INDIANA ROBOTIC NAVIGATION

Technical Paper

DARPA Grand Challenge 2005

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Abstract

This paper describes the approach used by Indiana Robotic Navigation for competing in the 2005 DARPA Grand Challenge. This team used readily available components and applied them in a conservative manner to create a very reliable vehicle on which to apply a custom computer system using custom software.

Introduction

This paper describes the Indiana Robotic Navigation (IRN) Team's technical approach for competing in the DARPA Grand Challenge 2005 and addresses the 16 items outlined in the DARPA Grand Challenge 2005 Technical Paper Guidelines, dated July 19, 2005.

These items are divided between 2 sections: "Vehicle Description" and "Autonomous Operation". The paper is limited to 15 single-sided pages, including any cover pages, diagrams, or attachments. The IRN Team's approach was to use as much readily available and fully tested equipment in a conservative manner to insure the reliability of the vehicle. When necessary, custom designed equipment, both mechanical and electrical, was created. The overall computer systems and the software were custom made for this project.

1.0 Vehicle Description

The Indiana Robotic Navigation's vehicle, Spirit of Christianity (SOC) is a 2-door, 1996 Ford Explorer vehicle modified for autonomous driving (Figure 1).

1.1 Vehicle Specifications

This vehicle had these original specifications:

1996 Ford Explorer Sport 2 Door

Control Trac 4 Wheel Drive

4.0 Liter V6 Gasoline Engine

Front Axle Rating = 2510 lbs.

Rear Axle Rating = 2550 lbs.

This vehicle was selected because of common parts availability, automatic 4 wheel drive features, and because we liked the color.

1.2 Vehicle Modifications

The vehicle had the following modifications made to it:

The shift mechanism had a linear electric servo actuator added to provide for autonomous operation. A touch screen monitor provides for manual operation, since the gear shift lever cannot be moved manually.

The braking system was modified by adding an air cylinder operated duplicate brake master cylinder, with vacuum booster, to the existing brake system. An electromagnetic transducer provides adjustable air pressure for various braking conditions. An air actuated crossover valve provides for either manual or automatic brake operation. The touch screen also allows for driving by wire for testing operations.

The standard cruise control was modified to provide for servo accelerator input. The standard gas pedal or the slider on the touch screen may be used for manual operation.

The standard power steering on the vehicle was modified by adding two electrically operated servo valves and two air operated crossover valves. One servo valve controls the steering hydraulic pressure, while the other controls the direction of the movement of the front wheels.

The two crossover valves provide for manual or automatic steering. The touch screen provides a slider bar to manually drive by wire for testing.

The vehicle electrical system was upgraded by removing the original battery and replacing it with three 200 amp-hr lead acid batteries placed where the rear seat was originally located. The standard alternator was upgraded to 135 amps and an additional 24 volt, 110 amp alternator was added. This provided for a 12 volt vehicle electric bus, using the 12 volt alternator and one 200 amp-hr battery. The 24 volt alternator and the remaining two 200 amp-hr batteries, connected in series, provide 24 volt power for the added equipment. A 2400 watt inverter was connected to the 24 volt system to provide 120 VAC for the computers and other equipment.
A welded stainless steel rack was fabricated and attached to the roof of the car for mounting scanners, compasses, and antennae.

An additional spring leaf was added to each of the rear springs to allow for the extra weight of the batteries and other equipment. This added approximately 1000 lbs. to the rear axle load capacity.

2.0 Autonomous Operations

This vehicle has been equipped for autonomous operation (computer controlled).

2.1 Processing

Processing of the data required to operate this vehicle is done by PC type computers.

2.1.1 Computer Systems

This vehicle has a total of six PC Pentium computers on board. One computer is used for steering, one for the user interface touch screen, and the four remaining ones are used for navigation. Of the four navigation computers, one is used for scanning, one for observer software, one for top level navigation, and one for the command pilot to process data and issue control commands.

The computers use Windows 98 or Windows XP as operating systems. The Windows 98 systems were selected because of the ability to support VXDs for low level control. The Windows XP was used because of the compatibility with the latest version of JAVA. JAVA programming language was selected to expedite the programming process and the running of high level commands. Assembler language was used for low level control where timing issues were identified. For improved reliability, solid state hard drives were used.

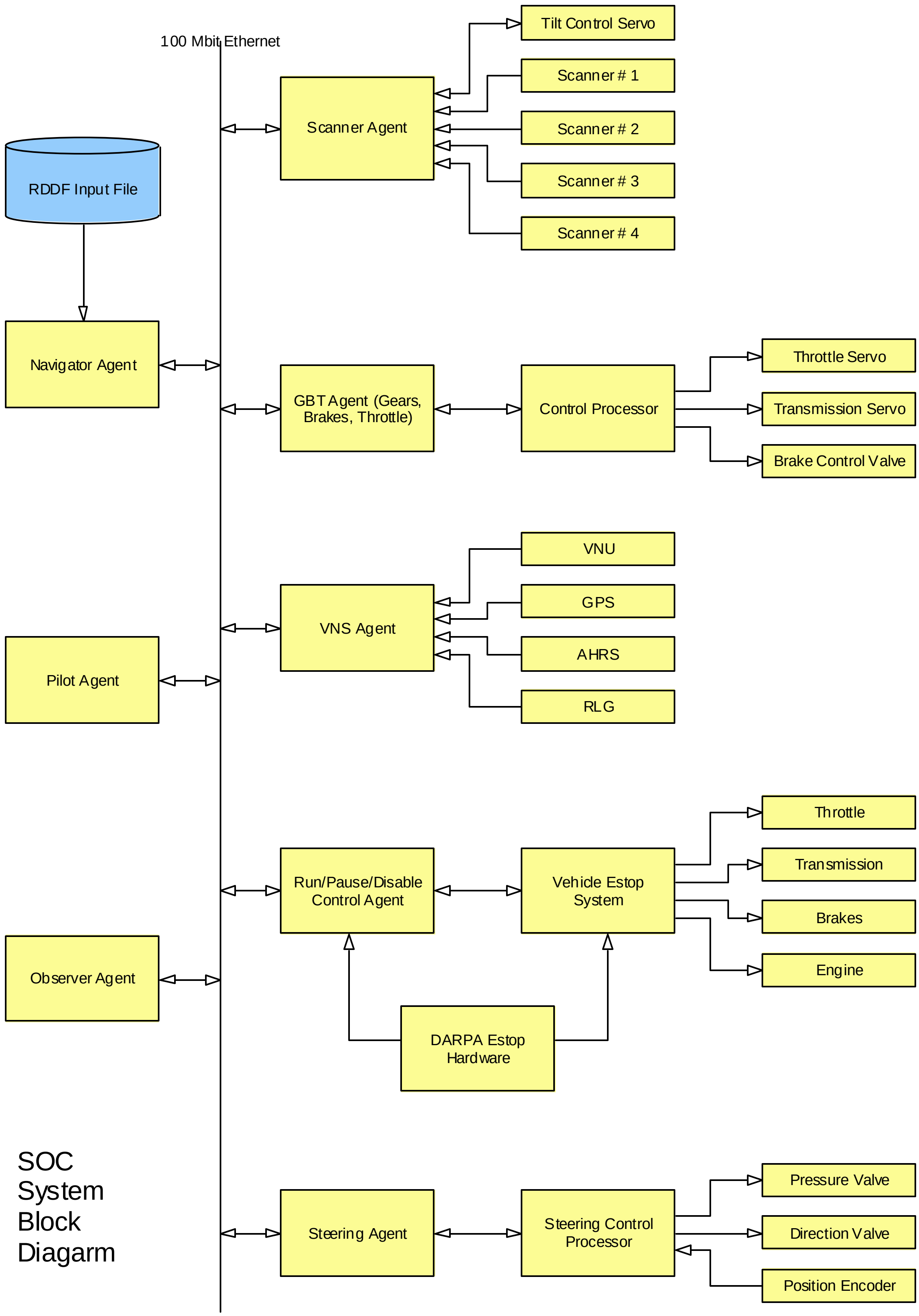
2.1.2 Block Diagram

Please see Figure 2 on the next page for a functional block diagram of the processing architecture for this vehicle.

2.1.3 Development Process

The development process for the software on this vehicle generally followed the path described below:

A software module, for example the gear shift operation, was written and the hardware, such as the electric actuator, bench tested where possible. Where this was not feasible, the hardware and software were developed and tested on the vehicle. The vehicle easily carried two or three people and each function could be switched from automatic to manual operation and vice-versa quickly and easily. This allowed for a test driver to perform testing of each software module and then the programmer could immediately update the code as necessary and test again. This provided for rapid software development in many cases. The system also provided a log of data and decisions for review after each test.



100 Mbit Ethernet
Tilt Control Servo
Scanner # 1
Scanner # 2
Scanner # 3
Scanner # 4
Scanner Agent
RDDF Input File
Navigator Agent
GBT Agent (Gears, Brakes, Throttle)
Control Processor
Throttle Servo
Transmission Servo
Brake Control Valve
VNU
GPS
AHRS
RLG
VNS Agent
Pilot Agent
Throttle
Transmission
Brakes
Engine
Run/Pause/Disable Control Agent
Vehicle Estop System
Observer Agent
DARPA Estop Hardware
SOC System Block Diagarm
Pressure Valve
Direction Valve
Position Encoder
Steering Agent
Steering Control Processor

Figure 2

2.2 Localization

The following is a description of the navigation system used by this vehicle.

2.2.1 GPS System and Inertial Navigation

A Navcom GPS receiver with a “StarFire” differential correction system for improved accuracy is employed on this vehicle for determining location. Dead reckoning is performed using data from a VNU, a miniature attitude and heading reference system, and a ring laser gyro. This system is updated with data from the GPS system. Our target mission time without GPS is ten minutes.

Errors introduced when the system GPS drops out, or becomes inaccurate were very difficult to deal with. Having a rather long target mission time without GPS required us to very precisely measure the distance traveled and maintain a correct heading. Very precise inertial heading equipment was used combined with a special sensor in the vehicle drive train that could sense down to zero speed and provide direction and distance information.

2.2.2 Map Data Required

There is no map data required by this vehicle navigation system.

2.3 Sensing

The sensing systems used on this vehicle are described below.

2.3.1 Location and Mounting

The sensing devices on this vehicle include four laser scanners with approximately 200 ft. range. The first of these is mounted at the front bumper height, facing forward. This unit has a scan angle of 180 degrees and the scanning plane is fixed at horizontal. A second laser scanner is mounted on the roof rack, facing forward. This scanner has a scan angle of 90 degrees and the scanning plane is horizontal. This unit is pivoted and is moveable using a linear servo actuator. This scanner can look up to 10 degrees above and down to 45 degrees below the horizon. There is a scanner with a scan angle of 180 degrees mounted on the roof rack at each side of the vehicle, pointed downward. These scanners sense road contour looking forward and rearward.

In addition, there is an ultra-sonic sensor mounted at the front bumper height and pointed forward. This unit has a range of approximately 20 ft.

Finally, there is a team designed sensor mounted on the right hand side of the vehicle, looking downward. This sensor measures the relative direction and the speed of movement of the vehicle.

2.3.2 Sensing Architecture

The overall sensing architecture is that all the sensors and the "Scanning" computer are connected to the "Observer" computer, which integrates all the data from all the sensors and forwards information to the "Navigator" computer for interpretation. The "Navigator" computer merges the data and issues high level commands to the "Pilot" computer for decisions and action.

The four laser scanners are integrated with a proprietary fusion algorithm developed by our team engineers. The information is combined and stabilized to present a coherent, logical description of the terrain and any obstacles in the path ahead.

2.3.3 Internal Sensing System

There are numerous types of sensors used internally by the vehicle to monitor its state. A speed sensor is mounted on the transmission and outputs a voltage proportional to the to wheel speed. This voltage output is input to the cruise control (accelerator), speedometer, and the control computer. The navigation system has sensors to monitor magnetic heading, side-to-side tilt angle, and front-to-rear tilt angle. This information is sent to the main control computer for use.

There is a digital encoder on the front wheels to monitor wheel steering direction. There is a digital encoder on the tilt actuator on the upper front scanner to monitor the angle of tilt. There is a digital encoder on the transmission shift actuator to monitor which gear the transmission is in.

2.3.4 Sensing-to-Actuation System

The vehicle uses the GPS coordinates of its current position and the GPS coordinates of the next way point to calculate the true heading and distance required to reach that point. Using scanner input, the heading is modified for the vehicle to clear any obstacles in the race course path and return to the main path. The pilot agent will initially direct the vehicle course to the side with the greatest clearance. If this becomes impossible, a course to the other side will be tried. If an obstacle cannot be steered around, the vehicle will pause. Four different braking forces are programmed into the computer. Depending on vehicle speed and distance required to stop, the appropriate braking force will be used. Braking will also be used to reduce speed when vehicle exceeds proper speed or is on an incline. The steering will be set properly according to the change of heading needed, the speed, and the location of course centerline. The accelerator will be set to give the desired speed. Depending on the actual speed, this will be adjusted up or down to maintain the proper speed (for example the speed limit for this segment of the course).

2.4 Vehicle Control

The vehicle control system is described below.

2.4.1 Contingency Handling

The methods of handling contingencies by this vehicle vary with the type of problem encountered. Using the inertial navigation as the primary navigation method and updating it from the GPS navigation system provides for less dependency on the GPS system. In our system, if there is a missed-waypoint, the vehicle continues. If the vehicle gets out of the LBO, it will be directed towards the next waypoint and will return to inside the course boundary. A detected obstacle-in-path will cause the vehicle to be directed to the side of the obstacle with the most clearance. If factors cause the vehicle to be unable to pass the obstacle on this side, the vehicle will then pass the obstacle on the opposite side. If the vehicle becomes trapped, or stuck, it is anticipated that we will have software that will reverse the vehicles path for the past 200 feet and then plan a new course that is different from the previous course.

2.4.2 Methods of Maneuvering

Methods used to maneuver this vehicle are generally quite simple. Braking is initiated when the vehicle is exceeding the course limit for that segment. In addition, braking is used to slow the vehicle for turning, depending on vehicle speed and the angle of turn required. For a pause, and at the end of the course, braking is used to stop the vehicle and the transmission is shifted to "park". Starting on a hill with this vehicle is accomplished by applying the brakes to maintain position, shifting the transmission to drive, applying the accelerator to move the car, and then releasing the brakes. If the vehicle wheels do not turn as shown by the transmission speed sensor, additional throttle will be applied. If the wheels rotate, but there is no forward motion as shown by the navigation system, less throttle will be applied. Making a sharp turn, or actually any turn, with this vehicle is accomplished by comparing the distance to waypoint to the distance to the nearest edge of the course for the next leg and starting the turn as soon as that boundary is reached. Also, the amount of vehicle turning is based on the angle of turn required and the speed of the vehicle.

2.4.3 Integration of Navigation and Sensing

The integration of the navigation and the sensing information is performed by a separate computer system called the Navigator Agent.   All the sensor data is collected by the Scanner Agent and forwarded to the Observer Agent and then to the Navigation Agent. All the navigation data is collected by the VNS (Vehicle Navigation System) Agent, correlated and processed, and then forwarded to the Navigator Computer. The Navigator processes all this data and then forwards high level data to the Pilot Computer, which then issues commands. In a typical operation, the vehicle heads toward the next waypoint using closed loop steering to the waypoint. As sensors detect obstacles, they send data to the Navigator, which generates repulsion vectors to bias steering to one side or another and to keep within course limits.

2.4.4 Manual Operation

This vehicle can be driven normally in the manual mode, except for gear shifting, which must be done on the touch screen. It is very quick and easy to change from manual to autonomous mode control and vice versa on this vehicle. The change takes less than a minute. To change from manual to autonomous mode, it is best to have the vehicle stopped, gear shift in park, and the engine idling. Press the brake “Automatic” pushbutton and the steering “Automatic” pushbutton to move the crossover valves to the automatic position. The manual brakes and the manual steering can no longer be used. The vehicle may now be operated in the drive-by-wire mode using the touch screen located at the right hand side of the steering wheel. This touch screen controls the gear shift, brakes, accelerator, and steering when in this mode.

To switch to autonomous mode, two data selector switches must be changed to the automatic position. This allows the computer navigation system to control the vehicle. The next step is to start the navigation software. When the software is up and running the DARPA Run/Pause control system will be active. At this point the system is ready and waiting for the RUN command.

2.5 System Tests

This vehicle was tested quite extensively to prove that all systems were operational and that all contingencies were anticipated.

2.5.1 Testing Strategies

The primary method employed in our testing of this vehicle was to start simple and then add complexity to the testing. The first testing was done with the transmission shift mechanism. After designing and building the transmission shift mechanism, it was installed into the vehicle and tested. Modifications were made until the unit performed as desired. The same procedure was used for testing the braking system. In addition data was collected to correlate the braking air pressure used to the braking action obtained for a range of settings. This data was later used by the software to make various types of moves. Similar testing was performed on the steering system and the other mechanical systems.

The GPS and Dead Reckoning systems were installed and tested by establishing a test course, using the GPS coordinates for each desired waypoint. The vehicle was then driven over this course until all software changes were completed and the vehicle was able to follow the course reliably. Next, the sensing systems were installed and made operational. These were then tested by placing obstacles in the vehicles path and then correcting software until this system was reliable in dodging obstacles. In all cases, code was developed then installed into the vehicle and tested by running the vehicle over the test course. Data was collected in a data log for each run and then reviewed to improve operation.

2.5.2 Test Results and Key Challenges

Early in the testing of this vehicle, it was determined the braking action could not be controlled closely enough due to excessive friction in the air cylinder actuator. A different type of air actuator solved this problem. Also, during the testing of this vehicle, it was found that the magnetic compass system being used was not stable enough for our needs. This unit was replaced with a gyro stabilized unit, which provided more reliable operation. The key challenge on this project was the integration of all systems and the development of all the system software that was required to operate this vehicle reliably.