



# HEPHAESTUS

## 13<sup>th</sup> Annual Intelligent Ground Vehicle Competition June 2005



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College of Engineering and Science  
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Department  
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Detroit, Michigan

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We certify that the engineering design of the original vehicle *Hephaestus*, presented in this report, has been significant and that each undergraduate team member has earned six hours of senior design credit for the work accomplished on this project.

Dr. Mohan Krishnan (EE)

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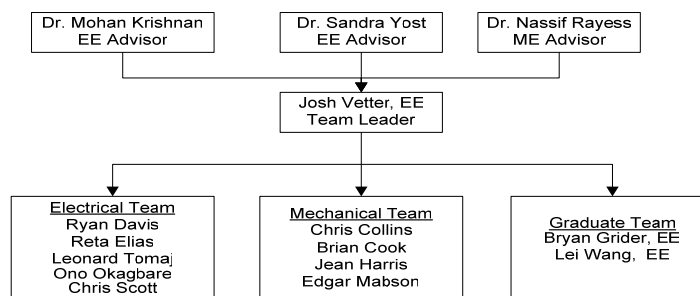
Dr. Nassif Rayess (ME)

## Introduction

This report presents the autonomous vehicle *Hephaestus*, the University of Detroit Mercy's entry into the 13<sup>th</sup> Annual Intelligent Ground Vehicle Competition (IGVC). Hephaestus, Greek god of the smiths, especially the blacksmith's fire, was the patron of all craftsmen, principally those working with metals. The vehicle *Hephaestus* is a completely new design. With elegance, simplicity and function as the primary criteria, *Hephaestus* is an omni-directional vehicle with a triangular wheel pattern. *Hephaestus* is designed to participate in the Autonomous Vehicle Challenge.

## 1. Team Organization

The *Hephaestus* team is interdisciplinary and composed of senior Electrical & Mechanical Engineering students, as well as graduate Electrical Engineers. The team has an elected leader and is advised by three faculty members. The organization chart is displayed in Figure 1 below.



**Figure 1- Team Organization Chart**

The development of *Hephaestus* started during the 2003-2004 academic year by a team of mechanical and electrical engineering seniors. Last year's senior class started the research, and designed and built the mechanical systems, including the frame and drive train. The 2004-2005 *Hephaestus* teams' focus has been on improving the mechanical system, completing the electrical system and software algorithms, and building a competition-ready vehicle. The graduate students were primarily responsible for the image processing and navigation systems. The total number of person-hours spent on *Hephaestus* over two academic years is approximately 4500 hours.

## 2. Design Planning Process

The *Hephaestus* design started with an extensive benchmarking of the competition. Detailed study of the rules, published competitors reports, and previous results were analyzed to determine the design attributes of the “winning” vehicle. Performance specifications such as turning radius and refresh rate were determined and became design targets. Following the benchmarking was a period of extensive literature and patent surveys to determine the state of the art of vehicle architecture, drive train design, image processing and navigation algorithms. A variety of alternatives were researched, explored and evaluated against other potential solutions. As a result of this design process, *Hephaestus* emerged with the following broad characteristics:

- Three-wheeled, zero turning radius with mechanically linked drive train.
- Heuristic logic based image processing and redundant ladar obstacle detection.
- Navigation strategy based on fuzzy logic.

The team also coordinated a field trip to the 2004 competition and held meetings in Fall Term 2004, even the Capstone Design Course sequence began in January 2005.

## 2. Vehicle Architecture and Design

The main design features of *Hephaestus* are its two platforms and its three articulating wheel hubs that turn simultaneously to produce a zero turn radius. In this manner, the vehicle can translate in any direction allowing for absolute freedom of movement. The design of the wheel assemblies will be described in detail later but the important feature is the mechanical coupling throughout the drive and steering systems. Two gear motors run the driving and steering functions of the vehicle. As a result, a relatively simple controller with two input and two output channels could be used to effectively control the speed and direction of the vehicle.

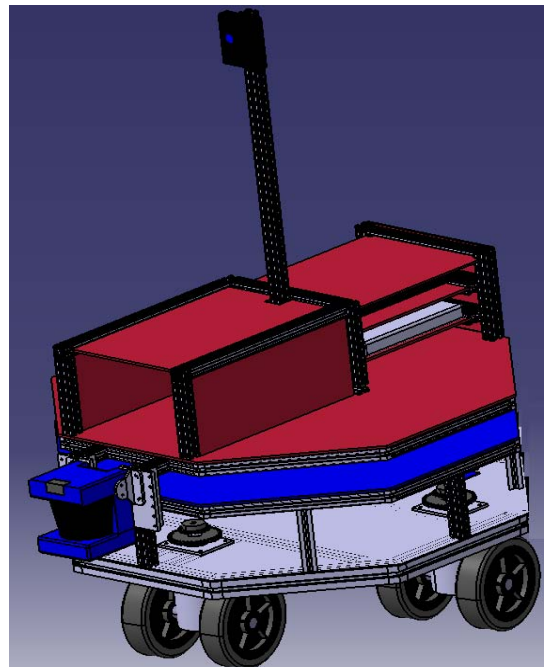


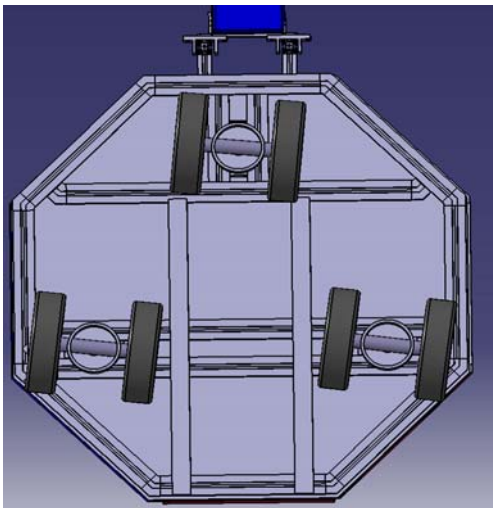
Figure 2 – Catia 3D Model

All wheels rotate and pivot simultaneously, but the platform to which they are attached does not rotate and will remain in the same orientation throughout the entire travel. This platform houses the mechanical systems, motors and controller. An upper platform (referred to as the “electrical” platform) housing the camera, ladar and computers is coupled to the wheels and thus rotates to point in the direction of motion. Thus the “eyes” of the autonomous vehicle remain pointed forward. Figure 2 shows a 3D rendering of the vehicle. The two platforms are connected via a centrally located tube which allows for an organized wiring arrangement. The communications between the navigation computer on the top platform and the motor controller on the bottom are done using a spiral wire harness that is routed through the central tube.

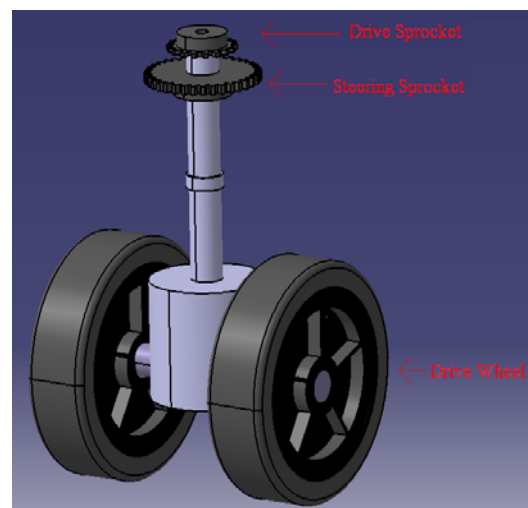
### ***3.1 Lower Platform/Drive System***

The drive train components, including the steering and drive motors, are mounted on the lower platform. This platform is supported by a triangular wheel pattern consisting of three wheel “pods” as shown in Figure 3. Each wheel pod consists of a pair of wheels, one is driven, the other is free-wheeling and is used to improve stability.

The steering motor rotates the entire wheel pod assemblies. As seen from Figure 4, the wheel pods have two separate sprockets connected to two separate chain drives. The top sprocket connects the drive motor to the vertical drive shaft which in turn drives the wheel through a bevel gear. The bottom sprocket connects to the steering motor and in effect serves to turn the entire wheel pod, thus orienting the wheels in the direction of motion.

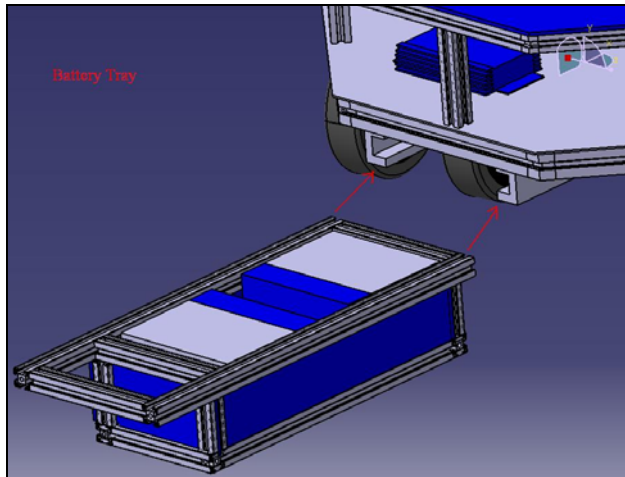


**Figure 3 – Wheel Configuration**

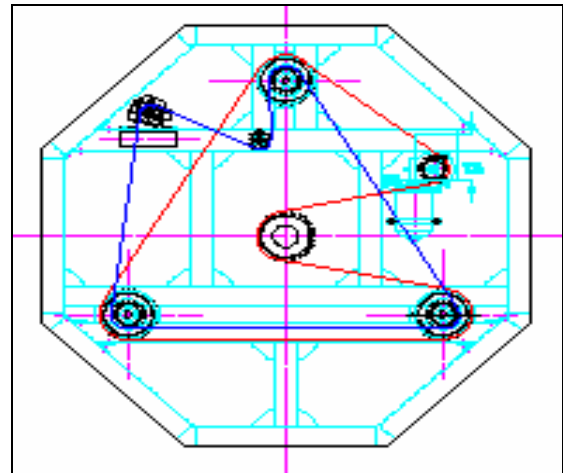


**Figure 4 –Wheel Pod Schematic**

For the sake of stability, particularly while climbing ramps or during turning maneuvers, it is imperative to keep the center of gravity as low as possible. To accomplish this, the battery housing, including two 40-pound batteries, is placed under the lower platform as illustrated in Figure 5. The battery tray is designed to slide in place on heavy duty rollers and engage the electrical connectors. A simple latch mechanism is designed to keep the tray in place. This quick connect/disconnect battery system affords a rapid change of batteries as well as easy battery removal in case the vehicle needs to be lifted.



**Figure 5 – Battery Housing**



**Figure 6 – Drive Train Configuration**

As stated earlier, two motors are used to control this vehicle. A drive motor controls the speed and a steering motor controls the angular position of the wheels. Figure 6 displays an AutoCAD model of the top view of the lower platform. The drive chain is shown in blue and the steering chain is shown in red. Note that the red chain is wrapped around the center shaft, which causes the upper platform to rotate with the wheels.

### ***3.2 Upper Platform & Shaft***

The upper platform houses the main electronic systems. A layout of all the major components is displayed in Figure 7. These are: Vision Computer, Control Computer, Power Distribution Box, Batteries and the payload required by the IGVC competition. The ladar, a laser distance-measuring device, is suspended from the upper platform by a bracket assembled from aluminum extrusions as shown in Figure 8. Mounting the ladar lower allows for the detection of shorter objects. The camera is mounted centrally atop a shaft reaching the maximum allowable height, which provides the best view of the course.

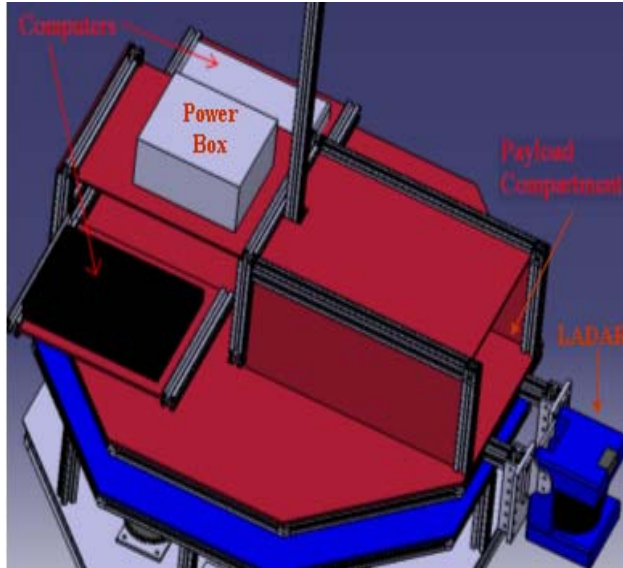


Figure 7 – Electrical Component Layout

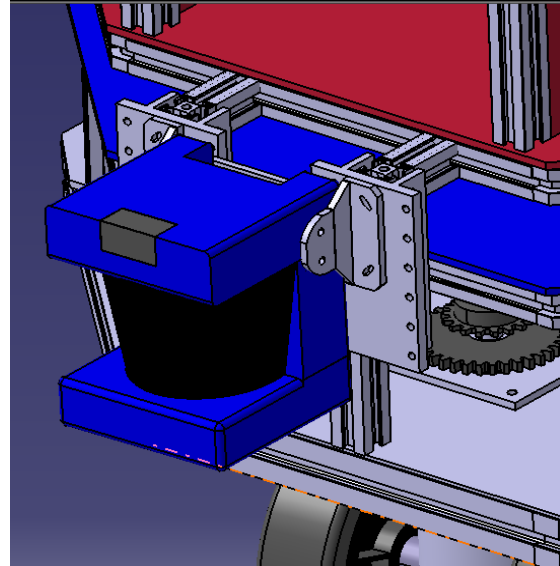


Figure 8 – Ladar Mount

## 4. Electrical Subsystems

### 4.1 Roboteq® DC Motor Controller

The controller chosen for *Hephaestus* is the Roboteq® AX2850. This controller offers two configurable channels for separate closed-loop speed and position control, a wide operating voltage range (12-40VDC) and the ability to provide enough current to the chosen motors.

The AX2850 can be configured to control the motors by means of an analog joystick, RC joystick, or standard serial commands. It also comes with a PC-based run utility that aids diagnostics and testing. *Hephaestus* is used in RC joystick mode when being driven manually, while serial port control is the mode implemented during closed-loop autonomous operation.

### 4.2 Motors

The motors are selected based on function (gearing, self-locking, etc.) and performance (horsepower, stall torque and RPM). Sufficient power ensures that the vehicle is capable of moving at a speed of 5 mph up the maximum incline of 15%. Stall torque calculations take into account the motor's ability to propel the vehicle from a stationary position up the incline. Motor RPM is used in conjunction with gearing and wheel size to ensure that the vehicle can achieve the intended speed of 5 mph.

Using the vehicle parameters and requirements, the drive motor selected was the Dustin 2, a modified DeWalt drill motor with the following specifications: 24V, 50.4:1 Gear Ratio, 450 RPM, .98 HP and 62.14 Nm Stall Torque.

The steering motor was selected based on its ability to turn the wheels. After initial measurements of the necessary torque, a ½ Hp AME 24V right angle motor with a built-in 50:1 worm-gear reducer was chosen. The self-locking feature of the steering motor's worm gear allows for a mechanical means to maintain wheel direction. A similar self-locking effect in the drive motor allows the vehicle to stay stationary when power is lost or shut off. This acts as a fail-safe mechanism in case of power outage while climbing or descending a ramp.

#### ***4.3 Encoders***

Optical encoders with quadrature outputs are used to measure speed and position. Two MEH-17 series hollow shaft micro encoders from Microtech Laboratory Inc. are connected to the shafts of the steering and drive motors. They provide accurate speed and direction feedback to the controller. These controllers draw 30mA each and have a resolution of 300 pulses per revolution.

#### ***4.4 E-Stop***

The vehicle is equipped with manual and wireless emergency stop options. A pushbutton plunger is located to the rear of the vehicle, on the upper platform. When pressed, the plunger connects the emergency stop pin of the motor controller to ground, cutting power to the motors and halting the vehicle. The same result is achieved by activating the wireless emergency stop via a Bosch automotive Remote Keyless Entry transmitter-receiver unit. Pressing the transmitter causes a relay to connect the same pin to ground.

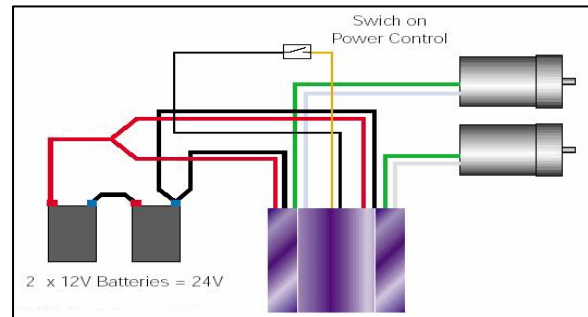
#### ***4.5 Power Distribution and Electronics Box***

The electrical power distribution box resides on the upper platform. It contains most of the fuses, switches and indicators, and serves as a power distribution hub for all electrical subsystems. These subsystems include E-Stop mechanism (RF & manual), R/C receiver, ladar, camera, encoders, and controller.

Along with the power distribution, the electrical box contains interfacing circuitry for all the electrical subsystems on the vehicle. Power to each subsystem is made visible through LED indicators employed to display proper functioning and acceptable power levels for all subsystems. Switches have been utilized for a safer power-up sequence, reducing the possibility of power surges and blown fuses.

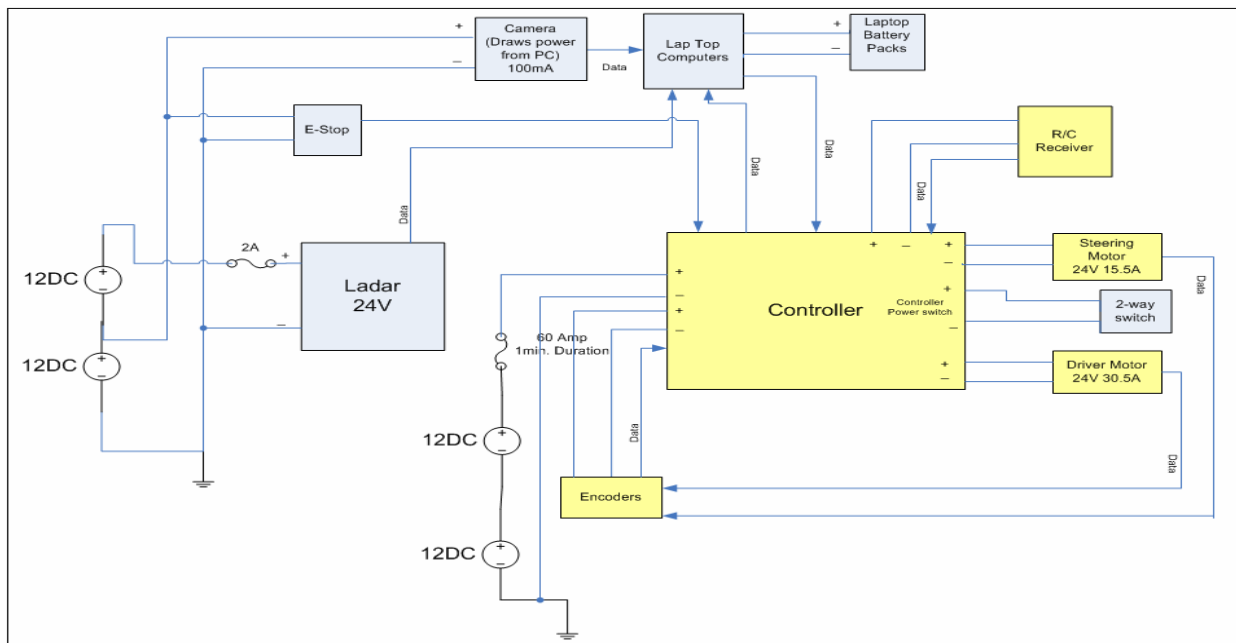
**4.6 Power System**

*Hephaestus* is composed of two completely independent power systems. The first provides power to the motors and controller and is located on the lower platform. The second provides power to the electronics located on the upper platform.



**Figure 9 – Roboteq Power Distribution**

With the laptop computers using their internal power sources, the upper platform batteries need only to supply power to the ladar, camera, and RF receiver. Two 12V, 5 amp-hour batteries are used to provide the estimated maximum power draw of 2.3A and the 24V needed for the ladar. The upper platform has over 2 hours of run-time battery life.



**Figure 10– Controller Power Distribution**

The current draw in the lower platform is more significant, with the two 24V motors drawing a combined 46A during normal operation and a stall current of 120A. The Roboteq power scheme used to route this power to the motors is displayed in Figure 9 (courtesy of [www.robotiq.com](http://www.robotiq.com)).

To provide the needed voltage and power, two 12V, 55Amp-hour lead acid batteries are connected in series, and are fused and stowed inside the battery tray attached to the bottom of the lower platform. A conservative estimate of the lower platform's battery life is around 1.2 hours. Figure 10 is a schematic for all the component power routing.

## 5. Sensory/Software Architecture

The *Hephaestus* sensory system hardware consists of a 2.0GHz IBM® notebook that interfaces with the navigation sensors via a serial adapter. The serial adapter is a PCMCIA card that provides multiple serial ports to enable the notebook to interface with multiple sensors including the ladar and motor controller. *Hephaestus*' vision algorithm runs on its own dedicated laptop, a 3.0GHz Hewlett Packard® connected to a Uni-Brain® fire-wire camera.

The two computers are linked together using Ethernet cables. This setup allows for high speed transfer of data between the two onboard computers. Both laptops are equipped with wireless communication capabilities, allowing for remote monitoring of the vehicle's status using an external computer. The sensory and vision systems configuration is depicted in Figure 11. All software was completed using a combination of MATLAB® and Simulink® operating under an optimized Windows® operating system.

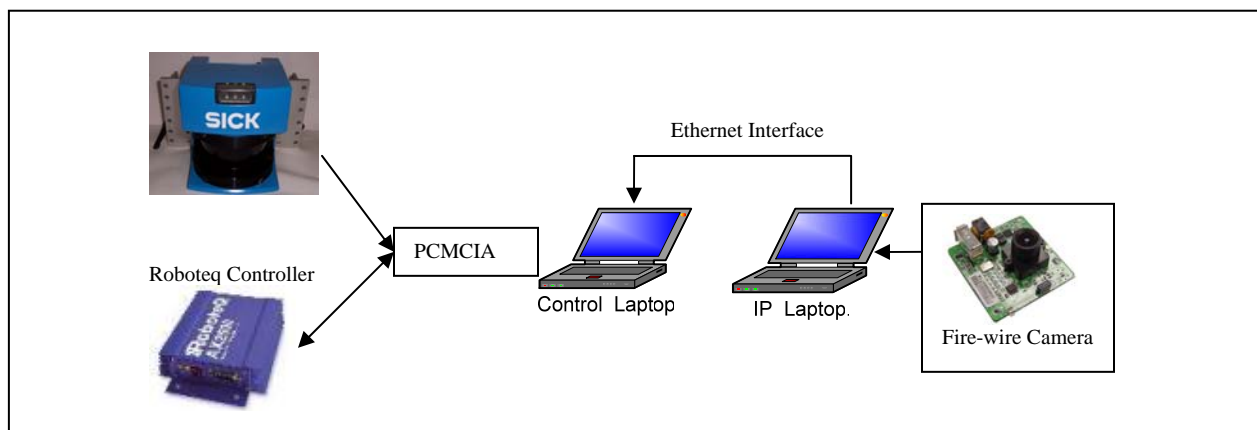


Figure 11 – Sensor and Vision System Integration

### 5.1 Vision System

The Uni-Brain® Fire-I Board Camera shown in Figure 12 (courtesy of [www.unibrain.com](http://www.unibrain.com)) captures the images used for lane and obstacle detection. This camera is a single board, fully operational Fire Wire color camera, capable of 400Mbps data transmission, with a native resolution of 640x480 pixels and 80.95° horizontal view angle for uncompressed VGA picture acquisition at 30 frames per second. The latest 1394 Texas Instruments® chipsets and Sony® CCD sensor provides a high quality subassembly for image capturing. A plastic weatherproof box was constructed to encase the camera.



Figure 12 – Camera

### 5.2 Image Processing Strategy

The image processing strategy determines which obstacles, potholes and lines are present in the camera's field of view. A preliminary direction is determined by examining an image and establishing a preliminary direction between the lane boundaries. In order to determine this preliminary direction, the captured image is processed in a Matlab® environment. The algorithm, broken down into separate tasks, is outlined in Figure 13.

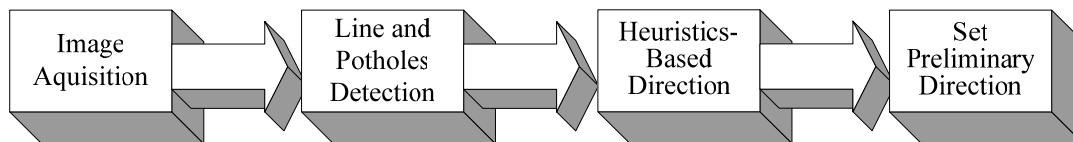


Figure 13 – Flowchart of Image Processing Algorithm

First, the image is acquired from the Fire-I camera with YUV color space. Then the color space is transformed to RGB space. After that, adaptive threshold techniques are applied to all three planes and are accompanied by region-based color segmentation. The image in Figure 14b shows the changes made to the image in Figure 14a during the initial color filtering. The binary image in Figure 14b coupled with a Hough transform-based technique detects the existence of the painted lines in the image field. The white pothole is considered a distinct region in the binary image and is detected by an area threshold. As a result, a pothole flag is triggered if the area of the distinct region is bigger than the area threshold.



**Figure 14a-Course Image before IP**



**Figure 14b-Course Image after IP**

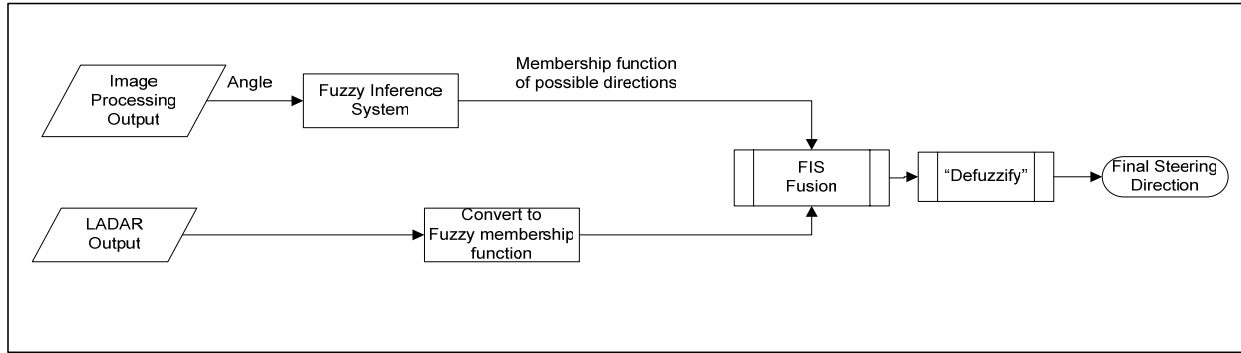
The purpose of heuristics is to aid in the preliminary direction setting. The strategy is designed with the number of the edges detected and their pixel positions as its main decision-making factors. To deal with dashed lane boundaries, the program determines the optimal direction by comparing the current image to the most immediate achieved image in which the solid lane line appears, and extrapolates the expected lane from this previous image. Based on heuristics logic, this preliminary direction is set and passed to the navigation software.

### ***5.3 Ladar System***

The ladar system used is the SICK® LMS 200. The laser scans horizontally through a 180-degree range at 0.5° resolution, for a distance up to about 80m. The measurement information is transmitted via serial communication to the navigation computer. For this application, the ladar is configured so that the farthest distance is approximately 8 m. Using this laser scanner, the width of obstacles and their distance away from the front of the vehicle are determined.

### ***5.4 Navigation Strategy***

The purpose of the navigation algorithm is to merge the preliminary direction angle provided by the image-processing algorithm with the obstacle avoidance information obtained from the ladar system to generate a final direction for the vehicle. The algorithm is implemented in Simulink® using fuzzy inference techniques as shown in Figure 15.

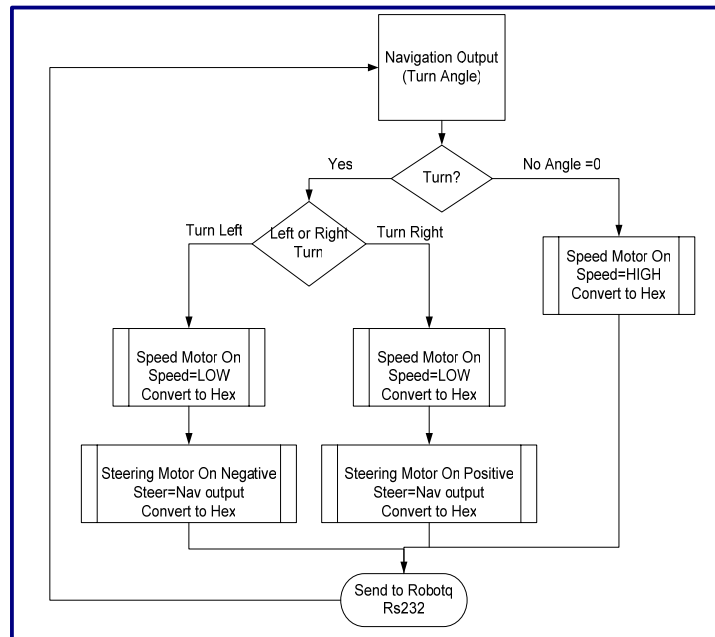


**Figure 15 – Navigation Algorithm Flow**

The direction provided by the image-processing computer is the input to a Fuzzy Inference system, whose output is a fuzzy membership function of possible steering directions. The lidar output, which is a 180° map of obstacle locations in front of the vehicle, is converted to an equivalent fuzzy membership representation. The two sets of membership functions are then fused to produce an overall fuzzy membership function of possible steering directions. This membership function is then “defuzzified” to produce a final steering direction, which is the input to the steering control algorithm.

**5.5 Speed/Steering Control**

The navigation angle is the input for the steering and speed system. The flowchart is shown in Figure 16. The speed control is based on a two-speed strategy. If it is determined by the navigation algorithm that the vehicle is to be turned, the Roboteq controller is commanded to operate in a low-speed mode. High-speed mode is initiated when no turns are required. Note that the Roboteq controller has built-in speed and position control capability, so the steering and speed system have only to generate the appropriate command signals.



**Figure 16 – Steering/Speed Control Algorithm**

Experimentation is in process to determine the best choices for the two speeds.

## **6. Predicted Performance**

### ***6.1 Reaction Distance***

The reaction distance is defined in terms of distance traveled along the path per image frame processed, since image processing is the slowest algorithm. The processing time between consecutive image frames is essentially a time when the vehicle is traveling blind. The expected refresh rate of 8-10 frames per second yields a reaction distance of 0.733-0.917 feet when moving at the maximum permitted speed of 5 mph. Since we expect our vehicle to operate at lower speeds, the reaction distance will be even shorter. Multiplying the speed in mph by a conversion factor of 1.467 and dividing by the refresh rate give the reaction distance.

### ***6.2 Speed and Turn***

The gear ratios of 2:1 between the 450 RPM drive motor and the 9-inch wheels produces a maximum theoretical speed of 6 miles per hour. In reality, the vehicle speed is set by the navigation capability and not the motor, and the control algorithm will limit the speed to stay within the allowable range. As for turning rate, the limiting factor is the dynamic stability of the vehicle and not the ability of the motor. The dynamic stability is related to the square of the velocity and the height of the center of gravity, and calculations predict that the stability is very robust. For example, the vehicle running at 5 miles per hour would have to be turning at a rate of about 250° per second to cause it to tip. Testing has confirmed that under normal operating conditions, the vehicle is dynamically stable.

### ***6.3 Ramp Climbing Ability***

*Hephaestus* is driven by nearly a 1 hp drive motor. It has low center of gravity (9-10 inches above ground), 4-inch ground clearance and 9-inch wheels. These attributes guarantee that the vehicle can traverse the course with relative ease as was observed during test runs. The low center of gravity assures that the vehicle will not tip while climbing or descending a ramp. This has been verified through testing.

### 6.4 Estimated Battery Life

As seen in Table 1, the total worst-case power consumption of *Hephaestus* is 1357W most of which is due to the drive and steering motors. The motors themselves consume 1103W. The rest of the electrical subsystems (2 computers, ladar, camera, emergency-stop, encoders) consume a total of 254W. Two 12 volt, 55 amp-hour lead acid battery packs are used for the lower platform (mainly the drive and steering motors) to provide a minimum of 71 minutes of run time. In the upper platform, two 12V 5A-hr lead acid batteries are used to power all the electrical subsystems except for the two laptop computers, which will be powered by their own independent battery sources. The minimum run time in the upper platform is expected to be 136 minutes.

Lower Platform (Mechanical)	Current (A)	Voltage (V)	Power (W)
Drive Motor Dustin 2	30.46	24	731.04
Steering Motor AME	15.5	24	372
Controller	0.1	12	1.2
Encoders 1 (directly from controller)	0.03	5	0.15
Encoders 2 (directly from controller)	0.03	5	0.15
R/C Receiver	0.1	5	0.5
<b>Total Lower</b>	<b>46.22</b>	<b>75</b>	<b>1105.04</b>
Upper Platform (Electrical)	Current (A)	Voltage (V)	Power (W)
Lap top1	6.5	18.5	120.25
Lap top2	4.5	18.5	83.25
LADAR	1.8	24	43.2
Camera	0.09	12	1
RF E-Stop	0.1	12	1.2
<b>Total Upper</b>	<b>13.3</b>	<b>85</b>	<b>252.7</b>
<b>TOTAL POWER</b>			<b>1357.24</b>

Table 1- Power Estimation

## 7. System Integration

System integration is important to the design process since multiple subsystems are being separately designed and implemented. *Hephaestus* is integrated bottom – up. Specifically, the steering and drive system layout were first established, then the Roboteq controller was chosen. After the drive/steering system was verified to function correctly using the Roboteq run utility, the controller was then tested and verified using the speed/steering control algorithms executed in Simulink®.

Wiring and documentation protocols were established for the wiring distribution to the upper platform, power box, batteries, the two laptop computers, ladar, Roboteq controller, and camera. The system integration between the image processing algorithm, the navigation algorithm, and the control algorithm is most critical. Based on the captured image and the ladar sensor, a desired position and speed will be commanded using the Roboteq controller. The weekly design review meetings helped structure and integrate the individual subsystems into the overall design.

## 8. Cost Breakdown

Table 2 provides a detailed retail cost and team cost of the components.

Component	Retail Cost	Team_cost	Supplier
Driver motor and accessories	\$352	\$352	Robot combat: Dustin
Steering motor	\$91	\$91	Robot combat: AME
Encoders	\$140	\$140	Microtech Laboratories Inc.
Laptop computers	\$3,700	\$2,000	HP & IBM
LADAR_LMS-200 plus accessories	\$6,046	\$4,580	SICK
Camera	\$100	\$100	Unibrain
Miscellaneous electrical components	\$300	\$100	Various
Roboteq controller	\$632	\$632	Roboteq
Batteries	\$238	\$238	Panasonic & PowerSonic
Remote control	\$101	\$101	Futaba
E-Stop control (RF)	\$60	\$0	Bosch
Structural material	\$1,300	\$680	Bosch
Wheels (6) plus drive train	\$900	\$900	Various
Miscellaneous mechanical components	\$300	\$200	Various
<b>Total Cost</b>	<b>\$14,260</b>	<b>\$10,114</b>	

Table 2 – Vehicle Component Cost Summary

## 9. Summary

*Hephaestus*' most unique feature is its drive train, which gives it omni-directional capabilities. We believe that the vehicle's maneuverability is critical, particularly in light of the tighter turns incorporated in the course this year. *Hephaestus* also features an integrated controller, which simplifies wiring and troubleshooting. Final tests to optimize the image processing and navigation algorithms are ongoing.