Team Gray Technical Paper

DARPA Grand Challenge 2005

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ABSTRACT

Team Gray has approached the 2005 DARPA Grand Challenge from the standpoint of integrators rather than inventors. This design philosophy has driven its decisions in choosing proven technologies such as the AEVIT vehicle control system and the Oxford integrated INS/GPS, rather than trying to develop these types of technologies itself. This has allowed Team Gray to focus its considerable manpower on the algorithms and innovative ideas necessary to win the 2005 DARPA Grand Challenge.

Chapter 1

Introduction

Team Gray was created by Michael T. Gray, Eric Gray, and Walter Gray. It primarily consists of the employees of The Gray Insurance Company in Metairie, LA and students from Tulane University's School of Engineering in New Orleans, Louisiana. Team Gray also maintains an advisory board of leading experts in industry and academia to help guide it in everything from vehicle and sensor selection to software and mechanical design.

Chapter 2

Vehicle Description

2.1 Vehicle Selection

Team Gray chose to use a 2005 Ford Escape Hybrid for is entry in the 2005 Grand Challenge. This vehicle was chosen for multiple reasons. First, it uses a hybrid drive system which provides excellent gas mileage, especially in low speed driving conditions similar to those expected in the Grand Challenge. This efficiency is due to the pairing of a small gasoline engine with an electric engine. The electric engine operates virtually all of the time and the gas engine starts and stops automatically to either provide extra horsepower or to recharge the electric engine's battery. Secondly, the hybrid's electrical system, which is powered by a 330-volt battery, provides over 1300 watts of power to the equipment mounted in the vehicle. This alleviates Team Gray from having to use a generator to provide power for the computer equipment. Thirdly, the Escape Hybrid is a very narrow four wheel drive vehicle with a very smooth suspension. This gives our vehicle more space with which to avoid vehicles or navigate through a narrow tunnel, yet it still provides four-wheel drive for off-road driving. The smooth suspension also ensures that the rough terrain will have less impact on the equipment mounted in the vehicle. Lastly, the Escape Hybrid truly is a perfect fit for the requirements of the Grand Challenge. The Grand Challenge could require a vehicle to be paused for extended periods of time. This could cause problems for many vehicles due to excess fuel consumption during the pause. Most vehicles will not want to shut down their navigation systems during a pause, so an extended pause could tax both their generator's fuel supply and the vehicle's own fuel supply. The Escape Hybrid will run off electrical power during pauses and will only start the gas engine when necessary to recharge the battery. This will help ensure that Team Gray's vehicle will not need to shut down any systems, yet still have the fuel necessary to finish the Grand Challenge.

Figure 2.1: Team Gray modified a 2005 Ford Escape Hybrid for its entry in the 2005 Darpa Grand Challenge.

2.2 Physical Vehicle Controls

Team Gray installed an AEVIT “drive-by-wire” system from Electronic Mobility Controls (EMC) to physically control the car. The AEVIT system uses redundant servos and motors to turn the steering wheel, switch gears, apply throttle, and apply brake. A primary reason that this system was chosen was because it has a proven safety record in the automobile industry due to its use of redundant hardware. One of Team Gray’s primary goals in all of their designs is redundancy, and the AEVIT system satisfies this goal. As an added benefit, the AEVIT system also has an integrated kill system that meets the requirements for DARPA’s E-Stop mechanism. This level of reliability in the physical vehicle controls has allowed the team’s efforts to be spent on other critical projects rather than wasting time solving vehicle control problems.

2.3 Vehicle Modification and Power Sources

Team Gray has made several modifications to their vehicle to better adapt it to the Grand Challenge. First, it installed a two-inch suspension lift to allow the body to have better clearance. Next, it replaced the standard tires with off-road tires that provide an extra inch of clearance. The new tires also have reinforced sidewalls and thicker tread to help prevent flat tires due to the rocky terrain. Finally, Team Gray installed a custom-fabricated aluminum brush guard and skid plate to help protect the vehicle from the treacherous terrain.

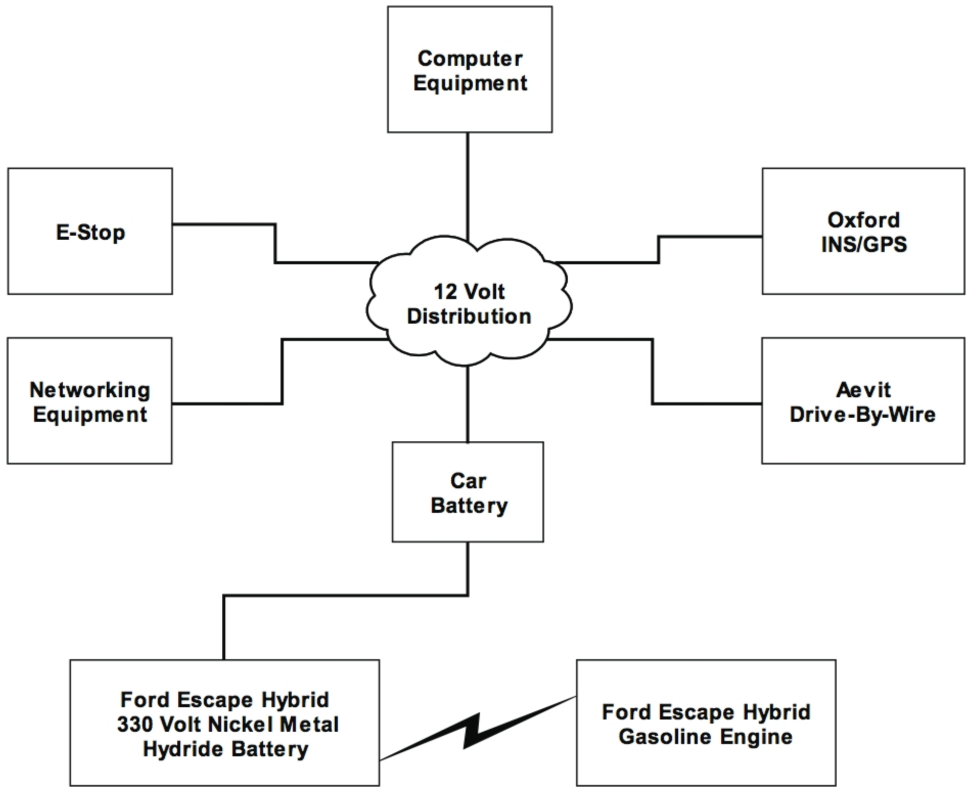

Figure 2.2: The 12-volt system of the vehicle is powered indirectly off of the electric motor/generator.

Rather than use a generator, Team Gray chose to use the Escape Hybrid's integrated electrical system to provide 12 volts of power for all of its computer and navigation equipment. The Escape Hybrid provides 110 amps of power at 12 volts, which is more than adequate to power all of Team Grays equipment. A schematic of the 12 volt power distribution system is shown in Figure 2.2.

All of Team Gray's LADAR sensors require 24 volts. Rather than provide this power from the hybrid's 12 volt electrical system, Team Gray chose to instead provide a separate 24 volt electrical system for these sensors. This electrical system consists of two large-capacity 12 volt batteries connected together to provide 24 volts of power. These batteries alone will provide over ten hours of power. This would provide enough power for the race alone, but not if the vehicle was paused for an extended period of time. A schematic of the 24 volt power distribution system is shown in Figure 2.3.

To ensure that the batteries will always be near full capacity, Team Gray installed six solar panels on top of the vehicle. These solar panels are high efficiency, and will consistently

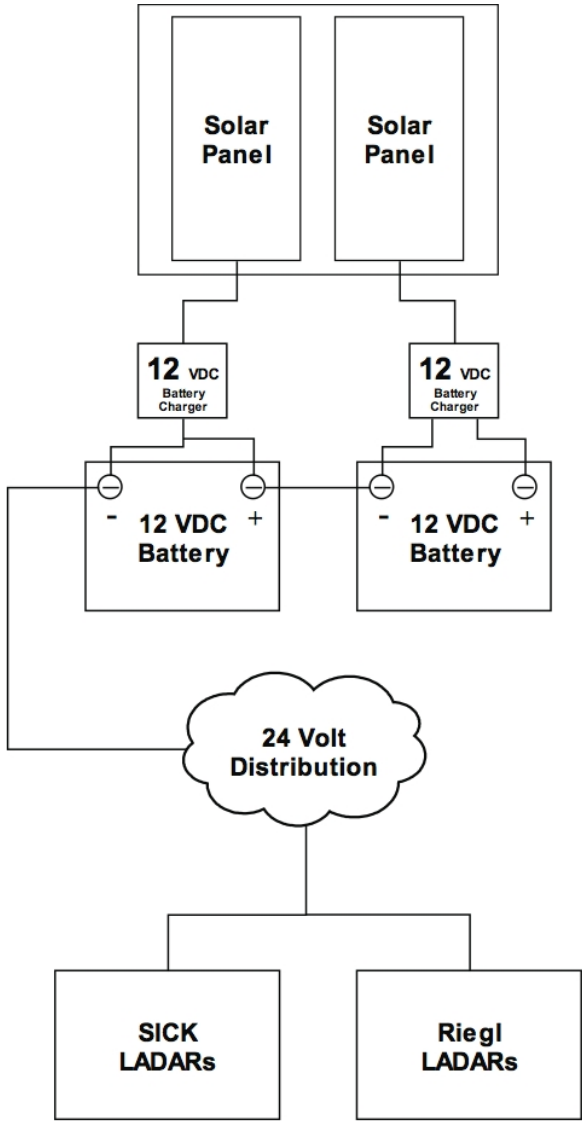

Figure 2.3: The 24-volt system of the vehicle is powered by six solar panels.

provide over 150 watts of power even in low-light conditions. Since the Grand Challenge will be run in the desert during the day, a sufficient light source is expected to be available at all times.

Chapter 3

Autonomous Operations

3.1 Processing

Early on in the planning process for the Grand Challenge, Team Gray's development team decided that they would use the Java programming language to develop as much of the software as possible. This decision was made due to Java's proven track record of stability, rapid development, simple threading capabilities, and portability. Using Java allowed the development team to concentrate on the real issues, rather than having to spend considerable time debugging memory leaks and complex threading issues.

In order to ensure that the best computing hardware was chosen, Team Gray investigated the leading computing hardware used by several different industries. The marine industry offered a ready made system that included protection from excessive shock, high temperatures, and other environmental issues. This system is based on a 2.8 Gigahertz Intel Pentium III processor and includes 2 gigabytes of RAM. As an added benefit, it runs off a native 12 volt power supply, so an AC to DC power inverter is not needed. This system was chosen to become "Gray Matter," the brains behind Team Grays Grand Challenge entry. "Gray Matter" runs on Fedora Core 2 (a distribution of Linux based on the 2.6 kernel) and it hosts all of the main computing functions, such as sensor communication, vehicle controls, and artificial intelligence.

To ensure that Team Gray's main navigation computer, "Gray Matter," never becomes overburdened by the processing required to perform path-planning, Team Gray chose to use several 1.42 Gigahertz Apple Mac Mini computers to host the path-planning software. These Mac Minis perform all of the path calculations in a redundant cluster. This ensures that the path planning software does not become a single point of failure. The Mac Minis are all running Apple OS X 10.4 (Tiger). The Mac Minis were chosen due to their low power consumption (less than 2.3 amps at peak) and powerful vector math processing capabilities.

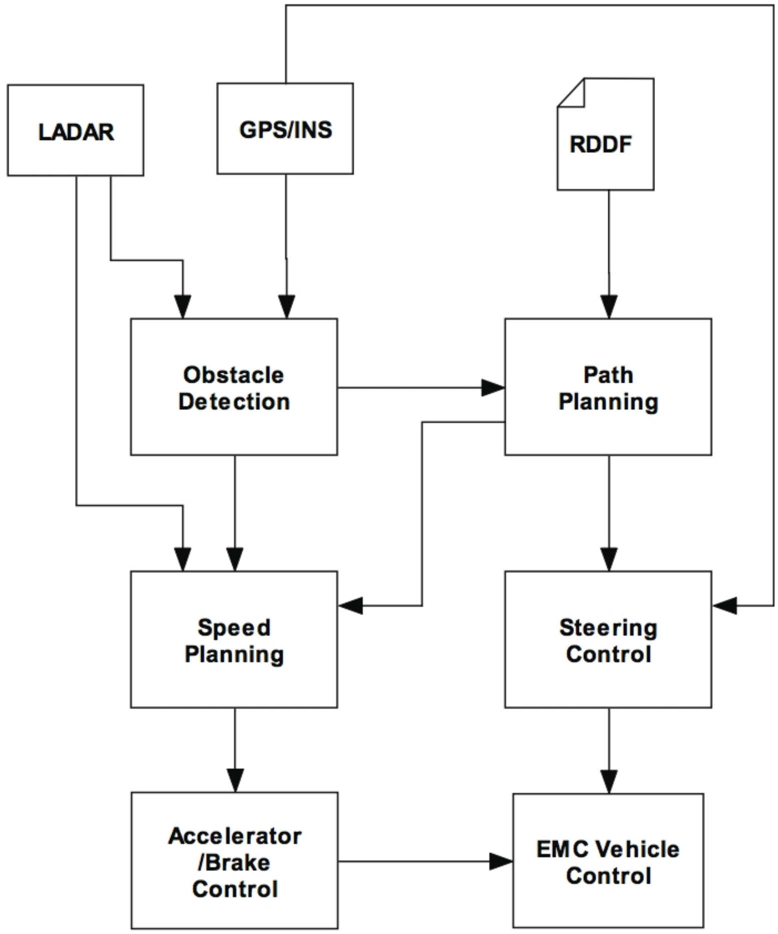

Figure 3.1: The modularity of the systems used in Team Gray's entry allows for targeted modification of a single system without adversely effecting other systems.

A functional block diagram of the systems used by Team Gray is shown in Figure 3.1.

In order to reduce errors, Team Gray has chosen to integrate the powerful unit testing framework JUnit throughout its entire development process. By using JUnit, Team Gray can write tests for independent modules of its code base and then automatically run these tests whenever new code is deployed to the autonomous vehicle. This ensures that as development progresses no bugs are introduced into pieces of code that were previously working.

3.2 Localization

Team Gray chose to use the RT3000 from Oxford Technical Solutions to provide vehicle localization. The RT3000 uses Omnistar HP differential GPS signals to provide position accuracy of 10 centimeters or less. The integrated INS allows the RT3000 to survive GPS outages of up to 30 seconds with virtually no performance degradation. Because the GPS and INS are integrated together, each can compensate for problems with the other. For example, if the INS started to drift laterally, the integrated GPS will automatically correct that drift.

Team Gray considers the GPS its most important piece of hardware. As a result of this, it has installed two Oxford RT3000 GPS units on its vehicle. Rather than try to integrate the data from both units at the same time, Team Gray instead chose to use the two units in a primary/secondary role. Both units are always active, but if one unit stops sending data for some reason, the other unit immediately takes over and becomes the primary unit. This configuration ensures that Team Gray will have accurate GPS information at all times.

3.3 Sensing

Team Gray has mounted three Sick LMS 291 LADAR units and one RIEGL LMS-Q120 LADAR on the front of its vehicle. These LADAR units are split into three different roles. The RIEGL LADAR is mounted vertically in the center of the vehicle and is used for long range (up to 80 meters) obstacle detection. Two Sick LMS 291 units are mounted vertically on either side of the RIEGL. They are used for short range obstacle detection (up to 50 meters). The other Sick LMS 291 is mounted horizontally on the center of the vehicle and is used for analyzing terrain features.

In order to protect these sensors from the elements as much as possible, a sun/weather guard was constructed over the sensor mounts. This guard protects the LADAR units from being blinded by direct sun glare, a common problem with Sick LADAR units. Since LADAR units produce their own light source, low light conditions have no effect on the sensors. In fact, extensive testing has shown that low light conditions actually produce better results than bright conditions, due to excessive reflections under bright sunlight. These reflections, along with dust or rain, can produce ghosting patterns or other anomalies in the sensor readings. To counteract these anomalies, Team Gray has developed several innovative filtering algorithms to correct for these glitches before they can cause problems in the path planning software.

Stereographic cameras capable of producing a three-dimensional point cloud are also mounted on the front of the vehicle behind the windshield. These cameras operate in a secondary mode to the LADAR units, and they are only used to help identify the road and to confirm the existence of obstacles. If a LADAR unit identifies an obstacle and the stereoscopic cameras also detect an obstacle in that area, the obstacle avoidance algorithms increase the confidence level associated with that obstacle. Confidence levels are used to help decide which obstacles must absolutely be avoided and which obstacles are possible anomalies that the car may actually be able to drive over without damage.

Spatial indices are used to correlate the sensor data with the localization data. Timestamps are taken with each LADAR scan and GPS reading. These timestamps are then correlated based upon position and heading to produce a geospatial location for obstacles. These obstacles are then placed into a set of spatial indices for processing by the path planning algorithms. Instead of storing all obstacles in one large spatial index, each segment of the RDDF path corridor has a corresponding spatial index. This ensures that obstacle lookups can be performed quickly and efficiently.

The path-planning systems use several innovative algorithms designed by Team Gray to avoid obstacles and stay within the corridor. These algorithms are incapable of providing a path that leaves the corridor, so the vehicle should never voluntarily leave the corridor. However, should the vehicle leave the route corridor for some reason, the navigation system will detect this and provide a safe route back into the corridor. If a waypoint is missed, the navigation system will simply continue to the next feasible waypoint on the path. It will not backtrack or skip large sections of waypoints. If the path is obstructed by an obstacle, the path planning systems will attempt to find the best path around the obstacle.

The path planning systems use a Level of Detail (LOD) based obstacle avoidance algorithm along with several other proprietary planning algorithms to plan paths around obstacles. The path planning algorithms run using several different parameters until they find a valid path. The initial parameters use large safety margins around obstacles, while the final parameters use no safety margins around obstacles. This ensures that if a path is available that will avoid an obstacle with a large margin of error the path planning software will use it. Otherwise, it will keep reducing the safety margin around obstacles until it finds a valid path.

Smooth paths alone are not necessarily drivable by the vehicle. The car must be able to slow down proportionally from straight-aways down to hairpin turns. To accomplish this, the path-planning systems use an innovative speed-planning algorithm to slow the car down either for turns or when performance degradation (such as GPS inaccuracy) occurs. An example of the output from this algorithm is shown in Figure 3.2.

The path planning systems are responsible for ensuring that any path they generate is drivable by the vehicle. To accomplish this, the path planning systems use cubic b-splines to interpolate a path between waypoints. These smoothed paths allow the vehicle to make much more accurate sharp turns. In testing, Team Gray has successfully navigated several 180 degree hairpin turns with extremely low radii.

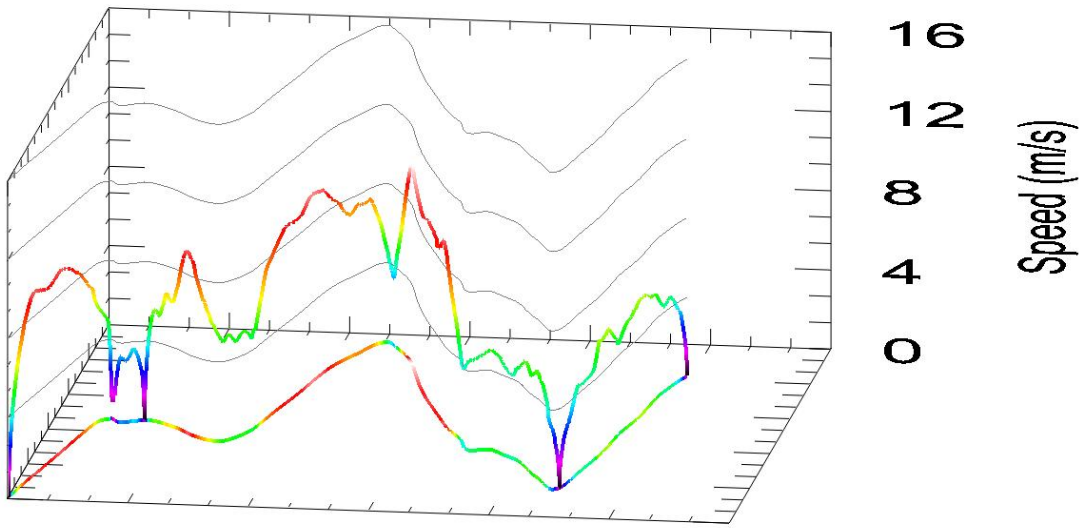

Figure 3.2: The speed-planning algorithm reduces speed (represented by the Z-Axis) based upon the curvature of the path (represented by the XY-Axis).

3.4 Vehicle Control

Accelerator and steering wheel control is achieved through two separate processes, which are both independent of the path-planning systems. Once a path is decided on by the path-planning systems, acceleration and steering is used exclusively to remain on the chosen path. Since paths are checked for feasibility upon creation, it is assumed by the control systems that all paths given are possible for the vehicle to achieve, and thus it becomes the burden of the control systems to decide how best to proceed in order to follow the path.

The accelerator control provided by AEVIT is a single system that controls both accelerator and brake with the same output, thereby eliminating the need to coordinate the two physical controls. Speed control is accomplished by the use of a proportional-integral-derivative (PID) controller. The PID combines the current error (proportional), past error (integral), and possible future error (derivative) in a certain way in order to provide an output for the accelerator position. Under normal conditions, the inputs to the PID are weighted and summed; however, if necessary, it is possible to turn control over to a more adaptive neural network system coupled to the PID.

When the vehicle is not in autonomous mode, the vehicle can be driven normally. The only difference between driving a standard Ford Escape Hybrid and Team Grays vehicle is that gear shifting and vehicle ignition must be performed through the AEVIT control panel rather than by manually turning a key or sliding a gear-shift.

3.5 System Testing

Besides the aforementioned unit testing performed on individual sections of code, Team Gray performs an extensive amount of full system tests. Most of these tests are carried out at Team Grays custom testing range, affectionately known as the "Pit." The Pit contains switchbacks, tunnels, hills, gates, sand pits, gravel roads, rough terrain, and many other hazardous conditions. It also has many tree covered roads, which allow Team Gray to test extended GPS outages.

At this point, Team Gray has performed many system tests, including several ten hour stress tests. These stress tests were designed to test the entire vehicle and its components in conditions as similar to the Grand Challenge as possible. The stress tests allowed Team Gray to observe how the vehicle handled for long periods of time in autonomous mode, and to measure how much power was utilized by the equipment.

Besides the stress tests, Team Gray has also performed several torture tests that were designed to truly test how much damage its equipment could take. These torture tests included autonomously driving at speeds of over 40 mph in extremely rugged terrain. Another extremely effective test involved manually steering the vehicle off course at high speed and then switching back to autonomous mode. This simulated a GPS jump, which can occur rather frequently. After noticing that the navigation system abruptly turned the steering wheel to counteract this jump, the navigation system was updated to eliminate this abrupt movement. After only suffering a few hard drive read/write errors throughout the rigorous testing, we have determined that Team Gray can handle any challenge that the desert can throw at it.

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