

***Virginia Tech presents:***



# Chimera

## IGVC 2007:

**Yong Kim, Daniel McQuail, Derek Self**

**Jesse Farmer\*, Peter King\***

**\*Graduate Students**

### **Required Faculty Advisor Statement**

I certify that the engineering design of the vehicle described in this report, Chimera, has been significant, and that each team member has earned six semester hours of senior design credit for their work on this project.

A handwritten signature in black ink, appearing to read 'C. F. Reinholtz', written over a horizontal line.

Charles F. Reinholtz, Department of Mechanical Engineering, Virginia Tech

## **1. Introduction**

The Autonomous Vehicle Team of Virginia Tech is pleased to present Chimera, a vehicle that has been specifically redesigned to compete in the 2007 Intelligent Ground Vehicle Competition (IGVC). Chimera won top honors in last year's Design Competition. It has been re-entered this year with the goals of improved performance in the dynamic events as well as an increased focus on customer needs. Chimera gets its name from the mythical beast that had the features of a lion, serpent, and a goat all in one body. The combination of the three animals is symbolic of the design of our vehicle; it is powerful like a lion, has the ability to slither through obstacles like a serpent, and handles rough terrain like a goat. Chimera is a single-body, three wheeled vehicle with excellent mobility. The design features a zero-turning radius electric drive system, an integrated power distribution board and refined software all housed within a weather-tight enclosure. Chimera exemplifies the 2006-2007 team's effort to develop a refined platform with attention to safety, quality, reliability, and durability. The team believes Chimera will continue to build upon Virginia Tech's success in IGVC.

## **2. Innovations**

Virginia Tech's vehicles have been successful in the past. An important goal of this year's team is to continue this tradition of excellence in competition. To accomplish this goal, the team determined that a major redesign of Chimera was necessary. Many aspect of the vehicle have been improved, including a totally new approach to suspension that makes the vehicle more stable and offers improved performance at higher speeds and on rougher terrain. In addition, the size of Chimera has been reduced. This will enable it to pass through denser obstacle fields and will make it easier to transport.

Another major innovation is the use of a commercial weather-tight enclosure to house all of the computational, electronic and power distribution component. This allows us to run in heavy rain, and it results in a more modular system. The enclosure can be detached from the chassis to expedite repair or replacement, or the box can be used on another vehicle.

### 3. Design Process

The design process used by the Virginia Tech Autonomous Vehicle Team is known as DDP or the Definition, Design, and Produce approach to system development. It is a custom-developed, iterative process, shown in Figure 3.1 that relies heavily on experience and previous examination of successful design solutions. The process provided organization and a methodical approach throughout the design of the vehicle.

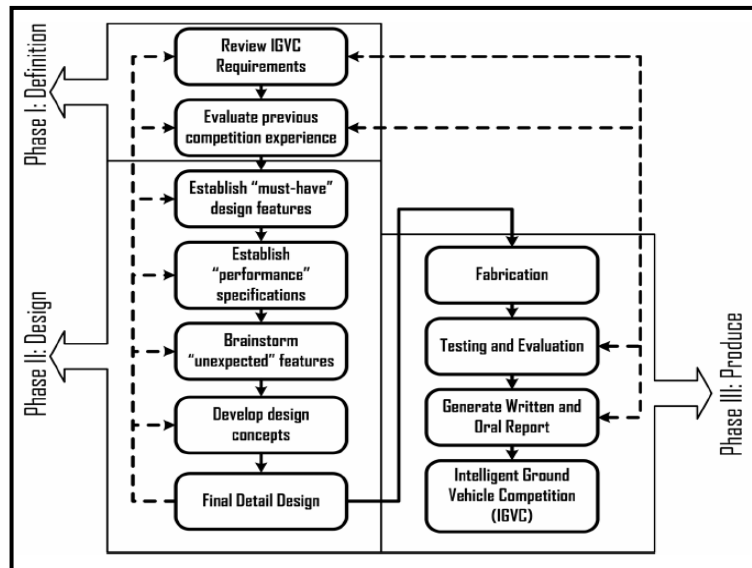


Figure 3.1: Layout of the iterative DDP design process

#### 3.1. Definition Phase

The first stage of the DDP process is the *Definition* phase. This began with a reviewing of the competition rules, defining customers and their needs, and evaluating performance of prior designs. The team identified several primary customers including the IGVC judges, the design team, project advisors, sponsors, other research and educational project teams that may use the vehicle, and Virginia Tech. This lead to several needs to be addressed by the design: (1) meet all the rules of the 15th annual IGVC, (2) provide performance and value to the customer, (3) build a reliable test platform with a small turning radius, (4) provide extended run time, (4) develop a

simple, compact system that is easy to transport and operate.

The evaluation part of the *Definition* phase was also a period of discovery where the team made modifications to Chimera. These changes were used to guide the eventual design of the current version of Chimera. Figure 3.2 illustrates the changes first explored

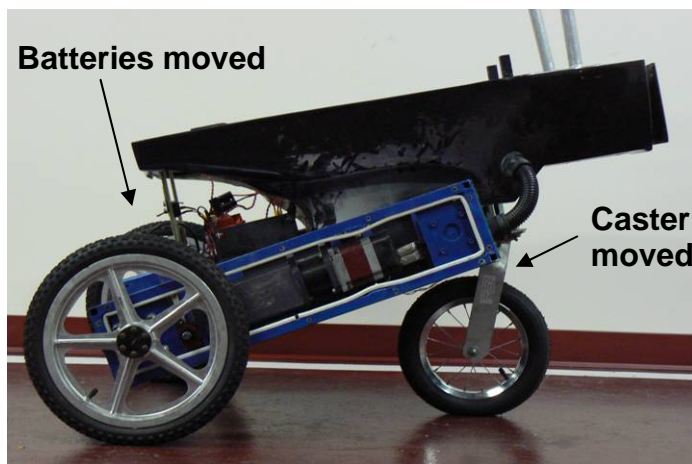


Figure 3.2: Reworked Chimera highlighting the changes explored

by the team. Significant improvement in performance was made by lowering the center of gravity and moving it toward the driven rear wheels. The caster wheel was also moved back, effectively shortening the wheel base.

### 3.2. Design Phase

In the *Design* phase, the team lists “must have”, “performance”, and “unexpected”, features that are desired in the final design of the vehicle. This year the team used the KANO design described in *Attractive Quality and Must-Be Quality Method* (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996) to aid with the *Design* phase. Figure 3.3 shows the methodology of the KANO process. This design method consists of three main components; “must haves”, “performance features” and “delighters.”

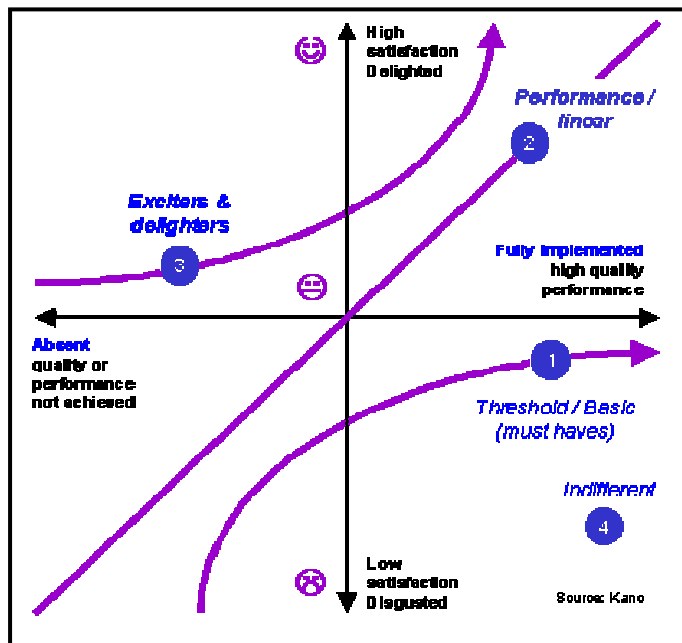


Figure 3.3: KANO design methodology

The KANO model predicts customers’ satisfactions and dissatisfactions for particular design features. The team’s goal is to design a vehicle that will perform well, exceed competition requirements, and contain delighters that will increase customer satisfaction. Delighters are features that are not needed for high-quality performance but enhance customers’ interest. Furthermore, safety, mobility, autonomy, 5 mph max speed, E-Stop, and payload space are a few “must haves” listed by the team.

### 3.3. Design Variations and Challenges

The team’s first exposure to Chimera was with the challenge to make it able to perform on par with the other award-winning vehicles at Virginia Tech. The first approach was to make as few changes as possible to improve performance. The previously mentioned modifications to the caster position and the redistribution of weight produced noticeable improvements in

dynamic performance. After reviewing specifications and determining the needs of our customers, it became apparent that a more drastic redesign would be necessary. In the redesigned Chimera vehicle, the swing-arm suspension previously used on the rear wheels has been replaced by a suspension on the single front caster. This helped to reduce the overall size, which makes the new vehicle easier to transportation and more nimble in obstacle-rich environments. The custom made fiberglass shell used on Chimera last year has been replaced by a Hammond enclosure with a NEMA 4 rating. This means that the top surface is water-tight.

### **3.4. Production Phase**

The *Production* phase of the design process consists of the manufacturing, testing, and evaluation of the vehicle. From design specifications and CAD models, the team was able to modify the vehicle's frame and place components and sensors in the most efficient locations within the enclosure. The autonomous vehicle was fabricated completely by the team. Extensive testing and evaluation of the vehicle are also important steps in the *Production* phase. The vehicle's performance is tested during comprehensive field trials. The trials also allowed for trouble shooting and debugging of the vehicle. The final step of the *Production* phase is competing in the 15<sup>th</sup> annual IGVC.

### **3.5. Team Organization**

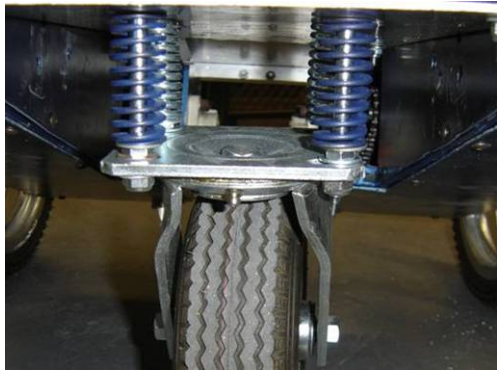
The team initially had all the members of Virginia Tech's contingent working together to improve the 2006 model of Chimera. Soon after, the students split into different teams for the vehicles with Dan McQuail, Derek Self, and Yong Kim bringing Chimera back to competition this year. Assisting the undergraduates were graduate students Jesse Farmer and Peter King, as well as the faculty advisor, Dr. Reinholtz.

## **4. Base Vehicle**

Chimera is a three-wheeled, differentially steered vehicle. The frame was fabricated from ¾" square 6063 aluminum tubing with 1/8" thick walls. The 6063 aluminum reduces magnetic interference with the digital compass and signal lines, as well as reducing the overall weight of the vehicle. Furthermore, Chimera's total weight of 200 lbs is distributed in a ratio of 45/55 between the front and rear wheels, respectively. As a result, greater traction is created from the

additional weight on the rear drive wheels. Chimera is 26 inches wide, 30 inches tall, and 30 inches long, allowing it to easily fit through a 32 inch doorway for easier transportation less hassle when trying to test.

As opposed to the swing-arm suspension of the past year, the motor boxes are rigidly bolted the vehicle's base plate. This will allow for the motor boxes to be removed for easy repair and maintenance, but removes some of the instability of having a three-wheeled vehicle

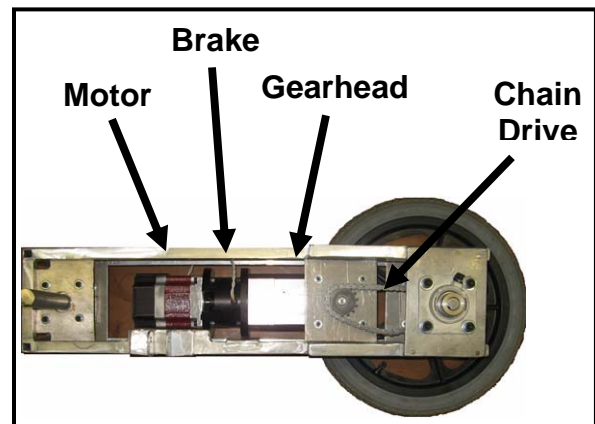


**Figure 4.1:** Suspension on the front caster

independently suspended on two wheels. The team did not want to lose the advantage of the suspension, so the front caster is now suspended. Figure 4.1 is a close up image of the suspension solution on the caster. This will have a greater sprung weight than the swing-arm suspension did and stabilize the part of the robot that has the cameras and other sensitive components. The suspension can have a maximum travel of 1.5 inches.

#### 4.1. Drive train

Each drive box on the bottom of Chimera contains a QuickSilver I-Grade 34HC-1 brushless DC servomotor. The motors have a maximum power of 0.76 horsepower at 2.03 ft-lb of torque with a continuous stall torque of 6.78 ft-lb. The motors are controlled by QuickSilver I-Grade N3 SilverNugget controllers. Directly coupled to each motor is a fail safe brake which is in turn coupled to a 10:1 reduction NEMA 34 right angle gearhead. Figure 4.2 shows the drive train and drive box design. The gearhead is connected to a custom driveshaft and wheel hub via chain and sprocket, reducing stress on the gearhead. This driveshaft is supported by two Timken polycarbonate eccentric locking bearings and connected to the wheel outside of the drive train box.



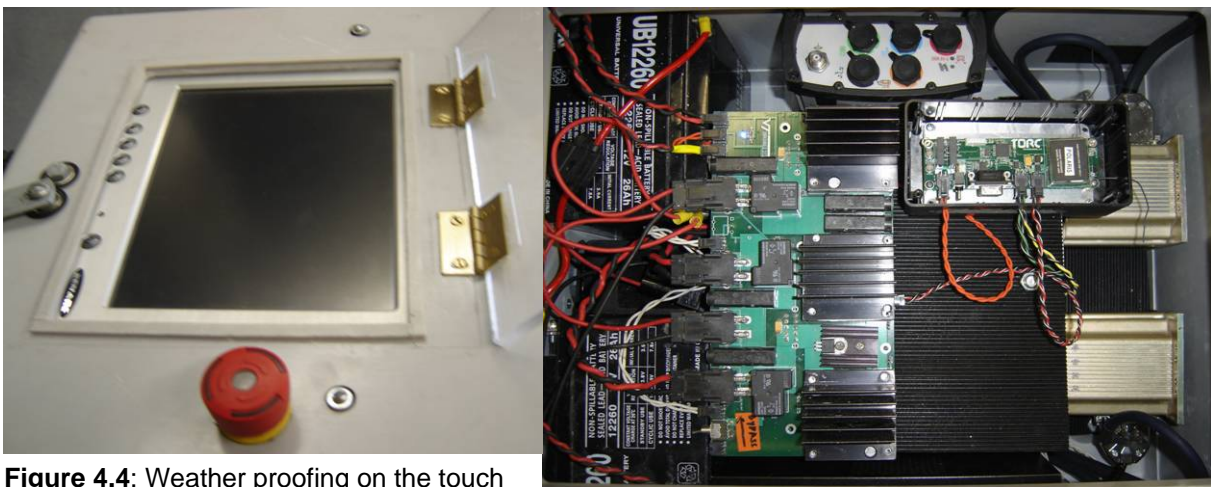
**Figure 4.2:** Motor box and drive train

## 4.2. Enclosure

All of the components that are not housed within the motor box have been placed into a Hammond watertight enclosure (figure 4.3). This enclosure is large enough to allow easy access and maintenance, but small enough to fit on Chimera's petite frame. The inside is made simple by its two-tiered design, as shown in figure 4.4. The lower tier has the larger current carrying wires and components that do not need to be reached for conventional maintenance. The upper tier houses components that need to be reached more often such as the power board and connections to the larger components such as the GPS and ITX computer. Any penetration point has been environmentally sealed to preserve the resistance to the elements. The team has put a high priority on this aspect of the design. In the past, Virginia Tech has never produced a vehicle capable of operating in more than a light rain, but Chimera's new design opens up the prospect of operation beyond a sunny day in a grassy field.



**Figure 4.3:** Enclosure on Chimera



**Figure 4.4:** Weather proofing on the touch screen and the environmentally sealed E-stop button (left) and inside the enclosure (right)

This versatility in operating environments, along with the modularity provided by the enclosure are two things that the team has identified as customer desires. It is now possible to remove the box and attach it to another platform of mobility and still be able to maintain a common system and software. In addition, a new component enclosure could be fabricated to operate with the current platform that could provide a new degree of versatility.

### **4.3. Safety**

There are several key features of Chimera that contribute to the safety of the vehicle. Solid lead acid batteries are used to reduce the risk of hazardous material spillage during operation and transportation. Fail safe brakes that engage whenever the vehicle is E-stopped are installed behind the gear head that can stop the vehicle within 6 inches at top RC speed and even hold the vehicle on aggressive inclines.

## **5. Electrical System**

The electrical system in Chimera is extremely compact and uses a minimal amount of wires. The overall electrical system is best described by breaking it up into two main sections; the power distribution and the sensor/component communication.

### **5.1. Power Distribution**

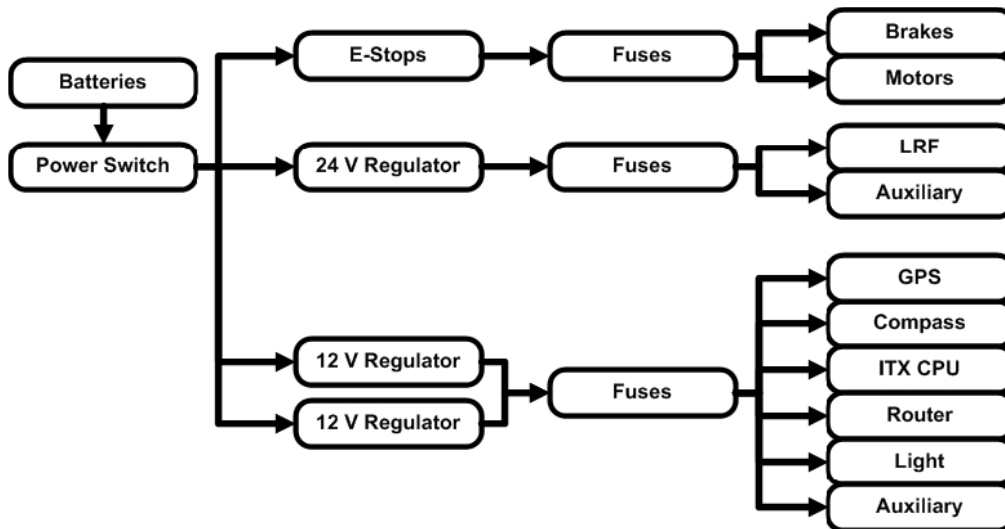
The power distribution for the vehicle is accomplished through the two custom designed circuit boards shown in Figure 5.1. These boards are stacked together in the vehicle during operation. The first board is responsible for power input and regulation. Two 12 Volt sealed lead acid batteries connected in series supply the board with 24 Volts at two separate inputs. The first input sends the 24 Volts through three DC to DC Voltage regulators; one 24 Volt regulator and two 12 Volt regulators which supply power to the second board. The second input is used to send an unregulated 24 Volts to the motors and the brakes. This power can be interrupted by a remote emergency stop or a hard wired button, triggering the brakes and immediately stopping the vehicle. The vehicle uses one main power switch to control the entire electrical system.

The second board receives regulated 12 and 24 Volts and is responsible for power distribution and monitoring. The regulated 24 Volts is distributed to the optional Laser Range Finder (LRF) and to an auxiliary connector. The regulated 12 Volts is sent to the ITX Computer,

compass, GPS, router, JAUS light, and to an auxiliary 12 Volt connector. Each of these connectors has an individual fuse to avoid damage from a power surge. The board incorporates a microcontroller, allowing sensors to be turned on and off electronically via relays. This microcontroller is also capable of monitoring the voltage that each sensor is receiving, as well as the board temperature. All this information can be monitored by the computer through an RS-232 connection. The entire power distribution system is outlined in Figure 5.2.



**Figure 5.1:** Power distribution boards: Input & Regulation (left), Distribution & Monitoring (right)








**Figure 5.2:** Chimera's power distribution system

## 5.2. Sensors, ITX Board, and System Integration

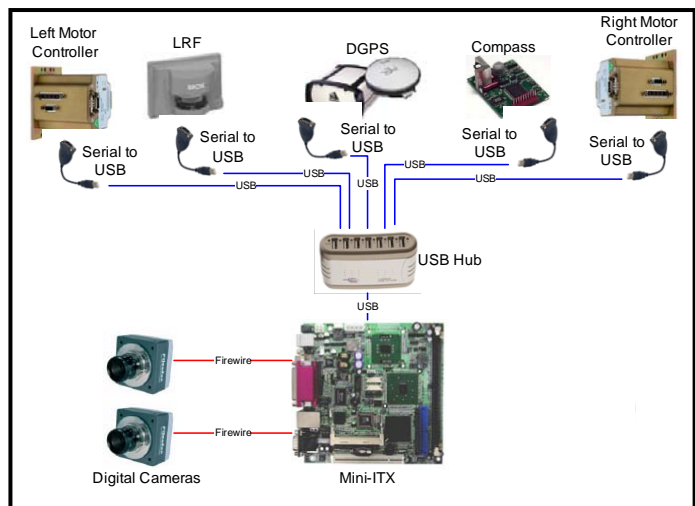
Four sensors are implemented in the design of Chimera to better perceive the vehicle's surroundings. Table 5-1 lists and describes the main sensors mounted on Chimera along with the equipped ITX board computer. Additionally, there is a touch screen located toward the rear of the vehicle to provide direct interface with the computer. This coupled with the LabVIEW graphical interface makes Chimera a user-friendly vehicle.

**Table 5-1: Summary of sensors used on Chimera**

Sensor	Description	Picture
OEM Unibrain Camera	Chimera utilizes two OEM Unibrain Fire-i board Firewire cameras with a native 640 by 480 pixel resolution and 15 frames per second (fps) update rate. The lenses are 2.1 millimeter fixed focal lenses that provide an 80.95° horizontal view angle. The cameras are used for both detecting lines as well as obstacles.	
SICK LMS-221 Laser Rangefinder	The SICK LMS-221 laser rangefinder (LRF) scans in a horizontal plane and returns the distance to obstacles within 80 meters at a resolution of 1°. The LRF is an option on Chimera, as Chimera can also use cameras to detect obstacles.	
Novatel ProPak-LB DGPS	The location of the vehicle is determined by a Novatel ProPak-LB Differential Global Positioning System (DGPS). Position information improvements are enabled by using the OmniStar HP correction service. This high accuracy service outputs 99% of all position readings within 15cm from the true position.	
PNI TCM2-20 digital compass	The PNI TCM2-20 digital compass senses vehicle heading relative to magnetic North. It is a tilt compensated instrument and is used in the Navigation challenge to determine vehicle heading. In addition, it is accurate from 0.5° to 1° depending on tilt.	
ITX board	The ITX board is a compact and inexpensive alternative to a laptop computer. The board is equipped with a Pentium M 735 processor and 1 GB RAM. In addition, the ITX board is protected by a steel ventilated case and is located in the rear of the vehicle.	

### 5.3. Sensor/Component Communication

An important goal of the electrical team was to minimize the number of wires routed through the vehicle. The digital cameras are connected directly to the ITX via Firewire, while the motors, compass, GPS, and LRF are equipped with serial to USB converters. USB cables from each sensor are then connected to a USB hub at the front of the vehicle. By using the USB hub, only a single USB cable is required to connect the sensor suite to the ITX board computer. The serial to USB converters allow for the sensors and motors to be disconnected individually as needed for quick removal and repair. A diagram of the communication setup is illustrated in Figure 5.3.



**Figure 5.3: Sensor/Component communication diagram**

## 5.4. Remote Control & E-Stop

New to the vehicle this year is a digitally enhanced remote control unit. Using the Spektrum DX6 technology, the transmitter will digitally scan its frequency range to find two open channels and synch up with the receiver. This dynamic selection allows for multiple vehicles to be operating at the same time without fear of interference. The E-Stop was developed by TORC Technologies, a corporate partner made up of former Virginia Tech students, many of



**Figure 5.4:** RC receiver shown with a quarter for sizing

whom were involved with the IGVC. Figure 5.4 shows the receiver for the remote unit. The E-Stop has a range greater than the line of sight. In addition to the traditional power-cutting function, the new E-Stop includes a pause feature that will bring the vehicle to a stop without

cutting off power to the motor circuitry. This is an incredibly useful feature when used in conjunction with the on board serial port. Now the software on the vehicle monitors the state of the remote E-Stop, which allows the user to pause the vehicle remotely for use in debugging.

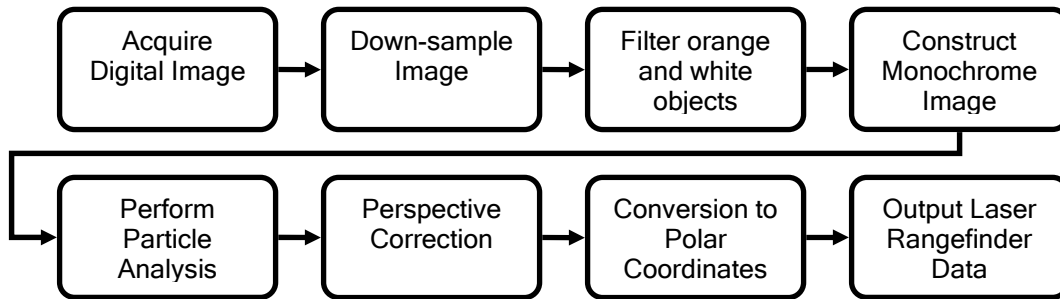
## 6. Software

The software design of Chimera is an evolution of previous competition software with a focus on value engineering. Eliminating the laser range finder and detecting obstacles solely with the computer vision system proved to be challenging, but the result are also immensely rewarding. The two-camera arrangement used to provide an expanded field of view also allowed the team to lower the camera masts, eliminating the typically large masts found on most other vehicles. The result is a much less expensive, more compact and lower profile vehicle with all the functional capabilities found in our earlier designs.

### 6.1. Obstacle Detection and Avoidance

The Autonomous Challenge and Navigation Challenge both depend on the detection and avoidance of obstacles. Chimera uses a vision-based obstacle detector, eliminating the weight and cost associated with the traditional laser rangefinder. Through processing and manipulation, images may be used to simulate the functionality of a laser rangefinder. Two cameras are used to

expand the field of view, but this is not an application of stereo vision. Figure 6.1 shows the steps used to detect obstacles in an image.



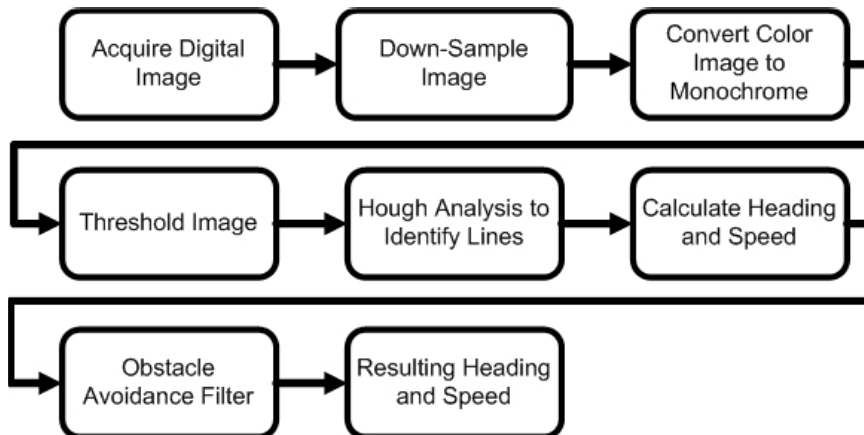
**Figure 6.1:** Process used to detect obstacles using an image

The raw images from the cameras are first down-sampled to reduce processing time. Each image is then filtered to isolate orange and white objects; from this, a monochrome image is constructed. Using geometric criteria such as minimum area and aspect ratio, a particle analysis identifies objects within each monochrome image. Next, a perspective correction algorithm then uses the position of the objects within each image to calculate where they are in relation to the vehicle. The resulting set of coordinates mimics the output of a laser range finder and the results are output as an array of polar coordinates spaced  $1^\circ$  apart. The left and right images are processed separately. These the two sets of polar coordinates are then combined and sent to the obstacle avoidance software. It will appear as LRF data to the software so that it will integrate seamlessly.

## 6.2. Autonomous Challenge

The Autonomous Challenge software uses two Unibrain firewire cameras to navigate through the course. The steps to complete this task are shown in Figure 6.2. First, the cameras acquire a color image of the course in front of the vehicle. These images are resized from 640x480 pixels to 160x120 to reduce processing time. After the image has been resized, it is converted to a monochrome image and thresholded to separate the white lines from the rest of the image. A Hough transform is then performed on the thresholded image to identify the most dominant line in the image. Line characteristics, such as orientation and score, are then passed to a decision tree where heading and speed are determined.

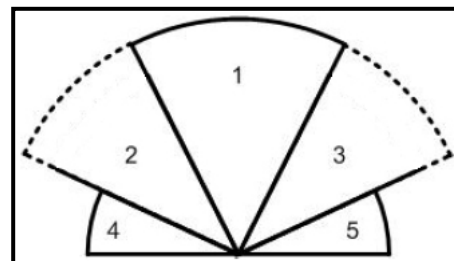
Once heading and speed are determined, this information is processed through an obstacle avoidance filter. This step combines the heading and speed with the information about any obstacles in front of the vehicle. A heading is selected that is closest to the one suggested by the line following algorithm while avoiding the obstacles.



**Figure 6.2:** Autonomous Challenge Software Algorithm

### 6.3. Navigation Challenge

The Navigation Challenge software takes input from the differential GPS for positioning, digital compass for heading, and cameras for obstacle detection. The vehicle first computes a heading directly to the waypoint from the vehicle’s current position. It will then compare the ideal heading with the obstacles present in its field of view. Figure 6.3 shows the five regions which are used to calculate the actual heading of the vehicle. Once a heading has been computed, motion commands are sent to the motors to move the vehicle.



**Figure 6.3:** Obstacle processing regions used in the Navigation Challenge.

There is always the possibility that the course is constructed in such a way that the GPS signal is lost, or weakened to the point where the GPS receiver is unable to compute a solution. In this situation, the vehicle relies on its motor encoders to approximate its position until it reaches an area where the GPS signal can be re-acquired.

## **6.4. JAUS Challenge**

Virginia Tech has been exposed to JAUS messages for over two years. Previous students have developed a LabVIEW toolkit that can parse the JAUS header and handle many of the defined JAUS messages. Having worked with JAUS in the previous competition, the learning that took place was mostly reviewing the specific messages needed in the reference architecture.

Level 1 of the JAUS competition was completed last year and has remained unchanged. As dictated by the rules, the team wrote a separate JAUS component that will be running on the vehicle node to respond to the global waypoint query after validation of the message header. An Operator Control Unit (OCU) from last year was also modified to be able to send the query and interpret the response. There were no problems implementing JAUS on Chimera.

## **7. Predicted & Actual Performance**

Several factors were calculated for the vehicle's predicted performance. These factors include; speed, reaction time, runtime, battery life, ramp climbing ability, obstacle detection distance, traps and potholes, and accuracy of navigation waypoints. The predicted performance was compared to the actual performance after many trial runs.

### **7.1. Speed**

QuickSilver brushless DC motors with 10:1 reduction gear heads have a no load rotational speed of 3000 rotations per minute. When using 14" tires, the vehicle can obtain a maximum rated speed of 14.2 mph. In testing, the vehicle was able to achieve speeds of about six mph on a level surface. However, the motor speed is limited to a maximum speed of five mph through motor-control software for competition.

### **7.2. Reaction Time**

The reaction time of the vehicle is based on the computational time for a single cycle of software repetition during the autonomous challenge. A summary of the results is shown in Table 7.1. The table shows the maximum time for each process. With a total maximum cycle time of 115 ms, the software will update at a minimum rate of approximately 9 Hz. This rate will increase if there are few obstacles near the vehicle or under other simplified cases of navigation.

Reaction times for the navigation challenge are approximately 15 Hz. Reduced complexity in the processes of waypoint navigation is the main factor in the increased reaction speed.

**Table 7.1:** Autonomous Challenge Software Cycle Times

Process	Time (ms)
Vision based Line Analysis	36
Vision based Obstacle Detection	46
Obstacle Avoidance	33
Total	115

### 7.3. Runtime

Table 7.2 lists the vehicle’s components and power requirements. These estimates are determined from the maximum power consumption specifications listed or experimental results. All power is supplied by two sealed lead acid batteries in series with 26 amp hour capacity. The vehicle run time is determined by the battery life. From the data listed Chimera has an estimated runtime of over 3 hours.

**Table 7.2:** Sensor/Component Power Requirements

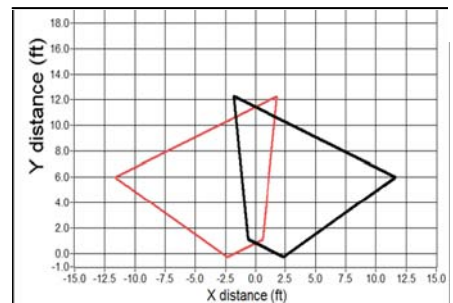
Component	Voltage (volts)	Current (amps)	Power(watts)
Compass	12	.02	0.24
GPS	12	.53	6.36
ITX	12	5	60
Motors	24	5	120
Brakes	24	.42	10.08
		<b>Total Watts</b>	196.68

### 7.4. Ramp Climbing Ability

During competition the vehicle is expected to clear a 15% grade (8.5 degrees) ramp. However, for future applications it is valuable for the vehicle to climb even larger ramps. During testing it was possible to drive the vehicle up an incline of 26% grade (15 degrees).

### 7.5. Obstacle Detection Distance

During the autonomous and navigation challenges, obstacles will be detected using two Unibrain Fire-i cameras. Each camera has a usable range of 10 ft. Figure 7.1 shows the overlap of the views from each camera and the “blank spots.” Chimera also has the option for a laser



**Figure 7.1:** Field of view of each camera

range finder. The scanning laser rangefinder has a range of 80 meters (262.5 feet), but the current navigation software ignores obstacles that are further than three meters (9.84 feet) away from the front of the vehicle. This range is sufficient to allow consideration of multiple obstacles and obstacle trends prior to determining the best forward path of the vehicle.

## **7.6. Dead Ends, Traps and Potholes**

The best way to prevent dead ends and traps is by efficient path planning in the software. However, in the event of a dead end or a trap situation, the software is designed to perform a zero-radius turn until the vehicle is extricated. This software feature along with the single body design of Chimera allows it to turn away from obstacles and find a clear path. Large white regions, designating a pothole, that are encountered during the Autonomous challenge are detected by the two Firewire cameras and are treated as obstacles.

## **7.7. Accuracy of Arrival at Navigation Waypoints**

Testing showed Chimera can consistently navigate to GPS waypoints to within less than one meter, given good quality GPS signals and a reliable differential correction. Specifically, the Novatel GPS unit provides for sub decimeter accuracy when coupled with OmniStar HP correction service.

## **7.8. Accuracy of Headway and Lateral Deviation Maintenance**

The digital compass displays a  $\pm 0.5^\circ$  to  $\pm 1^\circ$  heading accuracy depending on the amount of tilt experienced by the unit. The GPS unit is able to track the global position of Chimera within centimeters of its actual position and continually augments the navigation algorithm to assure the lateral deviation is minimized.

## **8. Vehicle Cost**

Throughout the design and fabrication of Chimera, the team was able to attain donations and discounts from a number of companies and vendors. Thanks to their support the development cost of Chimera was greatly minimized. In addition, we were able to share some equipment with other research teams at Virginia Tech and previous autonomous vehicles that are not competing in the 15th Annual IGVC. Table 8.1 provides a cost summary for Chimera.

Upgrading to the full laser rangefinder equipped version adds more than \$5,000 to the manufacturing cost of the system.

**Table 8.1:** Cost breakdown of Chimera

<b>Part Description</b>	<b>Retail Cost</b>	<b>Cost to Team</b>
Digital Compass	\$700.00	\$0.00
Cameras (x2)	\$269.00	\$219.00
GPS	\$8,000.00	\$0.00
Motors (x2)	\$1,290.00	\$1,075.00
Gearheads (x2)	\$2,356.00	\$2,142.00
Brakes (x2)	\$548.00	\$498.00
Caster Wheel	\$30.00	\$30.00
Skyway Wheels	\$53.00	\$53.00
6063 Aluminum	\$82.00	\$82.00
Batteries (x2)	\$113.00	\$113.00
Battery Charger	\$159.00	\$159.00
Hammond Enclosure	\$92.00	\$0.00
Computer System	\$735.00	\$735.00
Electrical System Components	\$432.00	\$432.00
<b>Total</b>	<b>\$14,859.00</b>	<b>\$5,319</b>

## 9. Conclusion

Chimera is an autonomous vehicle designed, fabricated, and tested by a team of undergraduate students at Virginia Tech. Its innovative and original design has been modified to emphasize the characteristics that separate Chimera from previous Virginia Tech vehicles. The durable construction, reliable electronics, and refined software contribute to Chimera’s overall performance. The use of removable motor boxes for the drive train and a simple, integrated printed circuit board electronics system allow for easy troubleshooting and future upgrades. Furthermore, creating a vehicle that can run in more than a light drizzle, we have created a versatile vehicle that can satisfy more of our customers. By following a rigorous design process, the team was able to design and manufacture a fully autonomous vehicle that we expect to perform at a high level in all three events at the 15<sup>th</sup> annual IGVC.