DARPA Grand Challenge 2005

Technical Paper

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Prepared by:
Axion, LLC

Team Lead

Bill Kehaly
Axion, LLC
4607 Lakeview Canyon Blvd. #428
Westlake Village, CA 91361
818-597-2703 Office #
805-497-6897 Fax #
BKehaly@AxionRacing.com

Team Members

Josh O' Briant
Greg Jones
Richard Kalling
Jeremy Pollock
Walter Phillips
Dana Redhair
Puneet Khattar
Trevor Kehaly
German Eichberger
Barry Ehlers
Melanie Dumas
Tim Doyle
George Spalding, III
Joël Chenu
Mat Jones
Paul Kimmelman
Andi Idarto
Pat Jones
Clark Guest
Ryan Kehaly

Abstract

The DARPA Grand Challenge provides tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The Challenge can be broken down into distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology.

Axion, LLC (Axion Racing) has merged these various solutions into an autonomous racing platform leveraging speed, modularity, and reliability.

1. Vehicle Description

1.1 Describe the vehicle. If it is based on a commercially available platform, provide the year, make and model. If it uses a custom-built chassis or body, describe the major characteristics. If appropriate, please provide a rationale for the choice of this vehicle for the DGC.

The Axion, LLC Challenge Vehicle (Spirit) platform is a four door 1994 Jeep Grand Cherokee Limited 4x4. It is a standard four-wheel-drive production vehicle (see Figures 1) with enhancements for off-road activities. It was chosen for the DGC because of it's off road capabilities and exceptional operational gas and maintenance costs versus a H1 Hummer from General Motors. Spirit will contact the ground with four (4) mud terrain tires with a heavy duty inner tube filled with standard tire sealant for puncture fighting. The tires are B.F. Goodrich Mud/Terrain T/A® tires (stock # 417-972) with the following specifications:

Tire Size	Sidewall	Rim Width Range (Inches)	Section Width on Measuring Rim Width	Overall Diameter	Tread Depth (in/32nds)	Revs/Mile at 45 mph	Max Load Single (lbs@psi)
35x12.50R15/C	**RWL**	**8.5 – 11.0**	**12.5 on 10.0**	**34.8**	**21.0**	**598.0**	**2535@35**

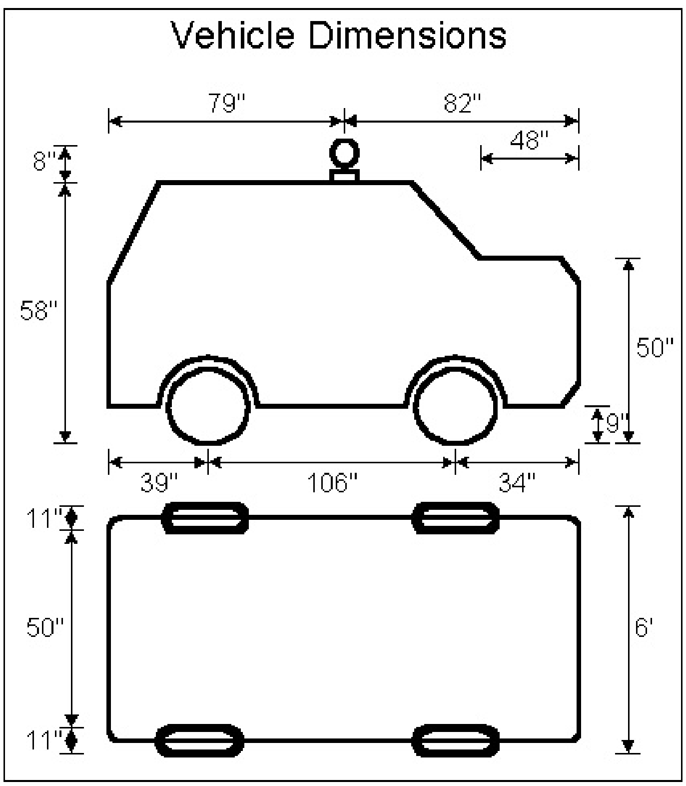

Figure 1: Spirit's Description

1.2 Describe the unique vehicle drive-train or suspension modifications made for the DGC including fuel-cells or other unique power sources.

Spirit features a manufacturer-standard internal combustion engine burning unleaded gasoline, and a bank of four (4) 12V heavy-duty automotive batteries. Two (2) independent alternators operating redundantly will charge the batteries. A portion of the battery reserve will provide electrical power to the Spirit. The remaining portion of the battery reserve will in turn power two (2) Zantrex Prosine 2.0 inverters, which will provide clean 120V, 60Hz AC to the computational portion of the Spirit.

2. Autonomous Operations

2.1 Processing

2.1.1 Describe the computing systems (hardware and software) including processor selection, complexity considerations, software implementation and anticipated reliability.

Spirit utilizes five (5) shock-mounted Pentium class servers and one (1) National Instruments Compact Field Point system. The five servers are motherboard-based 19" rack-mounted computers, 2 server-unit (2U) form-factor in height. The table below itemizes the servers and describes their respective functions, which are also displayed in Figure 2.

Computer Type	Purpose	Serial #	CPU
Dell 2650	Linux system to make Arbitration decisions, interface to LADAR, GPS	F25HG21 (Linux1)	Dual Xeon 2.4GHz
Dell 2650	Linux system to process map database and real time local map creation	5BCK941 (Linux3)	Dual Xeon 2.4GHz
Dell 2650	Windows system to interface to the 5 Bumblebee cameras	F4N7N31 (Windows1)	Dual Xeon 2.4GHz
Dell 2650	Windows system to interface to the Color Camera	CSHH421 (Windows3)	Dual Xeon 2.4GHz
Dell 2650	Windows system to provide the user interface and LabView controls	3BRQ431 (Windows4)	Dual Xeon 2.4GHz
National Instruments (NI) Compact Field Point	Real time controller to actuate steering, gas, and brake	777317-2020	Embedded ARM

Table 1: Computing Hardware

Five Dell Servers have proven reliability while working in the field. In addition, support contracts from Dell allow uncommon hardware failures to be replaced within hours. The Dell hard disk drives are configured with RAID, so a disk may fail without bringing down the system. The dual Xeon processors allow all the computationally expensive processes to run to their full capacity. Software implementation and complexity is considered in the following sections.

The National Instruments Compact Field Point is a real-time embedded system. Code developed with the LabView tool runs on this platform, controlling vehicle acceleration, warning lights, siren, and the emergency stop. Commands are sent and received through the gigabit Ethernet using the standard message format of the system.

Spirit's Artificial Intelligence software is written in Linux, which is know for its reliability, quick processing, and protection from hacking. Other software used in Spirit comes from established vendors with a long history of application success. This software is utilized by Spirit's stereo cameras, thermal cameras, and RADAR.

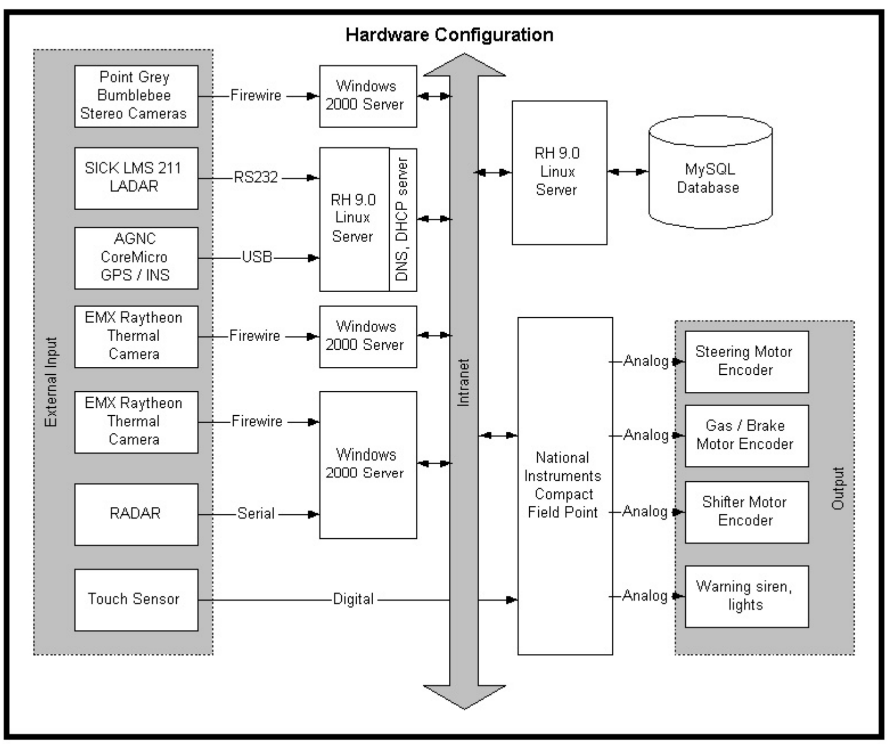

Figure 2: Computing Systems

2.1.2 Provide a functional block diagram of the processing architecture that describes how the sensing, navigation, and actuation are coupled to the processing element(s) to enable autonomous operation. Show the network architecture and discuss the challenges faced in realization of the system.

The Axion Arbitrator is a behavioral control system, accepting input from distributed processes to combine the results into a decision for which way to turn, and how fast to drive. Each sensor is connected to one server. That server runs one or more behavioral processing algorithms for the sensor. The input to the behavioral control algorithms is from the raw sensor data, and it outputs a vote to the Arbitrator for which way to turn. The Arbitrator is responsible for determining speed and weighing the behaviors accordingly for the best solution to find the road ahead.

The network architecture is very simple: a gigabit Ethernet connection extends between all the servers. A standard message interface allows all the behaviors to communicate over TCP sockets.

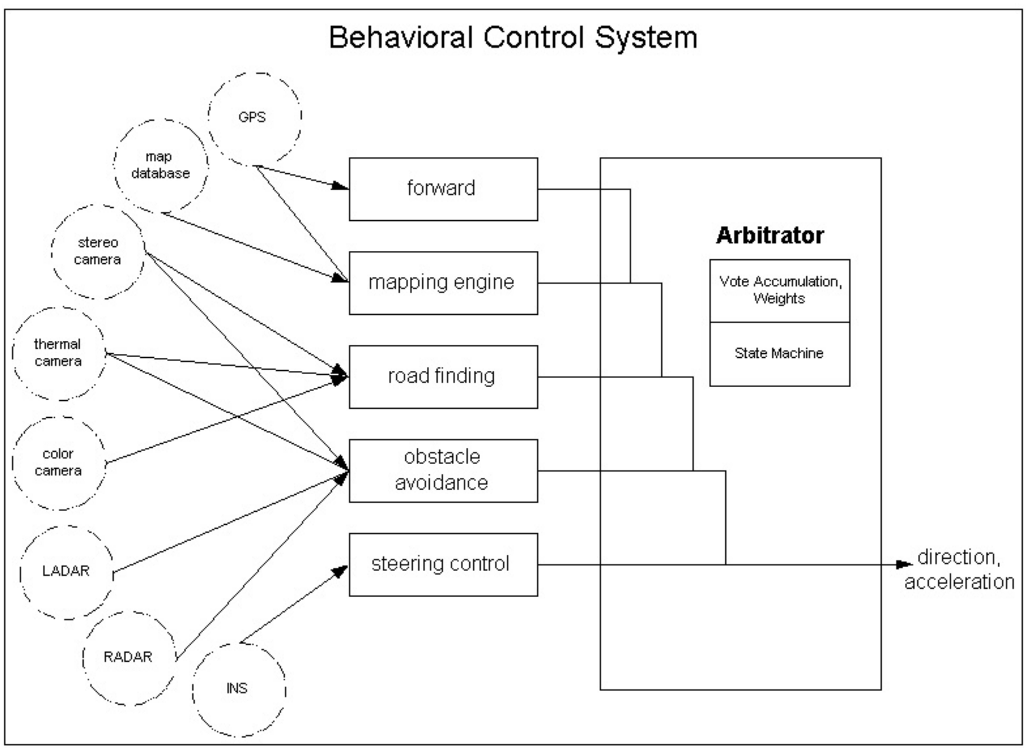

Figure 3: Processing Architecture

2.1.3 Describe unique methods employed in the development process, including model-driven design or other methods used.

Axion Racing's driving philosophy is that each component to autonomous racing has been solved, and our development team is fundamentally systems integrators. This driving philosophy has allowed our team to focus on the results of off the shelf components, rather than building the components themselves. As a result, we are out in the field quickly, with a reliable platform capable of making changes to adapt to the varied terrain.

2.2 Localization

2.2.1 Explain the GPS system used and any inertial navigation systems employed during GPS outages (as in tunnels). Include a discussion of component errors and their effort on system performance.

Spirit uses two NavCom SF2050G GPS devices, which are aligned along the centerline of the vehicle. These devices precisely locate the front and the rear of the vehicle, as well as provide heading in the event of an Inertial Navigation System loss.

Axion Racing has a high quality Northrop Grumman LN270 Inertial Navigation System (INS). This device accepts GPS input from the NavCom system, and calculates the GPS position when the GPS antennas experience an outage, or when the GPS figure of merit value sinks below a threshold. In addition, the INS provides heading, roll, pitch, and velocity measurements that allow finer driving control. The INS system runs at 100Hz, so its performance solidly assists Spirit's navigational algorithms. Errors in inertial or GPS measurements are accounted for in a GPS server that blends the solutions together into precise vehicle localization.

2.2.2 If map data was an integral part of the vehicles navigation system, describe the requirements for this data and the way in which it was used.

A navigational database is based on commercial and freely available data obtained from Internet and other public resources. The data varies from one to 30 meters resolution. Information contained may include presence of a road, an off road track, elevation, slope, vegetation and water probability. The sources for the data used to create the database tables are primarily from the United States Geological Survey (USGS). The source used for elevation data is the National Elevation Dataset (NED) at 30-meter resolution in ArcGrid format. The National Land Cover Data (NLCD) from the USGS was used for water, vegetation, and surface type, also in NED at 30-meter resolution, ArcGrid format. The isRoad variable was extracted from TIGER 2000 line files, at 1m accuracy. Topologically Integrated Geographic Encoding and Referencing (TIGER) 2000 hydrography line files in combination with the NLCD increased the accuracy of the water variable. A Spatial Analyst extension tool created all of the tables used.

2.3 Sensing

2.3.1 Describe the location and mounting of the sensors mounted on the vehicle. Include a discussion of sensor range and field of view. Discuss any unique methods used to compensate for conditions such as vibration, light level, rain, or dust.

Sensors are mounted on the top, sides, front, and back of Spirit. Axion Racing uses the patent pending Axion Racing Sensory Enclosure (RSE) to keep light, rain, and dust from all sensors affected by these conditions. The RSE also uses wiper blades to keep mud and rain from blocking the stereo and color cameras. The RSE is reactive, detecting when particles obstruct the camera's field of view to actuate the wipers and remove the obstruction.

The range of sensors and stopping distances used by Spirit is displayed in Figure 4. This display indicates the sensor, number used, and each sensor's range. Axion Racing has also determined the required distance to stop at specific vehicle speeds. This information is used to insure that Spirit always has enough time and space to complete all necessary stops.

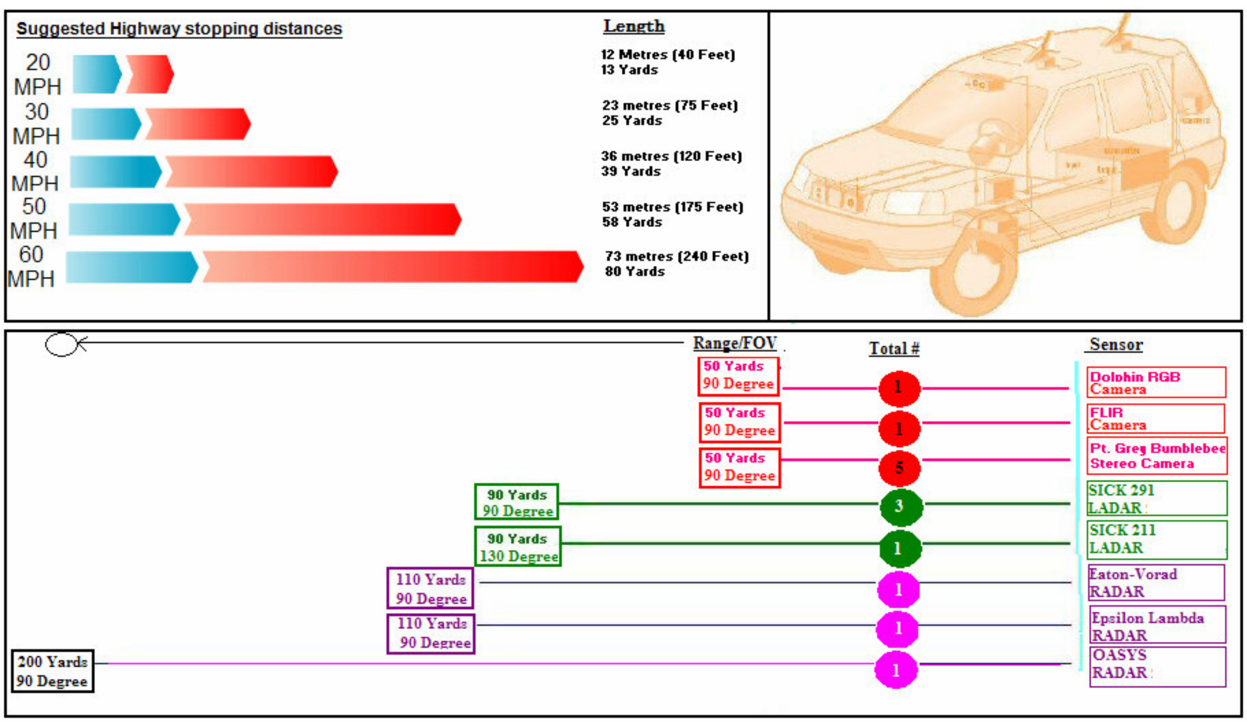

Figure 4: Sensing & Stopping Distances

2.3.2 Discuss the overall sensing architecture, including any fusion algorithms or other means employed to build models of the external environment.

Each sensor operates independently to construct a partial view of the environment ahead of the vehicle. The sensor provides its data to one or more behavioral algorithms. The behavioral algorithms are tasked to either find the road ahead or calculate obstacles ahead. The majority of our behavioral control algorithms act independently.

One component of our sensory architecture combines the ranging information from multiple sensors in front of the vehicle to detect obstacles. This "local mapper" application stores the position of all obstacles Spirit has encountered in the world. This application enhances the independent sensor behavioral algorithm and votes just like the independent behavioral algorithms.

2.3.3 Describe the internal sensing system and architecture used to sense the vehicle state.

The Northrop Grumman LN270 Inertial Navigation System provides vehicle localization and rotation information. In addition, some elements of the vehicle's performance are measured by the National Instruments (NI) software, to ensure that the expected vehicle state matches the actual vehicle state. For example, the NI software is capable of detecting when the wheels are moving, but the vehicle is not actually moving, so the wheels must be slipping. Special code detects and responds to these awkward conditions.

2.3.4 Describe the sensing-to-actuation system used for waypoint following, path finding, obstacle detection, and collision avoidance. Include a discussion of vehicle models in terms of braking, turning, and control of the accelerator.

The steering wheel is actuated by means of a DC electric servo motor system consisting of the following components: one DC motor connected to the steering wheel, with a gearbox, one potentiometer steering feedback system connected to the steering motor, one AMC Servo Steering Motor Controller, part #25A8K-ANP. It's important to note the steering wheel can be disengaged from the motor, allowing for manual operation of the steering system. The analog signal sent from the Arbitrator goes directly to the AMC Servo Motor Controller, which directs the steering servo motor to the desired position. The servo motor gearing turns the steering wheel in the desired direction.

The Electronic Mobility Controls (EMC) Electric Gas Brake (EGB-IIF) unit is a single servo motor with an arm that travels 270 degrees, that is set up to apply pressure on the factory brake pedal in a travel position from 8 o'clock to 3 o'clock, where 3 o'clock is full brake. Swinging from 3 o'clock to 8 o'clock will bring you to a position of no pressure on the brake and idle on the vehicle motor. Continuing to swing up to 12 o'clock, the same mechanism pulls a cable, which in turn pulls the throttle of the vehicle. This system is commercial off-the-shelf, installed according to manufacturer's specifications. The EGB is controlled by an analog signal from the National Instruments.

The shifting is controlled by means of a linear actuator. The linear actuator provides analog positional feedback information. Spirit will utilize park, reverse, neutral, and drive, depending on the circumstances. The linear actuator is controlled by a signal from the National Instruments.

2.4 Vehicle Control

2.4.1 Describe the methods employed for common autonomous operation contingencies such as missed-waypoint, vehicle-stuck, vehicle-outside-lateral-boundary-offset, or obstacle-detected-in-path.

Extensive testing in the field has led to extensive development of these corner cases. Spirit does not return to missed waypoints, since in many cases the road is not wide enough to make a full turn to reach the missed waypoint. The vehicle will continue along the assigned path in this case.

When the vehicle is "stuck", this may occur with wheels slipping, and the vehicle is not actually driving forward. For this case, we detect this condition in the National Instruments software, and reverse a few meters to free ourselves from this condition.

If the vehicle travels out of bounds, the “boundary” voter immediately pushes us back into bounds by providing a strong negative weight along any path that continues out of bounds. If an obstacle is detected in the path, the vehicle detects this with either the four LADAR sensors or the five bumblebee cameras. Upon detection, the vehicle’s path is adjusted to pass the obstacle by with a safety margin.

2.4.2 Describe the methods used for maneuvers such as braking, starting on a hill, or making a sharp turn without leaving the boundaries.

There are two cases for braking – brake the vehicle to 0 mph, or brake to a value greater than zero. If the vehicle velocity is commanded to zero, than the brakes are immediately and fully applied. If the vehicle velocity is reduced from the current velocity, and greater than zero, than the brakes are applied according to a control loop that commands the desired speed.

When Spirit starts on a steep hill, the acceleration logic has a control loop to ramp the vehicle up to the desired speed, independent of the road’s slope. The Arbitrator may decide that a sharp turn is required to stay in bounds, based on information from the boundary and other behavioral voters. This condition is easily met with the architecture.

2.4.3 Describe the method for integration of navigation information and sensing information.

The sensors that require navigation information are all obstacle detectors, to localize the obstacle in world space. A simple translation and rotation of obstacle data from the sensor calculates where the obstacle resides in world space. The vehicle location is simply sent to the behavioral algorithms as an input to their processing algorithms, and the obstacle is pinpointed in the world throughout its useful lifespan.

2.4.4 Discuss the control of the vehicle when it is not in autonomous mode.

The vehicle easily switches between manual and autonomous mode by flipping a lever on the steering column and removing a pin from the shifter actuator bar. With autonomous control disabled, Spirit drives just like any regular Jeep Grand Cherokee. The vehicle is street legal and satisfies all California state vehicular safety requirements.

2.5 System Tests

2.5.1 Describe the testing strategy to ensure vehicle readiness for DGC, including a discussion of component reliability, and any efforts made to simulate the DGC environment.

1) SICK LADAR: The LADAR unit has been installed on the Spirit and the vehicle has been driven around the San Diego test area. Data received is incorporated into the Inertial Measurement Unit to help build 3-D map processing.

2) GPS: Spirit's GPS system has been tested for accuracy against other COTS GPS system. The accuracy and dependability has matched the team's hopes when the unit was purchased.

3) ODB-II Information: Utilizing the ability for a 1994 Jeep Grand Cherokee to attempt to deliver vehicle data to a COTS monitor has proven to be less than useful information. The team continues to do cost analysis of the race use of this information.

4) Bumble Bee Cameras: These stereo cameras have been tested under numerous conditions. The results have confirmed the team's belief in this technology.

2.5.2 Discuss test results and key challenges discovered.

Cliffs are a serious issue that Axion Racing has encountered, for cliffs generally imply wide open space, which is typically a safe place to drive. Axion Racing will meet this challenge by adjusting its LADAR sensors over the side of the vehicle, to detect and avoid the cliffs.