



The 12th Annual Intelligent Ground Vehicle
Competition
Oakland University
Rochester, Michigan
June 12th-14th, 2004

Vehicle Design Report for PUMA



Team Members:
David Sueper
Tracy Musil
Hasan Khasraw
Jason Volesky
Sawyer Larkin
Mike Duffy

Faculty Advisors: Brian Atkinson & Robert Grabbe

1 Introduction

The PUMA autonomous ground vehicle from the University of Colorado at Denver represents a significant technology refresh from the previous vehicle design, known as CUGAR. The PUMA is outfitted with some of the latest electronic technology and sensory subsystems, as well as a new mechanical framework. The PUMA integrates a high performance CPU motherboard running the Linux operating system, a video subsystem consisting of three cameras and a PCI frame grabber card, an ultrasonic subsystem for obstacle avoidance, consisting of six ultrasonic sensors and a custom-designed controller board, and a navigational system consisting of a Garmin Etrex Vista GPS receiver connected directly to a CPU motherboard serial port. PUMA's mechanical framework is comprised of an aluminum cage, housing the vehicle electronics, and a drive train consisting of three wheels with independent drive and steer motors.

2 Design Process

In late 1982, a new requirements specification model evolved at Boeing and culminated two years later in the successful FAA certification of a complex, real-time embedded avionics system for use in the airline industry¹. The methods consist of the requirements and architectural model, which describe *what* the system must do, *when* the system should do it, and *how* the design will be structured.

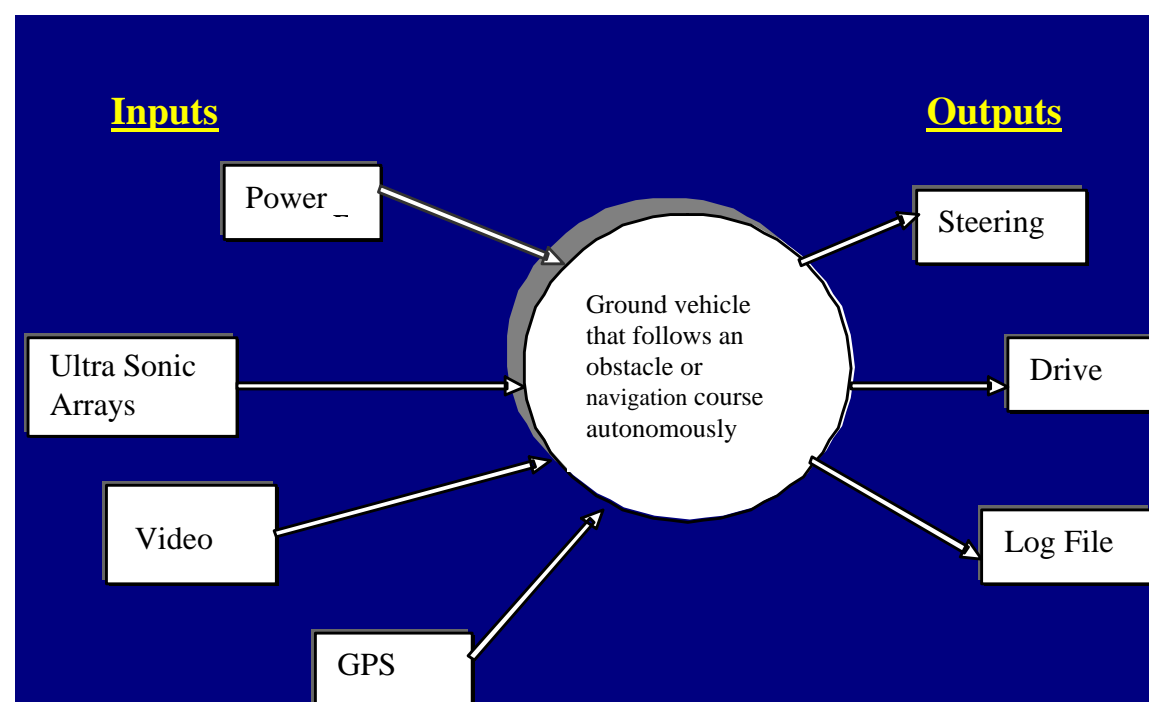


Figure 1 - Top level context diagram.

Our design process consists of the following: context diagram, data/control flow diagram (the what and when), architecture diagram (the how), design, implementation and testing/verification. We employed this process model in the design of the PUMA vehicle. First, we created a top level context diagram, shown above in **Error! Reference source not found.**. The context diagram identifies external entities with which we require the system to communicate, and states the major purpose of the system in the form of a single system process.

The system requirements are captured through a model that views the system from two aspects: its information processing and its control behavior. We created a data flow diagram (DFD), shown in Figure , and a control flow diagram as part of this design process. The DFD partitions the requirements into component processes, and represents them as a network of data flows.

The architectural flow diagram (AFD) is the primary tool depicting the system architecture. It shows the physical partitioning of the system into its component pieces and the information flow between them. The AFD for PUMA is shown in Figure . The main purpose of the AFD is to allocate the functional processes of the requirements model to physical units of the system.

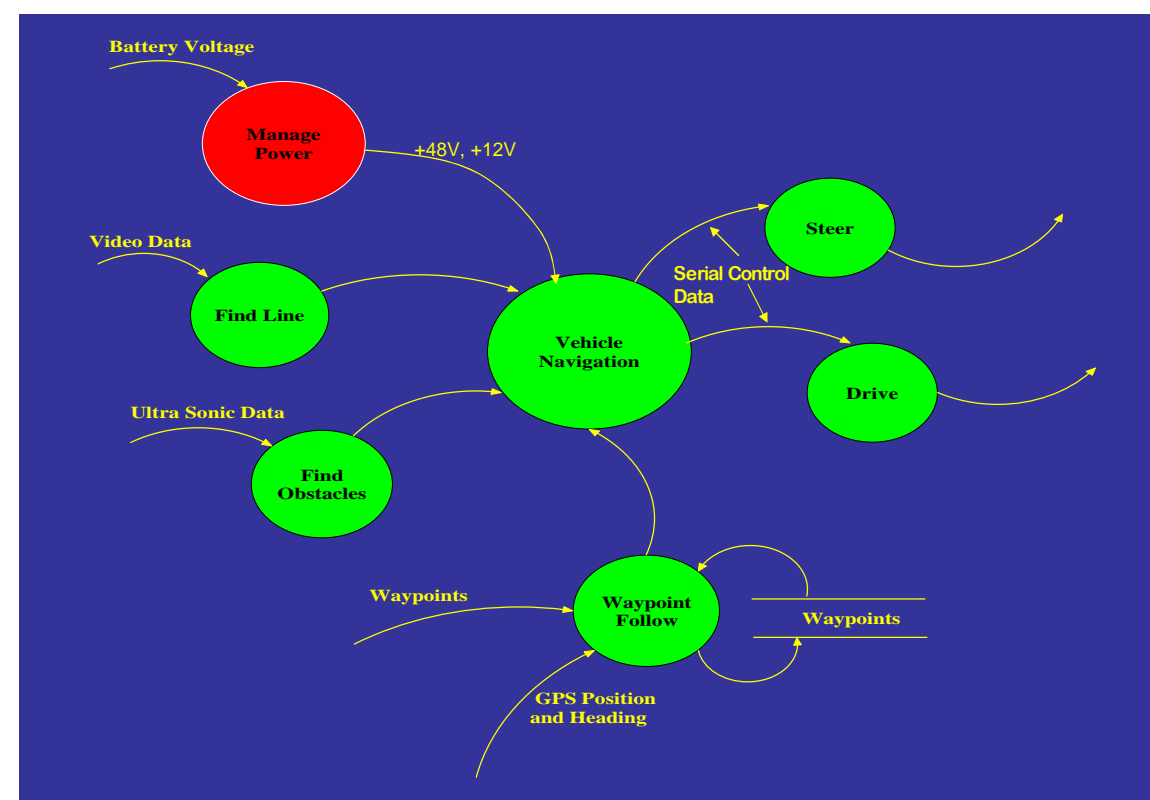


Figure 2 - Data Flow Diagram for PUMA

The design and implementation phases of the process model involve capturing the details of our design in schematics. Our chosen capture tool is Orcad; we have over twenty pages of Orcad schematics that detail each connection in our design. Our architectural flow diagram was our guiding model in creating our schematics

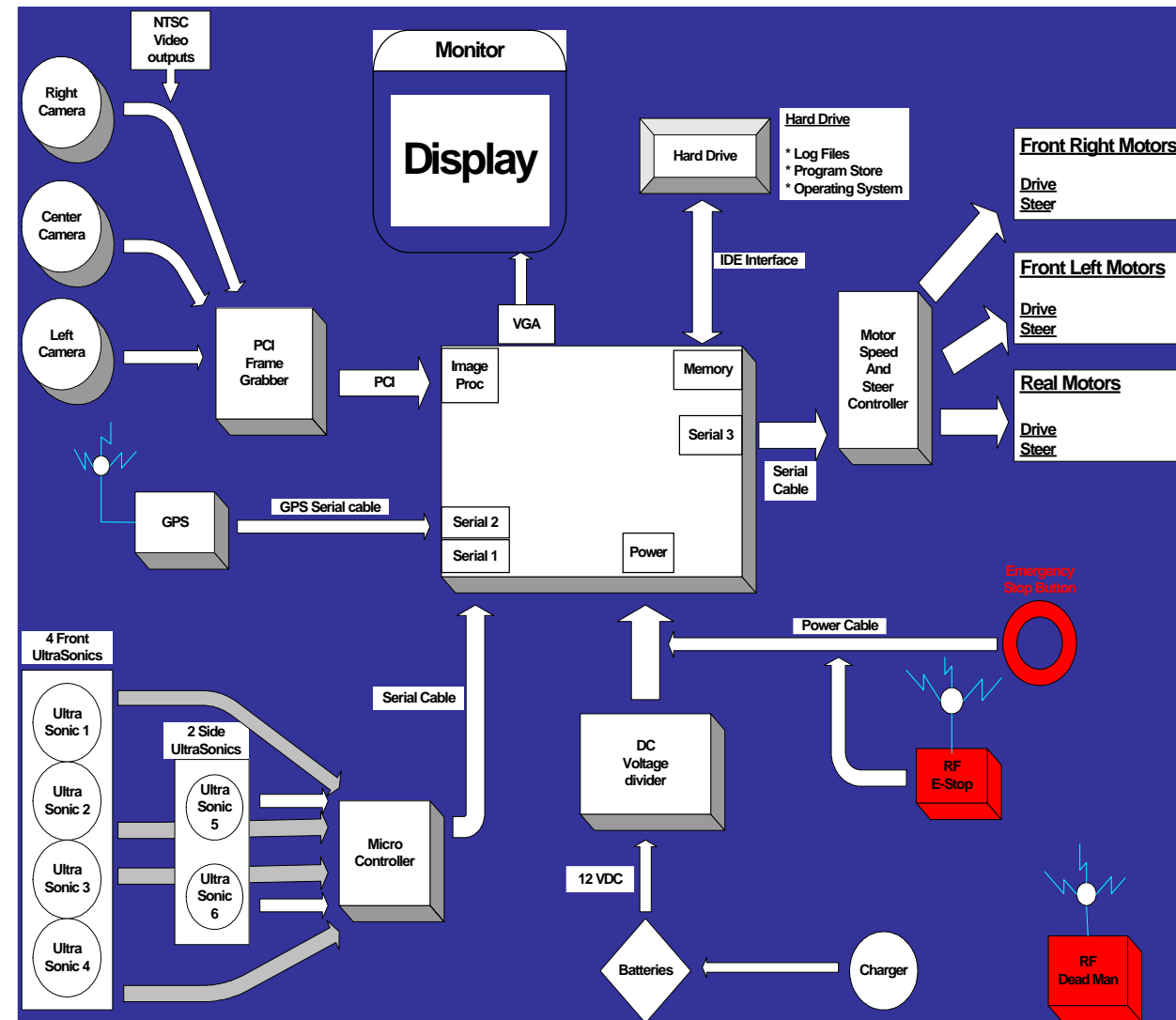


Figure 3 - PUMA Architectural Flow Diagram

The architectural flow diagram shown in Figure 3 is very similar to the top level schematic for PUMA, shown in Figure 4. The schematics are self documenting; each page includes vendor information, part number, and other pertinent information.

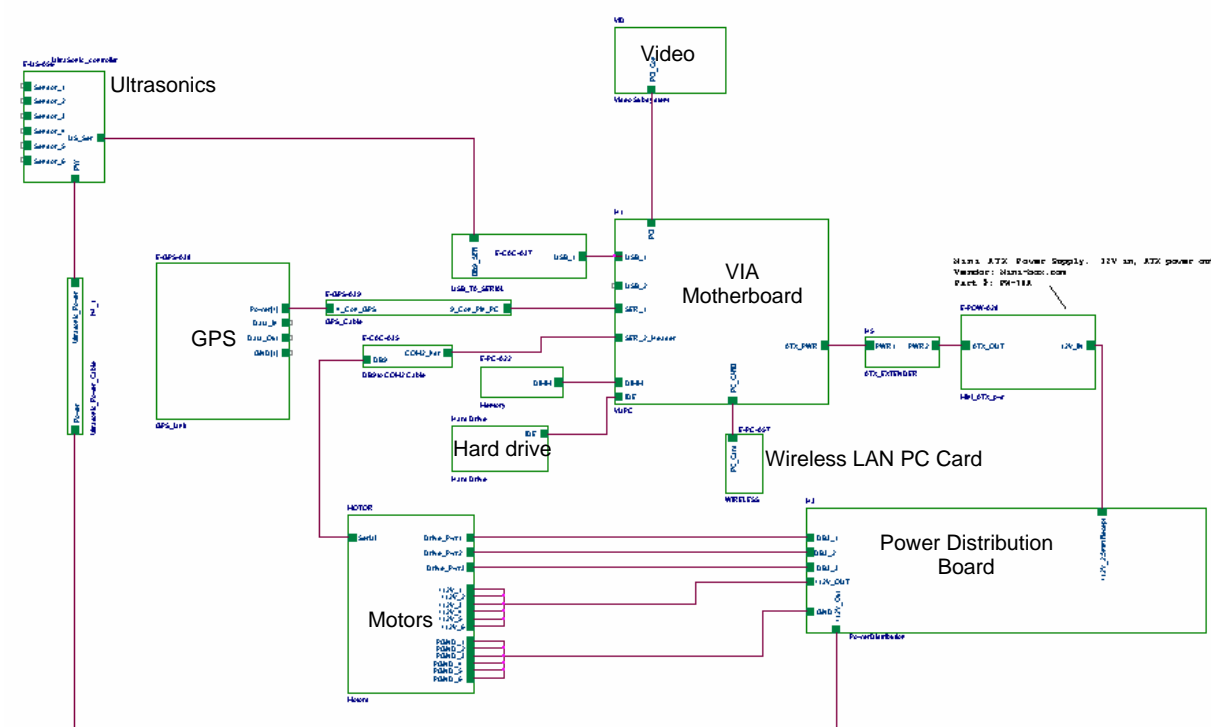


Figure 4 - Top Level Schematic for PUMA

3 Vehicle Design

The PUMA autonomous vehicle is CU Denver's next-generation ground platform, and as such it has been designed with a high performance CPU, new advanced sensory subsystems, and incorporates the latest technologies including USB and 802.11 wireless. The main electronic subsystems of the PUMA are the CPU motherboard, video, ultrasonic array, GPS, motors, and power management. The following sections describe each of these subsystems.

3.1 Motherboard

The heart of the PUMA ground vehicle is the VIA EPIA-MII 10000 Mini-ITX motherboard. This motherboard is powered by the VIA Nehemiah™ 1GHz processor. This motherboard was chosen because of its small size, low power, and very low cost. The motherboard is a small 17x17cm form factor and includes several standard features including two IDE interfaces, two USB ports, a PCI expansion slot, one DDR266 DIMM socket, a CardBus Type I & Type II socket, integrated 10/100 Ethernet port and a IEEE 1394 socket. The processing of all sensory input data, and all motor control, is performed by software running on the VIA CPU. Because the motors, GPS, and ultrasonic array all require RS-232 serial interfaces

for control, the motherboard must provide four serial interfaces (two for motor control). Since it is equipped with only two serial ports, the two USB ports on the motherboard are converted to serial interfaces via USB-to-serial adapters. The PCI slot is occupied by a four-channel frame grabber card.

The PUMA motherboard runs the Linux operating system. Linux was chosen as the operating system because of availability of drivers and applications from the open-source community.

3.2 Lane Following: The Video Subsystem

PUMA uses a video subsystem for lane following. The video subsystem incorporates three cameras along with a four-channel frame grabber card from Linux Media Labs. Three Sony TRV118 Hi8 camcorders are used to view the solid and dashed lines that define the lane. One camera is positioned on the front center of the vehicle and one on each side of the vehicle. NTSC video is sent from the camera to the frame grabber card via the mini-A/V output. The LMLBT44 frame grabber card digitizes the video using YUV 4:2:2 format at 60 frames per second. Video processing software on the VIA motherboard processes the incoming data to evaluate where the white line is relative to the vehicle.

The white lines painted on grass that marks the course boundaries are particularly difficult to detect when sun angles are low. Specular reflection can add a significant amount of white to the image making it almost impossible for even a human to distinguish the line.



Figure 5 - Camera Orientation

For the best possible signal to noise performance, the line-viewing camera should look directly at the line with the highest possible angle, as shown in Figure . This will result in an image similar to that shown in Figure .

It is observed that the information about the position of the line is similar as one looks from left to right. However, a small vertical slice (20-pixels wide) of the image contains the data necessary to find a point estimate of the line's position particular to the front edge of the vehicle to be controlled. Taking this narrow slice also reduces processing time. The whitest 2% of the pixels are then considered to qualify as possibly part of the line.

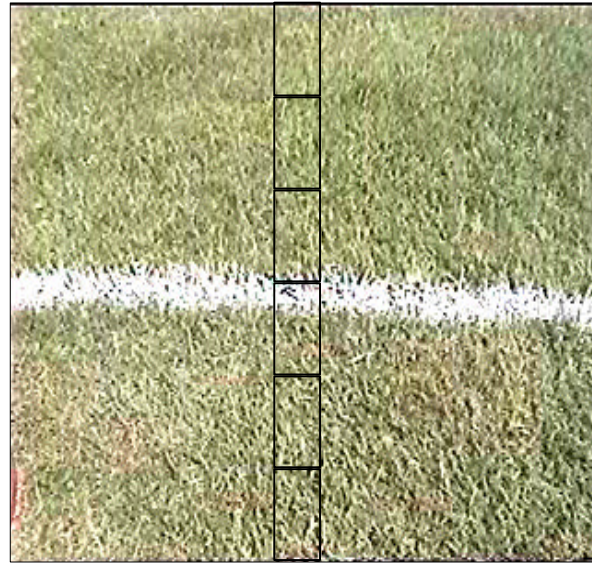


Figure 6 - Image of Line as Seen by Camera

Reflection noise experienced during the morning hours where reflected sunlight off of the contest track makes it hard for the vehicle to discern the course lines from the scattered noise, compromising our navigation on the course until the sun risen enough to cut back on reflections or clouds block the direct light altogether. This is solved using a pair of Sunpak 37 millimeter circular polarizing filters on the two side cameras.

3.3 Vehicle guidance based on line position.

The line position detected (above) gives the vehicle's position relative to the line. If there are no obstacles in front of the vehicle, the ideal position of the vehicle is in the center of the course. (Obstacles will be discussed in the next section.) The difference between the line position

detected and the center of the image is taken to be an error signal which needs to be corrected by steering.

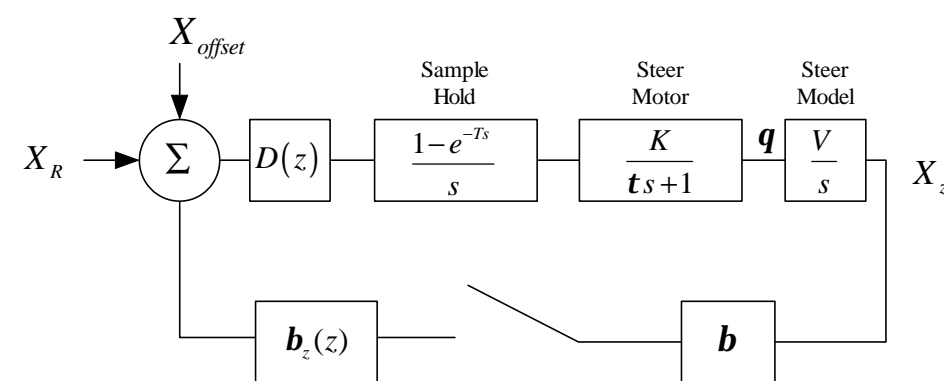


Figure 7 - Diagram of closed loop steering control.

Control of the vehicle can then be modeled as a discrete time feedback control system as shown in figure 7th. In this model, the action of the steering motor causes the vehicle to rotate about the center of its steering axis at some rotational frequency ω . This rotation ultimately causes the desired correction which, when linearized, is actually motion of the vehicle orthogonal to its direction of travel.

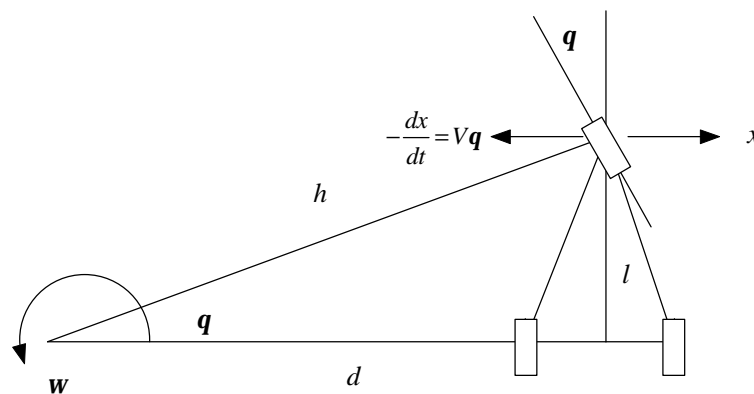


Figure 8. Illustration of orthogonal motion relative to steering angle.

As illustrated in figure 8, the desired correction of vehicle position is proportional to the integral of the velocity of the vehicle. This is a key feature of the control system (figure 4) since the vehicle velocity is essentially the gain term in the feedback loop and is a source of control loop instability.

The control system (figure 7) has been simulated using MATLAB to check for stability. The simulation shown in figure 9 shows the response of the system for a worst case steering scenario.

In this model, a ramp input represents a curve in the road. The scenario simulated begins on a straight line to right curve cusp followed by a left curve.

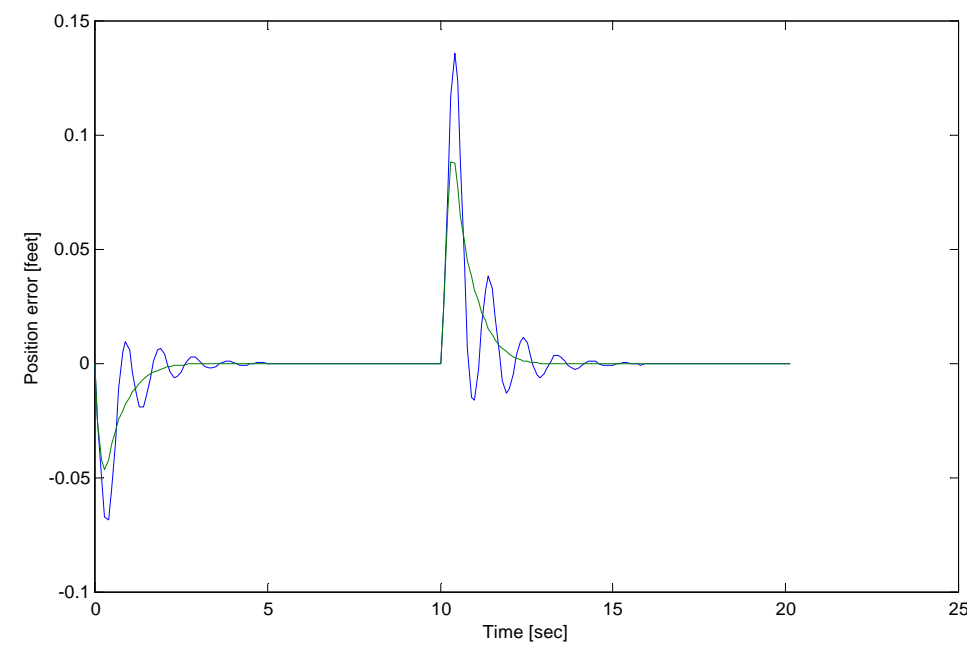


Figure 9. MATLAB simulation of steering system performance.

The ordinate in figure 9 represents vehicle-position error in feet vs. time on the abscissa. The smoother of the overlaid plots shows near ideal performance when the system parameters are optimized and delay due to image acquisition time (the sampling switch in figure 4) is not significant. The second overlaid plot shows the performance of the vehicle when the delay time in image acquisition is increased. The resulting oscillation in the steering is a direct consequence of sampling delay. Sampling delay is ultimately limited by the video frame rate in conjunction with computer hardware speed, the speed of the vehicle and the angular position of the camera looking forward or back along the line. ⁱⁱⁱ

3.4 Obstacle Avoidance: The Ultrasonic Array Subsystem

The PUMA vehicle incorporates an ultrasonic array subsystem for obstacle avoidance. Eight electrostatic transducers are mounted around the front of the vehicle in a semicircular pattern. Each of these eight transducers is connected to a controller board. This custom designed

controller board contains an Atmel ATmega16 microcontroller chip that powers and controls the ultrasonic sensors. The ultrasonic sensors and the custom controller board are shown below in **Error! Reference source not found.** Software on the microcontroller chip controls the transmit output of each sensor, and calculates distance to the object based on the time it takes the ECHO output to go high after transmission. We designed a custom board to reduce the number of connections to the main CPU board. The controller board interfaces to the main CPU motherboard via a standard serial cable. The controller board does all distance calculations, and then simply transmits the resulting information to the main CPU motherboard via the serial RS-232 interface.

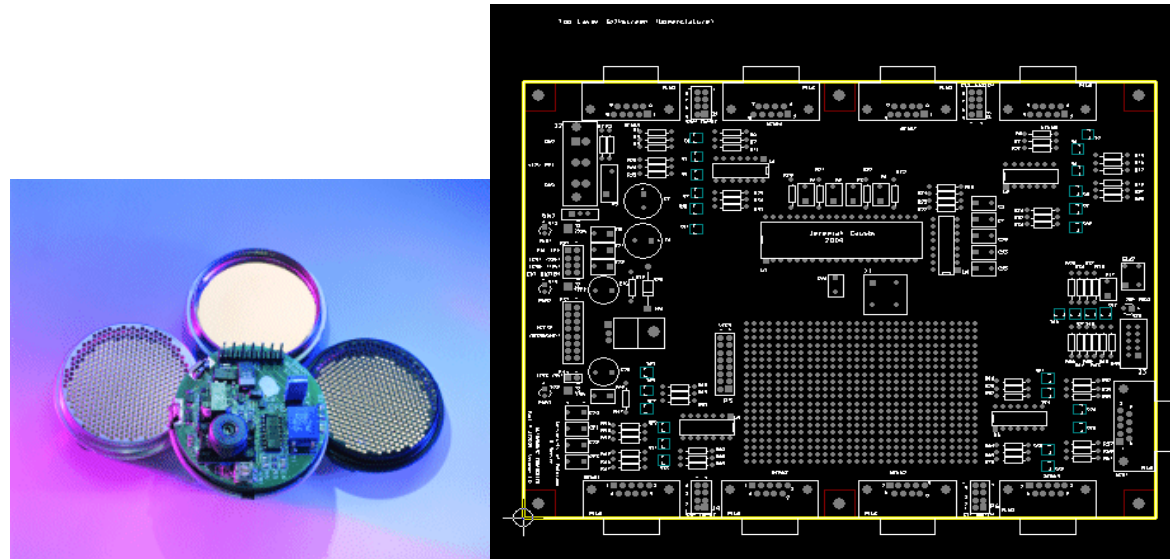


Figure 10 - Ultrasonic Sensors and Controller Board

Each sensor has a distance range of 0.15 to 10.7 meters (0.5 to 35 ft). The beam pattern from the transducer is typically 15°. The software algorithm scans through all eight sensors once every second and notifies the main CPU when an object is detected that is within 10-15 feet. The decision loop on the main CPU takes input from the ultrasonic subsystem and turns the vehicle in a direction that will avoid the obstacle indicated by the ultrasonic subsystem.

3.5 Navigation: GPS

After researching other navigational choices, we decided to stay with the current handheld GPS Receiver, the Garmin Etrex Vista. The Garmin Etrex Vista was introduced in the 2002 competition with outstanding results. The Garmin Etrex Vista contains a built-in electronic

compass. It is cost effective and will give the 2 meter accuracy needed in the contest (WAAS compatible). The major change to the GPS in this year's competition is that it will be plugged directly into the PC. The Etrex sends navigation information out of its serial port in ASCII characters using the National Marine Electronics Association Code: NMEA 0183. Currently the simple ASCII output contains time, position, and velocity data in the fixed width fields.

3.6 Power Management

PUMA is powered by three 7-amp hour 12-volt lead acid gel cell batteries in series, providing a 36 volt effective power supply. The 36 volt supply is connected to a custom designed power distribution board. The context diagram for the power system is shown below in **Error! Reference source not found.**

The power distribution board design fuses the power and distributes it to many connectors on the board. The design also incorporates a Datel DC-DC converter to convert the 36 volts down to 12 volts, which is needed by the VIA motherboard, the motor breakout modules and the ultrasonics controller board.

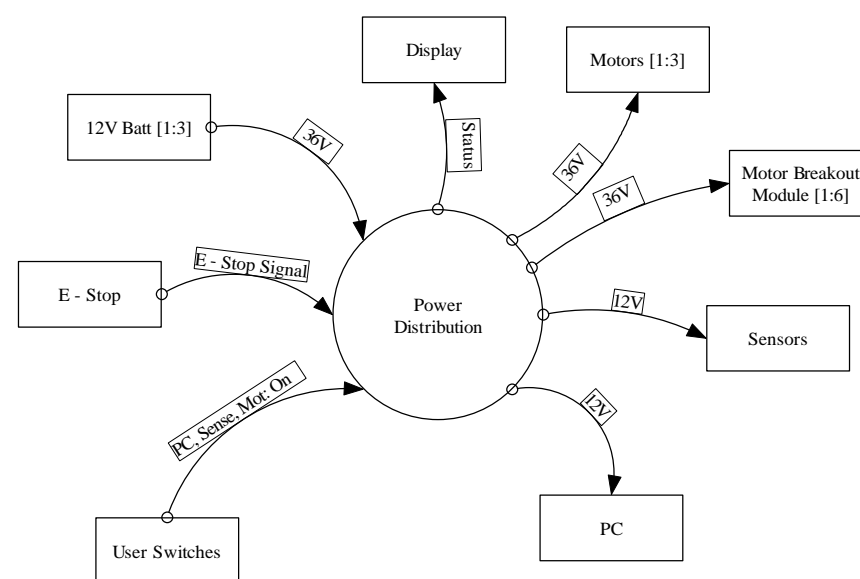


Figure 11 - Power System Context Diagram

The drive motors require a power cable separate from the control, whereas the steering motors receive 36V power via the interface cable. To power the VIA motherboard, a separate mini-ATX power supply was purchased that plugs directly into the VIA power connector. This power supply receives 12V from the power distribution board.

Power is divided into three separate domains: main CPU power, motor power, and ultrasonic power. In this fashion, the CPU receives power so that the main program can begin without powering the motors. This prevents the motors from lurching the vehicle forward at power on. Switches for each of these three domains are present on both the board and the vehicle exterior. This allows the user to disconnect power to a subsystem without gaining access to the inside of the chassis. The power board incorporates many LEDs as well as a digital display that indicates the battery voltage.

3.7 Mechanical

This vehicle has taken the ideas and concepts from the previous Intelligent Ground Vehicle (IGV), and modified certain aspects to improve the overall design and function of the vehicle. PUMA weighs approximately 165 pounds with a payload of 20 pounds to be applied at the competition. PUMA is capable of turning in place or sideways due to a three wheel independent steering and driving design. In compliance with the rules of the IGVC, the autonomous vehicle will not exceed a maximum velocity of 5 mph.

3.8 Vehicle Frame

In designing the frame for PUMA, the team assessed the CUGAR for preliminary ideas. After reviewing the previous vehicle, three important factors were involved in creating the new design: the amount of space needed to hold the electrical components, the type of material being used for cost and strength analysis, and the amount of weight that is being applied to the frame.

PUMA's frame is 17 inches wide, 27 inches long and 10 inches high. Square 1x1 inch aluminum tubing with wall thickness of 0.12 inch is welded together to form the frame of the vehicle. This material was chosen for its low cost, light weight and durability. The size of the frame was largely determined by the need to house all the electrical subsystems. PUMA's mechanical frame is depicted in Figure 2.

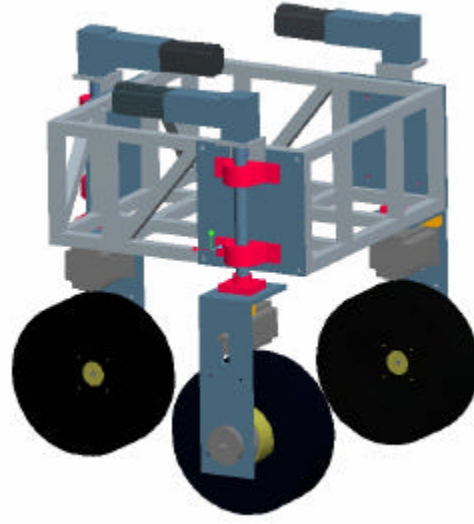


Figure 12 - PUMA Mechanical Structure

3.9 Drive System

PUMA uses three wheels with independent drive and steer to maneuver the vehicle. This drive system was chosen for its flexibility and maneuverability. With this drive system, PUMA can change its direction of motion without altering the orientation of the vehicle; it can stop going forward and start moving sideways. The mechanical design of the wheel/motor assembly is shown below in

Figure 3.



Figure 13 - PUMA Wheel/Motor Assembly

3.10 Motors

PUMA incorporates three drive motors and three steering motors. The SilverMax® E series motors from QuickSilver Controls are used in PUMA. The 23H-5 motors are used for steering, and the more powerful 34N-1 motors for drive. All motors operate from 36 volts. The motors have a gear reduction ratio of 16:1, using an in-line planetary gear system for the steering motors and a Cyclo-Reducer for the driving motors.

Six network breakout modules individually control each motor. These network breakouts are connected back-to-back in two groups of three; the driver motors and the steer motors. Each group of three network breakout modules connect to a serial port on the VIA motherboard. The network breakout modules and motors are shown below in Figure 4. A cable connects each network breakout module to its respective motor for actual control of the motor.

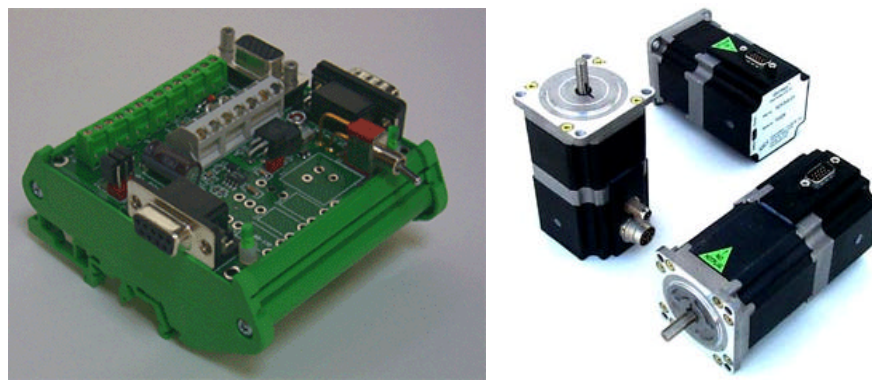


Figure 14 - Network Breakout Module and Motors for PUMA

4 Analysis of Predicted Performance and Results

Table 1 – Performance analysis

| Performance Measure | Performance Prediction | Performance Results |
|--|--|---------------------|
| Speed | 5 mph | 4.75 |
| Ramp Climbing | 20% | 20% |
| Battery Life | 2 hours | 1.5 hours |
| Distance at which obstacles are detected | 0.15-10.7 M | 0.15-10.7 M |
| How the vehicle deals with dead ends and traps | Relays motor information to log file for traps and dead ends | TBD |
| Pothole Detection | Cameras | TBD |
| Accuracy of arrival at navigation waypoints | 2 meters | 2 meters |
| Refresh Rate for Sensors | 5 Hz | 5 Hz |

5 Safety

Safety was the most important concern in all aspects of the design, fabrication and operation of PUMA. There are four modes of stopping PUMA in case of an emergency. The first is a circuit breaker in series with the main batter feed. The second is the Radio Frequency E-Stop System. The third is the actual onboard, hard-wired, 60 mm emergency stop switch. In the event all of these were to fail, an onboard toggle switch can be used to stop the vehicle.

6 Vehicle Costs

The time spent on the design and construction of PUMA to date is approximately 1500 man-hours. The table below shows the expenditures to construct the vehicle.

Table 2 – Vehicle Costs

| Subsystem | Cost |
|---------------|--------------------|
| Video/Sensory | \$1,312 |
| Motors | \$10,382 |
| Mother Board | \$317 |
| Power | \$253 |
| Frame/Body | \$800 |
| GPS | \$300 |
| Total | \$13,364.00 |

7 Conclusion

PUMA will be ready to meet the challenges at the IGVC this summer, and the team is looking forward to another successful run. This project would not be possible without the help of Electrical and Mechanical Engineering Senior Design students, the CU-Denver Robotics Society and its volunteers, CU-Denver Electrical Engineering instructors and faculty, and the ongoing support of Engineering Department Dean Renjeng Su.

References

ⁱ Hatley, Derek, and Imtiaz Pirbhai. *Strategies for Real-Time System Specification*. New York: Dorset House Publishing, 1988.

ⁱⁱ Phillips, Charles L. and H. Troy Nagle, *Digital Control System Analysis and Design*, Prentice-Hall, 1984.

ⁱⁱⁱ Atkinson, Brian, Michael C. Duffy, Thomas Klingensmith, and Robert Grabbe. *Vision Based Robotic Control*, Journal of Robotic Sciences, Wiley and Sons, 2004.