Team Mojavaton
Technical Paper
DARPA 2007 Urban Challenge

May 31, 2007

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Abstract

Team Mojavaton has designed and built an autonomous ground vehicle for the purpose of competing in the 2007 DARPA Urban Challenge. This vehicle, dubbed the White Knight, utilizes the same 2001 Nissan Xterra chassis that competed in the 2005 DARPA Grand Challenge. It has been modified with additional sensors and software to enable it to drive in traffic. Our approach to the design problem of the Urban Challenge has been to use Commercial Off The Shelf (COTS) components, integrate them using the standards of good machine design, and write clever software. Rather than rely heavily on any one type of sensor, we have developed a more balanced approach that utilizes four basic types of sensors: LIDAR, radar, stereo vision, and CCD cameras (both color and black and white). Because each type of sensor has its strengths and weaknesses, a blend of these four types provides a more complete and reliable view of the world. A unique algorithm has been developed to process the stereo vision data into useful information. Sensors are mounted on the roof on a rotary actuator in order to look in any direction and are used to detect traffic on other roads and around corners. Obstacles are detected with one or more sensors then are evaluated to determine if the obstacle is stationary or mobile. The threat level of each obstacle is evaluated. Obstacles whose threat level exceeds specific criteria are used to modify the planned course and the planned velocity when necessary. Waypoints, sensor data, and the planned path are displayed graphically for testing and debugging purposes. A proprietary algorithm has been developed to drive smoothly and precisely at low and high speeds.

Figure 1 – Team Mojavaton's White Knight

Project Overview

The basic components of this design problem are:

- Design and install hardware in a vehicle to drive by wire. This includes steering, throttle, brake, and transmission actuators.
- Write code to plan a path from any starting point to a given end point that connects a given sequence of specified waypoints (checkpoints).
- Write code to provide a smooth path through intersections. Unlike the two previous Grand Challenges, waypoints will not be provided to direct a path through sharp corners (i.e. turning at intersections)
- Detect other vehicles in all directions and at a distance of at least 150 meters at intersections
- Detect stationary obstacles that are large enough to require a change of course or a change of velocity
- Write code to evaluate and choose the proper vehicle behavior – wait or go, pass or follow, swerve or follow the planned course.

Analysis

The choice of vehicle was an easy decision. The Nissan Xterra that we used in the 2005 DARPA Grand Challenge (DGC) fulfilled almost all of the requirements for the Urban Challenge. In addition to being a great choice for the 2007 race, the fact that it was already configured for drive-by-wire, would accommodate the DARPA e-stop system, and already had some of the sensors necessary for the next race meant that software testing could begin much sooner than if we had to start over with another vehicle.

Analysis of our vehicle's performance in the 2005 DGC illustrated several weaknesses:

- The critical flaw had been the decision to activate the throttle with a stepper motor that was mounted under the hood. It was this motor that overheated and failed at mile 23 and ended the race for us.
- Another serious flaw was an undersized DC power supply. This unit failed the day before the final race during the test start and had to be promptly replaced.
- Our inertial navigation unit (INU) was independent of our DGPS system. Our software that combined information from these two units was not sufficiently developed and this resulted in the DNF on our 3rd run at the NQE.
- Our path planning software produced a planned course that swung wide at both the beginning and the end of a turn. This resulted in the DNF on our 4th run at the NQE (in the mountain pass section) and in excessively wide turns during the final race.
- Our path planning to avoid parked cars was inadequate. Our sensors saw them, but the path planning did not always do the right thing. This resulted in clipping several of the junk car obstacles at the NQE.

Analysis of the design problem posed by the 2007 Urban Challenge produced these decisions:

1. The type of vehicle chosen by each team for the Urban Challenge will probably be largely irrelevant. It will be a contest of sensors and software, not of vehicles. We could see no reason to switch to a different vehicle.
2. There are longer range LIDAR sensors available, but they are quite expensive. We elected to use 10 sensors whose total list price value is $38K. We wanted to design an autonomous system that would not be prohibitively expensive to commercialize. Designing a system that could be commercialized at a reasonable cost seemed to be consistent with the overarching purpose of the Urban Challenge.

Figure 2 – view of White Knight rear compartment

Design

The primary design flaw of mounting the throttle actuator under the hood was corrected by mounting a new actuator in the cabin of the vehicle where it would be cooled by the air conditioning system. All power supplies were replaced with new and more reliable systems.

Exeltech provided a fully redundant MX1A DC-to-AC inverter that provides clean 120 VAC power. This power supply produces a true sinusoidal wave, rather than the more common chopped wave. This true sinusoidal wave produces cleaner (less noise) power that is always preferable, especially for computers and delicate instruments. The 12 and 24 volt DC power is produced using this clean 120 VAC supply and is also a fully redundant power system.

The separate DGPS and INU systems were replaced with a Novatel SPAN DGPS system that works in conjunction with a Northrop Grumman LN-200 Inertial Measurement Unit. The Novatel software combines the information from the LN-200 with its own DGPS information and provides a blended location solution. The Novatel GPS uses OmniStar's HP subscription service to further enhance its accuracy. We also use the Navcom Starfire DGPS system and the Navcom subscription correction signal. Having dual GPS systems is part of our philosophy of design redundancy whenever possible.

A key aspect of our system design is to use a variety of sensors and to fuse their data into a coherent picture of the world. Each type of sensor has strengths and weaknesses and sees the world in different ways. Our approach has been to use each sensor in a manner that plays to its strengths.

Two laser range finders (SICK LMS-291) are used – one on the front bumper and one on the rear. Each is configured for a 180^{o} field of view.

Two color DVT cameras are used to detect the roadway surface and any painted road lines.

A Cognex SafeTRAC lane departure warning system is used to detect the road lines and compute the location of the car relative to the center of the lane. This system consists of a small black and white CCD camera that is mounted to see the road ahead of the car and a microprocessor that analyzes the camera data. The output from this microprocessor is transmitted on an RS232 line. This is not raw camera data, but it has been processed and provides the following information:

- The location of the car relative to the center of the lane. This is based on both left and right road lines when both exist, or on one line if only one exists. This is expressed in feet relative to the center of the lane. A negative value indicates the car is to the left of the center of the lane.
- A confidence level for this lane position calculation. This is expressed as 0% to 100%.
- Whether the road line on the left is a solid or a dashed line. The information in the RNDF about the center line has precedence over actual road lines, so this information will be used if the RNDF does not specify a center line type.

Radar units are mounted on both the front bumper and on the roof. These units can accurately detect the presence of other vehicles at a distance of 200 meters. They will report the other vehicle's speed and location.

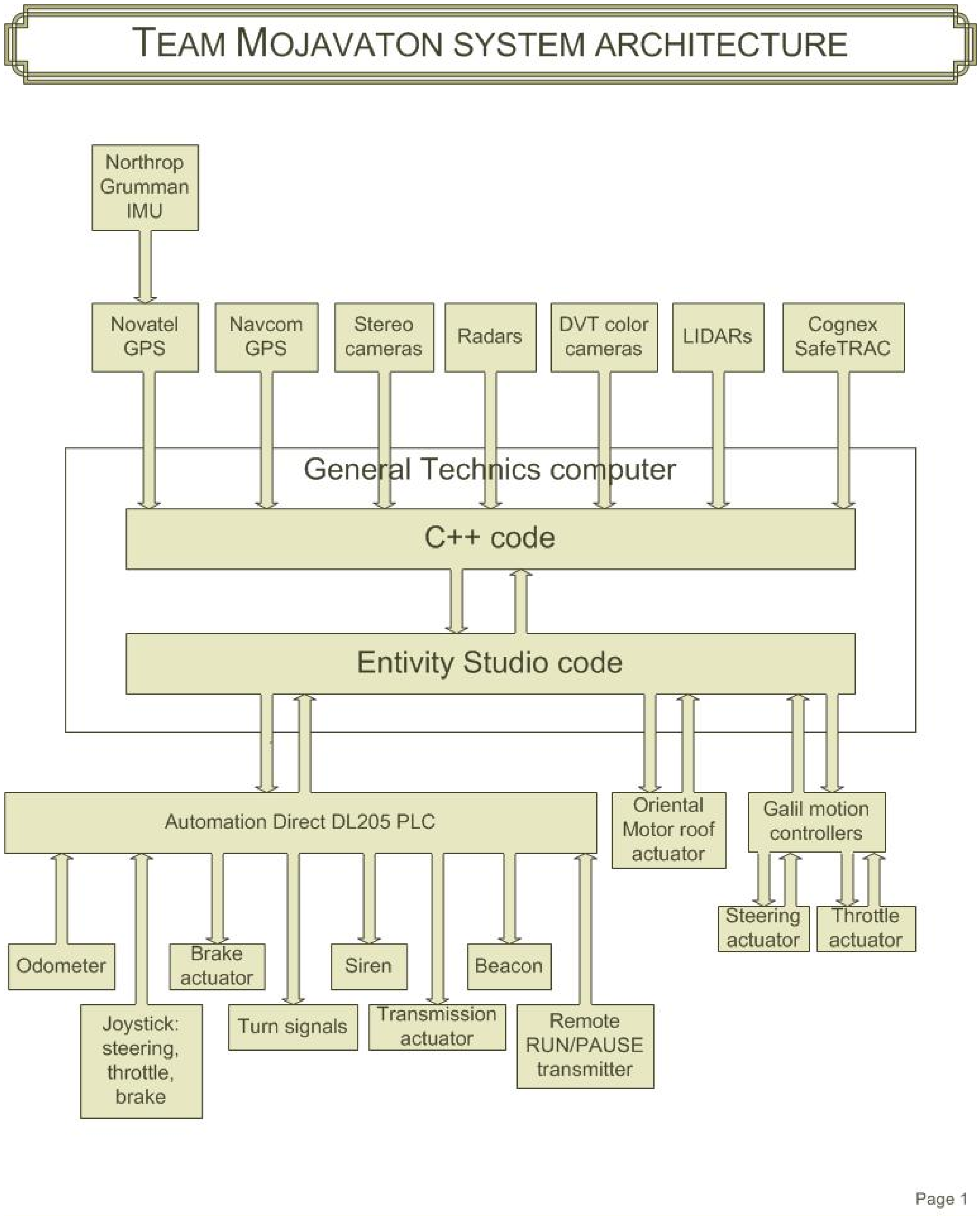

Figure 3 – system architecture, page 1

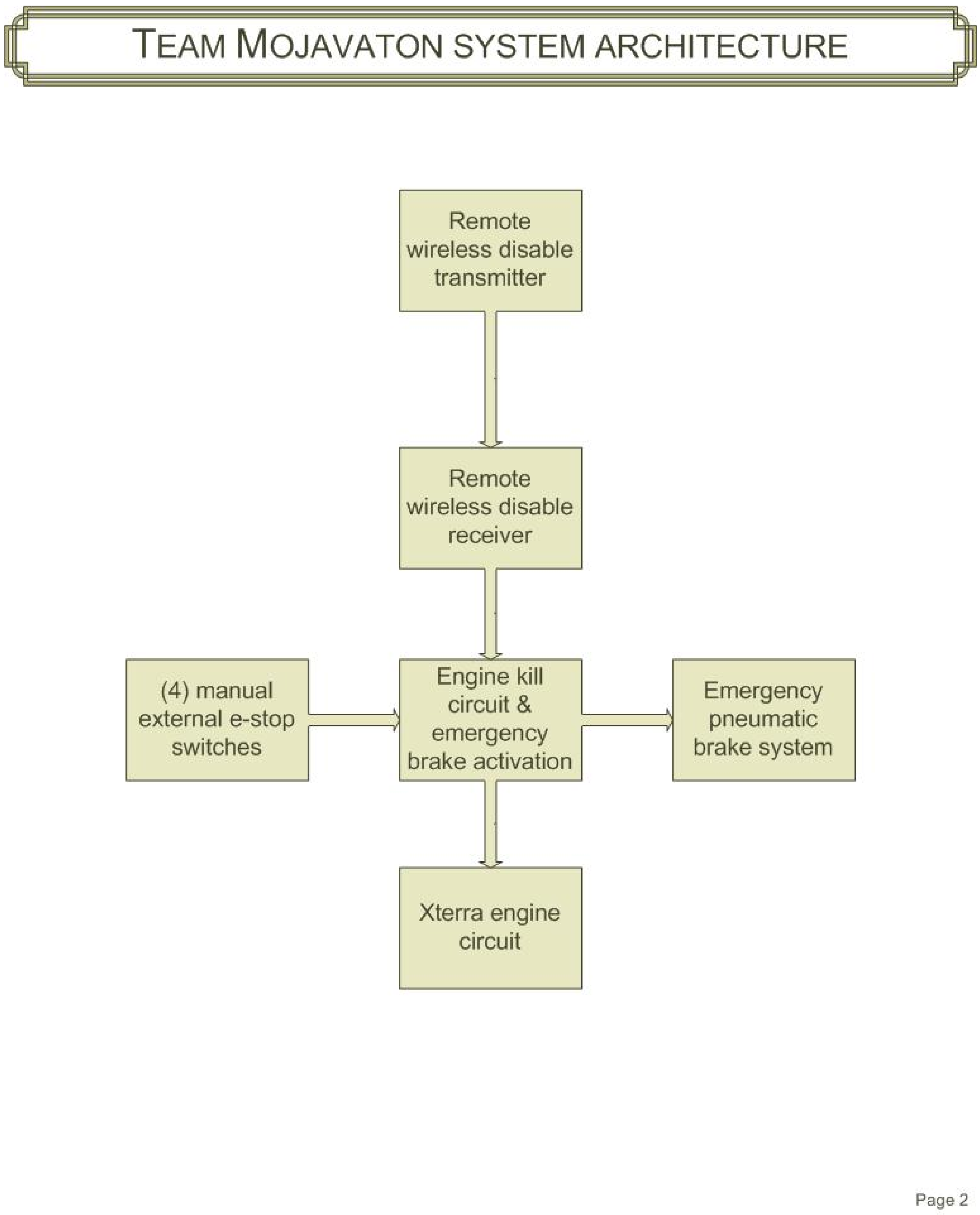

Figure 4 – system architecture, page 2

Two other radar units are mounted on each side of the vehicle to detect other vehicles alongside the Xterra. The computer considers information from these side radars before initiating a pass and before returning to its lane.

Two Point Grey color stereo cameras are used. One is mounted on the roof and the other is on the dashboard of the car looking forward. Data from these cameras are the XYZ Cartesian coordinates of points on the surfaces in its field of view. These data are always incomplete as the system cannot correctly match every pixel in its left side image with a pixel from its right side image. When the color or shading of a surface varies, the stereo camera is very good at correctly estimating its distance. When the surface is very uniform in color and appearance (a white wall for example), it cannot.

The roof sensors are mounted in a weather-proof enclosure that is mounted on an Oriental Motor rotary actuator. This hollow shaft actuator allows all cabling to pass through the center of the actuator. This roof suite of sensors can be rotated around a vertical axis so it can be pointed in any direction. The computer system decides where to point this roof suite depending on where it wants to look for other cars. For example, at a crossroad, it will point the roof sensors at the three other roads to determine what traffic is on each road. The computer will use the RNDF waypoints of these three other roads to determine exactly where to position the roof sensors.

All external sensors are protected from water so that the car can operate in the rain.

The Mojavaton software system is multi-threaded C++ code that works in conjunction with Entivity's Studio™ software program. Studio™ is a PC based machine control software program. The sensor data is fed into the C++ programs with sensor analysis, path planning, and path driving all being done in C++. The final answer of desired velocity and desired steering wheel position is passed to Studio™. Studio™ processes this information and controls all drive-by-wire functions. Studio™ communicates with an Automation Direct DL 205 programmable logic controller (PLC) via an Ethernet connection. The DL 205 provides the interface to all analog devices, the wireless e-stop RUN/PAUSE signal, the siren and beacon, joystick for manual operation of steering and velocity, odometer, and tachometer (Figure 3).

This "division of labor" between the custom C++ programs and the Studio system has greatly simplified the system development. The Studio/Automation Direct PLC combination has been optimized to work well together. The steering and throttle stepper motors are controlled with Galil motion controllers. Entivity Studio™ has all the necessary drivers for communicating the Galil controllers and this greatly facilitated development. The Galil controllers provide closed loop control on both steering and throttle motors. In addition, the Galil controllers provide "auto-tune" to find the optimal PID parameters to use in controlling these motors. The performance of the Entivity/Automation Direct/Galil system has been flawless.

RS-232 serial communication uses a Comtrol Device Master serial-to-Ethernet device. This device enables the SICK LIDAR devices to communicate at their maximum baud rate of 500K.

The wireless e-stop DISABLE signal that kills the engine and applies the brake is not wired through the computer in any way. It has its own custom designed and dedicated circuitry that operates independently of all other systems. In that way, a total computer failure or the failure of the brake actuator will have no effect on the DISABLE signal's ability to stop the car in the event of an emergency. OSHA regulations for emergency stop systems (hand buttons, light curtains, etc.) on all machinery require this type of e-stop system independence. Our wireless e-stop system was provided by Remote Control Technology and was custom built for Mojavaton. This system will be used at the site visit for control of the vehicle. The transmitter will be housed in another car stationed near the center of the course. The receiver is mounted in the White Knight. This system contains two separate wireless transmitter/receiver channels. One channel, operating at 27 MHz, is a toggle on/toggle off circuit that runs through the DL205 PLC and serves to alternately PAUSE and UNPAUSE (RUN) the driving system. The other channel operates at 151 MHz and is a heartbeat circuit. It transmits a momentary signal every two seconds. This heartbeat signal is monitored by the receiver and activates a latching circuit. As long as the heartbeat signal is received every two seconds, the latching circuit stays closed. This closed circuit is wired directly into the engine ignition and is required for the engine to run. If the heartbeat signal is not received every 2 seconds, the latching circuit opens. This immediately applies an emergency brake and kills the engine. If communication between the transmitter and receiver is lost, the heartbeat latching circuit will automatically open and stop the White Knight. This "fail open" circuit design is an important safety feature of the car's overall system and again follows OSHA regulations for machine design.

The two previous Grand Challenge races provided an ordered series of GPS waypoints that defined the route. This year's event does not. Roads are defined with waypoints in the RNDF but the actual course must be determined from a Mission Data File (MDF) containing an ordered series of specific waypoints (checkpoints) that must be attained in the specified order. Hence, the path planning software must devise its own route using only the given roads and the knowledge of how these roads connect with each other.

The path planning process begins by adding cubic spline Hermite curves between every pair of adjacent waypoints. All exit and entry waypoints in intersections are also connected with Hermite curves. Each Hermite curve contains interpolated waypoints every 2 meters that define a path between adjacent DARPA waypoints. Since Hermite curves use a tangent at both ends, we design this tangent to point directly towards the adjacent waypoint. The end point of the Hermite looks forward for its tangent direction and the start point of each Hermite looks backward to find its direction. In this way, we exit each curve with a heading that is optimal for driving to the next waypoint. In addition, the Hermite curves can be adjusted for "tightness" so that we can tune the algorithm to provide exactly the kind of path that we want through each intersection. These interpolated Hermite waypoints assist the driving software by providing more frequent waypoints and a smooth path through intersections.

Once the Hermite curves have been computed, the planning program searches for the best path that begins at the location on the earth of the White Knight and then connects all specified checkpoints in the order they are given in the MDF. This search uses a modified version of Dijkstra's algorithm. Dijkstra's algorithm is a "greedy algorithm that solves the single-source shortest path problem for a directed graph with non negative edge weights".[1]

Once the path for the next mission has been planned and Hermite interpolated waypoints have been inserted, the path is evaluated in several ways. First, the software looks for any portions of the path that would require a turning radius that is too small for the Xterra. A path that makes a U-turn on a two lane road would be one example. A flag is set that will request a 3 point U-turn at these points. Waypoints are then evaluated and marked as either being in a safety area or a travel area depending on their proximity to an intersection. All waypoints in zones are marked as being in a safety area.

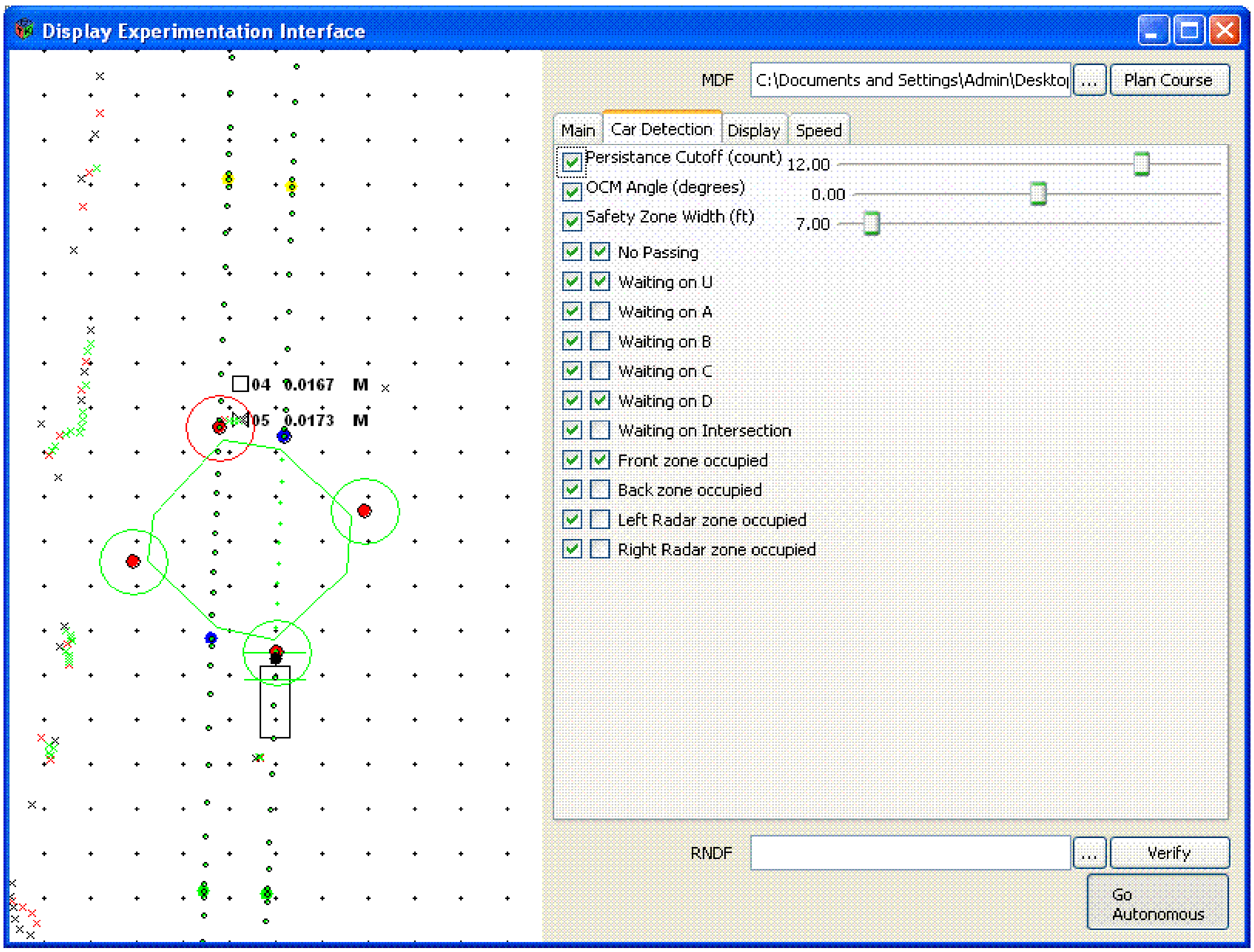

Figure 5 – Operator interface

Figure 6 – White Knight at 4-way intersection facing another car

All Mojavaton C++ code uses the open source GUI development tools of Glade-3 and GTK+ (the GIMP toolkit). These are free tools that can run on Windows, LINUX, and MAC operating systems. This produces code that is more cross platform compatible. The Mojavaton C++ code uses the STL (standard template library) set of algorithms written by the community of C++ developers. One of the intents of the STL is to avoid mistakes in memory allocation when using memory structures that resize themselves dynamically. Code is compiled using the Eclipse compiler, also an open source community project.

An operator interface screen has been developed to display sensor data and path data. The interface has slider bars that allow on the fly adjustment of system parameters. This greatly facilitates testing and optimization of new code and of system parameters. An example of this screen is shown in Figure 5. Figure 6 shows the position of the White Knight and another traffic car at the time that the screen shot in Figure 5 was taken.

The operator interface is composed of two parts – a map display which is a graphical representation of sensor and path data on the left and some system information on the right. The following items are represented in this operator interface:

- The White Knight itself is represented by the largest black rectangle. The front of the car is at the top of this rectangle (so the car is looking towards the top of the image)
- A 10’ x 10’ ground grid is shown with the smallest black dots.
- The waypoints at the 4 stop lines are larger red dots with a black border. A circle around each stop line represents the general area around the stop line.
- An octagon defines the area within the intersection.
- The status of the intersection and each stop line (occupied or not) is represented by the color. In this instance, there is another car at the opposite stop line (as shown in Figure 6). Hence the circle around this stop line is red. The intersection and the left and right side stop lines are clear; hence the octagon and the other two stop line circles are green.
- Obstacles detected by the LIDAR are shown as red and green X’s.
- The path that has been planned is shown by small circles. Each circle is a waypoint. If the waypoint was from the RNDF, its circle is green. If the waypoint is a checkpoint, its circle is yellow. Blue dots are intersection exit waypoints. All others are the interpolated Hermite waypoints.
- The two thin green horizontal lines close to the front of the vehicle (at the top of the black rectangle) represent the ± 1 meter area in which the vehicle must stop at every stop line. During this screen shot, the Xterra was approximately 1 meter short of the stop line.
- The other car is represented by both LIDAR x’s and by black squares from the radars.
- Since the other car arrived at the intersection first, the Xterra is waiting for it to proceed. This is shown on the right hand side by the double check in the box labeled “Waiting on D”.
- The double check in “No Passing” indicates that the car is in a safety zone.
- The double check in “Front zone occupied” is the conclusion from the LIDAR that there is an obstacle in the zone ahead of the car. This is independent of its being at an intersection.
- The lack of a double check for “Back zone occupied”, “Left Radar zone occupied”, and “Right Radar zone occupied” indicates that the areas on the left, right, and behind the car are clear.
- As soon as the other car pulls into the intersection, the octagon will turn red indicating the intersection is now occupied, there will be a double check for “Waiting on intersection”, and the circle around the opposite stop line will turn green indicating that that area is now clear. The White Knight will not move until all cars that have precedence have left the area and the intersection is clear.

The map display in this operator interface is shown in the vehicle coordinate system. That is, the vehicle is the datum and everything else is displayed relative to it. Hence, the black rectangle that represents the White Knight is in a fixed position on the screen so it always appears to be driving towards the top of the screen. All other features (obstacles, path, etc.) move and rotate relative to the Xterra’s motion. The scale of the map display can be easily adjusted using two of the slider bars – one for the X axis and the other for the Y axis. This allows the operator to zoom in and zoom out on the fly.

Our vehicle uses only one computer. It is a General Technics' industrial 4U rack mounted server featuring two Intel 5130 Dual Core Xeon processors, an Intel S5000VSA server board, and 4GB of system memory. The Windows XP operating system is installed on a redundant RAID 1 mirror of two Fujitsu 80GB mobile SATA drives, featuring a high operating vibration tolerance. Entivity and all C++ programs run easily together and consume only 50% of the CPU capacity.

Results and performance

At this writing, the White Knight has been tested by driving more than 150 miles in fully autonomous mode (this does not include the testing that was done for the 2005 DARPA Grand Challenge).

The White Knight's entire autonomous system uses only 350 watts of power. The stock alternator in the Xterra was replaced with a 130 amp alternator to accommodate the extra 25 amp load.

The path planning software has performed exactly as expected and is capable of planning complex missions. The operator interface will display the planned path, so it is easy to see the path that the computer has planned. We have not found any instances in which we felt the need to modify the planned path.

Our proprietary path driving algorithm produces very smooth and repeatable driving. Some of the testing during last winter occurred with fresh snow on the ground in an industrial park on the weekend. The Xterra would make multiple runs through the same 1.5 mile mission course and the tracks in the snow did not vary by more than ± 30 cm. Most of the mission was driven in tracks that varied less than ± 15 cm.

The undesirable "swinging wide in the turns" facet of the Xterra's driving during the 2005 Grand Challenge is completely gone.

Sensors on the roof can detect oncoming cars at a distance of 200 meters. At this 200 meter distance, their speed is measured to an accuracy of ± 1 mph and their distance to an accuracy of only ± 25 meters. When a car is 100 meters away, a more accurate (± 1 meter) measurement of its distance can be made.

The Xterra can follow the road by using the Cognex SafeTRAC lane departure warning system and the color DVT cameras. The computed confidence level that the SafeTRAC reports about its calculation of vehicle location relative to the lane is highly reliable. If the system reports 100% confidence, you can be very certain that it has determined the lane markings and has correctly assessed the car's position in the lane. This Cognex/DVT combination will assist in driving in areas of sparse waypoints where a straight line path between DARPA waypoints is not on the roadway. We can currently drive at 25mph using only information from the Cognex and DVT cameras (without the aid of any GPS or INU information).

The Point Grey stereo camera data is analyzed with a proprietary Mojavaton algorithm. This algorithm will produce information about the presence and location of obstacles to a distance up to 30 meters. The factor that limits this effective distance is the spacing between the two cameras in the stereo camera. A wider camera spacing would allow the same algorithm to see further.

At this writing, the White Knight has the ability to perform all Basic Navigation and all Basic Traffic criteria. It will pass a stationary car in a travel area and will do so in the specific windows required for leaving its lane and returning to its lane. It will stop at a stop line and correctly assess whether one or more other cars arrived first, and if so, will wait indefinitely (as specified for the site visit) for all other cars with precedence to leave the intersection. Once this occurs and the intersection is clear, the White Knight will proceed through the intersection. Missions that require a U-turn on a stub road are executed with a 3 point U-turn. The Xterra will convoy behind a slower car and maintain a safe distance. It will queue behind a stationary car in a safety zone and will pull ahead as the car in front moves ahead. It will drive smoothly at 30mph and will stop for a stop line. The wireless e-stop will start and stop the car remotely. The heartbeat system will disable the car on command or if the connection between the transmitter and receiver is lost.

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We have received tremendous support from these corporations. Our entry would not have been possible without their generous assistance.

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