IGVC 2008

μCERATOPS

Design Report

Team Members	Faculty advisors
Kevin Barry *(Graduate)* Mohammed Horani *(Graduate)* Phuong Nguyen *(Graduate)* Cheng-Lung Lee *(Graduate)* Li-yi Lu *(Graduate)* Keyur Patel *(Undergraduate)* Ray Slowik *(Undergraduate)* Bryan Thomas *(Graduate)* Preethi Venkat *(Graduate)*	Dr. Mohan Krishnan Dr. Mark Paulik Dr. Nassif Rayess

Faculty Advisor Statement:

We certify that the engineering design in this vehicle undertaken by the student team, consisting of both undergraduate and graduate students, is significant and qualifies for course credits in senior design and in the Master's program respectively.

Dr. Krishnan/ Dr. Paulik/ Dr. Rayess______________________________

May 12, 2008

1. Introduction

For the 2008 Intelligent Ground Vehicle Competition (IGVC), the University of Detroit Mercy (UDM) presents the all new µCERATOPS. This vehicle is the product of an extended 2-year joint effort of a diverse group of UDM Electrical & Computer and Mechanical Engineering students. The mechanical architecture of µCERATOPS is based on THOR (our successful 2006 entry). The vehicle team adopted the following mission: "The 2008 UDM IGVC team will improve upon the achievements of the 2006 and 2007 teams to design and construct a highly competitive autonomous ground vehicle." The team put in roughly 8 months of focused effort that resulted in this robust high performance articulated vehicle.

2. Design Process

2.1. Design Methodology

Designing an entry for an annual performance-based competition, such as the IGVC, is an exercise in continuous improvement based on the lessons learnt from the previous years. UDM's two previous IGVC entries shown in Figure 1 - THOR in 2006 and Capacitops in 2007 - have been our most successful vehicles to date, with both placing third overall (the Lescoe Grand Award). As can be seen from Figure 1, THOR had an articulated 4-wheeled, 2-body structure while Capacitops was a more conventional 3-wheeled, differential drive vehicle.

Figure 1:
Thor (2006)
Capacitops (2007)

While the dynamics of an articulated chassis exceeded the competition requirements, THOR's performance in 2006 was largely limited by its own specific mechanical constraints, such as not being able to turn at higher speeds, rather than by its software algorithms. It was decided then to undertake an effort to build a new improved articulated vehicle. It was realized that due to the complexities associated with designing and building a sophisticated articulated chassis completely in-house, it would have to be undertaken over multiple years. The result is the 2008 entry, µCERATOPS.

While THOR was not limited by its software capabilities, in a competition of this nature software intelligence is the frontier that needs to be continually advanced. New algorithmic sophistication needs to be matched up with an execution speed that enables the vehicle to drive as fast in its course environment as its mechanical dynamics will permit. So a decision was made to design and construct a 3-wheel differential drive vehicle called Capacitops for IGVC 2007 that would serve as an interim platform to continue software innovations. Due to its simpler mechanical architecture it was possible to complete the job within a year. So in a sense μCERATOPS (shown in the cover picture) is the progeny of THOR and Capacitops. The continuity provided by the faculty advisors and good documentation has enabled the exercise of continuous improvement strategies over multiple years, a key aspect of product engineering.

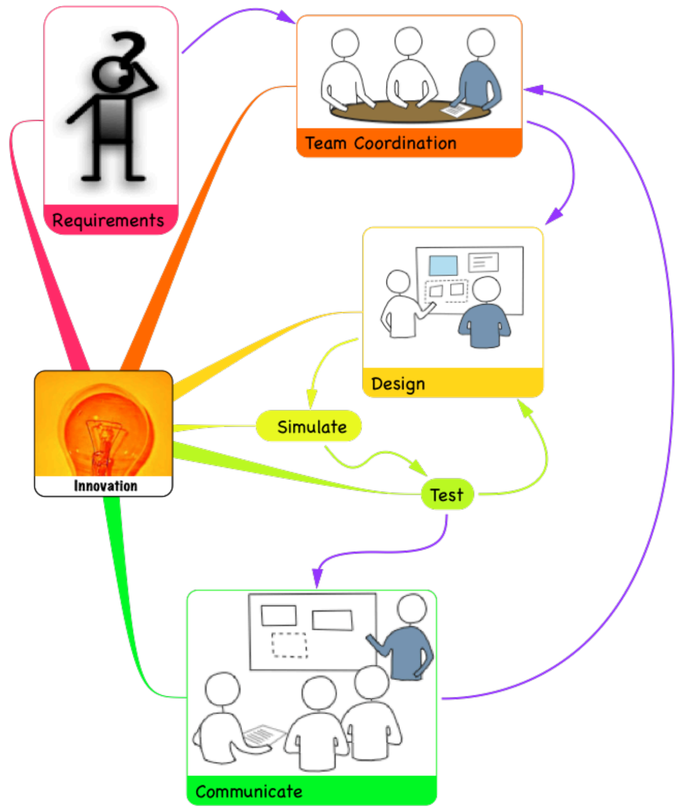

Figure 2: Iterative Design Process Followed

The team concurrently conducted the mechanical, electrical, and software design and implementation tasks. Facilitating an iterative design process was a meeting and reporting structure as shown in Figure 2 to ensure that all of the mechanical, electrical/electronic, and software systems would optimally integrate with each other. It consisted of three components: a) weekly design oral review meetings with faculty advisors to provide task updates, identify problems and formulate solution strategies, b) weekly (as well as on a ad-hoc needs basis) sub-team meetings to discuss specific design and implementation issues, and c) weekly 3-hour lab periods to execute the design strategies with full team attendance to implement the concurrent design philosophy.

A standard product development methodology was used in designing and setting the performance specifications for the vehicle. The team used a technique called the Quality Function Deployment (QFD) which relates customer requirements and competition benchmarking to produce design specifications (e.g. ratios of vehicle weight to wheel torque and wheel base to center of gravity height). With these design specifications, the team used Catia solid modeling software to flesh out the design and ensure geometric fit and kinematic compatibility. In parallel, the team used a Design Failure Mode and Effects Analysis (DFMEA) process in order to identify subsystems with high Risk Priority Numbers (RPN) and to investigate preemptive remedies. Among the failure modes with high RPN were loss of wheel traction and breaking of the 2DOF joint. The traction failure mode was addressed by changing the bicycle tires used in prior designs to wider, more aggressive wheelchair tires. Also, the stiffness of the 2DOF joint was improved by using press fit precision bearings and larger cross-sectional area. The result has been a superb design that materialized into a very competitive vehicle.

2.2. Team Organization

The composition and organization of the 2008 IGVC team is shown in Figure 3. Team μCERATOPS is a multi-level group comprising seven graduates and two undergraduate students. The team has devoted approximately 2500 hours towards the development of μCERATOPS.

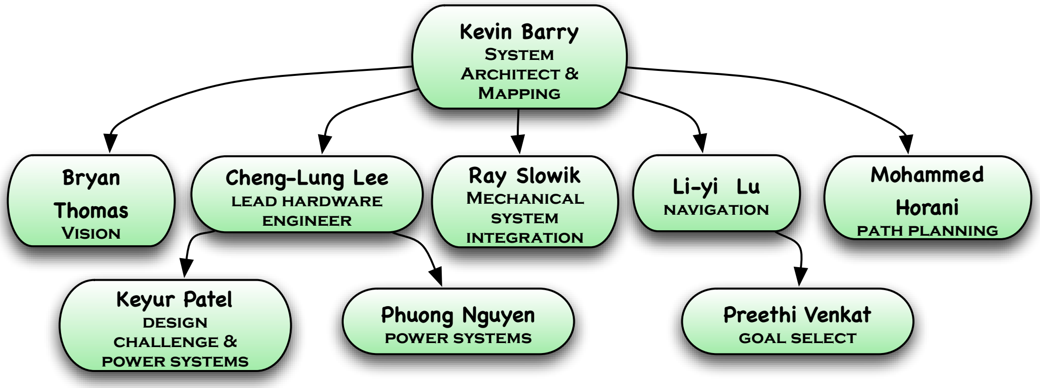

Figure 3: Team Organizational Chart

3. Design Innovations

μCERATOPS builds on and incorporates design features developed in earlier UDM IGVC entries including:

- Diagnostic microcontroller-based remote controls (Warrior 2005);
- Articulated two-body chassis and intelligent power system electronics (THOR-2006);
- Surface mounted PCB electronics, integrated smart-motor controllers and distributed-computer system, Player-Stage/Matlab operation and simulation environment (Capacitops 2007).

μCERATOPS is also a completely new vehicle based on a two-body industrial-grade welded aluminum chassis which introduces multiple noteworthy innovations. These are listed here and presented in greater detail in Sections 4 & 5 later in the report. For ease of identification, an innovation-icon (lightbulb) is used to indicate when innovations are being discussed in this document.

Mapping, Path Planning, and Navigation Suite: A group of three integrated modules which include dynamic, confidence-based mapping, D* path planning, and VFH* navigation are introduced. These are used in the autonomous and navigation challenge software.

Kalman-based vehicle pose estimation: Vehicle global coordinates and direction are derived by fusing data from DGPS, wheel encoders and vehicle compass. This allows GPS outages to be managed and vehicle and obstacle locations to be accurately mapped.

Dynamic Camera and LADAR Image Calibration: Arbitrary cameras, lens, and mounting configurations are automatically analyzed and corrected for optical aberration, perspective distortion, and vehicle coordinate calibration. Thus, a geometrically correct camera/LADAR registered image can be generated without external calibration fixtures.

4-Quadrant Kalman-Stabilized Hough Transform: Lane locations are stabilized in the image frames by applying a Kalman filter to the Hough Transform calculated in each of the four image quadrants. Lane-quadrant boundary intersections are used to assign confidence measures.

4. Vehicle Design

4.1. Mechanical Systems

Vehicle architecture is, perhaps, the highest-value strategic design decision. As Figure 4 shows, the team chose an articulated platform with a differential drive front end and a free wheeling trailer. The degree-of-freedom afforded by the 2-body design enables the vehicle to maneuver better in cluttered environments as compared to other vehicle configurations. The center of gravity is low and laterally symmetric and the associated 60:40 weight distribution between the front and rear bodies contributes to drive traction and vehicle stability. The mechanical systems are primarily concerned with how the vehicle is held together and moves (chassis), as well as how power is generated and transferred to the ground (drive train). Also important is the geometric placement of subsystems for proper weight distribution, ease of accessibility, and the efficient use of space.

4.1.1. Chassis

μCERATOPS' chassis is a welded backbone of heavy gauge aluminum covered with thin aluminum side panels. The mast is made up of extruded aluminum bars that are thicker and wider than the predecessor vehicles to reduce camera vibration. The vehicle is 28 inches wide, 72 inches tall (including the camera mast), and 39 inches long (not including the LADAR), and weighs approximately 375 pounds when fully loaded. The use of right-angle gearboxes in the drivetrain narrows the vehicle (see Figure 5). This along with the articulated property permits it to be more easily driven through a standard doorway. The layout of the drive train components can be seen in Figure 5. The overall vehicle layout achieves an approximate 60:40 weight distribution (front to rear). Placing 60% of the total gross vehicle weight in the front body is necessary to generate sufficient traction between the front wheels and the ground.

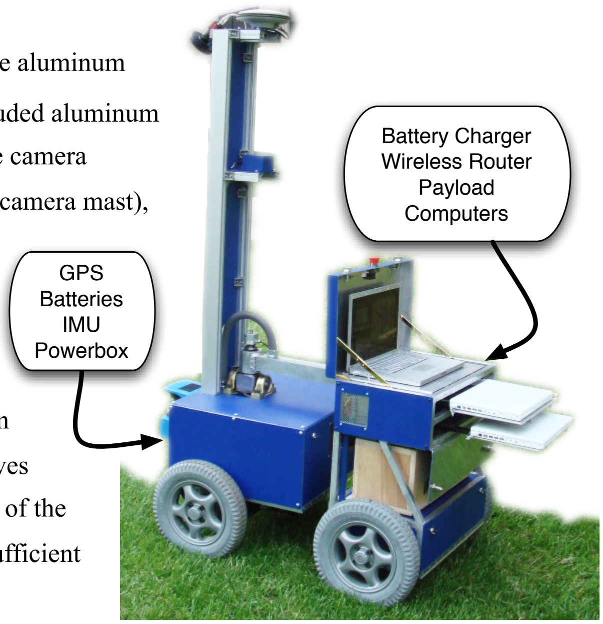

Figure 4: Vehicle Front body

4.1.2. Drive Train

Periodically, UDM sets its sights on designing and constructing a new vehicle for the IGVC. One area in which each team experiences great difficulty with the mechanical design is the assembly of the drive train for the new vehicle. To remedy this, μCERATOPS incorporates a modular drive train requirement into its design philosophy. This also helps if a critical failure occurs in a drive train subsystem.

As seen in Figure 5, the vehicle's drive train comprises two 3/4-HP Quicksilver 34HC-2 motors, coupled to 10:1 planetary 90 degree gear heads, which are connected to two 14-in. wheels by lovejoy couplings.

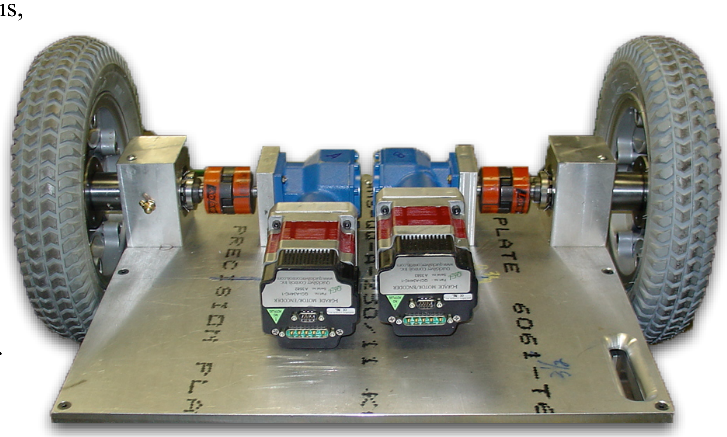

Figure 5: Drive train

4.2. Electrical and Electronics Systems

4.2.1. Power Distribution System

μCERATOPS derives its power from 4 Powersonic gel-sealed batteries of which two are rated for 35 Ah and two for 18 Ah. Under normal operating conditions these batteries will allow the vehicle to be operated for about 5 hours. A 480W DC battery charger positioned inside the vehicle can be powered from the AC mains to fully recharge the batteries in approximately 2.5 hours.

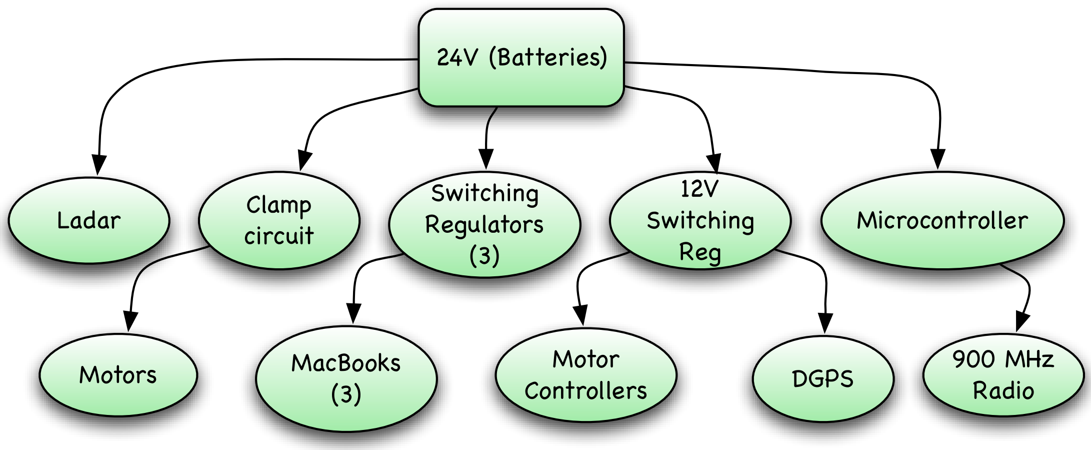

Figure 6: Power Distribution System

The power necessary to properly operate the vehicle and its electrical/electronic sub-systems is distributed via a custom-designed printed circuit board (PCB) to implement the power distribution scheme shown in Figure 6. The 24V supply provides power for a LADAR unit, two motors, filtered by a clamping circuit; four switching regulators provide power to a WIFI router, cooling fans and up to 3 laptops. The 16.5V 6A regulators provide power for the laptops. Power is delivered to a DGPS and the motor controllers via a 3A-12V regulator. The 12V regulator also feeds into a 5V and a 3.3V linear regulator, which regulates the appropriate voltage supply to the microcontroller and the 900 MHz radio.

To help ensure that μCERATOPS is safe, reliable, durable, and easily serviceable, several special features have been incorporated into the power distribution system. The PCB is designed such that high power components are isolated from lower power components. Fuses are strategically positioned on the PCB to prevent electrical damage due to unexpected current surges. The incorporation of high efficiency switching regulators provides stable outputs with low ripple. In addition, these regulators have been designed to protect the PCB from low battery-voltage levels, short circuiting, and overheating, thereby extending the life cycle of the circuitry. A clamper circuit is connected to the motor power supply to absorb the motor's back EMF. The status of the power box is conveyed via a series of panel-mounted light emitting diodes (LEDs). Finally, vehicle-wide systems integration is addressed by the use of a real-time current and voltage monitoring system that sends status information from the power box to the main laptop through a USB connection. Thus, if a problem occurs, its source can be potentially quickly located and diagnosed.

4.2.2. Sensor System

µCERATOPS incorporates four sensors into its compact design: a camera, a LADAR unit, a DGPS, and a digital compass. In order for the vehicle to perform at its optimal level, great care was exerted to ensure the continual, proper and accurate operation of these devices. Each sensor is mounted in a waterproof case and secured to the vehicle in such a manner that effects of normal vehicle motion are minimized. At the same time, the mounting arrangements for each sensor subsystem are designed to facilitate their easy removal and replacement if it becomes necessary. The following is a brief description of the four sensors that are used by µCERATOPS as shown in Figure 7.

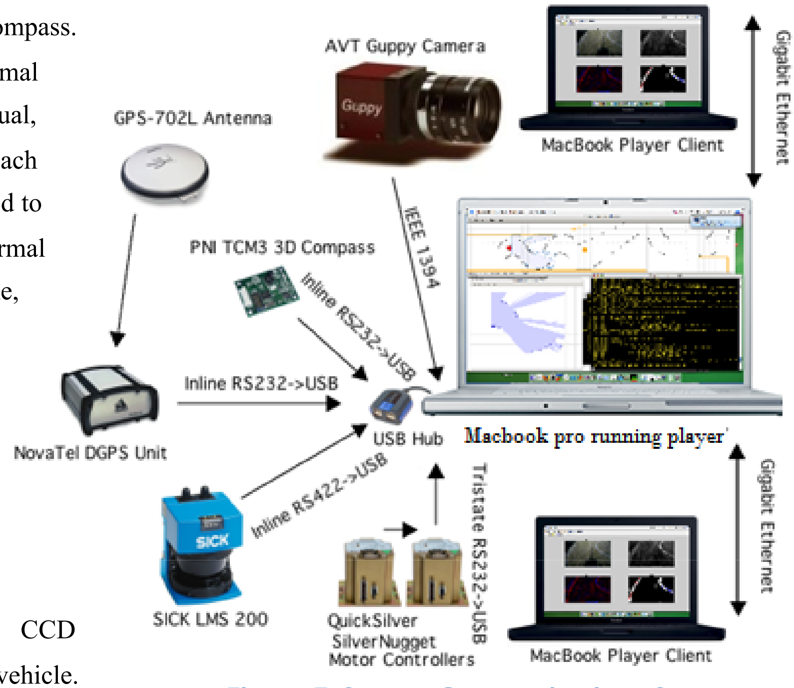

Figure 7: System Communications Structure

Camera: The AVT Guppy F-033C 1/3" CCD camera was selected as the vision sensor for this vehicle. This camera uses the IIDC IEEE 1394 protocol to relay images, which is ideal for machine vision applications, because the frames are uncompressed and various options such as region of interest and lookup tables can be set and executed in hardware. Also, the camera's progressive scanning and high frame rates minimize motion blurring. The CS-Mount design enables the camera to accept very wide angle lenses which provides a field-of-view adjustable between 144.2° and 79.4°. A wider angle increases the effective image area and makes navigation heuristics easier to implement.

LADAR: The SICK LMS200 LADAR unit was employed for the purposes of obstacle detection. The unit is capable of collecting data over a 180° field-of-view with 0.5° resolution and a range of 8m. µCERATOPS uses a 75Hz scanning rate which, at this resolution, requires a 500Kbps data connection. To accomplish this, an RS422-to-USB adapter was constructed to connect the LADAR to the computer.

DGPS: To obtain positioning data in the Navigation Challenge, Novatel's ProPak-LBplus DGPS system was selected. The DGPS antenna is mounted to the top of the vehicle's mast while the receiver is securely positioned inside the chassis. Using Omnistar HP's DGPS system, the signal is corrected to a level of $\pm$ 0.1m accuracy. This system provides data at a rate of 20Hz, which is adequate for µCERATOPS speed and desired performance.

Digital compass: A PNI TCM3 digital compass was integrated into the vehicle to help determine vehicle heading. This compass provides a heading accuracy of 0.5° and updates at 20 Hz, which is sufficient for the vehicle's speed and desired performance.

4.2.3. Remote Control & E-Stop Systems

Although µCERATOPS must be capable of navigating itself in competition, incorporation of a remote control facilitates manual operation of the vehicle. The remote control, which can operate in one of two modes (PC or RC), comprises a custom-designed PCB housed within a durable Futaba remote control shell. When the remote control is set to operate in PC mode, it transfers control of the motors to the PowerBook. If placed in RC mode, the operator is capable of manually driving the vehicle.

The transceivers that are used in μCERATOPS' design are Aerocomm AC4490-200A transceivers. Although the vehicle is only required to be controlled from a maximum distance of 50ft, with the implementation of the aforementioned transceivers, the vehicle is capable of being controlled from nearly a mile away.

A twist-to-release remote E-Stop button is integrated into the remote control unit. As an added measure of security we transmit encrypted data over a spread spectrum wireless link for two way communication between the AGV and remote.

4.2.4. Electrical and Electronics Communication System

The various electrical and electronics systems were interfaced in the manner illustrated in Figure 7. The AVT Guppy is connected via Firewire to the MacBook Pro. This connection provides the control interface and frame-streaming interfaces (IIDC), as well as power (unregulated 12 V). The DGPS system is connected to the computer through a USB interface using an inline RS-232-to-USB adapter. The SICK LMS200 LADAR is connected to the computer via a custom inline RS-422-to-USB converter. The PNI TCM3 digital compass uses RS-232 and requires 5 V at 20mA for operation. Finally, all the laptops are networked via gigabit Ethernet, which is fast enough to transfer all sensor data between machines, in real-time.

5. Development Environment, Processor Architecture & Software

The aspects of this project that are most critical to μCERATOPS' performance are the overall software development environment, the processor architecture, and the design of the algorithms for scene interpretation and navigation in the Autonomous and Navigation Challenges of the competition.

5.1 Software Development Environment

As introduced in our 2007 IGVC entry, ***Player/Stage**,* an open-source, Unix-based (Linux or Mac OS X) robotic software system which serves as an interface between computers and the vehicle. *Player* offers standard interfaces for typical sets of robotic peripherals (LADAR, cameras, motors, etc.) while *Stage* is a set of drivers that simulate standard hardware. By creating *Player*-compatible drivers for all of μCERATOPS' hardware, we are able to work in a modular environment that facilitates and simplifies robot development. *Stage* permits software to be fully simulated by allowing algorithms to talk to simulated sensor and actuator interfaces for retrieving data, sending velocity commands, and plotting the vehicle path. An added advantage is that the *Player/Stage* arrangement also promotes future code reuse through its modularity. Furthermore, efficient wrappers have been written that allow Matlab to serve as a system client providing a wealth of proven code resources and an interactive development environment.

5.2 Multi-Computer Networking

In order to increase the overall frame processing rate for the vehicle, μCERATOPS can divide and pipeline its computational tasks amongst up to three laptop computers (6 cores). Setting up this distributed computing architecture is facilitated by the move to the *Player/Stage* environment. The first computer, a MacBook Pro, is designated solely for the purpose of running vision algorithms, while a second MacBook is responsible for accepting the data from all of the vehicle's sensors, implementing heuristics on the vision results and navigating the vehicle. In addition, since this computer is still relatively unburdened, a portion of the vision algorithm chain (Hough transform) is performed on the MacBook as well. This allows the computer to process the next frame concurrently, and thus reduce the time needed to completely process the frame.

The architecture can be easily extended in the future to incorporate additional laptops as needed to further improve the cycle time and/or to accommodate further enhancements in vehicle intelligence.

5.3 Mapping, Path Planning and Navigation

This year μCERATOPS implements an integrated multipart Mapping, Path Planning and Navigation Suite. This Suite is designed to provide a single, integrated, solution to the navigation problem, while simultaneously providing reusable individual software modules.

µTopMapping

The main use of map making for autonomous robots is to allow for advanced path planning. With a global map, the optimal path between any two points can be determined. But mapping also has other uses which include offline debugging and improved simulation with physically derived maps. µTopMapping provides a real-time, in-progress map, while the vehicle drives. This can be used by a dynamic path-planner to plan a route for the vehicle to take.

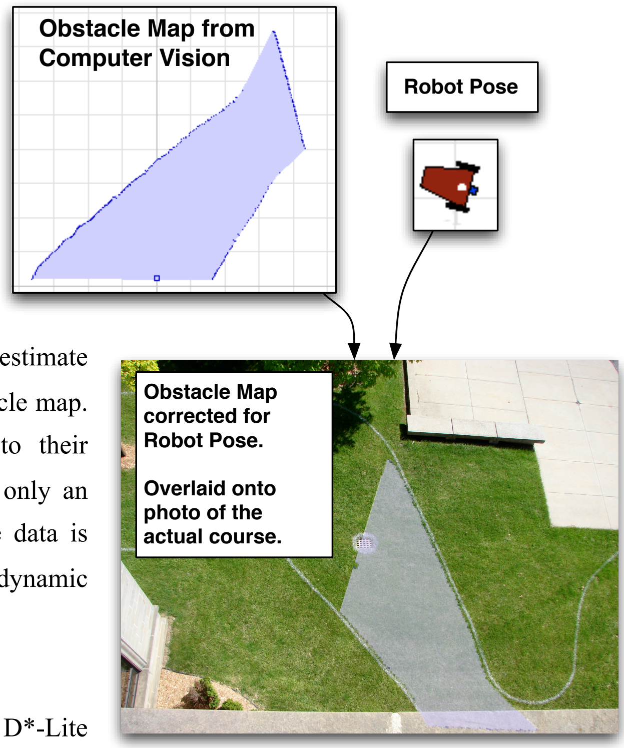

Figure 9: Local obstacle data to map

µTopMapping works by using a vehicle pose (X, Y, Yaw) estimate and confidence measure, as well as an estimate of the local obstacle map. Using matrix transforms, local obstacles can be translated to their respective global positions. The global positions are of course only an estimate, and have an associated confidence measure. As more data is gathered, confidence is increased or decreased which, allows for dynamic and erroneous data to be analyzed and treated.

µTopPlanner

Path Planning on μCERATOPS is implemented using the D*-Lite algorithm. D*-Lite examines a partial global map, such as one created by µTopMapping, and plans a path between two points. As the map grows to include more data, D*-Lite replans the path, to ensure that the proposed path is always the optimal path, given all available data. Once µTopPlanner has determined a path, waypoints are generated every 3 meters. These waypoints are sent to µTopNav.

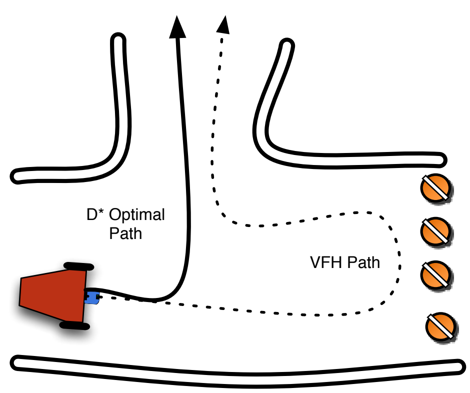

Figure 10: Optimal Path versus VFH Path

µTopNav

Local Navigation is done using the VFH* algorithm, which is an enhancement to the VFH+ algorithm. VFH uses a local polar histogram, composed of obstacle density versus direction of vehicle steering. The graph to the right shows a polar obstacle map, with the red sectors considered blocked and the green sectors considered passable. The graph in Figure 11 shows an example of a local polar histogram. In the histogram (Figure 12), the blocked sectors are blue. In addition, the threshold shown on the histogram, indicates how blocked or passable sectors are chosen. The destination goal is represented by the red line in the figure, however, in the situation depicted, the destination is behind an obstacle. The VFH algorithm then choses to travel in the direction marked with the pink line so as to drive towards the destination but avoid nearby obstacles.

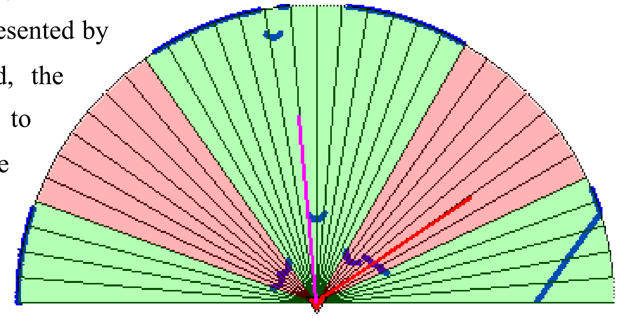

Figure 11: LADAR data with VFH Sectors

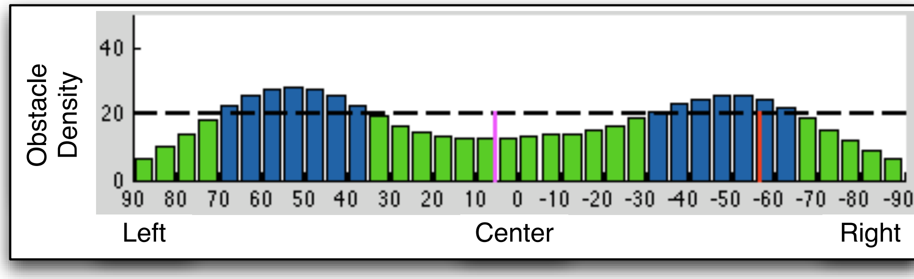

Figure 12: Histogram used to determine blocked sectors

VFH* expands on the basic VFH and VFH+ algorithms by adding look-ahead functionality. This means that after picking a target angle, the VFH* algorithm simulates that decision and evaluates if the decision was good or not. This prevents getting caught in traps. Because µTopNav is primarily used by µTopPlanner, some of the look-ahead is redundant. However, the global map can take time to update, so it is possible for µTopPlanner to miss a newly discovered trap, in which case VFH* will still prevent the robot from entering the trap.

5.4 Dynamic Lens Correction and Camera/LADAR Calibration

The wide angle lenses commonly used for robotic vehicle systems are subject to serious barrel distortions and geometric aberrations. Furthermore, camera mounting height, angle and direction dramatically affect image plane geometry and world/vehicle coordinate correspondence. Thus it is necessary to develop a fixture or external calibration map (T-squares, fixed reference images etc.) to calibrate the camera system so that measurements taken from the 2-D camera image plane can be mapped to the vehicle world coordinate frame. This is often a tedious process which needs to be repeated if the camera is jostled or misaligned due to vehicle vibrations over rough terrain. An automated and dynamic camera calibration system has been implemented for µCERATOPS . This system utilizes the LADAR system scan of obstacles in the field of view and a series of transforms to develop an accurate association between the two imaging systems. Furthermore, if a simple calibrated one-meter square object is placed in the field of view, lens distortion and inverse perspective transformations are computed and included in the image transform operation sequence.

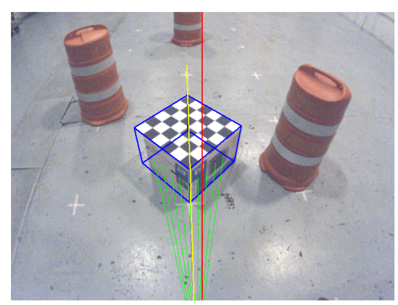

Figure 13:
Camera Calibration Object

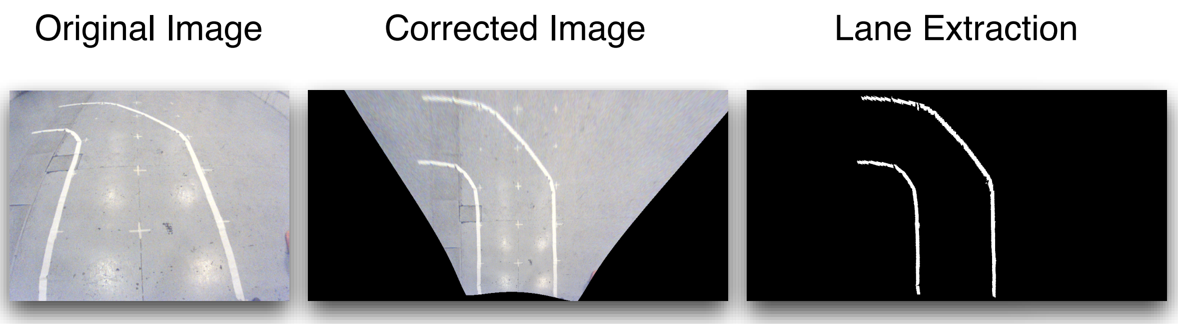

Figure 14: Example of image correction

5.5 Kalman-based Vehicle Pose Estimation

A Kalman Filter was implemented to estimate Vehicle Pose. This filter makes use of the DGPS, the digital compass, and the motor encoders. This allows GPS outages to be managed and provides an pose estimate to be used by the mapping software.

5.6 Software: Autonomous Challenge

The software for the Autonomous Challenge can be broken into three main parts. Machine Vision, Goal Selection, and Navigation. Though we actually run all of these tasks in parallel, taking advantage of the multi-computer/multi-core system architecture, the system can still be explained sequentially as each part provides data for the next.

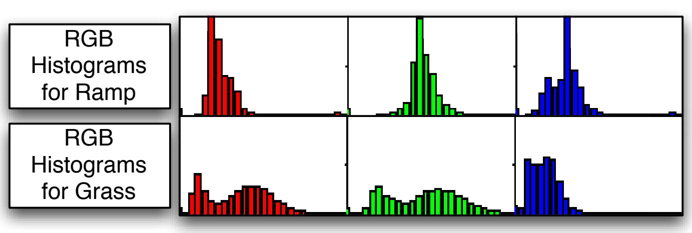

Figure 15: Color histograms

The Machine Vision used on μCERATOPS works by first acquiring a color image from the camera. Then color histograms are analyzed to determine the content of the image (Lane lines on grass, Ramp, Sandpit, Etc).

Once the content is known, a specific optimal-contrast algorithm is applied to provide a gray scale image that emphasizes the lane lines against the background. An edge-detecting filter is run over this grayscale image. The filter emphasizes the start (rising edge, displayed in red) and the end (falling edge, displayed in blue) of the lane lines. Because the approximate width of the lane lines is known (~3 inches, according to IGVC 2008 Rules), geometrically-paired rising and falling edges can be associated with high-confidence with lane-line locations.

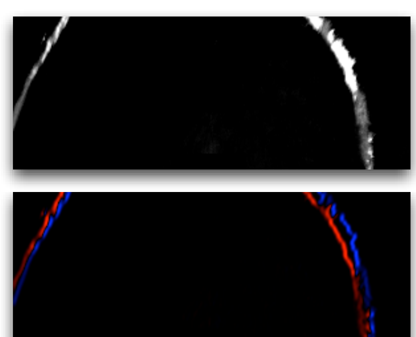

Figure 16: Optimal-Contrast and Edge Detection

Next, the edge image is divided into 4-quadrants and a Hough Transform is computed for each to allow us to track highly curved lanes. Imaging artifacts due to glare, shadows, and camera movement can cause lane estimation errors. To stabilize the final lane images we implement Kalman filters to track and predict lane locations in each of the 4 quadrants. Finally, the lane-to-quadrant intersection patterns are analyzed to group lane segments into complete lanes (see Figure 17). These lines are then converted into an obstacle map for the obstacle-avoidance navigation software to use.

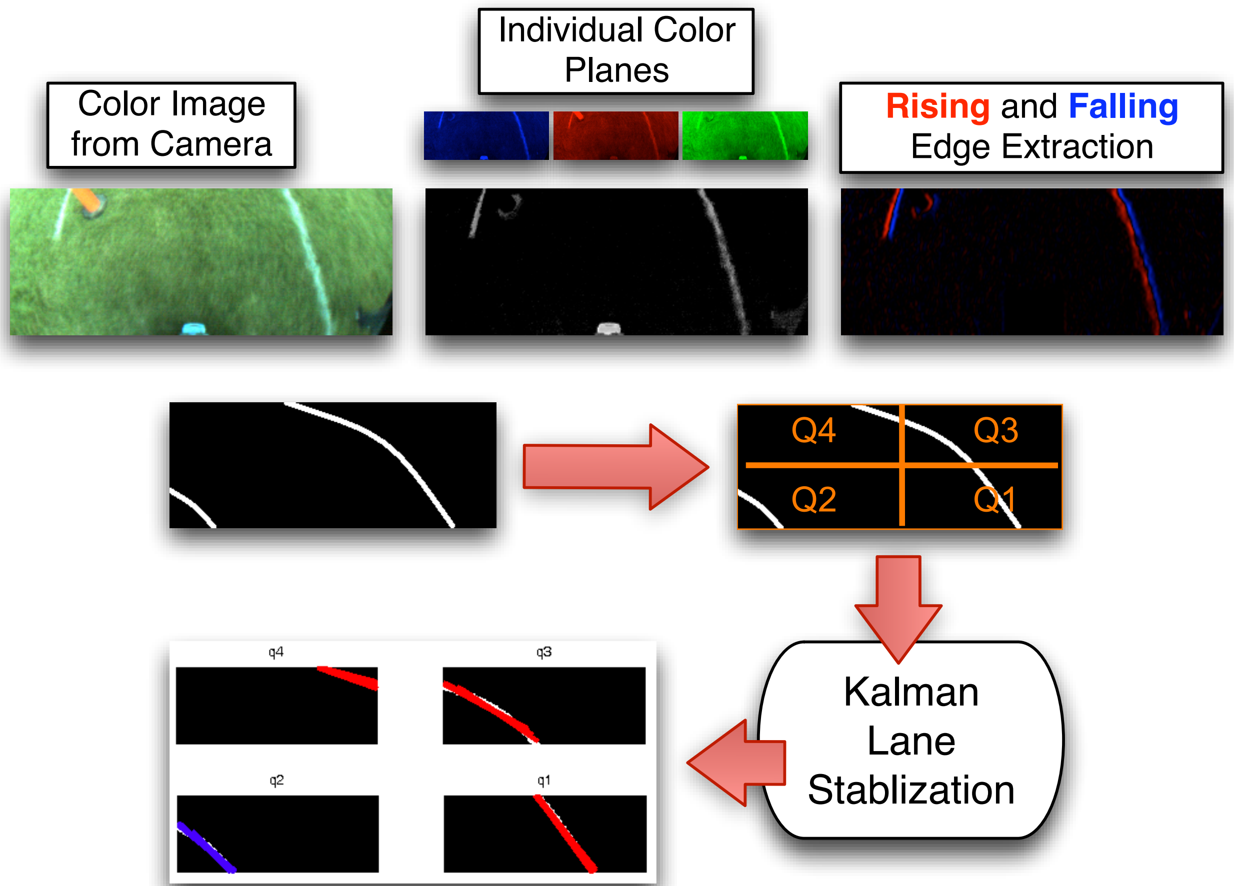

Figure 17: Diagnostic Screen for the Machine Vision software

The goal selection algorithm is concerned with determining the "forward" direction. For situations like the Navigation Challenge, this is relatively easy, as forward is towards the next waypoint. However in the autonomous challenge, the forward direction is less easy to determine. In complex obstacle arrangements, such as a switchback, the VFH algorithm can easily let a vehicle turn around. By analyzing the switchback and various "trap" scenarios we decided to address the goal problem by defining the forward direction based on the 4-meter directional history. That is, by identifying "forward" using this history, the vehicle becomes insensitive to local goal redirections due to obstacle avoidance and maintains a goal which pulls the vehicle consistently "forward" through even complex obstacle fields.

To implement this algorithm we record our position over time. Then a forward facing vector is computed by "looking back" a fixed distance, mirroring this reverse vector. Even in awkward situations, such as the one shown on the right, the vehicle still knows which direction is forward. This algorithm works very well for switchback-like obstacles. However, heuristics are needed for complex lane-line situations, such as dashed lines and sharp corners. In these situations the output of the Machine Vision block is analyzed to bias the forward goal direction appropriately.

Finally, the Mapping, Path Planning and Navigation Suite is notified of the forward direction to chose the optimal path, and maneuver the vehicle along it.

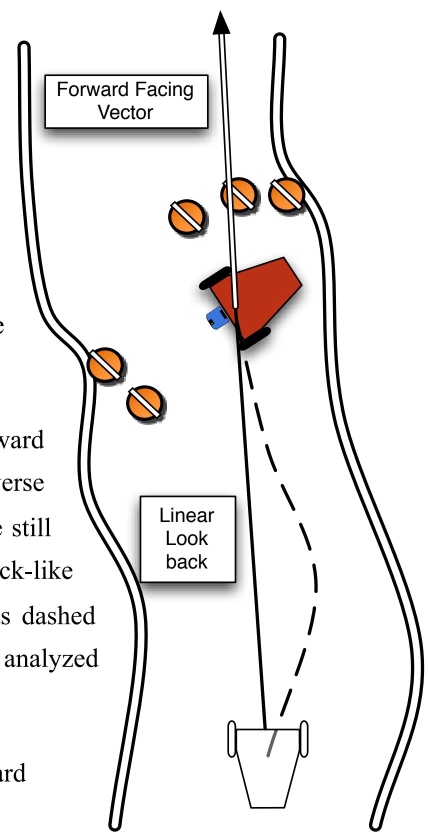

Figure 18: Example of Forward Facing Vector

5.7. Software: Navigation Challenge

For the Navigation Challenge the vehicle must autonomously navigate to several waypoints in an obstacle field. To fulfill this objective, μCERATOPS utilizes our previously mentioned Mapping, Path Planning, Navigation Suite. By taking advantage of this Suite, the only additional software needed for the Navigation Challenge is a program which determines the optimal waypoint and calls the Mapping, Path Planning, Navigation Suite with the chosen waypoint as the goal.

5.8. Software: JAUS Challenge

This year UDM's μCERATOPS will compete in the JAUS Challenge. The purpose of this challenge is to encourage exposure and familiarity with JAUS. To demonstrate familiarity, teams must implement basic JAUS compliance by receiving and transmitting JAUS messages. The μCERATOPS team approached this task by first investigating the protocol using the publicly available Reference Architecture documents from the JAUS Working Group.

In an attempt to leverage the success of other groups, we investigated the OpenJAUS project, an open-source implementation of JAUS. Though this initially looked promising, it turned out to be difficult to integrate with our Player-based robotic system. Additionally, it is a very large and complex project, which would take a long time to master.

Because we decided against using OpenJAUS, a custom implementation had to be designed. The μCERATOPS team decided that the best implementation would be simple and lightweight, facilitating easy use in the IGVC JAUS Challenge. But to further engage in the spirit of the competition, we decided our code would be released as open-source software so that it would have value beyond the IGVC. To meet these needs, we decided to implement a *Player* driver for the JAUS protocol.

Though this requires a bit more work on the JAUS side of things, it requires less work for other users to take advantage of the JAUS protocol.

The *Player* driver created by the μCERATOPS team can be used stand-alone for very basic JAUS compliance, such as responding to "pings". The real value, however, comes from the integration with *Player*, which means the driver publishes a standard *Player* message, that any client can easily listen and respond to.

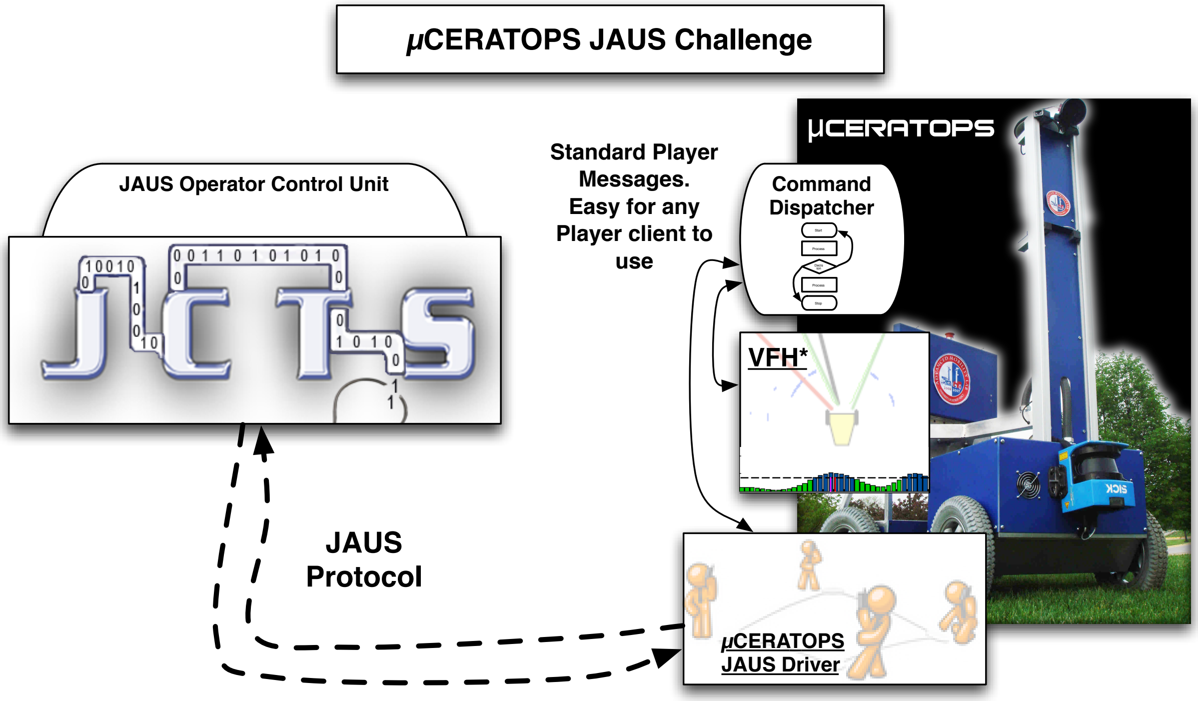

Figure 19: Diagram of JAUS Connectivity

5.9. Simulation

As stated earlier, a software simulator was developed to accommodate the testing and evaluation of μCERATOPS' performance in environments similar to those expected to be encountered during the Autonomous Challenge and the Navigation Challenge at the IGVC. A substantial benefit comes from the use of such a simulation system - the team can rapidly construct highly complex situations and quickly test performance, making any necessary algorithm adjustments or modifications.

Stage, which is a part of *Player*, is capable of simulating the LADAR, the motors and encoders. By using a separate MATLAB program, we added the ability to simulate image processing data as well. Using custom *Player* bindings for MATLAB, the lane map was retrieved and a set of operations generated an image similar to what the vehicle's image processing would create in the real world. Finally, the same data was captured from the final image and sent back to *Player*, where client applications retrieved the data and made decisions accordingly. With this enhancement, all algorithms can be tested for both the Autonomous Challenge and the Navigation Challenge.

6. System Integration

Naturally, this project was divided into subtasks to facilitate development and assignment of tasks to individuals. However, this then requires a process to integrate all the parts into a single, working product. From the beginning, the team decided to adopt the Player/Stage platform. This provides a standardized modular interface that can be reused on future vehicles. All hardware interaction was done through Player's common interface. This meant that all algorithmic code, being a Player client, could be developed and tested using the Stage driver set.

To facilitate software system integration we designed a couple of test courses on campus containing features anticipated on the actual IGVC course. Figure 20 shows one of the text courses.

Figure 20: Test course at University of Detroit Mercy

Physical integration of all the subsystems to fit inside the vehicle was a concern, but a minor one due to the design philosophy adopted. The vehicle was modeled extensively using CATIA. Subsequently a mock-up was built to facilitate evaluation of component and cabling access. Mock-ups were also built to represent the anticipated physical sizes of the electrical/electronic sub-systems. These were then positioned inside the vehicle mock-up in a way that took cable routing into account. Iterative adjustments were made to complete the physical design. After the vehicle chassis was built, placement, mounting, and interconnection of the subsystems for testing was completed in a relatively uneventful manner.

7. Predicted Performance

7.1. Speed

Given the vehicle's 14-inch wheels and 10:1 gear ratio, μCERATOPS' motors are capable of theoretically driving the vehicle at 6.6 mph at their power-optimal speed of 1600 rpm. Vehicle testing has yielded results close to this estimate. In accordance with IGVC regulations, however, the maximum speed of the vehicle has been limited to 5 mph by integrating speed control into the vehicle's software.

7.2. Ramp climbing ability

Based upon the rated torque output of the motors, the size of the vehicle's wheels and the selected gearing, calculations and testing have revealed that μCERATOPS has ample torque to ascend an incline with a gradient of up to 30% (16.7°) without stalling. According to the IGVC rules, the vehicle needs only to be capable of climbing a 15% (8.5^0) incline.

7.3. Reaction times

For the Autonomous Challenge, it takes approximately 50 ms (20 frames per second) to run the system algorithms (based on a physical timing estimates). At 5 mph, which is the maximum permitted speed, this cycle time translates to a decision being made for every ~11cm of travel. In the Navigation Challenge, the algorithms take approximately 30 ms to complete. At the 5 mph speed limit, that cycle time equates to a decision made every 7.5 cm.

7.4. Battery life

Device	Normal Operating Conditions			Worst-Case Conditions		
	Voltage [V]	Current [A]	Power [W]	Voltage [V]	Current [A]	Power [W]
LADAR	24	0.6	14.4	24	0.6	14.4
DGPS	12	0.2	2.4	12	0.2	2.4
Compass (USB)	5	0.02	0.1	5	0.02	0.1
Camera (FireWire)	12	0.17	2.04	12	0.17	2.04
Laptops	16.5	2.1	34.65	16.5	4.8	79.2
Motors/Controllers	24	6	144	24	20	480
Total (Watts)			**197.59**			**578.14**

Table 1. Power Consumed by Vehicle Components.

Table 1 lists the power consumed by the vehicle components under normal as well as worst-case operating conditions. Using these values, it is expected that the vehicle will be able to run for approximately 5 hours under normal operating conditions and slightly less than 2 hours under the worst-case conditions. These estimates have been borne out experimentally.

7.5. Distance at which obstacles are detected

The vehicle's LADAR unit is configured for a range of 8 meters. The camera is set up for a somewhat shorter range to eliminate glare and horizon effects (approximately 5 meters).

7.6. Accuracy of arrival at navigation waypoints

The waypoints at the competition will be designed as concentric 2m and 1m radius circles centered on the GPS coordinates of the waypoints. μCERATOPS' DGPS system provides an accuracy of $\pm$ 0.1 meters in DGPS mode, and $\pm$ 0.01 meters in real-time kinematic (RTK) mode. It can be seen that this accuracy is more than sufficient. This has also been demonstrated both via simulation and actual experimentation. Additionally, the use of Kalman-based sensor data integration allows positional accuracy to be maintained even with modest DGPS outages.

8. Safety, Reliability, and Durability

As with any product, it is not enough to perform well. One must also provide a strong and durable product that is capable of operating safely and reliably. μCERATOPS includes several features that not only contribute to its performance, but also increase its safety, reliability, and durability. Three E-Stop systems are implemented to ensure that the vehicle can be stopped safely, quickly, and reliably. These are the soft, hard, and remote E-Stops which are controlled by the microcontroller, the manual mechanical button on the rear of the vehicle, and the remote control, respectively. The vehicle is weatherproofed such that light rain will not cause electrical short circuits. This involves the incorporation of NEMA enclosures for the power distribution system, as well as a shell that surrounds the vehicle chassis and the various components. Also, both notebooks are housed in a shelving system that is placed inside the vehicle, between the battery charger and the top of the chassis. This efficient use of space serves as a means of protecting the notebooks while still providing easy accessibility. The shelves are lined with a cushion as well, to protect the notebooks from vibrations that result from vehicle movement. All electrical circuits are carefully fused to prevent electrical damage. Furthermore, individual currents and voltages are monitored in all circuits. Diagnostic software and LED indicator systems were developed so faults could be quickly identified and repaired. A wire harness is used for the safe routing of all electrical wires for power distribution, and sealed gel-cell batteries are utilized to eliminate potential safety problems associated with chemical leakage.

μCERATOPS implements two-levels of "watchdogs" on the motor controllers to prevent unintended vehicle operation. The first watchdog is a hardware watchdog, which prevents vehicle operation in the event of a hardware failure. Every 500ms the computer must send a specific message to the motor controller. If the message is not sent, an E-Stop is triggered. In the event of a hardware failure or computer crash, the message will not be received by the controllers and the vehicle will stop. The second watchdog is a software watchdog, to prevent vehicle operation in the event of a software failure. The motor driver will expect a new velocity command from the software algorithm (usually the Mapping, Path Planning and Navigation Suite) at least every 2 seconds. If such a command is not received, the driver will halt the motors until a new command is received.9. Vehicle Cost

The cost breakdown for the development of this vehicle is provided in Table 2.

Description	Retail Cost	Team Cost	Comments
Frame/Body	$586	$586	Some volunteer work was involved
Drive Train (Motors, Gearboxes, Accessories)	$3,944	$3,944	Purchased new
Front Wheels (4)	$600	$0	Donated by Invacare
Batteries (4)	$200	$200	Purchased New
Battery Charger	$149	$149	Purchased New
Power PCB and Components	$172	$122	
Remote PCB and Components	$304	$104	Transceiver donated by Aerocomm
Camera, Lens, Adapter	$937	$898	Used from previous vehicle
LADAR	$5,500	$5,500	Used from previous vehicle
DGPS and Antenna	$6,000	$6,000	Used from previous vehicle
Digital Compass	$1,096	$0	Donated by PNI Corporation
MacBook pro	$1,702	$1,702	Purchased New
MacBook (2)	$2,200	$2,200	Purchased New
Total	**$23,390**	**$21,405**	**Savings of $1,985**

Table 2: Breakdown of Component Costs

10. Conclusion

The UDM team is excited at the potential of μCERATOPS for this year's IGVC. Its performance in trial runs on the test courses on campus is very promising. We expect to have our best finish yet in 2008!