Culture Shock

Design Report

for the

2009

Intelligent Ground Vehicle Competition

prepared by

Lawrence Technological University

Culture Shock Design Team

Faculty Advisor Statement:

I, Dr. CJ Chung of the Department of Math and Computer Science at Lawrence Technological University, certify that the design and development on Culture Shock has been significant and each team member has earned credit hours for their work.

Overview

This report describes the Culture Shock robotic platform, designed and built for the Intelligent Ground Vehicle Competition (IGVC). Originally, Culture Shock was intended as an entry for the 2008 IGVC, but circumstances forced the team to withdraw prior to the competition. Culture Shock is therefore considered a new IGVC entrant for 2009.

This report is organized into sections describing the design team, the design processes, and various aspects of the design, followed by performance and cost information. Aspects of the design which are particularly innovative are highlighted throughout the document using a distinctive "Culture Shock Innovation" banner as follows:

Culture Shock Innovation

- These banners are used throughout the document to highlight innovative features!

Team Organization

The Culture Shock design team is comprised of the following members:

Name	Role
Dr. CJ Chung	Faculty Advisor
Brace Stout, MSCS (Team Captain)	Mechanical, Electrical, Software
Emily Trudell, MSCS	Software
Ryan Matthews, MSCS	Software

Concept Development

The Culture Shock concept was conceived following IGVC 2007. Even though the H_2Bot did well in the design competition, there were a number of areas in need of improvement. These included:

- Communications Interfaces – the USB-to-RS232 used adapters were unreliable and lacked positive locking. The 'COM' ports would frequently become unresponsive, requiring a reboot of the laptop computer to clear the condition.
- Mechanical Stability – sudden stops from top speed caused the platform to pitch forward nearly to the point of tipping. The rear caster would leave the ground and the resulting impulse to the systems and sensors on touchdown was considerable.

- Suspension – the rigid platform and small-volume pneumatic tires combined to provide a rough ride – even over relatively smooth terrain.
- Constrained Maneuverability – a significant amount of mass was located well behind the differential drive wheels, resulting in a large moment of inertia. The rear caster, depending on its position, would cause additional and unpredictable resistance to turns. These factors combined to encourage oscillations during certain maneuvers, especially at higher speeds. Additionally, even though the differential drive allowed the platform to perform a ‘zero radius’ turn, in actuality a significant space was required to accommodate the swing of the main body around the pivot point during such maneuvers.
- Sensor Limitations – the LIDAR sensor used provided distance data for a planar slice of space. When faced with either a change of platform attitude or change of terrain elevation, the sensor scan path would intersect the terrain, resulting in ‘phantom’ obstacle detection.
- Power Generation – DC voltage from the power source was converted to 120V AC simply to drive power supplies that converted that AC voltage back to DC for use by sensors. (Power is dissipated in the form of heat during each such conversion, leading to lower overall efficiency and reduced operational time between battery charges.)
- Performance in Soft Terrain – relatively small wheels with a narrow profile made for a small contact patch size. This resulted in poor performance in soft / loose terrain (such as sand) as the platform tended to sink and the wheels to spin.
- User Interface – The laptop computers used for platform control have displays that are not designed for viewing in direct sunlight. Additionally, pointer (mouse) manipulation is difficult under competition conditions.

A number of design concepts were considered, each addressing one or more of these issues. The final design addresses all of these issues. The choice of name for this new platform is considered appropriate. Besides recognizing our school through the “front and center” placement of “LTU” in the name, the design incorporates a number of features previously unseen (to our knowledge) in previous IGVC competitions.

The Culture Shock platform is dominated by its two 36-inch drive wheels. Nearly the entire platform is contained within the profile of these wheels. The center of gravity lies well below the axles of these wheels (due in large part to 70 lbs. of batteries slung in a ‘cradle’ below the axle), resulting in an inherently stable platform with neutral balance and low moment of inertia.

Culture Shock Innovations – Mechanical & Propulsion Design

- Neutrally-balanced, inherently stable platform provides improved maneuverability due to low moment of inertia and minimal loading on stabilizing casters.
- Large volume pneumatic tires absorb shocks on rough terrain and have a larger patch for greater traction and improved loose-terrain performance.

In a significant departure from previous platforms the laser range-measurement system (LIDAR), a staple for many IGVC entries, has been eliminated from the Culture Shock platform. In its place, stereo camera pairs are used for obstacle detection in addition to the surface feature detection normally performed with camera sensors. We find the stereo camera approach to be superior to LIDAR for this application in nearly all respects, including cost, weight, and power savings, as well as quality of data and ease of integration.

Culture Shock Innovation – Stereo Cameras

- Stereo cameras provide many advantages over the laser measurement device employed previously:
    - Reduced power consumption
    - No moving parts
    - Passive operation (no radiation)
    - Spatial (rather than planar) sensing
    - Lower weight
    - Lower acquisition cost
    - Less complex interface
    - Lower maintenance cost

The other main feature of the Culture Shock platform is its main computer. Housed in a narrow-profile Micro-ATX computer chassis, the 2.4GHz quad-core processor provides the processing power to handle the sensor data acquisition, sensor fusion (such as stereo image processing), planning, execution, and control functions of the platform. Robust I/O expansion cards (and associated drivers) provide high-reliability communications with peripherals, and an 800x600 resolution touch screen provides the primary user interface for the platform.

The power supply for this computer is an ATX format 450W DC-DC converter. This high-capacity supply also provides power to all platform peripherals, excluding the high-power propulsion components.

Culture Shock Innovations – Main Computer & Power Supply

- Needless power conversions are avoided by utilizing a single DC-DC power converter to drive all non-propulsion loads, including the main computer system (propulsion loads are driven directly from the 24V battery stack).
- High-reliability communications interfaces are integrated into the main computer system.
- High-contrast touch screen hosts an easy-to-use, intuitive user interface for platform operations.

Platform Design

Mechanical and Propulsion Subsystems - The design process for the mechanical subsystems started with the search for wheels. The platform concept required large-diameter wheels with pneumatic tires, yet narrow enough to minimize scuffing during zero-radius turns. Minimal footprint was a primary design goal, so wheels larger than the IGVC minimum platform length of 36 inches were not considered. An extensive search and tradeoff analysis determined that a wheel and tire produced by Coker Tire of Tennessee to be the best match. These wheels and tires, however, are available only as components of bicycles or unicycles sold by the company. Ultimately, it was decided to incorporate two of these unicycle frames directly into the platform physical structure, as this conveniently addressed a number of challenging aspects of the mechanical design. Specifically:

- The unicycle frames are designed to support more than 200 lbs. each. The pair provide more than enough weight capacity to support platform frame, electronics, payload and foreseeable future expansion possibilities.
- Complex issues relating to mounting the wheels and side loading have already been addressed by the unicycle manufacturer.
- The unicycles provide a ready-made interface for driving the wheels. Analysis shows that the torque required for platform maneuvers did not exceed that required for human-powered unicycle operation. The foot-powered cranks were removed and replaced with a chain sprocket adapted for the purpose.

Mechanical design was finalized only after the unicycles were delivered, as detailed dimensional characteristics could not be obtained from the manufacturer. To ensure that the performance and reliability characteristics of the unicycles were not compromised, a means was devised to incorporate the unicycle frames without modification into the Culture Shock platform structure. On each unicycle frame, a single bearing support was replaced by a machined aluminum bar in order to provide a robust and stable attachment point for the other platform components.

To facilitate development and testing in both indoor and outdoor environments, a design requirement for the platform was that it be capable of maneuvering through a standard size doorway (without removing the door from its hinges). This requirement in consideration with the overall width of the unicycles determined the maximum width of the vehicle carriage, which in turn impacted carriage structure as well as selection of batteries and computer system chassis.

The large-wheel design requires substantial torque at the axle to move the platform. Direct connection of motors to the drive axles was considered, but discarded in favor of a design that would move the considerable weight and volume of the motors below the main carriage, providing a more stable configuration as well as additional space for electronics. Analysis showed that a gear motor would be required, even if a large sprocket were used for the interface to the drive axles. A survey of motors led to the selection of high-torque 24V gear motors with integrated encoders and brakes. To reduce space claim, weight, and cost, smaller diameter chain sprockets were selected with ratios designed to achieve the maximum allowed speed when run at the maximum (continuous) rated power and load. Further analysis led to the selection of 40-pitch chain to withstand the considerable forces that would then be required to drive the wheels.

The motor controller selected is the AX3500 model manufactured by RoboteQ, Inc., of Scottsdale, AZ. Selection of this motor controller was based in part on its performance, configurability, drive characteristics, safety features, and sensor availability (encoders). Experience with this motor controller in prior IGVC competitions was a prime consideration in its selection.

A decision was made early on to construct the frame using t-slotted structural aluminum. This would allow the design to be modified and adjusted if it were deemed necessary, as well as being amenable to field repair. This approach also provides great flexibility in sensor selection and placement. Angle aluminum was machined as necessary to provide high-strength joins between the structural components. As a result, this vehicle has no welds other than those already present in the manufactured components and those made to adapt the chain sprockets to crank drive.

The design process for the frame was iterative and was dovetailed with the selection of various vehicle components, resulting in tight integration of vehicle systems. Constraints on report length prevent each design decision and tradeoff to be detailed individually, but those considered most significant are discussed. Emphasis was placed on achieving a lightweight, structurally sound platform with a low center of gravity while providing ample room for sensors and electronics. An A-frame concept (selected for structural integrity) was modified to accommodate the lateral placement of the payload (which fits snugly between the wheels and counterbalances the computer system). The need for access to computer power and I/O connections as well as to the batteries for charging led to the design of an up-and-out pivoting tray for the main computer.

While it was originally hoped that the two-wheel design would not require additional stabilization, the potential need was recognized, and so the design provides for the attachment of casters (with shock absorbers to accommodate uneven terrain). Trials in soft terrain later confirmed that these 'outriggers' are necessary.

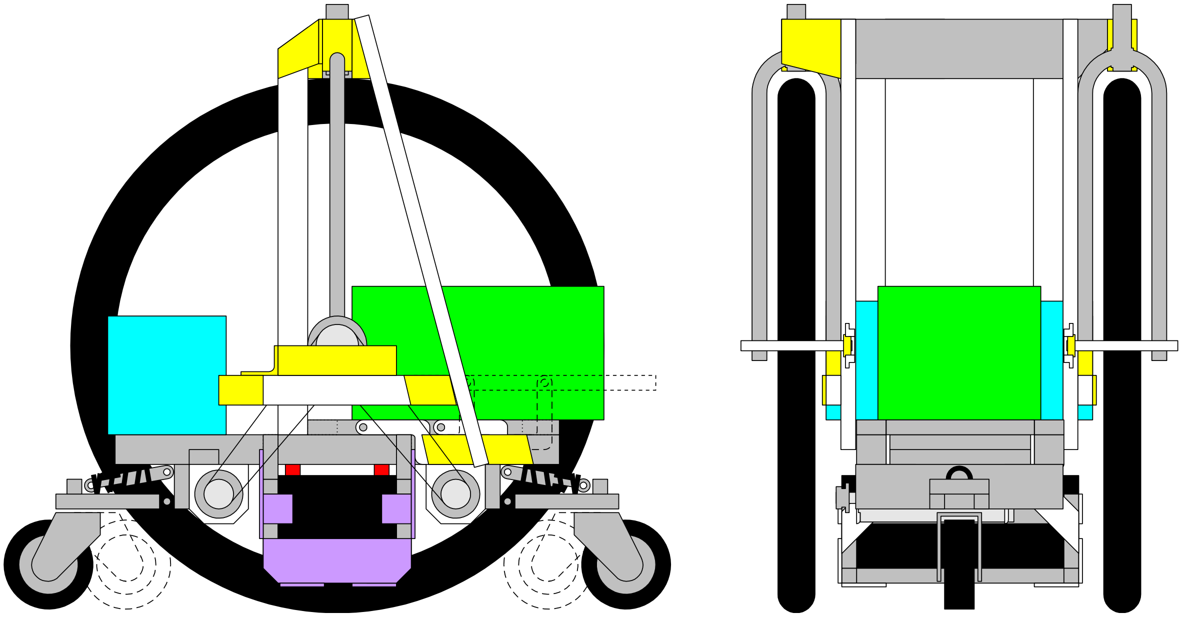
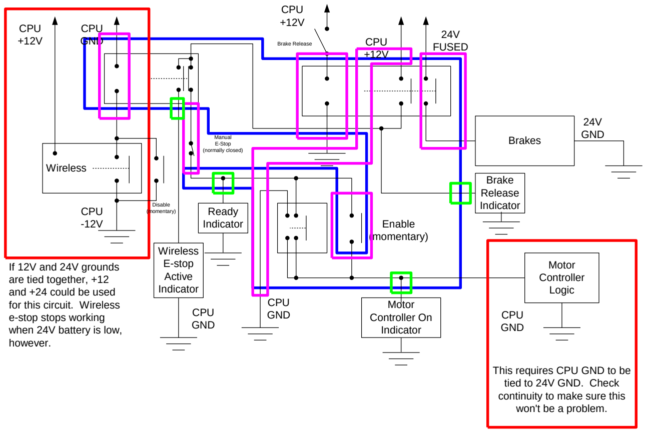


Figure 1 – Platform Mechanical Integration

Power and Emergency Stop Subsystems – Power is provided by three 12V deep-cycle AGM (gel) batteries located in the battery compartment which is centered below the axles of the platform. Each battery has a 33 amp-hour capacity. Two of these batteries are connected in series to provide the 24V required by the propulsion motors and fail-safe brakes. The third battery provides power to the remainder of the system, including the main computer and sensors. Access to the battery well and fuse box is obtained by moving the computer system up-and-out by means of a pivoting tray. (Offset arms pivot and then support the computer system in the accessible position.) Battery charging is achieved through the use of keyed connectors mounted to the sides of the battery well.

The power supply of the main computer is driven directly from the 12V battery, and was selected to have sufficient spare capacity to provide power to all anticipated external devices and sensors as well as having reserve for expansion. This DC-DC conversion, combined with careful sensor selection and the wide selection of voltages available from this power supply obviates the typical need for DC-AC inverters paired with AC adapters to produce required DC voltages. The result is reduced overall weight, complexity, and power requirements (power is typically lost as heat during voltage conversions). A convenient side-effect of this arrangement is that the main computer power switch becomes the power switch for the entire platform.

The emergency stop circuitry is integrated with the power control circuitry and provides multiple status indicators of the emergency stop and power subsystem states. Circuit design is based around four relays, and was captured using Microsoft Visio™ as seen in **Figure 2**, which shows the original block diagram and the realized implementation. Provision is made for status indications for main system power, failsafe brake status, emergency stop activation status, system ready status, and motor controller power status. The circuit board provides screw-type connectors for main power, the emergency stop switch, the wireless emergency stop device, the motor controller power control input, and all status indicators. While the circuit design is amenable to manufacture, the time and expense of printed circuit board fabrication was avoided by implementing the circuit on a 2x3-inch perforated experimenter's board using classical circuit construction methods.



If 12V and 24V grounds are tied together, +12 and +24 could be used for this circuit. Wireless e-stop stops working when 24V battery is low, however.

This requires CPU GND to be tied to 24V GND. Check continuity to make sure this won't be a problem.

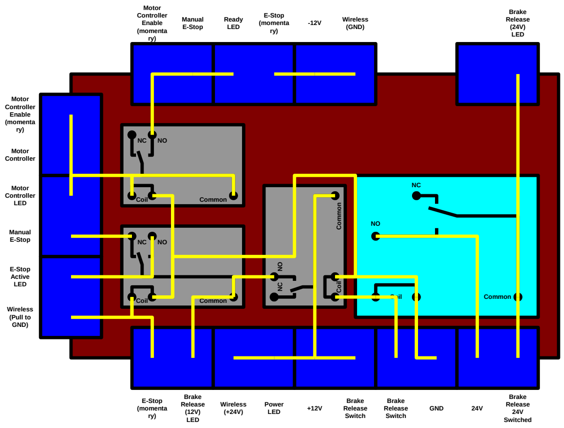


Figure 2 - Emergency Stop & Power Control Circuit Design

The wireless portion of the emergency stop subsystem requires a supply voltage between 18V and 30V. For safety purposes the -12V and +12V voltages available from the power supply are used to power the wireless receiver. As a result, the wireless emergency stop will work as long as the power supply is on. (When the power supply is off, the fail-safe brakes are always engaged.) Had the 24V battery supply been used for this purpose, the wireless emergency stop would have been rendered useless when battery voltage dropped below the device threshold (due to extended use or high transient load).

Sensors – The most robust and maneuverable platform is of little use without the sensors that capture information regarding the surrounding environment. Sensor selection for Culture Shock began with identification of the types of information necessary to perform the challenges. The following table summarizes the data requirements and possible sensors that provide the data:

Data Required	Challenge(s)	Possible Sensor(s)
Platform Pose	Autonomous, Navigation	Dead Reckoning, Compass
Geolocation (Lat/Lon)	Navigation	Dead Reckoning, GPS
Solid Obstacle Detection	Autonomous, Navigation	LIDAR, Acoustic, Camera
Surface Obstacle Detection	Autonomous	Camera
Lane Detection	Autonomous	Camera

As can be seen from the table, in most cases there is little choice for the type of sensor used in the acquisition of data. The biggest decision to make is the selection of sensor for solid obstacle detection. Choices considered were laser measurement-based (LIDAR) detection, acoustic detection, and vision-based detection. A survey of LIDAR devices found alternatives that were either limited in detection capabilities (planar) or prohibitively expensive in terms of cost, power, or volume. Acoustic detection systems were found to be limited in detection capabilities. Of the vision-based detection systems considered, the single-camera system lacked the inherent ability to distinguish between surface obstacles (painted on the ground) and solid obstacles. Ultimately, the use of a stereo vision system was determined to be the most cost effective approach for solid obstacle detection.

A number of stereo vision options were considered. Trade-offs included the cost and availability of hardware, the availability and performance of stereo vision software, camera field of view, and resolution of depth detection. After weighing all considerations, a pair of STH-DCSG-6cm systems was ordered from Videre Design of Menlo Park, CA. A primary consideration in selection of this unit was access to the highly optimized and configurable Small Vision System™ stereo vision software package included with the purchase. The stereo vision algorithms correlate data from two images to arrive at a two-dimensional depth mapping array, and so suffers somewhat in low-light / uniform light conditions where points of correlation are less distinct. An array of ten radially-arranged diode lasers that each project a crosshair pattern was devised that can be turned on under software control to aid in the production of correlatable points within the images. The device was realized through machining an aluminum block to accommodate the laser diodes. The design of this device and a simplified representation of the projected pattern is shown in **Figure 3.**

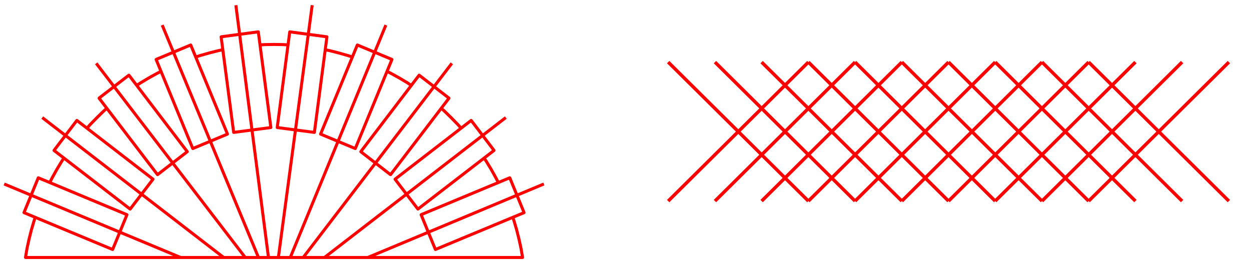


Figure 3 - Diode Laser Array Design and Approximation of Projected Pattern

For the GPS sensor, the SMART-V1-2US-VBS “smart” antenna from NovAtel of Calgary, Alberta, Canada was selected. This unit was selected due to its integrated package, small size, compatible power requirements, and ability to accept GPS corrections from a variety of sources. These include satellite based augmentation services (SBAS) such as CDGPS and OmniSTAR services as well as real-time kinematic (RTK) corrections such as are provided by radio beacons operated by the US Coast Guard. The Culture Shock platform is currently configured to use the OmniSTAR service for differential correction.

In addition to information provided by the GPS, platform pose information is derived from an electronic compass and quadrature-type encoders integrated with the propulsion motors. Encoder information is available via the motor controller interface. The electronic compass selected is the TCM 2.5 manufactured by PNI Corp. of Santa Rosa, CA. This compass was selected for its configurability, wide operating voltage range, 3-axis magnetic flux detection, integrated tilt sensor, and prior experience with compasses from PNI Corp. (Prior to the permanent addition of the stabilizing casters, tilt sensor information was used in the propulsion feedback loop in an attempt to mitigate what we termed the ‘Weeble™ effect’.)

Safety Devices – The Culture Shock platform is powerful and like all powerful machines is potentially capable of inflicting serious injury in the event of malfunction or carelessness. To minimize the chances of such an occurrence, the platform incorporates additional safety features beyond the emergency stop functionality required by IGVC rules. Specifically, the platform provides warning devices to alert persons near the platform of its presence and potential for movement.

The platform incorporates a USB-controlled relay board, the JSB-280-04 from J-Works, Inc. of Granada Hills, CA. Each of the four relays on this board is capable of switching up to 10A. Presently, in addition to the laser diode array used in conjunction with the vision processing system, these relays switch power to the GPS, the electronic compass, and the warning devices, all under software control.

Software Design

Overview – The platform main computer executes Microsoft Windows XP Professional™ as its operating system. This choice was made due to the availability of device drivers for all sensor peripherals as well as its support for multi-core processors. Both Windows Vista™ and Linux were considered as alternatives. Neither was supported by all of the desired peripherals.

For a number of reasons, the Java programming language was selected for all new software development on the Culture Shock platform. In cases where non-Java software libraries were required to be used, the Java Native Interface (JNI) facilities of the Java language were used to make features of those libraries accessible from Java. Specifically, the USB-controlled relay device and the Small Vision System™ came with Microsoft Windows™ 'DLL' libraries.

Development Process – The software architecture concepts were developed over the course of some weeks, during which infrastructure software classes (things like Distance and AngularVelocity) were defined. Major components were identified and requirements for each were developed, as well as Java interfaces that serve as Interface Control Documents for each. Stubs were developed for each of the components that conformed to these interfaces, and tests were developed against these stubs. The stubs were integrated into a master configuration, which was controlled by the team leader.

To help track progress, a component development schedule was generated that took into account the expertise and availability of the team members. This schedule was adjusted as needed to take into account actual progress. As components were developed, the previously developed tests were conducted to verify component operation. Components that passed these tests replaced their corresponding stubs in the master configuration.

User Interface – The main computer display is a Dynamix 816 Touch Screen Monitor manufactured by Dynamix Computers of Kernersville, NC. This is an 8" diagonal touch screen with 800 x 600 resolution. This unit is intended for use in vehicles, and so is somewhat brighter than regular LCD displays.

The main user interface for Culture Shock is a menu-based application that provides convenient access to the programs commonly used during platform maintenance, calibration, and competition. The menu is a tree structure that is fully configurable via an XML-format configuration file and is capable of launching both Windows™ (.EXE) executables and Java applications. Traversal of the menu tree is achieved through touching menu button icons on the touch screen. When the main menu invokes another application, it displays a fail-safe 'ABORT' icon (always on top) that allows the launched application to be terminated without recourse should it become unresponsive.

Simulated Platform – The platform simulator developed for the 2007 IGVC competition was expanded to include a Culture Shock simulated platform. A limitation of this simulated platform is that it derives solid obstacle detection directly from the scene database rather than interpreting the information from stereo images. This is due to a current limitation of the simulator that allows only a single image source (camera) to be defined. Future work on the simulator will allow multiple image sources to be defined which will open the path for integration with the stereo vision software. Only minimal algorithm development has been performed using the simulator due to the small team size coupled with high availability of the physical platform.

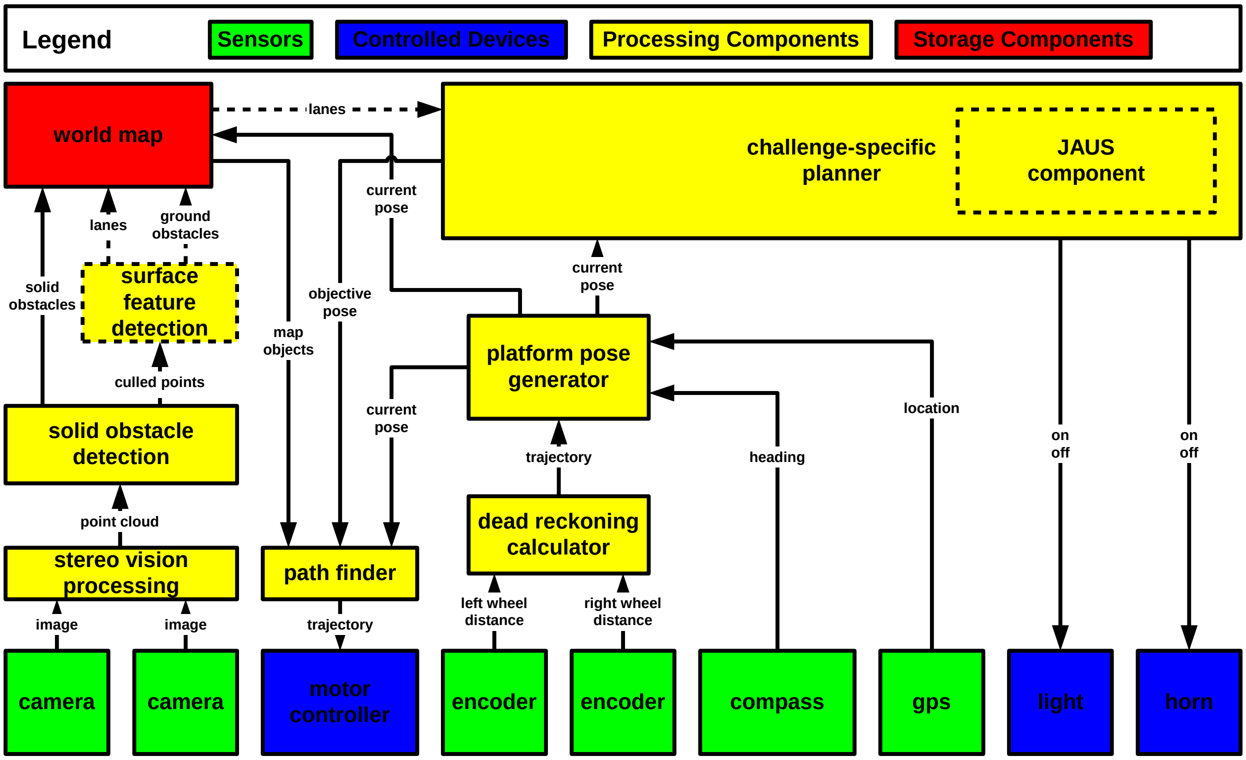


Figure 4 – Challenge Software Block Diagram

Challenges Software Overview – A block diagram of the software architecture for the challenges software is shown in **Figure 4**. Optional components have a dashed-line border. Components are colored according to their identifying characteristic and are described in the following paragraphs.

Dead Reckoning Calculator – This component receives distance information from the encoders and converts this into an estimation of velocity and turn rate (trajectory). This information is used in instances where GPS information is unavailable (typically due to overhead obstructions).

Platform Pose Generator – This component receives position and heading information from the electronic compass and GPS sensors to keep track of the platform's position within the world. When GPS information is unavailable, trajectory information from the dead reckoning calculator is used to maintain an accurate estimation of position.

Stereo Vision Processing – This component performs correlation on stereo image pairs. For those points that can be correlated between the images, 3D coordinates (in the camera coordinate system) for those points are derived. **(Figure 5** demonstrates the correlation process, using a false-color image to depict the distance of each correlated point from the camera.) These points are then transformed (via multiplication with an appropriate transformation matrix) into the platform coordinate system. The transformation matrix used is unique to each stereo camera and is determined during platform sensor calibration. Point data derived from any number of stereo cameras can be combined to form a detailed representation of the platform environment using this approach. The output of this component is the combined set of points as derived from each stereo camera. Each point includes the RGB color of that point as determined during correlation.

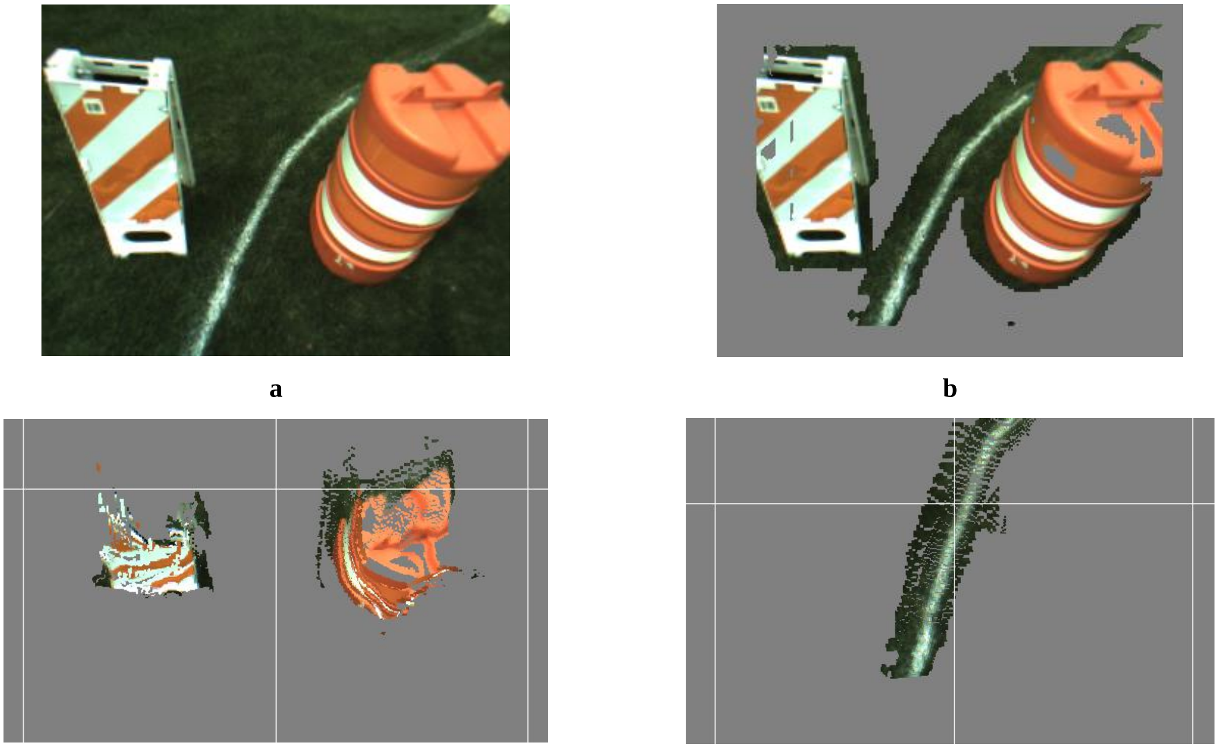
Figure 5 – Correlation of Points in Image Pairs

Culture Shock Innovations – Stereo Vision Obstacle Detection

- The use of stereo vision for solid obstacle detection does not rely on recognizing specific coloring to identify (solid) obstacles, as was used in previous years (in combination with laser-based detection).
- Stereo vision works well even with dark objects that absorb the radiation used by infrared laser-based systems.

Solid Obstacle Detection – The individual points received from the Stereo Vision Processing component are examined. Points with ‘z’ coordinate values above a configurable threshold value are classified as belonging to solid obstacles and are culled from the data set. Proximal points at surface level with similar color are considered to be part of the obstacle and are culled as well. The output of this component is the set of detected obstacles and the remaining points (assumed to belong to surface features).

This approach is depicted in **Figure 6**. Panel **a** shows the original image. Panel **b** shows the set of correlated points in the image (as seen from the camera). Panel **c** shows the overhead (x-y) view of the points identified as obstacles (the relatively high distortion of these points is due to the nature of the reflective surfaces of the obstacles – when using reflective tape, a single point can present different colors or intensities depending on the viewing angle). Panel **d** shows the points remaining after removing the solid obstacles from the point cloud. These remaining points represent the surface features.



a b

c d

Figure 6 – Extraction of Solid Obstacles from Point Cloud

Surface Feature Detection –This component is active only during the Autonomous Challenge. The remaining points are projected onto the x-y plane and Hough transforms are performed to identify lane boundaries (using the previous frame's results as a starting point). Additionally, distinct changes in ground coloring are evaluated against the criteria for potholes (two foot diameter). Obstacle and lane boundary information are provided as outputs.

World Map – This component maintains a catalogue of information about the objects in the world. Objects beyond a specified distance from the current position are culled from the catalogue. This lets the platform respond intelligently to changes in the world (such as obstacles being moved once the platform passes).

Path Finder – This component constructs a localized view of the objects around the current platform position and determines a trajectory that will best approach the objective position. A trajectory consists of a forward velocity and an angular velocity that when combined describe the path that the platform should undertake. Any movement of which the platform is capable can be expressed in this manner.

In constructing the localized view, the world map is queried to obtain information about objects in the local vicinity of the platform. All objects from the map are converted to the platform local coordinate system (x axis in line with the platform heading). The lane segments from the world map have a buffer distance applied, and the result is combined with the radius of awareness to form a polygon in which the center point of the platform can move freely, excepting obstacles. Each obstacle from the world map has a buffer distance added to its radius to designate an area in which the center of the platform is not allowed to enter. See **Figure 7** for a visual representation of the transformation to local coordinates, lane buffering, polygon construction, and obstacle buffering. The resulting track computed for the given objective (represented by the red cross) is shown in yellow.

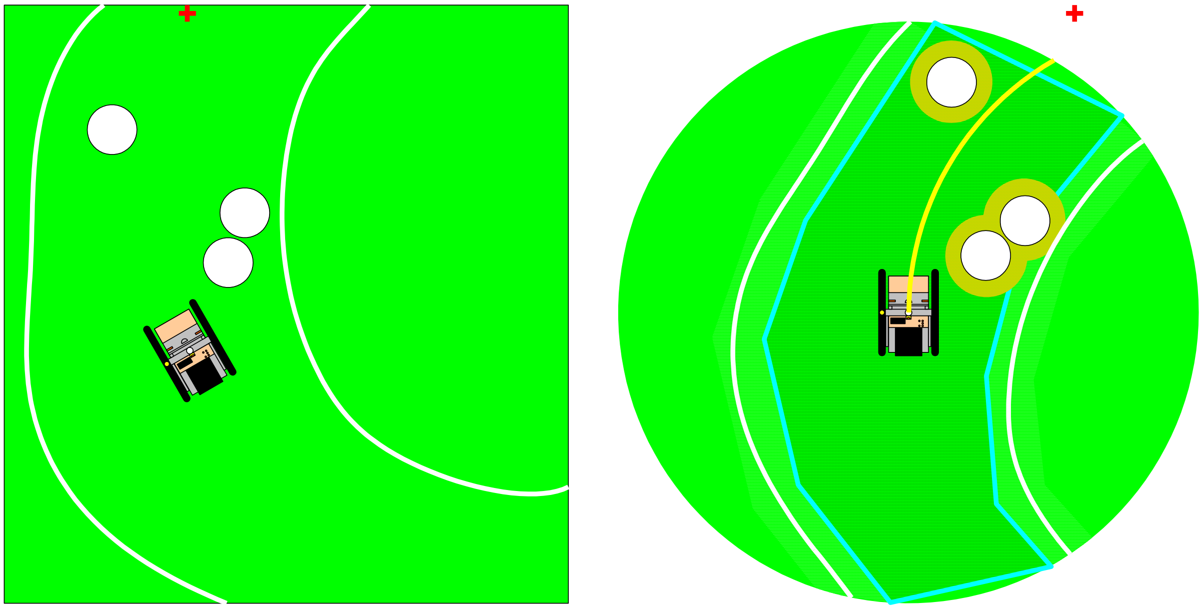


Figure 7 – Path Finder Operation

In determining a trajectory, a number of possible arcs are considered, with scoring principally based on anticipated progress made toward the objective. Arcs that are tangent to the current heading vector are given preference, but other arcs will be selected when they represent significantly better progress toward the objective. The algorithm limits the velocity component of the trajectory based on the radius of the selected arc and the distance that is known to be clear ahead. The angular velocity is then calculated to match the selected arc when combined with the velocity component. The resulting trajectory is provided to the motor controller for execution.

Challenge-Specific Planner – Each challenge has a planner component specific to the challenge that determines the current objective pose. These planners are described briefly in the paragraphs that follow.

Autonomous Challenge Planner – This planner continually moves the objective to a position believed to be in the center of the lane at some distance in the forward direction. As the platform position approaches the objective, the objective is moved farther out. When there is a low confidence as to the location of the lane (as may occur in the presence of obstacles or dashed lane boundaries), the objective is advanced incrementally in a line along its previous track. The light and audible alert are both active throughout.

Navigation Challenge Planner – This planner continually calculates the shortest route among the remaining waypoints, based upon known constraints and obstacles and sets the objective so as to traverse that route. As the platform position passes the waypoint position, that waypoint is removed from the set of remaining waypoints. The light and audible alert are both active until the platform returns to the starting point.

JAUS Component – For either the autonomous or navigation challenges, the platform can be configured to be managed via JAUS. If so enabled, the JAUS component will perform the JAUS discovery process (as described in the JAUS challenge rules), and allow the “COP” to control the platform via the System Access Control and System Management services.

Culture Shock implements the Local Pose Sensor Service and the Velocity State Sensor Service as defined by “JAUS Mobility Service Set” (SAE Aerospace Standard AS6009), allowing the COP to interact with the platform via these services to obtain position and velocity information during the challenge.

Predicted Performance

Speed – Propulsion system design and component selection were undertaken with a goal of achieving the maximum allowed speed of 5 miles per hour under load. This top speed is enforced by the motor controller configuration. Performance to this goal has been verified in trials.

Ramp climbing – Propulsion system design and component selection were undertaken with a goal of performing at top speed on a 15% gradient, the maximum allowed under IGVC rules. Performance to this goal has been verified in trials.

Reaction times – The vision system achieves a sustained throughput of more than 20 frames per second for each camera. Based on an analysis of latency in acquisition, processing, and communications paths, it is estimated that an obstacle presented within the field of effect will affect motor speed in 90 +/- 25 milliseconds.

Battery Life – Battery life is highly dependent upon the operational environment. In a quiescent state with failsafe brake disabled, the 24V battery life is estimated at 10 hours. Under continuous load, the 24V battery life is estimated at 2 hours. The 12V battery life is estimated at 3 hours under full processing and sensor load. At the time of this writing, none of the batteries has been depleted to the point of platform or subsystem failure and so these estimates are not confirmed.

Obstacle Detection Distance – This is configurable via parameters to the stereo vision processing software. Detection is presently limited to approximately 20 feet.

Complex Obstacle Negotiation – Switchbacks will be handled inherently by the path finding algorithm. In the case of traps, the path planning algorithms add ‘synthetic’ obstacles to the world map to prevent a trap from being reconsidered as a possible path once identified.

Navigational Accuracy – The geolocation equipment used is capable of sub-meter accuracy when used with satellite- or earth-based augmentation. Culture Shock employs satellite-based augmentation and is presently configured to use the OmniSTAR service for differential corrections, which often results in positional accuracy of 10cm or less.

Cost Data (USD)

Mechanical / Propulsion		Sensors		Processing / Electrical	
Unicycles	1,070	Stereo Cameras	1,755	Computer System	1,000
Chain & Sprockets	110	GPS System	1,760	Power Supply	250
Aluminum/Steel Stock	1,150	Compass	775	E-Stop System	100
Miscellaneous Hardware	250	Motor Controller	410	LED Beacon	55
Batteries	265			Touch Screen	315
Motors	1,790			Laser Diodes	85
Shocks & Casters	120			Misc. Electrical	200
				TOTAL	11,460