesign every step of the way.

3.1 Innovations

While simplicity was an important design consideration, Nero's hardware boasts an impressive array of innovations that will set Nero apart in design and quality. Modularity of individual components is integrated throughout the entire system for versatility and increased functionality. The use of large bike wheels will enable Nero to traverse more challenging landscapes while tightly secured components down to the very last circuit board will decrease natural vibrations. Within the circuit, innovations in the circuit design provide an efficient and organized power distribution network which also allows E-Stop functionality to cut power only to the Drive Train components. The battery circuit also features a "hot-swap" capability to allow Nero to switch batteries without powering down. For maintenance purposes, Nero has a rail-system so that the electronics can slide out and be examined. Lastly, heat management within the electronics was handled with a hybrid system: IP54 fans circulating cool air within electronics case and a large heat sink, which radiates to the atmosphere through a "Swiss-cheese" pattern of holes, to cool the battery. These innovations mentioned here will be covered more in depth later in the report with respect to each section.

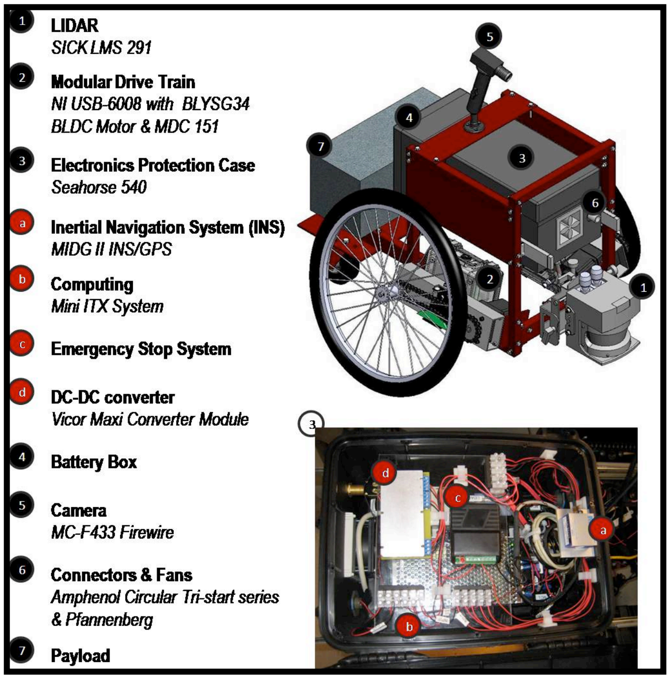


Figure 5: Overview of Nero and Sensors

3.2 Software and Hardware Processing

Table 2: Sensors Functionality

Part	**Description**
Computer [Kontron 986LCD-M/ mITX]	Processes the image, combines all available data to compute, and stores old data.
LIDAR [Sick LMS291]	Determines the distance from the nearest obstacles in a 180 degree range at different angles.
Camera [MC-F433 Firewire]	Takes pictures and performs basic preprocessing such as white balancing and scaling to detect lane lines, edges, and possibly other obstacles.
INS [Microbotics MIDG-II]	Obtains the current location of the robot in latitudinal and longitudinal coordinates and, if possible, calculates the confidence and height measures.
Motor Encoder	Calculates the current speed in revolutions per second.

The following sensors are selected and utilized in data processing: computer, LIDAR, camera, INS, and motor encoder. The function of each sensor is described in Table 2, and the location of each sensor is depicted in Figure 5.

3.3 Chassis

The general structure of Nero is broken up into a main chassis and a modular "pod," which serves as a balance point for the two wheels. The main chassis houses the electronics contained in two IP65 cases, the two drive train blocks, and the sensors including the camera mount.

Keeping in mind the principle of modularity, the payload is kept in the back away from the rest of the robot with the idea that it can easily be replaced in the future. This would ultimately lead to the ability to easily install a mine detection package while keeping the rest of the autonomous platform intact. The back pod is supported by two free-swiveling castor wheels, providing a relatively frictionless balance point for the two drive wheels.

Table 3: Mechanical Properties of Nero

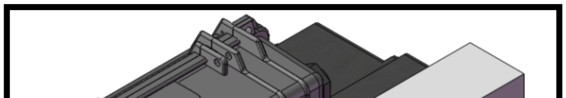
Property	**Specification**
Material	6061 Aluminum and 1018 Steel
Length	42.125 in
Width	39.50 in
Height	23.50 in (without camera mount)
Weight	45 kg
Ground Clearance	5 in
Payload Capacity	20 kg
Wheel Diameter	24 in
Drive Gear Reduction	75:1
Maximum Speed	4.86 mph
Speed on 15 ramp	2.5 mph
Torque required	43 N-m
Sprocket Reduction	10:17

3.4 Drive Train and Controls

3.4.1 Overview

The drive system consists of two identical units, referred to as "drive blocks." Each one turns a 24-inch bicycle wheel. The large diameter of the wheel gives us smooth performance over rough terrain, yet is lightweight. The drive blocks were designed to be simple, robust, and easily swappable. In the event of a drive train failure, a replacement block can be installed with simple tools in only a few minutes. The wheels can also be quickly interchanged. Currently there is only one set, but in the future, different wheels may be adapted for different conditions, and it will be easy to install the right one for the scenario.

Each block has a 220 W motor and gearbox combination. A pair of bearings supports the shaft of the bicycle wheel. The shafts of the motor and wheel are connected with sprockets and heavy chain. A tensioner unit



keeps the chain tight, and provides some shock absorption to protect the motor from abrupt loading. The motor driver and USB interface are housed in a waterproof case; there are connection points for power and for signal from the main computer.

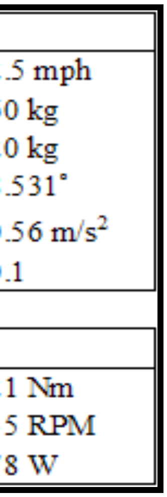
3.4.2 Motor & Gearing Selection

In order to find an appropriate motor, a worst-case design scenario from the competition was used. The most demanding situation for the motors is moving the vehicle up the ramp. Assuming that the vehicle starts with zero velocity at the bottom of the ramp, it must accelerate to some speed while climbing. The top speed and the rate of acceleration to that speed were taken as adjustable parameters, and required some adjustment to compromise between acceptable performance and reasonable power consumption. Fixed parameters included the projected weight of the robot, the distribution of weight, the angle of the ramp, and the friction from dragging the casters. Basic physics was then used to find the required torque and speed. A simplified version of the parameters and results of this calculation are shown in Table 4. Rather than being treated as a static calculation, this was used as a tool; the inputs and assumptions were changed to meet requirements of the various subgroups before settling on a final result.

Figure 6: CAD Model of a Drive Block

We selected a brushless 24V tri-phase motor from Anaheim Automation. In addition to its specifications, it was easy for us to implement this product, because the company sells a matching motor controller and 75:1 gearbox. The controller provided closed-loop feedback control and a variety of safety features. This greatly simplified the task of interfacing with the motor. The only modification was to add thermisters to monitor the temperature of the motor and driver, to ensure that neither would overheat.

Table 4: Performance Parameters and Results



.5 mph
0 kg
0 kg
.531°
.56 m/s^2
.1
1 Nm
5 RPM
8 W

To select an appropriate gear reduction for the motor, the factor of safety was calculated for a range of values. The motor performance was modeled using a linear fit between the no-load speed and the stall torque. The factor of safety was found using both the projected speed and torque. Graphing the minimum from each set yields a clear peak, as the left hand side is dominated by the speed requirement and the right hand side the torque requirement. It is important to note that the 75:1 gearbox and motor combination actually has a lower speed than is

Figure 7: Factor of Safety for Various Reductions

necessary for our application. The gear reduction in this case refers to increasing the speed by decreasing the torque. From the graph, we picked a gear reduction of 10:17. This gives a factor of safety of 2.16 in regards to torque, and gives a theoretical maximum speed on flat ground of 4.86 mph, just under the speed limit of the competition.

3.4.3 Results and Testing

Testing the drive blocks on the vehicle was successful. The platform achieves speeds of approximately 5 mph on flat ground, as predicted. Although we were unable to find a ramp of the exact angle specified, Nero is capable of climbing grassy slopes of a much steeper angle than that required for the competition. The motor controller also performs well. Performing a zero-point turn gives only negligible drift of the robot center, showing that the motor controllers responsible for setting the speeds performs as expected.

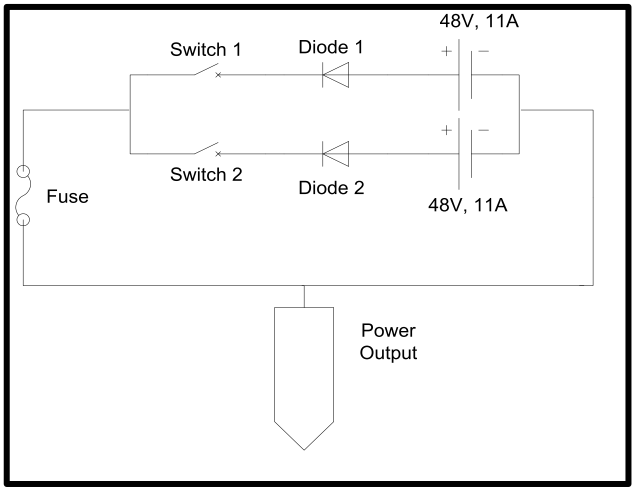
3.5 Power and Quality Control

To provide for a total power consumption of 310W at a peak of 30A with a factor of safety of 2 (Table 5), a high power supply system that could handle high power and amperage was required. As a result, with a minimum run-cycle of 30 minutes and up to 10 cycles expected per day, 51.8V, 518Wh polymer Li-Ion rechargeable batteries were selected for their high power source and peak current tolerance of 40 Amps. Nominal 48V systems are common in professional applications in the industry and are the military-specification norm.

Table 5: Electronics Power Consumption

Part	**Power (W)**
Camera	1
Computer	40
INS	1
LIDAR	20
Motors (x2)	246
Wireless E-stop	1
Total	**309**

The innovative battery circuit was built with a hot-swap capability (Figure 8). In other words, the batteries can be swapped without cutting off power to the robot, so the robot can operate continuously without being restricted by the battery capacity. Also, each battery is equipped with a LED gauge that displays the charge status of the battery to complement the hot-swap capability. In addition, the battery circuit allows for using external power through AC supplies for testing purposes and to minimize direct use of battery power. An innovative solution for heat management was the installation of "Swiss-cheese" shaped metal plating at the bottom of the battery case that draws heat away from the battery. With a fully charged battery, Nero was able to safely operate for 5+ hours. With a 3A battery charger, a quick recharge of the battery can be achieved in approximately 4 hours.



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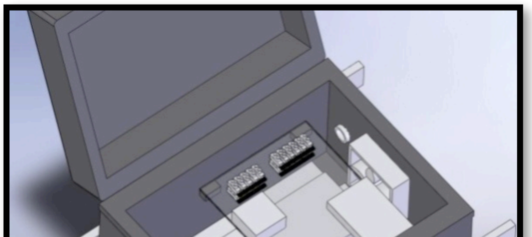
3.6 Electronics Protection and Safety



The primary design concern was to satisfy the following requirements: ensuring physical and electrical protection of the electronics and implementing a hardware-based wireless emergency-stop solution with an effective range of at least 50 feet that brings the robot to a quick and complete stop.

3.6.1 Electronics Protection

The electronics require proper protection to guarantee maximum performance and prevent any potential damage. Physically, the main electronics are securely mounted inside the electronics case and the battery case, both of which are IP54 rated waterproof and dustproof. Further, all connectors utilized for the connections through the electronics case and the battery case are IP65 rated waterproof. Electrically, heat management was the main design concern. The heat sink on the computer is responsible for managing heat dissipation of the computer, while the IP54 rated fans circulate air from one end of the electronics case to the other. Also, in the electronics case, direct contact between the floor of the case and the electronics is avoided. This is accomplished by raising the acrylic boards on which the electronic components are mounted to prevent concentrated heat flow. The innovative two-level stacking of electronic components in the electronics case is derived from the same principle as well as efficiently using the space within the electronics case. To prevent the effects of unexpected surge current, a circuit breaker is installed in the battery case, as well as diodes that are configured to handle 20-50 A of current. Heat dissipation was not a problem during the entirety of Nero's testing phase.

Figure 9: CAD Model of Electronics Case

In order to facilitate the maintenance of the electronics case, simple rail system was incorporated onto the electronic case so that it can be slid out and opened for examination. Throughout the system, United States Military Standard (mil-spec) wires are used to ensure safety and reliability. Efficient wire management was given particular attention as it enhanced organization and simplicity of the wiring scheme, avoided potential voltage drops due to long wire connections, and allowed for convenient maintenance. Also, the use of Amphenol connectors, Eurostrip, and Molex connectors permit not only safe and secure connections, but also modularity, enabling a convenient and easy replacement of components and transportation. Eurostrip, in particular, enables parallel distribution of power so that the electronic components can be connected without affecting the rest of the system.

3.6.2 Wireless E-stop

For the wireless e-stop solution, we purchased a COTS RF receiver with a guaranteed reception range of 100 feet and a RF transmitter with a set/reset toggle functionality. The purchased module was incorporated in series with the mechanical e-stop circuit to cut off power to the motors exclusively, bringing Nero to quick and complete stop while leaving other electronics functional. The set/reset capability and the guaranteed range of over 100 feet with line of sight were tested and confirmed. At full speed, Nero completely stops within 3 seconds and 6 feet.

4 Software

4.1 General Framework

4.1.1 Platform

Nero runs on an Ubuntu Linux platform. The primary consideration in the decision was that many of the libraries utilized are only supported by Linux. In addition, Ubuntu is open source, well-documented, familiar to the team, and has less overhead than Windows. Programs are written in C++ using the Eclipse Integrated Development Environment (IDE). C++ runs faster than Java but still has the benefits of modularity associated with the object-oriented design.

4.1.2 Structure

The core of the data processing is the Data Processor class whose main objective is to delegate work to the other processors, namely the LIDAR, camera, INS, and motors and combine the data received from these processors. Processed data is passed to the AI, which calculates routes and passes commands to the Motor Encoder which communicates with the motors to adjust Nero's speed and direction.

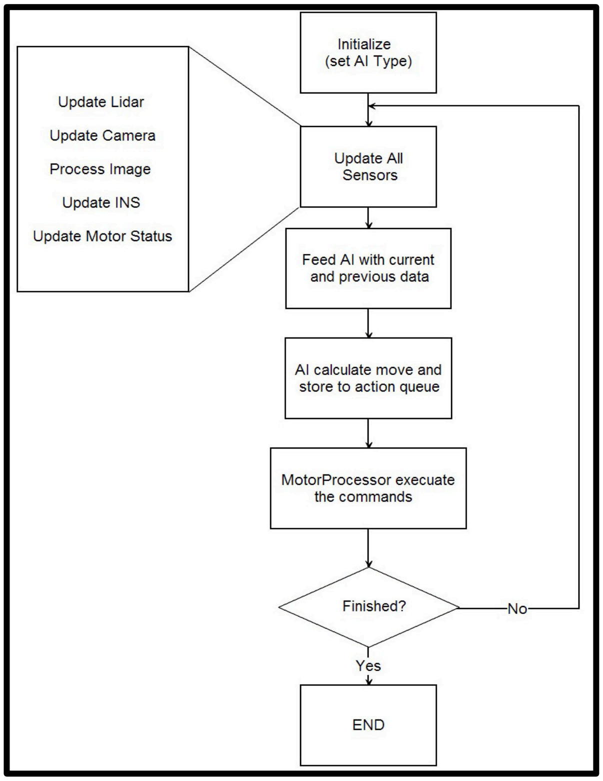


Figure 10: Software Flow Diagram

4.1.3 Modularity of Code and Hardware

Our code is designed such that the components are modular and they can be easily swapped or replaced. One example of this modularity is that the code related to each Input/Output (I/O) device is limited to a single class or package. For example, if the camera were replaced with 2 new cameras, the main structure of the code could be left unchanged as long as the new class that replaces the current camera processor used the correct interface. Thus, the sensors are quite modular and easily swapped out.

Similarly, we currently have two AI strategies, Navigation and Autonomous; however, we are in no way limited to these strategies. Again we have an interface for an AI strategy, and any number of strategies can be interchanged with minimal effort.

4.2 Software Innovation

A key innovation in the software design for Nero is the development of the Circle Algorithm (CA), used for obstacle avoidance. The algorithm is also the basis for path planning in the navigation challenge. See Figure 11 for an illustration. During the Navigation Challenge, a global map is maintained using results from the CA. Each time a circle is determined to be unclear, the values of grid squares within the circle are increased. Conversely, whenever the algorithm finds

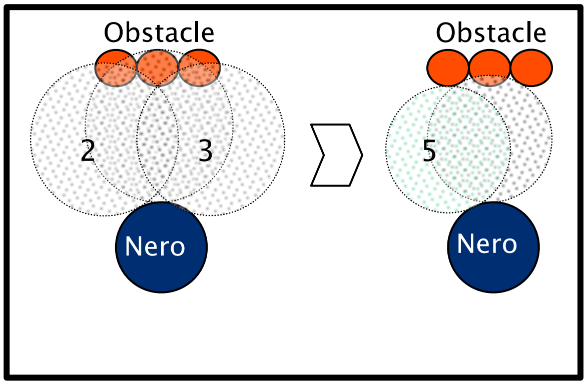


Figure 11: Circle Algorithm

a clear circle, the values of the grid squares are decreased.

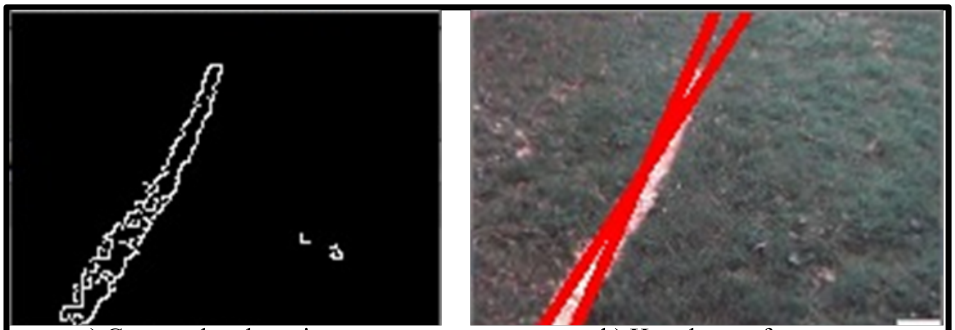
Circle Algorithm:

```
circle = circle directly in front of robot, with size MAXSIZE
circle_count = 1, turn_count = 0, turn_direction = left
while (circle is not clear && circle size > MINSIZE) do
    /* the circle is unclear so mark the map accordingly */
    update map information
    if (turn_count = num_turns_by_circle_count (circle_count)) then
        /* num_turns_by_circle count is a function that determines how many times the circle should be
        shifted before becoming smaller. The circle sweeps across a greater angle as it decreases in size */
        circle = circle_size * SCALING_FACTOR
        circle_count++
    else
        /* circle is swept from 0 degrees (directly in front of the robot) left or right */
        circle = rotate_circle (circle, turn_multiplier * TURN_ANGLE, turn_direction)
        /* turn multiplier increases the angle which the circle is moved at each step */
        turn_direction = turn_direction == left ? right : left
        turn_count++
    endif
endwhile
if (circle is clear)
    move
    update map information
else
    recalculate optimal path
endif
```

4.3 Data Acquisition and Preprocessing

4.3.1 Camera Processor

The camera's main function is line detection, which enables Nero to detect lanes and potholes. The open source dc1394 library interfaces with the camera, allowing for individual frame capture. Then, the opencv library is used for various corrections and detections. The camera, chosen for its wide range of vision among other factors, has a resulting mild fisheye distortion. To correct for this, the corners were detected on a series of pictures of chessboards and then the image was mapped to a non-distorted space using the opencv library.



a) Canny edge detection b) Hough transform

Figure 12: Stages in Lane Detection

Canny edge detection, implemented by opencv, is first used to identify edge points in the images. These detected edges serve as a starting point for a Hough transform. The Hough transform groups edge points together and estimates the most likely parameters for a line through the points. See Figure 12. When the processor has determined that a line exists, it stores the direction of the line in a vector and passes it to the AI. For pothole detection, Nero again relies on a Hough transform to fit a circle. The function Intersect Circle, used in the Circle Algorithm to determine whether a given circle is clear, determines whether or not there is a line or pothole in the proposed circle.

4.3.2 Lane Following

During the Autonomous Challenge, the first step in the algorithm is to check for any lane lines. If a lane line has been detected by the camera processor, it returns a vector determining the direction of the line. This direction is set as the next direction for Nero to travel. For dashed lines, the camera will still return a vector in the direction of the line and this will become the next direction for the robot. In between line segments, Nero will maintain the same direction, until the next line segment is detected and another command is passed to travel parallel to the line.

4.3.3 LIDAR Processing

The LIDAR is responsible for detecting all obstacles except for lines and potholes. The SICK toolbox provides a collection of libraries to interface with the LIDAR. The function Intersect Circle works analogously to the function of the same name in the camera processor. The goal is to determine whether a given circle from the CA is free of obstacles or not. Intersect Circle projects the circle currently considered by the algorithm onto the ray measurements given by the LIDAR. To speed up processing, only the data from the rays that intersect the proposed circle are analyzed. An intersection occurs when the ray ends before or inside the circle, indicating that the circle is not clear. The number of such intersections is counted, and when this value passes a threshold constant to be determined by testing the circle is determined to be not clear. The LIDAR is capable of detecting obstacles at a range of up to 30m, but the CA only requires detection of obstacles at a maximum range of the diameter of the largest circle, or 3m.

During the navigation challenge, the LIDAR processor also preprocesses data as it is received to determine which side of the track has fewer or farther obstacles. See Figure 13. If at a certain angle the LIDAR does not detect any obstacle or only obstacles beyond the track borders (like obstacle 1) or obstacles beyond the maximum distance considered (like obstacle 2), the data point for that angle has a value of 1. If the Lidar detects an obstacle at a point within the track boundaries and before the maximum distance to be considered (like obstacle 3) the data point for that angle will have a value of . The vertical distance is depicted by the orange line in Figure 13. To determine which side of the track

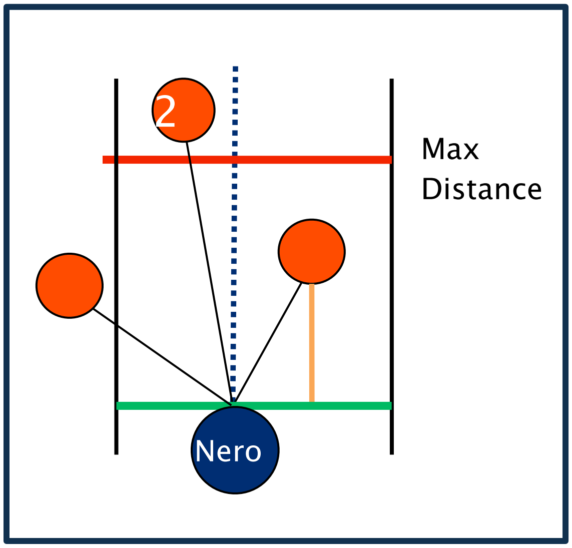


Figure 13: LIDAR Preprocessing

is better, the LIDAR processor sums all the values of the data points to the left and all the values of the data points to the right. The maximum of the two values indicates the side that contains the least or farthest obstacles and therefore is the better side. Then the direction of travel can be altered accordingly.

4.4 Artificial Intelligence

4.4.1 Navigation Algorithm

The algorithm for the Navigation Challenge employs an A* graph search on a global map. The map consists of a grid with each square storing the obstacle weight value. This weight represents the likelihood of an obstacle existing within that square, obtained through iterations of the Circle Algorithm. Each time a circle is determined to be unclear, the weights of all of the grid squares within that circle are increased. Conversely, whenever a clear circle is found, the values within the circle are decreased. Using the map generated by this process, the A* algorithm constructs a best path to the closest waypoint that has not yet been reached. Each grid point in the map is a node that A* considers. Edge weights between each pair of nodes are a function of the obstacle weight value for the destination node and the map distance between the nodes, which is either 1 or since the grid is a square grid. The A* algorithm will compute a new route to the closest waypoint each time that a circle is found to have an obstacle, since the map will be updated. Figure 14 below shows the Navigation Algorithm.

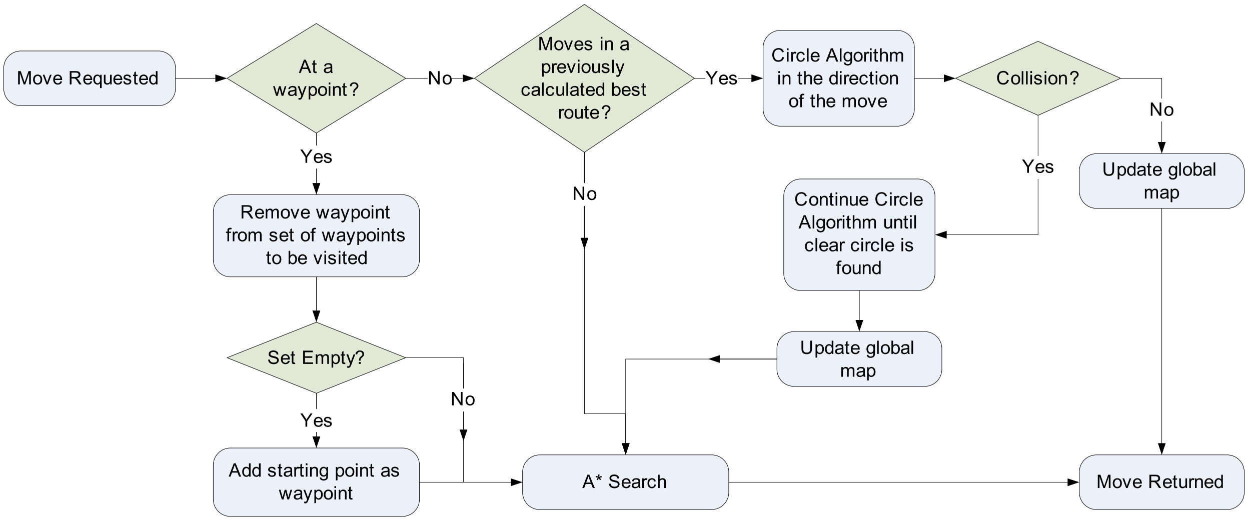
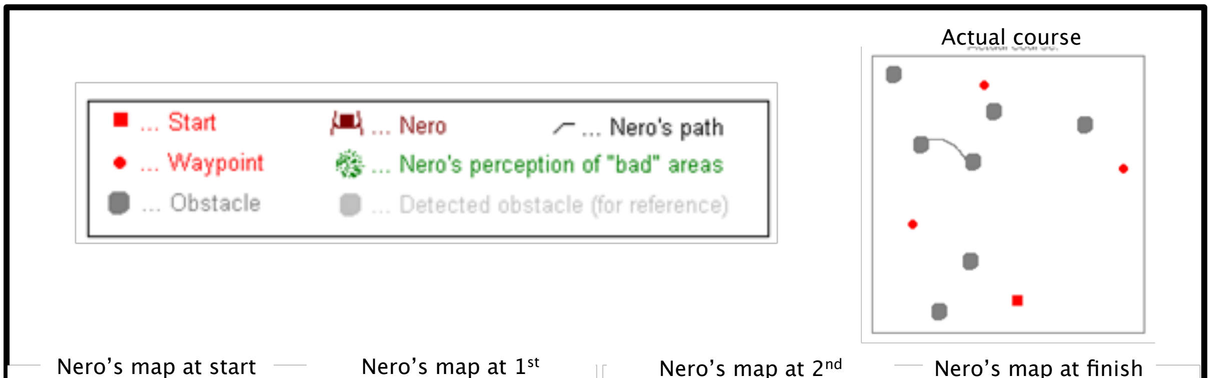

Move Requested
At a waypoint?
No
Moves in a previously calculated best route?
Yes
Circle Algorithm in the direction of the move
Collision?
No
Yes
Yes
No
Update global map
Remove waypoint from set of waypoints to be visited
Continue Circle Algorithm until clear circle is found
Update global map
Set Empty?
No
Yes
Add starting point as waypoint
A* Search
Move Returned

Figure 14: Navigation Algorithm

The GPS part of the INS is used to determine the current location of Nero. Both this position and orientation, obtained from the inertial measurement unit (imu), are required to update the global map as the CA finds clear and unclear circles. See Figure 15 below for an illustration of the path Nero follows during the Navigation challenge.



4.4.2 Autonomous Strategy

The general strategy for the autonomous algorithm is to continue to move forward if no lanes are detected, keep track of orientation, and maintain a global orientation that will be updated regularly to ensure that Nero's orientation coincides with the global orientation. The AI will keep a stack of previous movements and speeds. Data from the INS processor, only obtained from the IMU, is used to keep track of orientation, allowing Nero's past movements to be defined as vectors. The global direction is determined by adding the vectors followed during the last x moves, x being a parameter to be adjusted during further testing. The algorithm is detailed in Figure 16. The Modified Direction is determined to be validated or not according the Figure 17.

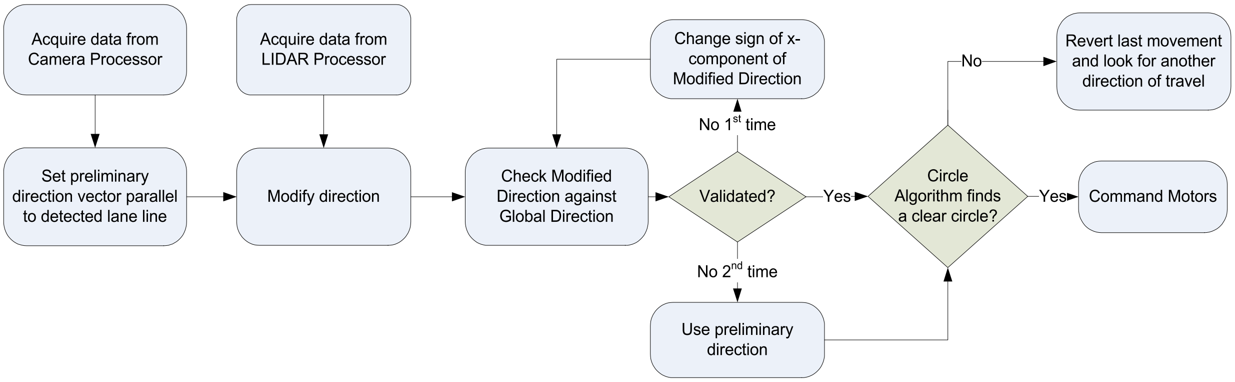

Acquire data from Camera Processor
Acquire data from LIDAR Processor
Change sign of x-component of Modified Direction
No
Revert last movement and look for another direction of travel
No 1st time
Set preliminary direction vector parallel to detected lane line
Modify direction
Check Modified Direction against Global Direction
Validated?
Yes
Circle Algorithm finds a clear circle?
Yes
Command Motors
No 2nd time
Use preliminary direction

Figure 16: Autonomous Algorithm

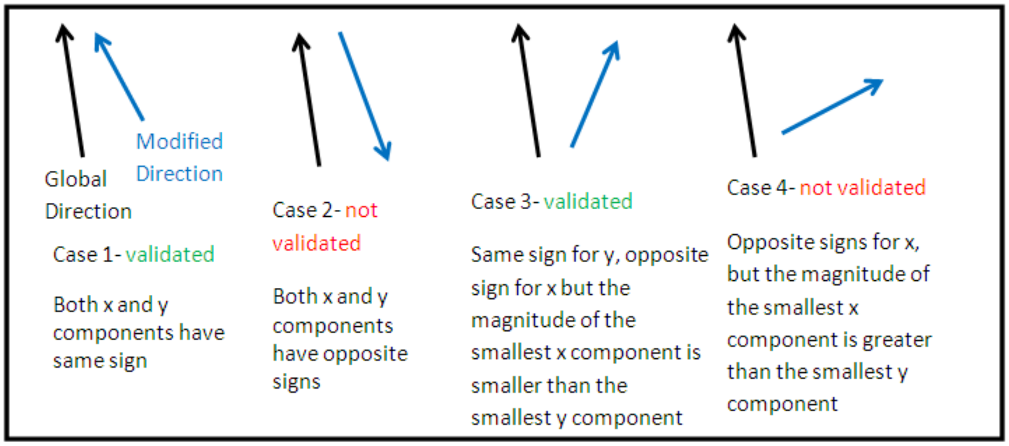
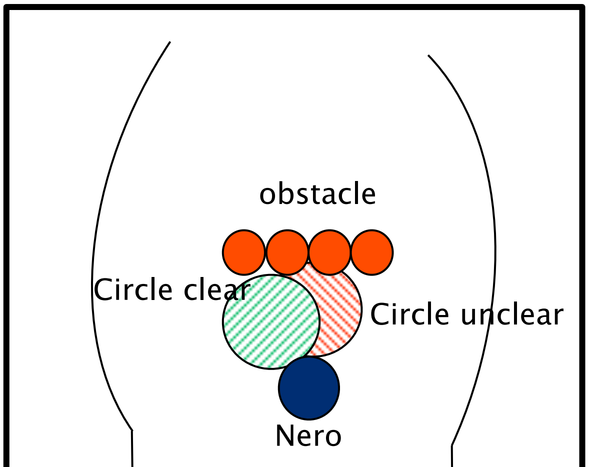

Global Direction
Modified Direction
Case 1- validated
Both x and y components have same sign
Case 2- not validated
Both x and y components have opposite signs
Case 3- validated
Same sign for y, opposite sign for x but the magnitude of the smallest x component is smaller than the smallest y component
Case 4- not validated
Opposite signs for x, but the magnitude of the smallest x component is greater than the smallest y component

Figure 17: Validation of Modified Direction

This algorithm will allow for navigation through switchbacks because the algorithm validates the modified direction with the global direction to prevent backtracking. Center islands will be circumvented by the CA as in Figure 18. If there is an obstacle directly in front of Nero, the algorithm then considers a circle rotated to the left or right.



Thus Nero has the freedom to travel slightly to the left or right of the modified direction suggested by the LIDAR processor.

4.4.3 Speed Control

The more circles that the CA considers before a direction is determined to be clear, the more obstacles are in the area and so Nero should be more cautious. Thus the Navigation algorithm only passes a command to the motors to go at full speed if the initial largest circle was clear. Each time the circle size is reduced, the speed will be reduced.

Figure 18: Avoiding Center Islands

5 Conclusion

Cornell Minesweeper is proud to present Nero as the result of the two semesters of dedicated effort. The use of the SE process allowed for effective, requirements driven design and quick systems integration. Significant innovations such as the modularity of the design, large wheels to traverse rough terrain, superior electronics protection, and hot swap battery capabilities set Nero apart from other robots and are extremely relevant to Cornell Minesweeper's ultimate goal of developing a platform for landmine detection. Nero is a reliable and effective autonomous platform that will perform well at IGVC. We look forward to testing Nero's capabilities in competition and continuing to improve upon our design in years to come.