Calvin College
Automated Designated Driver
2005 Intelligent Ground Vehicle Competition
Design Report

AUTOMATED DESIGNATED DRIVER

calvin college team three

CALVIN
MINDS IN THE MAKING

Engineering
Department

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I hereby certify that the members of this team have performed a significant amount of design and implementation work on this project, and have thus been given credit for their Senior Design course.

Signed,

Professor Steven VanderLeest

1. Introduction

Calvin College proudly presents its first entry to the IGVC, Automated Designated Driver. This vehicle implements intelligent navigation and obstacle avoidance on a rugged frame employing differential steering. It gathers visual information about its environment by use of a webcam, and determines its location and speed by using GPS, a digital compass, and dead reckoning. This information is processed by an on-board PC running a real time Linux operating system.

2. The Vehicle

2.1. Mechanical System

2.1.1 Frame

The frame was built from scratch by primarily one member of the team with the help of the school's metal shop supervisor. Two inch box aluminum was MIG welded in the form of a go-cart frame. Component holders were then welded to the frame.

2.1.2 Vehicle Body

The vehicle body was constructed out of sheet aluminum and was attached to the frame with screws. A removable section, the hood of the vehicle, allows for quick access to vital components as well as the various switches needed to power on components. Silicone sealant was used to fill in the cracks at places were one piece of sheet metal met another. The main purpose of the body of the vehicle was to protect the electronics of the vehicle from various weather conditions in addition to providing an aesthetically pleasing vehicle. Therefore the body of the vehicle resembles a pick-up truck complete with headlights, a bed and tailgate.

2.2. Power and Drive Systems

2.2.1 Motors

Two NPC-T74 motors were chosen as the drive motors for the vehicle. Each motor has a maximum of 1.5 HP which met the team's speed and gradient requirements. An NPC-T74 has a built in 20:1 gear box which allowed the motor to produce a maximum of 248 RPM. The motors were mounted to the frame using two socket head cap screws and one L-shaped piece of aluminum. Steel shafts were connected to the motor with four additional head cap screws.

2.2.2 Motor Controller

A Roboteq AX2850 motor controller was chosen to provide power to the motors. The controller is able to provide up to 6 HP of usable power. The motor controller is equipped with a dual channel optical encoder input. Mixed mode steering (tank-like steering) was chosen and the computer and controller are connected with RS-232 interfaces. The controller is powered from the main motor battery with a backup 12 volt battery. The controller is protected from over-current and temperature, and is able to accept an emergency stop signal.

2.2.3 Batteries

The vehicle is powered by three 12 V batteries. Two of the three are SLC (sealed lead acid), one providing 105 Ah and the other 55 Ah. The third battery has a capacity of 1.3 Ah. The 105 Ah battery powers the motors. The 55 Ah battery powers the computer, the motor controller, the GPS, the digital compass, the lights, and the PCB. The 1.3 Ah battery provides backup power to the motor controller. If the voltage of the 55 Ah battery ever drops below 12 V, the motor controller draws its power from the 1.3 Ah battery.

2.2.4 Wheels

The vehicle's drive wheels were donated to the team by Calvin College. The wheels were designed primarily for pavement driving; however, the team tested them on grass and found them to be suitable under relatively dry conditions. The wheels were connected to the shafts with friction mounts and set screws. The rear wheels of the vehicle are caster wheels with full 360 degree rotation. Each wheel is 10 inches in diameter, which allows the frame to be level.

2.3. Navigation Components

Three navigation components were integrated to provide a navigational solution for the car. The first is a GPS receiver which is able to give a good relative position of the car. The compass gives an accurate heading for the car and provides a means to check the heading obtained from the wheel encoders. By applying appropriate equations, position and heading of the vehicle are obtained from the wheel encoders; however, these are both relative to the initial position and heading of the vehicle.

2.3.1 GPS Receiver

The GPS unit is a Garmin GPS OEM 16A, and is used to determine the location of the vehicle. It is a 12-channel receiver and is WAAS capable. Without the WAAS the accuracy of the system is 3-5 meters; but once WAAS is activated the accuracy improves to better than 3 meters. As a result, the team has decided to employ the WAAS

setting. The GPS receiver outputs in standard NMEA 0183 format with selectable sentences and has a refresh rate of 5 Hz. It was connected to the computer via an RS-232 interface, and the receiver was mounted to the top of the roll bar of the vehicle using its magnetic base. This mounting position allows for an unobstructed view of the sky at all times.

2.3.2 Digital Compass

The digital compass is a KVH Azimuth 1000, and is used to determine the heading of the vehicle. The compass consists of a digital fluxgate compass with an LCD display in a watertight enclosure. It has automatic compensation which allows the compass to attain an accuracy of ± 0.5 degrees. The compass is gimbaled and has a range of ± 25 degrees which exceeds the requirements of the competition. It provides a 10 Hz refresh rate outputted in standard NMEA 0183 format. The compass is connected to the computer via a RS-232 interface.

2.3.3 Wheel Encoders

On each of the drive wheel shafts are Hohner Series 07 incremental hollow shaft encoders, which measure the angular displacement of the drive shafts of each of the two motors. The encoders have an accuracy of 200 pulses-per-revolution and the quadrature output which allows for determination of the direction of wheel rotation. This information is used in feedback control of the vehicle's differential steering system. The encoders are connected to the motor controller's optical encoder interface via a custom made connector.

2.4. Obstacle Avoidance and Detection System

2.4.1 Camera

The webcam is a Creative WebCam NX Ultra, and is used to provide visual input to the vehicle's computer, which the software uses to identify obstacles and determine their position. The camera is built with a charged coupled device (CCD) sensor that provides high resolution images in most lighting conditions. The camera is powered via USB and also is able to transfer live video at 640 x 480 resolutions and 15 frames per second. It has a field of view of 78 degrees.

2.4.2 Computer

The computer is a team-built desktop computer. Components for the computer were purchased with cost and functionality in mind. All of the parts in the computer are standard off-the-self components. The speed of the processor and motherboard was the most important parameter of the computer and thus the team obtained high-end components. Due to the number of RS-232 devices used in the vehicle an extra serial port card was also purchased.

2.4.3 Lights

Two strobe lights were mounted on the roll bar of the vehicle, providing an indication of the vehicle's status that is clearly visible from all directions. When the vehicle is in autonomous mode, the red strobe flashes. The blue strobe flashes when the vehicle has detected an obstacle. An emergency stop will cause both of these lights to stop flashing indicating that the motors are no longer being powered.

2.5. Emergency Stop System

The Emergency Stop system consists of a wireless remote system, two pushbuttons and an interconnect system. The system's reliability has been tested thoroughly and has been designed for redundancy. This system was implemented early in the design process to allow for safe testing at all stages of design.

2.5.1 Wireless Remote System

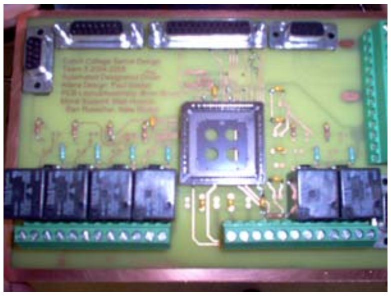
The wireless e-stop circuit was assembled from a kit. A remote, similar to that used to unlock one's car, controls the operation of the circuit. The circuit has four channels, each of which has one SPDT output relay, and is controlled by one of the four buttons on the e-stop remote. If the channel used for e-stop is activated, the computer receives the signal (5 V grounded by the relay across a pull-up resistor), and sends an e-stop command to the motor controller which stops the vehicle.

2.5.2 Pushbuttons

The two red e-stop buttons built onto the back of the vehicle serve the same purpose, with similar functionality, as the wireless e-stop circuit. If one of the buttons is pressed, the computer receives the signal (5 V grounded across a pull-up resistor) via a programmable logic device, and sends an e-stop command to the motor controller, which stops the vehicle.

2.5.3 Interconnect System

The interconnect system consists of a single PCB (Printed Circuit Board) which consolidates most of the vehicle's signal wiring onto a single board. The board also contains one 84-pin Altera chip, to provide redundancy in the emergency stop system. The board has serial connections to the computer for the GPS, digital compass, and motor controller as well as a parallel connector for the Altera chip. The board also contains a 15-pin serial connection to the motor controller, and connections to the GPS and digital compass through



terminal strips. The GPS and digital compass connections are not processed in any way on the board. The signals come onto the board via the terminal strips, and then immediately leave through the serial connectors. The board also houses six SPDT (Single Pole Double Throw) relays, which are used to control the lights and power to the GPS and digital compass. Not all of the relays are used, but the unused relays remain on the board in order to provide for future enhancements. The Altera chip would have to be reprogrammed, and a jumper would have to be placed on the board from the Altera chip to the relay's driving circuitry; but then the operation of another exterior component could be controlled from the board.

3. Design Considerations

3.1. Safety

Several safety systems are built into the vehicle. The most prominent of these is the emergency stop system. Two buttons on the vehicle, as well as the wireless e-stop button, operate in parallel. If any one of these is activated, the vehicle will stop. The Altera chip on the PCB also provides a redundancy in the system, so that the vehicle may still receive an e-stop signal even if the computer loses power. The other safety system is a passive system, and consists of the red strobe lights on the vehicle. Whenever the vehicle is in autonomous operation, the red strobe light should be flashing. This communicates to anyone in the vicinity of the vehicle that the vehicle is not under human control, and subsequently that they should exercise caution as the red strobe continues to flash.

3.2. Cost

Since the team was provided with a limited budget for the senior design class, additional funds were required. The team's budget was assembled with cost at the forefront, and many items in the budget where chosen due to their cost savings. A generous donation was provided by Smiths Aerospace of Grand Rapids, MI, which allowed for the procurement of many of

Part	Total Cost	Team Cost
Printed Circuit Board	$140.00	$60.00
Creative Labs WebCam NX Ultra	$70.00	$70.00
GPS Unit (OEM GPS 16A)	$275.00	$275.00
Digital Encoders	$350.00	$0.00
Digital Compass	$250.00	$250.00
Dual Channel Forward/Reverse Motor Controller	$620.00	$620.00
Two 24v,240RPM,20:1 Geared, 14.4 lb. Motors	$582.00	$582.00
Remote Emergency Stop System	$40.00	$40.00
Emergency Stop Buttons	$73.00	$73.00
Strobe Lights	$100.00	$0.00
Batteries	$415.00	$15.00
Battery Chargers	$200.00	$0.00
Computer	$628.00	$598.00
DC to AC Power Inverter	$30.00	$30.00
24 ft. Aluminum Pieces	$225.00	$225.00
Sheet Metal	$150.00	$150.00
Miscellaneous	$168.00	$168.00
Total	**$4,316.00**	**$3,156.00**

the parts.

3.3. Reliability and Durability

The emergency stop system was designed with several redundancies to minimize failure. First, two emergency stop buttons are implemented on the vehicle, rather than the required one. Similarly, two of the buttons on the wireless e-stop remote serve to e-stop the vehicle, rather than the required one. If any one of these four buttons is pressed, the vehicle will e-stop. Second, the Altera chip is included in the design so that the vehicle is still able to e-stop even if the computer loses power. If both of these options fail to send e-stop, an e-stop button is hardwired to the motor controller. With all of these redundancies in place, the likelihood of the vehicle failing to stop after e-stop is signaled is very low.

The frame of the vehicle was designed so that it would be able to withstand the rigors of operating in an outdoor, off-road environment. This was done by using strong, durable material (2 inch square tube aluminum), and by building the frame with more supporting members than were necessary, so that catastrophic failure of the frame would be prevented.

Many of the electrical components on the vehicle were selected, in part, for their durability and hence their reliability in harsh environments. The GPS and digital compass are both marine units. The assumption was made that implementation on a powerboat is more abusive to electronic components than implementation on a low-speed ground vehicle; since these units are adequate for use on a powerboat, they must also be sufficient for use on a vehicle such as this. The motor controller chosen is advertised as being ideal for use in autonomous robots. Additionally, the motor controller company is a sponsor for participants of the DARPA 2005 Grand Challenge. Since this controller can withstand the rigors of DARPA, it must also be able to withstand the rigors of IGVC. Both of the larger batteries are marine SLC batteries. They are able to operate while held at any angle relative to gravity, and will not leak under any such circumstances. The motors chosen are also advertised as being ideal for use in robotics.

4. Design Process

4.1. Team Roles

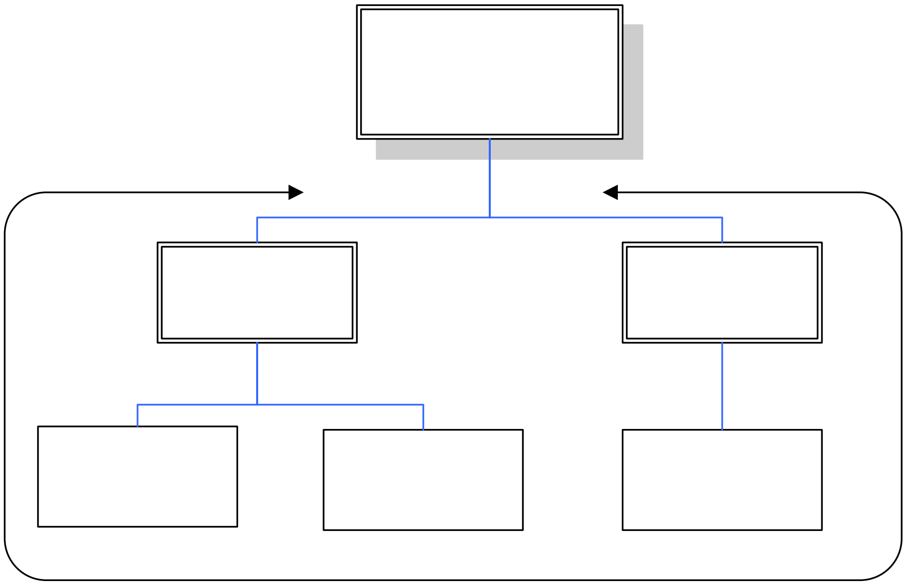


Figure 1 - Team Organization Chart

Even though team member roles were never formally defined for ADD, each member assumed roles based on their own strengths and preferences. Paul, a senior electrical engineering student, set up an off-campus server for the team’s electronic storage use, developed the project schedule in Microsoft Project, and was one of the primary software engineers for the project. Brian, also a senior in the electrical concentration, composed the weekly status reports, assisted in the building of the basic vehicle frame, and designed/manufactured the PCB. Matt performed the motor power analysis (size of the motors necessary for the vehicle to perform all of the desired tasks in the competition) and power consumption analysis (how much electric power the entire vehicle, including all of its subsystems, consumes). He was also the primary builder of the vehicle, and assisted with software development. Matt is a senior electrical engineering student. Dan, who is a senior computer science major, was one of the primary software developers for the project. Nathan, a senior in the electrical concentration, developed the basic system design (in block diagram form), and was the primary software engineers for the project. All team members were responsible for designing hardware for their sections, testing, and debugging.

4.2. Timeline

The project timeline was created using Microsoft Project. Tasks for the completion of the vehicle as well as deliverables for the Senior Design course are included in the timeline. Hours for each task were estimated using the team’s best judgment. Tasks were assigned based on each team member’s interests, as well as the amount of work already assigned. Overall, the team has spent a total of 1500 hours on the project.

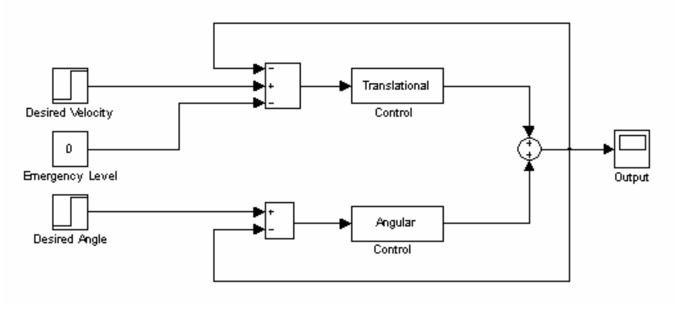
5. Software Design

5.1. Operating System

The sheer amount of processing that the obstacle recognition and obstacle avoidance systems would need; the timing constraints of the vehicles control system of the vehicle; and the fact that all the software was to be run on one CPU led the team to consider a deterministic operating system. The team originally chose to use RTlinux from FSMlabs, but during integration several problems were discovered with the deterministic response and process scheduling of the OS. Because of this problem the team ported the software code of the vehicle over to another Linux based real time (RT) operating system. The software of the vehicle currently runs on an RTAI Linux Kernel with a great deterministic response.

5.2. Navigation System

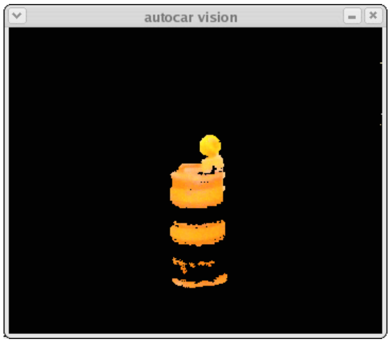
The navigation system of the vehicle is responsible for all aspects of steering the vehicle. It uses a digital compass and two encoders on the drive wheels to perform dead reckoning navigation. This result is then filtered with the position received from the GPS unit. A desired navigational path is derived from a queue of GPS waypoints which can be input in a variety of fashions. Using this waypoint queue and the current position of the vehicle the desired heading of the vehicle is derived. This desired heading is passed to the control system of the vehicle which is a simple hierarchal control system. A translational control system controls the forward speed of the vehicle, while the angular control system controls the change in speed to apply to each of the individual motors. The desired forward speed is set to the speed limit of the vehicle unless obstacle avoidance or emergency stop dictates otherwise. Emergency stop is usually enacted using the control system of the vehicle to prevent placing large amounts of shock on the drive shafts.

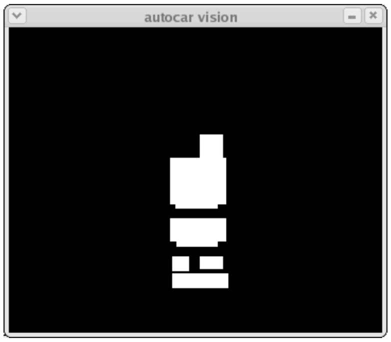


5.3. Obstacle and Line Recognition

Obstacle and line detection is performed using a webcam mounted on the top of the vehicle. Frames are captured from the camera driver as raw RGB (red, green, blue) values and can be passed through many image filters. Due to the wide variations of the surrounding environment that can greatly affect the image properties, these filters are easy to add and remove. They can also be adjusted with the

GUI (graphical user interface) as part of the calibration process, so that the best possible imaging is obtained for the next few minutes (while the current environment is relatively stable). All of these filters were implemented directly in our code and do not require external libraries. Among the available filters are: brightness normalization, brightness equalization, arbitrary transformation, RGB normalization, and exaggerate. Brightness normalization stretches the brightness values so that the full range of brightness values are utilized. Brightness equalization processes a small block of the image at a time and sets the block to its average brightness. Arbitrary transformation arbitrarily changes RGB values to new RGB values; this is accomplished by inputting a transformation curve, and is useful for changing gamma properties when inputting an exponential curve. RGB normalization tries to normalize the picture's RGB values from control colors (pure RGB) placed on the hood of the car and read by the camera. Exaggerate filter exaggerates the differences of RGB values among each channel making the differences more pronounced. After the image passes through the setup filters, it is ready to be parsed in order to find the obstacles and lines. The lines and obstacles are distinct in their colors so filtering is performed on the colors of the image. This must be optimized for speed, so a lookup table of valid colors, that are allowed to pass through the filter, is setup ahead of time so that each frame simply needs to lookup each pixel in the table to see if it is allowed through. There are two principle methods for populating the lookup table. First, the table can be populated from HSL (hue, saturation, lightness) color space values that can be easily adjusted in the GUI. This allows for easy calibration in a color space that is closest to how we humans perceive colors (perceiving hue colors, color saturations, and color brightness). The selected colors in the GUI are then converted to RBG color space to be either added to or subtracted from the current lookup table. A second method of changing the lookup table is to modify a set of pictures that contain all the possible colors, so that only the ones that should be changed are left colored and the rest be black. These sets of images are then read into the lookup tables. After the picture goes through the color selection filter, there is usually a fair amount of noise from valid colors that are not part of the obstacles or lines. This is called external noise. To minimize external noise, the image is put through a filter to shroud in the black that didn't pass through. As a result, the external noise is significantly reduced.





Lines must be handled separately from obstacles because of dashed lines. This is achieved by converting the final image of the lines into a mathematical model, represented by line segments. A fast algorithm is needed in order to process the images and to provide resilience against internal noise and incomplete obstacles or lines. We implemented our own scan line algorithm that can complete this task, and can be calibrated from the GUI to optimize it for a given environment. Once these perceived lines are identified, they are passed through a filter that connects the line segments within the GUI specified range and angle proximity.

5.4. Obstacle Avoidance

In order to properly avoid obstacles, the depth of the object must be known. The vehicle performs this operation by simply calculating the overhead map view of the current image based on the position of the pixel in the image. This method was chosen due to both simplicity and the fact that the maximum slope, a 15 percent grade, introduces negligible error from the assumption of a flat environment. The path of the vehicle is then calculated from the overhead view. This process begins by determining how far forward the vehicle can continue running straight. It then calculates how far the vehicle can travel in either direction from that point. The path that is ultimately chosen is the one in which the vehicle can travel the farthest without obstruction. After deciding whether or not a turn is necessary, the algorithm scans the possible paths of travel and chooses a heading that yields the apex of the turn. This ensures that the vehicle will stay on the inside of a curve allowing ample room for the back end of the vehicle to swing around.

The team decided that it would be very difficult to detect numerous types of traps before entering them. To mitigate this problem, the team has implemented a trap detection threshold. This threshold detects that the vehicle is inside of a trap and should reconsider its path of travel. Most often this will involve turning the vehicle around or putting the vehicle into reverse. The vehicle backtracks the previous path of travel for a predefined distance and then chooses a different path. The new path will take into account the information that has been acquired by entering the trap.

5.5. Integration

Integration of the separate parts of the vehicle was not easy. Many problems with the original design of the system were discovered during this process. The basic integration process involved separate testing of each component and then adding them to the overall system control function. The components were each given priorities and thread access as they were integrated into the system. After the real time operating system was implemented, a time period was assigned to each component to ensure that no process could overwhelm the system. Also by giving these time periods, the vital components, driving and emergency detection, were made certain to run.

6. Predicted Performance and Results

The vehicle's performance complies with all of the rules and requirements of the IGVC. The vehicle is required to pass within two meters of any given navigation waypoint: This vehicle will pass within one meter of each waypoint. Two weeks prior to the competition, the vehicle is unable to travel at a constant speed of 5 MPH; it can only reach 4 MPH. However, since 5 MPH is a maximum speed, the vehicle meets this requirement. When emergency stop is signaled, the vehicle stops within six feet, also meeting that requirement.

Performance Measure	Prediction	Result
Speed	5 mph	4 mph
Ramp Climbing	15 percent	15 percent
Avoidance Reaction Time	180 degrees/second	150 degrees/second
Stop Reaction Time	Almost Immediately	Almost Immediately
Battery Life	1.5 hours	Pending
Obstacle Detection Range	7 meters	6 meters
Waypoint Accuracy	1 meter	1 meter