University of Detroit Mercy

Proudly Presents

CAPACITOPS

IGVC 2007

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- Christopher Fox
- James Hadley
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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. Mohan Krishnan Dr. Mark Paulik Dr. Nassif Rayess

1. Introduction

The University of Detroit Mercy (UDM) is proud to present CAPACITOPS, a newly-designed vehicle, as its entry in the 2007 IGVC. Exuding the power, strength, and robustness that are often associated with dinosaurs, the name is a natural. The vehicle team adopted the following mission: "*The 2007 UDM IGVC team will fully utilize and expand upon the engineering knowledge and experiences of its members and the 2006 team to design and construct the most competitive autonomous ground vehicle, for as little cost as possible.*" Keeping this objective in mind, the team put in six months of intense effort to design and build this rugged, compact, and innovative vehicle known as CAPACITOPS.

2. Design Process

2.1. Design Methodology

Designing an entry for an annual performance-based competition, such as the IGVC, is an exercise in continuity and refinement, based on the lessons learnt from the previous years. A critical evaluation of our prior entries, coupled with competition benchmarking and an honest assessment of the abilities of the team, should form a vector in the direction that leads to the greatest success.

UDM's entry (THOR) in the 2006 IGVC was immensely successful as it placed third overall in the grand awards. It featured an articulated two-body structure, a state-of-the-art sensor package, a vision scheme characterized by multiple parallel algorithms for redundancy, and a navigation strategy using computational intelligence techniques. An analysis of its performance revealed that the articulated chassis is superior for the competition requirements. However, it requires an intricate understanding of its unconventional dynamics, especially at higher speeds. In fact, THOR's performance was largely limited by its mechanical abilities, not by its image processing or navigation software. Thus a strategic decision was made to build a

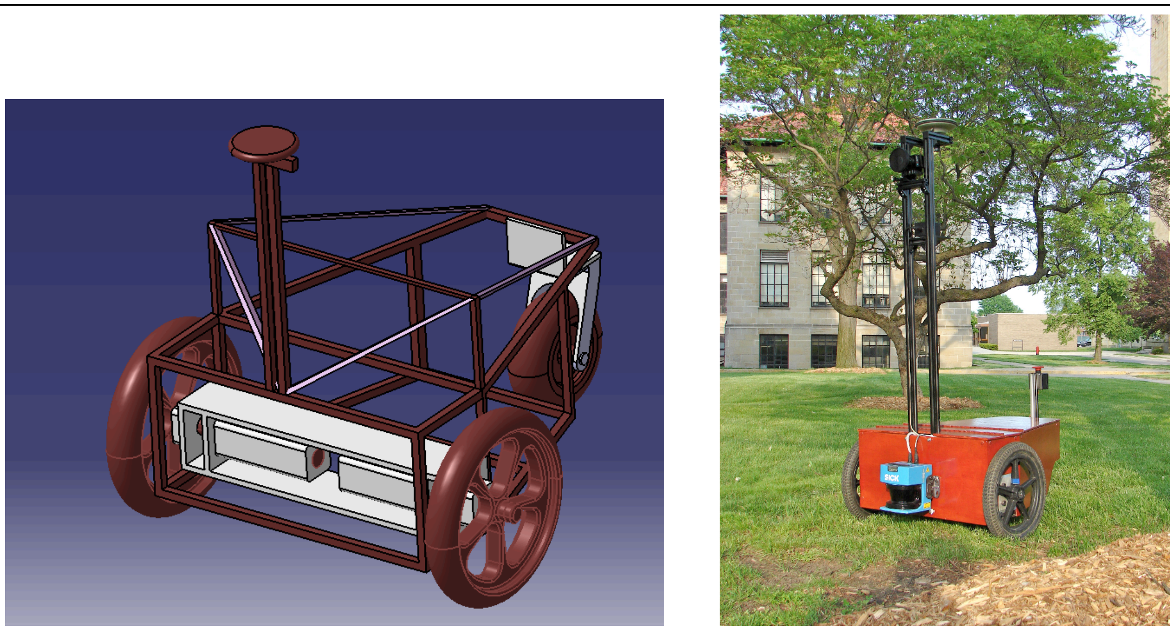

Figure 1. Design Rendering and Finished Vehicle

conventional mechanical platform for the 2007 IGVC (three-wheeled, tank-steering, free caster in the back as shown in Figure 1). This decision leverages the composition and talents of the 2007 student class; their outstanding electrical and computer engineering abilities enable us to push the envelope in the electrical hardware and software (vision, heuristics and navigation) areas. Another team that includes both Mechanical and Electrical engineers is currently working on an improved articulated platform – the successor to THOR – for entry into the 2008 IGVC. It is expected that the improvements incorporated into CAPACITOPS can be transferred to that vehicle in the 2008 competition.

The design process followed has been in place for sometime now in connection with our earlier vehicle efforts. The team concurrently conducted the mechanical, electrical, and software design and implementation. Weekly design meetings were held to ensure that all of these components would successfully integrate with each other. Iterative refinements of each sub-system/component design were driven by feedback gathered at these meetings. Figure 2 depicts the iterative design process adopted.

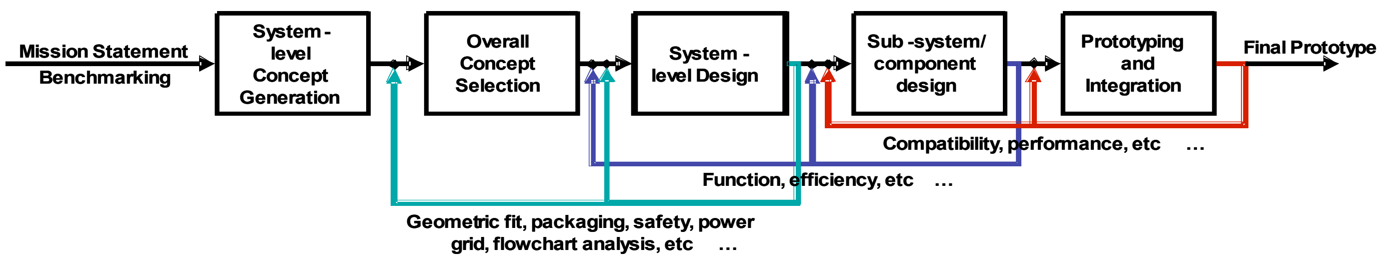

Figure 2. Iterative Design Process Followed

2.2. Team Organization

The organization of the 2007 IGVC team is shown in Figure 3. As it illustrates, Team CAPACITOPS is a multi-level group comprising 4 graduate EE and 6 undergraduate EE students. The mechanical aspects of the vehicle were addressed with the help of design advice from our ME faculty advisor, highly skilled manufacturing services from the ME technician, Mr. Chris Sassak, and volunteer help from 3 ME students. The team has devoted approximately 3300 hours towards the development of CAPACITOPS.

3. Design Innovations

Building upon the level of excellence that was achieved by THOR last year, CAPACITOPS includes a number of innovations in the design of its mechanical and electrical systems, as well as in its software. These are itemized below and explained in greater detail in Sections 4 & 5 later in the report.

Software development environment:

- Migration to *Player/Stage*—with a Matlab-Client architecture, with tremendous attendant benefits: *Player/Stage* is open-source software that facilitates robot application development.

Vision and navigation strategy:

- A-priori scene assessment utilizing color and geometrical analysis were used to develop an algorithm that combines morphological processing, color-based segmentation, directional gradient-based lane qualification and color plane-based contrast enhancement.

- An approach that combines the individual benefits of MATLAB and OpenCV (which is an open source library of programs for computer vision) was adopted for the development of the computationally efficient image processing algorithms.
- A sophisticated heuristics module for scene interpretation which utilizes path history and scanning has been implemented.

Processor architecture:

- A networked multi-computer architecture was developed to enable the division of software processing tasks and hence to increase the operational cycle time.

Simulation environment:

- Through significant value additions to *Stage* (which works with *Player*), a sophisticated simulation environment was enabled to facilitate algorithm development and testing.

Mechanical:

- A new modular drive train was designed that can be transferred to future vehicles.
- The vehicle mast was designed to be removable to facilitate vehicle transportability.

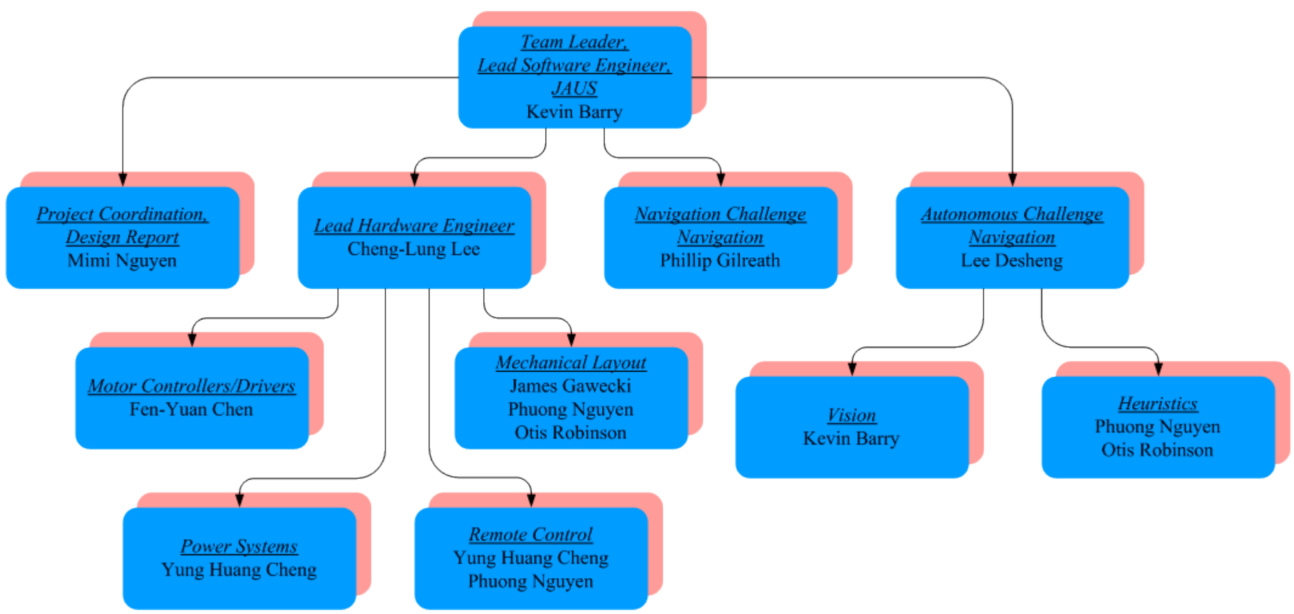

Figure 3. Team Organizational Chart

4. Vehicle Design

4.1. Mechanical Systems

Vehicle architecture is, perhaps, the highest-value strategic design decision. As Figure 1 shows, the team chose a triangular platform with a tank-steering wheel pair in the front and a free caster in the back. With a high-performance low-drag caster, CAPACITOPS' vehicle architecture allows for smooth and rapid turning and relatively easy control. It also has a low center of gravity giving it added 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 components for proper weight distribution, ease of accessibility, as well as the efficient use of space.

4.1.1. Chassis

CAPACITOPS' chassis is made as a welded construction of thin-walled steel tubing and covered with an BCX 3-Ply wood shell. The vehicle is 32 inches wide, 13.5 inches tall (not including the camera mast), and 38.5 inches long (not including the LADAR), and weighs just under 250 pounds when it is fully loaded. As a result of its small volume, the vehicle can pass through a standard doorway which makes it easy to transport.

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 is with assembling the drive train for the new vehicle, due to the attention that must be given to precision assembly. To remedy this, **CAPACITOPS** incorporates a new modular drive train into its design. As a result, future teams will now be able to quickly and easily incorporate this drive train into their vehicle.

As Figure 4 indicates, the vehicle's drive train comprises two ½-HP QuickSilver 34HC-1 motors, coupled to 10:1 planetary gear heads, which are directly connected to two 16-in. wheels. A standardized drive train that can be transferred to future vehicles was achieved by mounting motors, gearboxes and controllers on an independent aluminum frame.

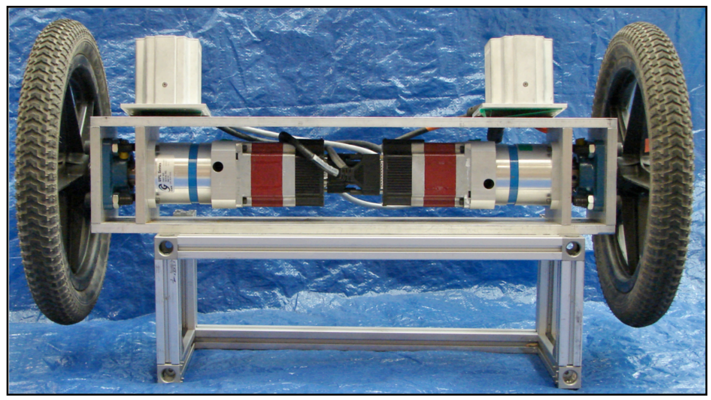

Figure 4. Modular Drive Train

4.1.3. Mast

Anchored to the front of the vehicle, the mast is constructed from 30 mm X 30 mm aluminum extrusion frame. It rises to the maximum permitted height of 6 feet (including attachments). The DGPS antenna is mounted atop the mast while the camera and the digital compass are mounted along its sides. The compass necessitated that the mast be made of a non-ferrous material, so as to not interfere with the magnetic field patterns and hence its readings. A unique feature of the mast design is that it is attached to the chassis by four hand screws and hence easily removable, which makes it easy to transport the vehicle.

4.2. Electrical and Electronics Systems

4.2.1. Power System and Distribution

CAPACITOPS derives its power from two Powersonic gel-sealed batteries rated for 55 Ampere-hours. Under normal operating conditions these batteries will allow the vehicle to be operated for about 4 hours. Should the batteries be depleted, 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. In addition, a set of backup batteries are available.

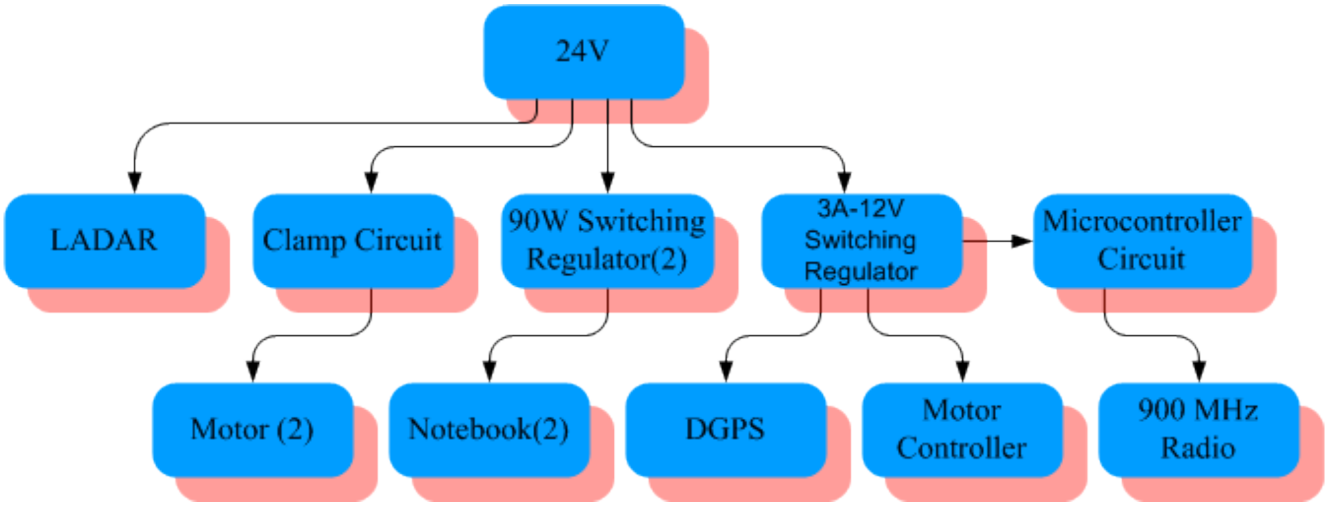

Figure 5. Power Distribution System

The power necessary to properly operate the vehicle and its components is distributed via a custom-designed printed circuit board (PCB) on which the power distribution scheme shown in Figure 5 is implemented. The 24V supply provides power for a LADAR unit, a clamping circuit that connects to the two motors, two 90W regulators, and a 12V regulator. The 90W regulators are used to power MacBook and PowerBook computers. 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, respectively.

To help ensure that CAPACITOPS' 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. Circuit breakers are strategically positioned on the PCB to minimize electrical damage from 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 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 computer through a USB connection. Thus, the source of an error or a problem can be quickly located and diagnosed. Furthermore, the PCB is enclosed in a weatherproof NEMA 4X polycarbonate box with weather-tight EN3 connectors.

4.2.2. Sensor System

CAPACITOPS 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 will minimize the effect of any movement or disturbances that may occur during normal operation of the vehicle. At the same time, the mounting arrangements for each sensor are designed to facilitate their easy removal from the vehicle if necessary. The following is a brief description of the four sensors that are implemented on CAPACITOPS as shown in Figure 6.

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, e.g., Computar's Varifocal 1.8mm – 3.6mm lens 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.

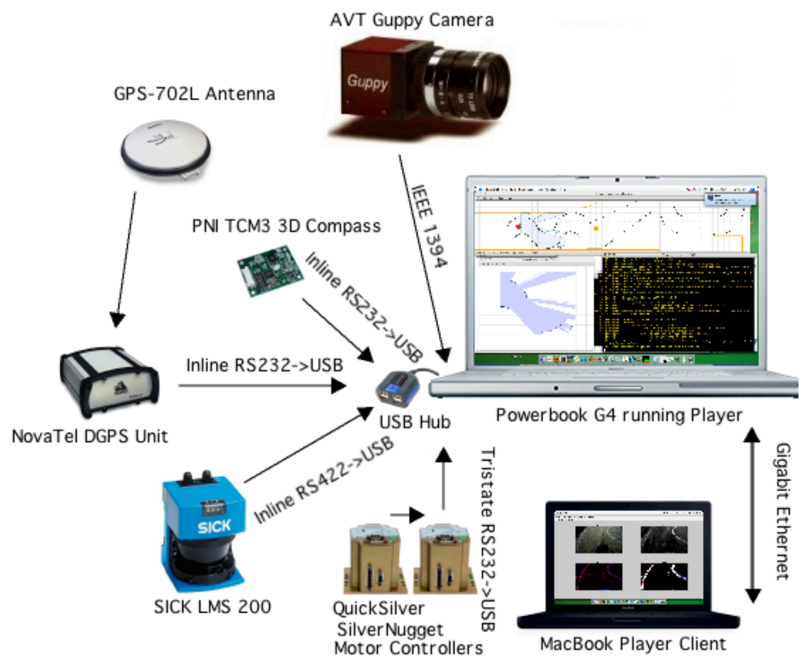

Figure 6. Systems Communication Structure

LADAR**:** The SICK LMS200 LADAR unit was employed for the purposes of obstacle detection. The unit is capable of collecting data over a 180º field-of-view with 0.5º resolution and a range of 8m. CAPACITOPS 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 Powerbook computer. A special mounting bracket was also designed for the LADAR unit to allow adjustability in both tilt and orientation.

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 CAPACITOPS' speed and desired performance.

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

4.2.3. Remote Control & E-Stop Systems

Although CAPACITOPS must be capable of navigating itself in competition, incorporation of a remote control facilitates manual operation. 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 controlling vehicle motion.

The transceivers that are used in CAPACITOPS' 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 two miles away.

A remote E-Stop button is integrated into the remote control unit. When this button, located on the outside of the durable and protective remote control shell, is pushed, the vehicle will immediately be brought to a stop. To ensure that the E-Stop button will not be carelessly deactivated by pushing the same button a second time, the team selected a switch that requires a clockwise turn in order for it to be released.

4.2.4. Electrical and Electronics Communication System

In order to improve system integration and minimize the number of wires routed, the team interfaced its electronics and electrical systems in the manner illustrated in Figure 6. The AVT Guppy is connected via Firewire to the PowerBook. This connection provides both 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 but also requires 5 V at 20 mA for operation. As such, a custom RS-232-to-USB adapter that also provides 5 V to the compass is used, thus avoiding the need for an extra power cable. Finally, the two computers are networked via gigabit Ethernet, which is fast enough to transfer all needed sensor data to the MacBook in real time.

5. Development Environment, Processor Architecture & Software

The aspects of this project that are most critical to CAPACITOPS' 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

A major innovation over our earlier efforts is the use of *Player/Stage* to serve as the interface between the vehicle and its sensors. *Player/Stage* is open-source Unix-based (Linux or Mac OSX) software that can be viewed as an operating system for robots. *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 CAPACITOPS' hardware, we are able to work in a modular environment that facilitates robot development. Implementing the *Player/Stage* system means that a vehicle's client-code (*Player* is the server) can speak to a position 2-D interface (in *Player*) to retrieve its current location, as well as to send velocity commands. The client neither knows nor is concerned with whether such data originates from the DGPS, compass, or motors, or if it is from the simulated environment. As an added advantage, the *Player/Stage* arrangement also promotes future code reuse through its modularity. Previous teams have experienced difficulty with code reuse, since they developed tightly integrated systems. By using *Player/Stage*, however, the client code can easily be run on another vehicle, and the drivers can easily be used with other client code.

5.2 Processor Architecture

In order to increase the overall frame processing rate of the vehicle, CAPACITOPS divides and overlaps its computational requirements between two computers as opposed to our earlier efforts that were built around a single computer. Setting up this distributed computing architecture is facilitated by the move to the *Player/Stage* environment. The first computer, an Apple MacBook, is designated solely for the purpose of running vision algorithms while the second computer, an Apple PowerBook, 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 PowerBook as well. This allows the MacBook 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 computers as needed to further improve the cycle time and/or to accommodate further enhancements in vehicle intelligence.

5.3 Software: Autonomous Challenge

Major innovations have also been made in the team's vision and heuristics strategies. CAPACITOPS implements a MATLAB-OpenCV combination to perform image processing for line and obstacle identification. The algorithms in OpenCV (an open-source library of vision programs written in 'C') run much faster than if equivalent MATLAB programs were developed to produce the same functionality. Moreover, OpenCV can interface with MATLAB by way of Mathwork's MEX interface, which makes the powerful MATLAB environment for debugging and testing available for application development. Another innovative feature implemented this year is the development of wrapper code to allow *MATLAB* to run as a *Player* client, thus giving us the best of both worlds: an open-source, modular, autonomous robotics operating system (*Player/Stage*), and a powerful, interactive, world-class, algorithm development system (*Matlab*).

The image processing subsystem begins by identifying and removing barrel (cone, post, etc.) obstacles via RGB color segmentation. Then the image is converted to grayscale. To do this, rather than converting the images by the standard "(R+B+G)/3" method, a grayscale image is generated using a weighted color-plane combination, (3*B–G–R) which capitalizes on the natural high lane contrast found in the Blue plane (due to low blue content in regional grass), and the correspondingly low lane contrast found in the Green and Red planes (due to green grass showing through the painted white lines in the case of Green, and the presence of dry and/or yellowed grass which has a strong Red component). This technique is clearly data dependent, as it is designed to take advantage of the particular characteristics of white lines painted on grass. However, the exploitation of a priori knowledge about the likely images for a specific application is, in general, an effective image processing technique.

The algorithm as implemented in CAPACITOPS does not rely solely on a fixed color-plane manipulation. This is due to the fact that although in most instances, the "3*B–G–R" combination provides very-high-contrast images, there are situations where the method amplifies more that just the lane lines (examples include blacktop/tarp and ramp images). The CAPACITOPS' algorithm therefore utilizes color distribution and area information to identify such cases and switch to code that uses only the blue plane as the grayscale image.

Next, edge detection is done using two, signed Sobel operations, one vertical and one horizontal. Because signed Sobel operations are used (as opposed to the far more common magnitude-only implementations) both the rising and falling edges are detected. Essentially, rising edges correlate to color changes from green/black to white/yellow, whereas falling edges correspond to changes from white/yellow to green/black. To exploit known image geometry, a set of morphological operations are then used to

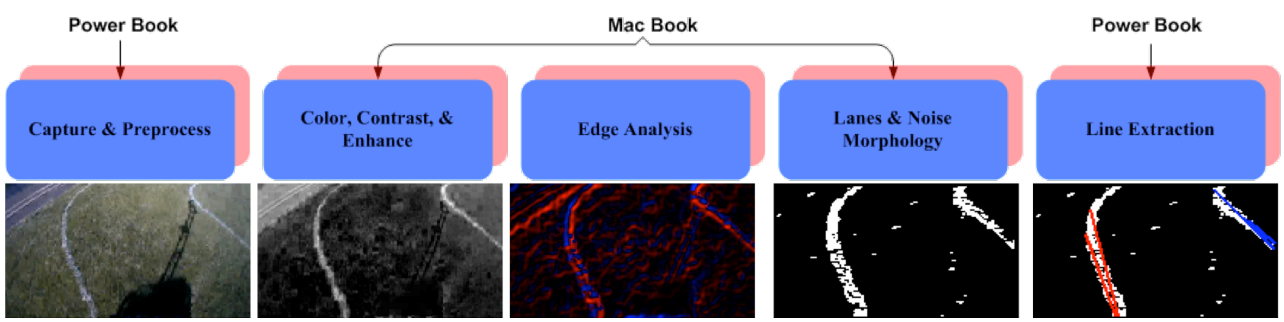

Figure 7. Image Processing Overview

connect the rising and falling proximal edges which are associated with actual lane lines rather than noise. As the lane line width is known and approximately fixed as specified in the IGVC rules, the morphological structuring element designed for these operations is optimized for lane lines thus reducing the possibility of generating false positives. The algorithmic sequence for the vision subsystem is summarized in Figure 7.

At this point, low-level image processing is complete and two methods are used to extract data from the image which are then used by the heuristics module for scene interpretation. The first extraction method converts lane/obstacle pixel coordinates into data similar to that seen by a LADAR device, that can be fed to a Vector Field Histogram (VFH) algorithm to avoid the lines. The second method converts the pixel coordinates into lines by using the Hough transform. This provides data that can be used to help give CAPACITOPS an idea of where "forward" is, and what its orientation to the path is. In addition, CAPACITOPS uses two arrays—N_S (North and South) and E_W (East and West)—to store the vectors obtained from the digital compass over time. Combining these two data sets provides a very reliable target. Data is captured from the compass based upon the distance that the vehicle has traveled. The weighted average that is calculated from these two arrays is used to determine the general direction that the vehicle has been moving. If the image processing results do not give a clear idea of where the next goal should be placed (for example, when the vehicle faces a horizontal line), logged compass data-history and "scanning" are used to determine the next action. In this context, scanning refers to making zero-radius turns to obtain course images to one or both sides of the current heading. These images in conjunction with heading history are used to resolve ambiguous navigation scenarios.

In addition to the history-based heuristics described above it is important to directly address the noise and lighting induced uncertainty of any data extracted from live image streams. A Kalman filter can be used to track, estimate, and predict lane locations in the presence of noise. The lane coordinates are thus smoothed to eliminate outliers (using a short term forgetting factor to retain responsiveness) prior to

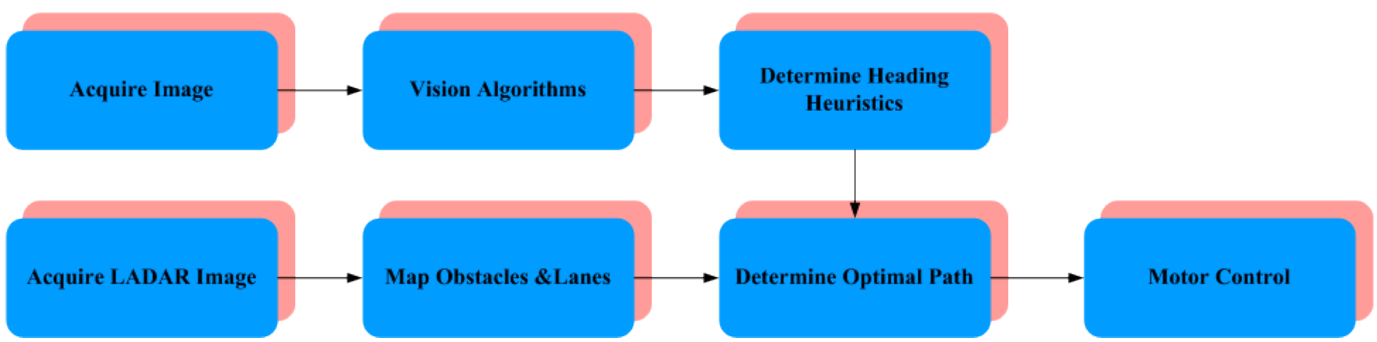

Figure 8. Autonomous Challenge Overview

processing by the heuristic subsystems. Furthermore, since the Kalman filter can predict the lane locations in the next frame, the search space in the Hough transform can be effectively constrained, thus reducing computational load. Figure 8 depicts the overall Autonomous Challenge analysis and decision sequence.

5.2. Software: Navigation Challenge

For the Navigation Challenge, it is the vehicle's objective to autonomously navigate itself to as many waypoints as it can reach within a period of seven minutes, while avoiding obstacles in its path. To fulfill this objective, CAPACITOPS utilizes the LADAR unit, digital compass, and DGPS system shown in Figure 6 in conjunction with data from the wheel encoders. Figure 9 provides an illustration of how the information from those components are used to complete the challenge. Detecting obstacles as far as eight meters in front of the vehicle, the vehicle's software uses that data to construct a memory map that not only indicates the locations of those obstacles in front of the vehicle, but also remembers the locations of the last 8 meters of obstacles that it passed. The reading from the compass reveals the current heading of the vehicle, while the DGPS data is used to determine the vehicle's current position (GPS coordinates). The vehicle's current position and the coordinates of the next waypoint are converted to a conventional polar representation, thus

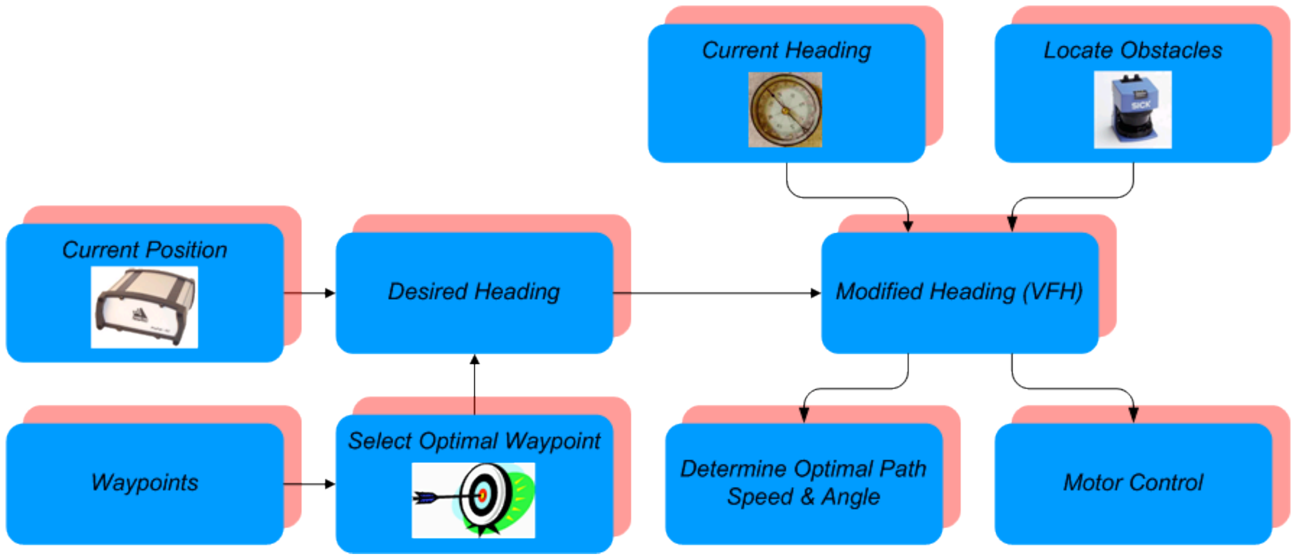

Figure 9. Overview of the Navigation Challenge System

establishing a target vehicle heading. This heading, however, does not take into consideration the presence of obstacles. Therefore, in order for the vehicle to effectively navigate itself to the waypoint, the Vector Field Histogram (VFH) algorithm is implemented to generate a modified steering direction that accounts for obstacles.

This VFH algorithm that is developed for *CAPACITOPS* also allows for its speed to be adjusted according to the obstacle clutter - that is, the vehicle speeds up when fewer objects are in its immediate vicinity and slows down when the field is cluttered with obstacles. This results in minimization of the time needed for the vehicle to traverse the distance between waypoints.

5.3. JAUS Challenge

This year UDM's *CAPACITOPS* will compete in the JAUS Challenge, the purpose of which is to demonstrate an understanding of basic JAUS compliance through the implementation and transmission of standardized commands that can be used to control the actions of an autonomous vehicle. In order to develop a familiarity of and knowledge about the JAUS standard, the team researched the OpenJAUS project. The team was also able to learn about how the JAUS standard was implemented in that project.

As previously mentioned, *CAPACITOPS* utilizes *Player* as the interface between the vehicle and its sensors. As such, a basic *Player* driver was written to provide information to a client about the JAUS messages.

5.4. Simulation

As stated earlier, a software simulator was developed to accommodate the testing and evaluation of CAPACITOPS' 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. To do this, two maps were created—one containing the obstacles and the other containing the lane lines. 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 made to *Stage*, all client side algorithms can be tested for both the Autonomous Challenge and the Navigation Challenge. Additionally, a sophisticated simulation environment has been developed to facilitate the testing and evaluation of CAPACITOPS' performance.

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. The Stage driver set appears like the physical robot to the Player client, but is actually interacting with a simulated world.

The only code that could not directly fit into the Stage model was the image processing. Stage cannot provide realistic images to test with. So, multiple runs by remote control, initially on a previous years' vehicle, were done to capture test images to test the vision algorithms.

Physical integration of all the subsystems to fit inside the vehicle was also a concern. Since the vehicle was modeled in CAD, component placement and cable routing was simple to complete. After the frame was built, the team mounted and interconnected the subsystems for testing.

7. Predicted Performance

7.1. Speed

Given the vehicle's 16-inch wheels and 10:1 gear ratio, CAPACITOPS' motors are capable of driving the vehicle at 7.6 mph at their maximum speed of 1600 rpm. Vehicle testing has garnered similar results. In accordance with IGVC regulations, though, 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 torque output of the motors, the size of the vehicle's wheels and the selected gearing, calculations and testing have revealed that CAPACITOPS has ample torque to ascend an incline with a gradient of up to 47% (25^0) without stalling. According to the IGVC rules though, 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 vision algorithms (based on a timing estimate). Although this is moderate, it is important to remember that CAPACITOPS utilizes two computers (MacBook and PowerBook). Accordingly, the rest of the processing requirements are conducted in parallel to vision, which means that the overall processing time for image processing, making a navigation decision, and having it executed by the motion control system – the cycle time - is not much greater than 50 ms as well. At 5 mph, which is the maximum permitted speed, this cycle time roughly translates to a decision being made for every 0.5 ft of travel. In the Navigation Challenge, image processing is not necessary. However, a more advanced and complicated navigation algorithm is used which requires approximately 30 ms to complete. At the 5 mph speed limit, that cycle time equates to a decision being made about every third of a foot.

7.4. Battery life

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 about 4 hours on the batteries under normal operating conditions and slightly less than 2.5 hours under the worst-case conditions.

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. How the vehicle handles complex obstacles (switchbacks, center islands, dead ends, etc.)

In addition to using vision for lane-line detection, they are also used to detect potholes. Potholes are mapped as an obstacle such that the VFH algorithm will navigate around them. Furthermore, the algorithms developed for CAPACITOPS incorporate an extensive set of heuristics that are intended to successfully navigate through switchbacks and past center islands, while avoiding traps and dead ends. If, despite this, the vehicle ends up in a trap, a scan maneuver accompanied by the use of path-history heuristics is used to exit this predicament.

7.7. Accuracy of arrival at navigation waypoints

The waypoints at the competition will be designed as concentric 2 m and 1 m radius circles centered on the GPS coordinates of the waypoints. CAPACITOPS' DGPS system provides an accuracy of $\pm$ 0.1 meters in DGPS mode, and ± 0.01 meters in real-time kinematic (RTK) mode. It can be seen that the accuracy is more than sufficient. This has also been demonstrated both via simulation and actual experimentation.

Table 1. Power Consumed by Vehicle Components.

Load	Normal Operating Conditions			Worst-Case Conditions		
	Voltage [V]	**Current [A]**	**Power [W]**	**Voltage [V]**	**Current [A]**	**Power [W]**
LADAR (LMS200)	24	0.6	14.4	24	1.8	43.2
DGPS (ProPak-Lb +)	12	0.31	3.72	12	0.31	3.7
Compass (USB) (PNI TCM3)	5	0.02	0.1	5	0.022	0.11
Camera (FireWire) (Guppy F0-80B/C)	12	0.166	1.992	12	0.166	2
PowerBook G4	19.5	2.5	48.75	19.5	4.5	87.75
MacBook Pro	16.5	2.5	41.25	16.5	4.5	74.25
Motor/Controller (QCI-A34HC-1-B-01)	24	8	192	24	13.5	324
Motor/Controller (QCI-A34HC-1-B-01)	24	8	192	24	13.5	324
Total			**494.212**			**859.01**

8. Safety, Reliability, and Durability

As with any product, it is not just enough to perform well. Rather, it must be a strong and durable product that is capable of operating safely and reliably, as well. CAPACITOPS 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. Among them 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 computers 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 computers while still providing easy accessibility to them. The shelves are lined with a cushion, as well, to protect the computers 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.

9. Vehicle Cost

The cost breakdown for the development of this vehicle is provided in Table 2. To keep the costs down an attempt was made to re-use/share components from earlier IGVC vehicle efforts as well as to secure discounts/donations from manufacturers.

Table 2. Breakdown of Component Costs

Description	Retail Cost	Team Cost	Comments
Frame/Body	$586.93	$586.93	
Drive Train (Motors, Gearboxes, Accessories)	$3,944.03	$3,944.03	
Front Wheels (2)	$66.26	$66.26	
Rear Caster	$44.52	$44.52	Used from previous vehicle
Batteries (2)	$100	$100	
Battery Charger	$149	$149	Used from previous vehicle
Power PCB and Components	$172	$122	Several components obtained as free samples from Texas Instruments
Remote PCB and Components	$303.99	$104	Transceiver donated by Aerocomm
Camera, Lens, Adapter	$937	$898	
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	$1,702	$1,702	
PowerBook	$2,000	$2,000	
Total	**$22,601.73**	**$21,216.74**	**Savings = $1,384.99 (6.13%)**

9. Conclusion

CAPACITOPS is an autonomous vehicle that combines substantial innovation, performance, safety, reliability, and durability into one compact design. With the team having successfully achieved its mission, it is evident as to how and why CAPACITOPS is, indeed, the tops.


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