Team CIMAR
DARPA Grand Challenge 2005

Sponsored by Smiths Aerospace

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Abstract

This paper describes the NaviGator, a fully autonomous ground vehicle developed for the DARPA Grand Challenge, 2005 by researchers at the University of Florida, Autonomous Solutions, Inc. and The Eigenpoint Company. Development started with a custom built base vehicle. Computational needs were met using single processor computing nodes targeted at individual computational needs. The architecture is based on the Joint Architecture for Unmanned Systems (JAUS), expanded by developing experimental components. Planning elements plan an initial route using the Route Data Definition File. An array of sensors including cameras, ladar, and radar are used for path modification due to obstacles and to acquire and track smooth terrain.

Introduction

The NaviGator is a fully autonomous vehicle developed for the DARPA Grand Challenge, 2005 by Team CIMAR. Team CIMAR is a collaboration of students, faculty, and alumni of the University of Florida and engineers from Autonomous Solutions, Inc. (Young Ward, Utah) and The Eigenpoint Company (High Springs, Florida). Together, they represent a cohesive group of researchers with aims to advance the current state-of-the-art of unmanned ground vehicles in support of national goals and objectives. This is the team's second year participating in the Grand Challenge.

1 Vehicle Description

The NaviGator (see Figure 1) is an all terrain vehicle custom built by Georgia All Terrain Monsters, Inc. to Team CIMAR's specifications. The frame is made of mild steel bar with an open design. It has 9" Currie axles, Bilstein Shocks, hydraulic steering, and front and rear disk brakes with an emergency brake to the rear. It has a 150 HP Transverse Honda engine/transaxle mounted longitudinally, with locked transaxle that drives front and rear Detroit Locker differentials (4 wheel drive that is guaranteed to get power to the road). The vehicle was chosen for its versatility, mobility, openness, and ease of development. The automation of the vehicle, to include power system design and actuation, was headed by personnel of Eigenpoint, Inc.

Figure 1: The NaviGator 2005

2 Autonomous Operations

2.1 System Architecture

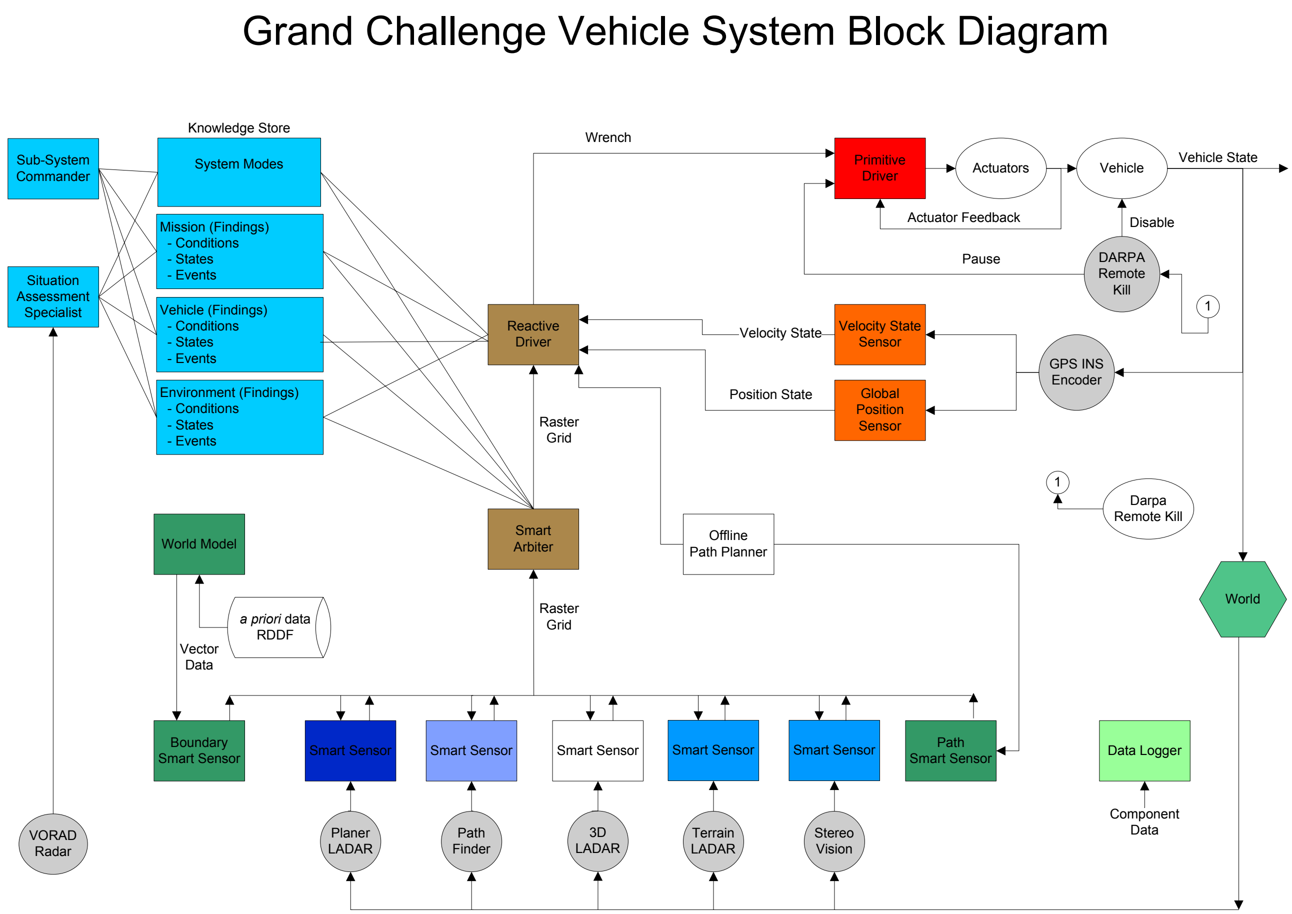

Figure 2: System Architecture

The system architecture is depicted in Figure 2. It is based on the Joint Architecture for Unmanned Systems (JAUS) Reference Architecture, Version 3.2. JAUS defines a set of reusable components and their interfaces. At the highest level, the architecture consists of four fundamental elements:

- Planning Element: The components that act as a repository for *a priori* data such as known roads, trails, or obstacles, as well as data that specify the acceptable boundaries within which the vehicle must operate, along with the components that perform off-line planning based on that data.

- Control Element: The components that perform closed-loop control in order to keep the vehicle on a specified path.

- Perception Element: The components that perform the sensing tasks required to locate obstacles and to evaluate the smoothness of terrain

- Intelligence Element: The components that act to determine the 'best' path segment to be driven based on the sensed information. These components generate a single traversability grid that combines the inputs from multiple sensors.

Recognizing that JAUS would greatly simplify system integration, Team CIMAR used it throughout the NaviGator development. Version 3.2 of JAUS was also augmented with experimental components and messages that defined the smart sensor messaging architecture that was implemented.

2.2 Computing Systems

The computing system requirements consist of high level computation needs, system command implementation, and system sensing with health and fault monitoring. The high level computational needs are met in the deployed system via the utilization of single processor computing nodes targeted at individual computational needs. The decision to compartmentalize individual processes is driven by the developmental nature of the system. A communications protocol is implemented to allow inter-process communication.

Figure 3: View into the clear faced computer enclosure on the NaviGator.

The individual computing node hardware architecture was selected based on the subjective evaluation of commercial off-the-shelf hardware. Evaluation criteria were centered on performance and power consumption. The deployed system maintains a homogenous hardware solution with respect to motherboard, ram, enclosure, and system storage. A processor family was selected based on power consumption measurement and performance to allow tailoring based on performance requirements with the objective of power requirement reduction. Currently three processor speeds are deployed. The operating system deployed is based on the 2.6 Linux kernel. System maintenance and reliability are expected to be adequate due to the homogenous and modular nature of the compute nodes. Back up computational nodes are on hand for additional requirements and replacement. Figure 3 shows the processors rack mounted in a vibration isolated and air conditioned enclosure.

2.3 Localization

The NaviGator determines its geolocation by filtering and fusing a combination of sensor data. The processing of all navigation data is done by a Smiths Industries Northfinding Module (NFM), which is an inertial navigation system. This module maintains Kalman Filter estimates of the vehicle's global position, orientation, as well as linear and angular velocites. It fuses internal accelerometer and gyroscope data, with data from an external NMEA GPS and external odometer. The GPS signal provided to the (NMF) comes from one of the two sensors onboard. These include a NavCom Technologies Starfire 2050, and a Garmin WAAS Enabled GPS 16. An onboard computer simultaneously parses data from the two GPS units and routes the best determined signal to the NFM. This is done to maintain valid information to the NFM at times when only one sensor is tracking GPS satellites. During valid tracking, the precision of the NavCom data is beter than the Garmin, and thus the system is biased to always use the NavCom when possible.

In the event that both units lose track of satellights, as seen during GPS outages which for example occur when the vehicle is under a tunnel, the NFM will maintain localization estimates based on inertial and odometry data. This allows the vehicle to continue on course for a period of time; however, the solution will gradually drift and the accuracy of the position system will steadily decrease as long as the GPS outage continues. After a distance of a few hundered meters, the error in the system will build up to the point where the vehicle can no longer continue on course with confidence. At this point, the vehicle will stop and wait for a GPS reacquisition. Once the GPS units begin tracking satellites, and provide a valid solution, the system corrects for any off course drift and continues autonomous operation.

The Smith's NFM is programed to robustly detect and respond to a wide range of sensor errors or faults. The known faults of both GPS systems, which generate invalid data, are automatically rejected by the module, and do not impact the performance of the system, as long as the faults do not persist for an extended period of time. If they persist, then the NFM will indicate to a control computer what the problem is, and the system can correct it accordingly. The same is true for any odometer encoder error, or intertial sensor error. The NFM will automatically respond to the faults and relay the relevant information to control computers, so the system can decide the best course of action to correct the problem.

In summary, the Smith's IMU fuses and filters information from the NavCom or Garmin GPS, as well as a vehicle odometer. The addition of odometer data improves the localization performance, and provides more precise vehicle speed measurements.

2.4 Path Planning

The Mobius software, developed by Autonomous Solutions, Inc., is an easy to use graphic based program for controlling and monitoring multiple unmanned vehicles. In the DARPA Grand Challenge 2005 Mobius will be used to plan the initial path for the NaviGator in both the National Qualification Event and the final Grand Challenge Event. Mobius utilizes *apriori* information about the environment such as roads, rivers, lakes, obstacles, etc., the DARPA supplied RDDF, and the NaviGator's kinemetic constraints to generate the most efficient path from the start line to the finish line. Downloaded USGS information and GPS data gathered from dessert reconnaissance trips make up the *apriori* environment data. The World Model component creates the RDDF corridor from the RDDF file. All other environment information is then clipped with the corridor such that only environment data inside the corridor is use in the planning process. The clipped environment data is imported into Mobius and displayed to the operator for verification. Mobius reads in the RDDF file and plans the most efficient path through the corridor from the first waypoint to the last waypoint utilizing roads where possible and avoiding a priori known obstacles when necessary. The path is displayed to the operator for verification. Modifications to the path can be made using the Path Builder tool inside of Mobius. Path vertices can be moved, path segments can be combined, and new routes can be planned. Once the path has been finalized, it is saved to a file and transferred to the NaviGator for autonomous operation.

2.5 Sensing

An array of sensors is mounted on a sensor cage on the front of the vehicle that was specifically designed for this sensor configuration. Figure 1 shows an image of the sensor cage on the vehicle. These sensors include five cameras equipped with automatic iris. Two of these cameras are used for obstacle detection by stereo vision. The remaining three detect the path in a scene. The cameras are each housed in a protective enclosure. They look out from an enclosure face that is made of lexan covered with polarizing, scratch-resistant film. Also mounted on the sensor cage are two SICK ladars: one rotating ladar for 3D obstacle detection, the other fixed to scan the ground ahead of the vehicle for terrain slope estimation, tuned for negative obstacle detection.

Also, a third SICK ladar for planar obstacle detection and a long-range Eaton Vorad radar for free space detection are mounted on the front of the vehicle at bumper level.

The basis of the sensor architecture is the idea that each sensor processes its data independently of the system and provides a logically redundant interface to the other components within the system. A common data structure, called the Traversability Grid, was introduced for use by all sensors. A visualization of this grid is shown in Figure 4.

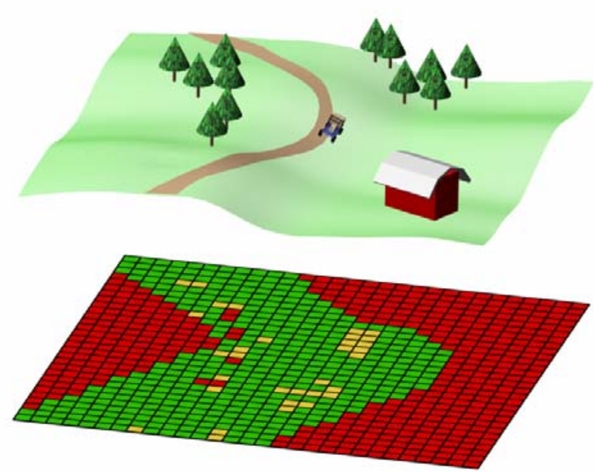

Figure 4: Traversability Grid - The upper level shows the world as a human sees it. The lower level shows the Grid representation based on the fusion of sensor information.

Each grid has 121 × 121 cells with the vehicle occupying the center cell. The grid is always oriented with North as the direction of increasing row values and East as the direction of increasing column values. Grid cell values range from 0 to 15, indicating how traversable the cell is, or some other information such as "out of bounds." Each sensor calculates its grid and passes the grid on to the Smart Arbiter component which fuses the data and passes it to the reactive planner. This process is shown in the system architecture diagram in Figure 2.

The Smart Arbiter's fusion algorithm is a hybrid that first uses an auction of input sensor values for the extremes (i.e., definitely an obstacle or definitely a road) and, if no sensor wins the auction for that cell, the traversability estimates from all sensors are averaged. In either case, the arbiter takes into account its previous value as part of its determination of the new value for a given grid cell.

2.6 Vehicle Control

The NaviGator uses a receding horizon approach for vehicle control. This means that closed loop control is achieved by planning through a sequence of possible actions and selecting the sequence that yields the least overall cost to goal. In this case, the actions correspond to steering and speed controller commands, and the cost is calculated by integrating the traversability along the projected vehicle path through a traversability grid map. The vehicle travels through the provided waypoints by maintaining its path to be within the supplied corridor. If any waypoint is missed because the vehicle happened to be outside the corridor, it will attempt to continue on course by planning to the next goal point.

Operational contingencies are detected as faults in the online planning controller. Each fault contingency is handled in a different way. In the case where the vehicle is stopped and there is an unavoidable obstacle in the immediate path, a vehicle blocked fault is thrown, and the vehicle will have to backup until a forward drivable path is found. If the vehicle is stopped out-of-bounds, or stuck on an obstacle, a higher level intelligence component is notified of the stuck fault condition, and it will decide if any correcting actions are possible.

Sensing information is incorporated into vehicle control by providing the receding horizon planner with an arbitrated traversability grid. Navigation information is incorporated into vehicle control, by informing the planner of the vehicle's current position and orientation in the grid map, and also by providing the vehicle's velocity to the closed-loop speed controller.

The NaviGator is equipped with manual operator controls that allow an operator to sit in the vehicle and drive. There is an auto/manual switch in the cab to override autonomous control and enable the manual driving systems. The fail-safe brake override is clearly marked in the cab.

2.7 System Tests

2.7.1 Test Facilities

Currently a test site has been built for use by Team CIMAR and the use of two other test sites has been arranged. All together, these sites represent three levels of difficulty.

The first site was designed and constructed at the University of Florida's Plant Science Unit located in Citra, Florida. The course (see Figure 5) was laid out in a wide open field and consists mainly of a figure eight, an oval and several left and right sharp turns. Various segments have continuously been added to this course to replicate terrain that is expected in the desert. While this course has a few tough obstacles it is basically the "safest" place to test. This is Team CIMAR's main test site and it has been used for extensive development of the system.

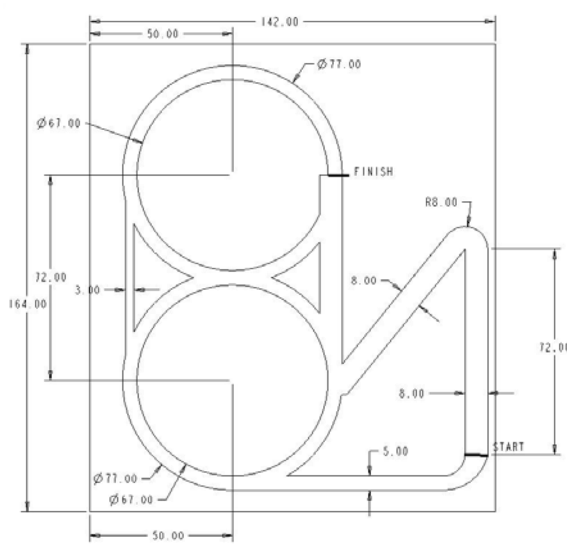

Figure 5: Layout of Team CIMAR's test course at the University of Florida's Plant Science Unit at Citra

The second and more difficult site consists of several miles of power-line access roads located in Gainesville, Florida. These access roads are an order of magnitude more difficult to navigate

Figure 6: The NaviGator performing tests on the course at Citra

and less forgiving of mistakes. They have giant ruts and washouts from the Florida heavy rains. In most places, they have deep ditches on both sides or a ditch on one side and a hill on the other and they wind up and down over relatively steep hills for miles. A relatively small amount of time is planned for the power-line roads testing.

The third and most difficult site is located in the off highway vehicle (OHV) area near Barstow, California. In the desert, there are a multitude of good places to test and we are planning on starting in the Stoddard Valley. In the Stoddard Valley we can push the limits of the vehicle in the final weeks leading up to the National Qualification Event. Of course, no testing will be performed in the area that was closed by DARPA on 29 July 2005.

2.7.2 Sub-System Test

The sub-system tests include: The base vehicle, Drive-By-Wire system, Position System, and each of the sensor systems independently. Sensor systems test include: Planner Ladar Smart Sensor, Terrain Smart Sensor, Boundary Smart Sensor, Path Smart Sensor, and Path Finder Smart Sensor.

2.7.3 System Test

One of the first system tests measured the NaviGATOR's ability to track a known path trajectory in a controlled environment. This was done by having the vehicle autonomously drive on the Citra test course. For this test, the centerline of the course track was mapped in GPS coordinates, and this known path data was uploaded to the vehicle. The system then autonomously navigated its way around the course, while recording its position and orientation. The recorded data was then post-processed and measurements such as average heading error and cross track error were used to analyze the path tracking performance of the vehicle. This has been repeated several times; the first runs conducted at low speeds and then gradually increased. Between each test, adjustments to onboard controllers were made as necessary to modify and improve the system performance.

The next System Test measured the NaviGATOR's ability to perform obstacle avoidance and path finding in real time. It has been tested in a controlled environment at the Citra test site where the size, shape, type and location of obstacles and terrain challenges can be varied. In this test, the Reactive Driver and System Commander are monitored to ensure that the vehicle is actively detecting and planning its way around obstacles and finding the best terrain.

Several endurance tests have been performed and more are planned. A 200 mile endurance run is planned at the Citra site once the system is complete and all other tests have been successfully completed. This tests the ability of all sub-systems to operate together for extended periods of time without failing. At least one 200 mile endurance test is planned for the desert after all the specific terrain challenges have been addressed. This final test will be conducted off-road in an OHV area near Barstow, CA, where the vehicle will have to plan its way through a set of waypoints, in spite of obstacles that are not known to the World Model, and then navigate through the planned path at high speed, while simultaneously re-planning the path around detected obstacles. We will look for terrain areas that closely represent those that we expect to encounter in the race. In essence this test will be a scaled down version of the Grand Challenge. It will be conducted several times for the various terrain scenarios, to allow for fine-tuning of all onboard components, so that the overall system will be able to perform successfully for the Grand Challenge event.