Design and Integration of the Sensing and Control Subsystems of CajunBot

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***Abstract*—This paper covers the design and integration of the sensing and control subsystems of the CajunBot autonomous ground vehicle, which competed and qualified in the 2004 DARPA Grand Challenge. The event took place 8-13 March 2004 near Los Angeles, CA, USA, and closed near Las Vegas, NV, USA. The challenge was to create a vehicle that would travel without intervention approximately 150 mi through desert terrain using a set of waypoints while avoiding obstacles, both natural and man-made, in under ten hours for a prize of US $1M. In order to make the route more challenging, the exact route was only provided the morning of the race, two hours from start time. The starting line, in Barstow, CA, USA, consisted of six chutes separated by concrete barriers from which a total of fifteen autonomous ground vehicles, or bots, were launched.**

I. INTRODUCTION

ON 18 MARCH, 25 bots came to Fontana, CA, USA, to the California Speedway for the Qualification, Integration, and Demonstration round (QID) to attempt to qualify for the event. The QID lasted from 8-11 March and consisted of navigating around an obstacle course approximately 1.5 mi in length. The bot's abilities to safely navigate the course and avoid obstacles in or surrounding the path determined its success in the qualifying round. CajunBot traveled 75% of the QID course, avoiding obstacles prior to coming too close to a wall wherein it was subsequently stopped manually. CajunBot and 14 other bots qualified.

After the QID, the bots were taken to Barstow, CA, the day before the event to unpack and give each bot test runs out of the starting chute. CajunBot performed well on its test run. All bots were stopped just prior to turning a corner approximately 150m from the starting line. On the morning of the race, CajunBot was in pole position number 7 based on its qualifying performance. CajunBot left the starting chute at a slow methodical pace. Unfortunately, CajunBot's steering was not calibrated properly and had experienced sensor trouble, causing CajunBot to drift toward the right side of the track, brush a fence, causing it to engage its emergency stop button. CajunBot is recorded as having traveled 50m; tying for the tenth position in the race results, with the farthest traveling 7.1 mi. Section 2 covers CajunBot's system and subsystems at a high level. Section 3 describes the design and construction of the drive by wire subsystem in detail. Section 4 explains in detail the sensing subsystem. Section 5 concludes the paper with lessons learned and future work.

II. SYSTEM/SUBSYSTEM DESIGN

The CajunBot Autonomous Guidance System encompasses all electronic and electromechanical subsystems of the CajunBot Autonomous Ground Vehicle, including sensors, electrical power supply, computer, controllers, and actuators.

A. Automated Driver Subsystem

First of all, the central component is the Automated Driver which consists of the computer and the software running on the computer and is driven by the navigation and obstacle avoidance algorithms and the path information provided by DARPA as a Route Definition Date File Consisting of waypoints (lat/long), lateral boundaries (widths of corridors between waypoints), and speed limits. The Automated Driver PC interfaces with the outside world primarily via serial ports and Ethernet, by virtue of two Digi

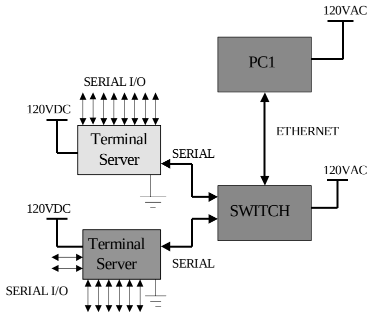

Figure 1 Automated Driver Subsystem

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TS-8 terminal servers that together create 16 serial ports that the PC may access through single network cable and driver software. The PC is an ASUS motherboard with an AMD 2500 Barton Core processor with 1 GB RAM and a 40 GB shock resistant laptop hard disk drive. The PC connects to the two terminal servers via Ethernet switch and, since it has no built in display, communicates with a host laptop temporarily connected to the bot for transfer of code and initialization.

The major contribution of the CajunBot lies not only in its use of COTS equipment, but also in its software. While a full discussion of the bot's software would require a paper in itself, an explanation of the basic algorithm is in order. CajunBot runs software that integrates navigation and obstacle avoidance. The algorithm has two modes, global and local navigation. During global navigation, the algorithm takes as input the waypoints and lateral boundaries from the RDDF, the route definition data file. These are converted to UTM, a grid coordinate system based on rectangular coordinates, accurate within the range at which the robot would be traveling. The bot's global navigation behavior is to seek the next waypoint.

The algorithm also takes as input a cost map, which is a two-dimensional array containing the cost of every coordinate around the bot. This is a rectangular area, whose size is about 10m wide by 30m long, chosen because of the sensor ranges and centered on the bot The grid spacing is 30 cm, as this approximates the size of obstacles. Each grid spot corresponds to an array element and is given a unit cost if there is no obstacle picked up by the sensors and a higher cost if there is an obstacle. The laser (to be described later) picks up obstacles as reflections and so the obstacle is there or not. As the bot drives forward, the laser picks up more and more obstacle data, which is then placed in the array as described earlier. If there is an obstacle in between the bot and its next waypoint, the algorithm goes into local navigation mode.

During local navigation, the bot seeks a short path around the obstacle (if possible). The algorithm treats the obstacle as a high-cost region in its map and plots a course that avoids this region, by generating intermediate waypoints around the obstacle leading to the original next waypoint. In this way, the algorithm is unique because it treats navigation and obstacle avoidance in a uniform manner.

B. *E-power Subsystem*

The Automated Driver and all other subsystems are powered by the E-power subsystem, which supplies three power sources: 120VAC, 12VDC, and 5VDC. The generator is a Honda EU2000 inverter generator capable of supplying 2000W at 120VAC. This in turn powers 525VA and 725VA UPS units, which support the unit during power glitches, such as when unplugging from shore power and plugging into generator power.

Three 12V 10A regulated power supplies connected in parallel form a 12VDC, 30A power supply that powers DC electronics. A 5V regulator in a TO-3 package and heat sink and fan comprise a 5VDC, 5A continuous power supply that feeds off the 12VDC supply. The 12V supply powers the steering actuators, and the 5V supply powers the microcontrollers, the throttle servo, and the emergency control subsystem. The vehicle battery/alternator magneto power supply is kept isolated from the E-power subsystem to avoid noise and spikes and to avoid excess battery drain and engine load. A 24V 2.5A switching power supply powers the laser measurement system. 120VAC powers the Automated Driver subsystem and the navigation sensors.

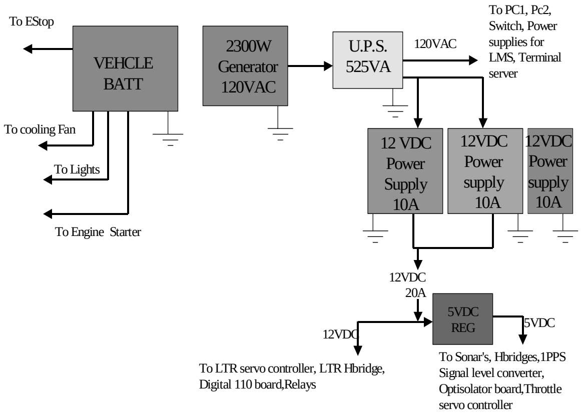

Figure 2 E-power Subsystem

C. *Sensors Subsystem*

The Sensors Subsystem comprises the navigation sensors, which are the Applanix POS MV inertial navigation system and the C-Nav supplemental receiver for enhanced accuracy via Starfire signal, and the obstacle sensor, which is the Sick LMS 221 laser measurement system.

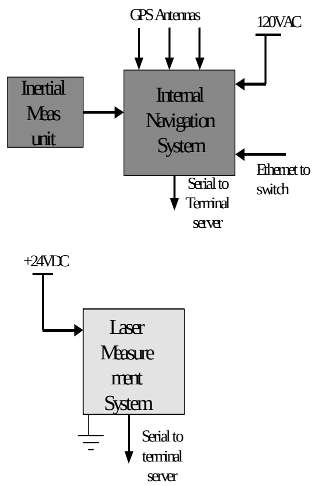

Figure 3 Sensor Subsystems

D. Drive-by-Wire Subsystem

The Drive-by-Wire subsystem consists of speed control, which is a servo and microcontroller suitable for receiving commands from Automated Driver, direction controls, which are a set of microcontrollers and high-thrust electromechanical pistons with positional feedback known as linear actuators, and signal controls consisting of a microcontroller and relays for siren, strobe lights, and turning/braking indicators.

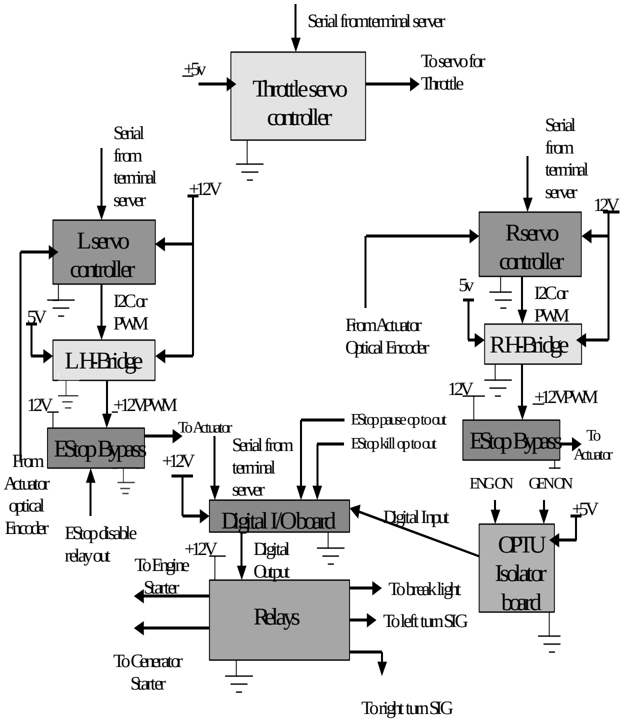

Figure 4 Drive-by-Wire Subsystems

E. Emergency Control Subsystem

Finally, the Emergency Control Subsystem consists of the DARPA-supplied emergency stop (E-Stop) radio receiver, which receives pause and disable commands via RF signal from a remote unit, another separate RF receiver that kills the engine via a key chain remote for testing purposes, and two buttons mounted on the front driver and passenger sides of the vehicle for local stopping capability. The same microcontroller employed in the signal control of the drive-by-wire subsystem monitors the pause and disable lines of the DARPA E-stop receiver in order to keep track of these events, although the disable signal is hardwired to stop the unit and kill the engine regardless of the Automated Driver's working. A short range wireless video game joystick with two analog levers and several buttons allow easy manual override for driving the vehicle out to a test site and is equipped with a dead-man switch so that if the remote drops, a trigger releases braking the vehicle.

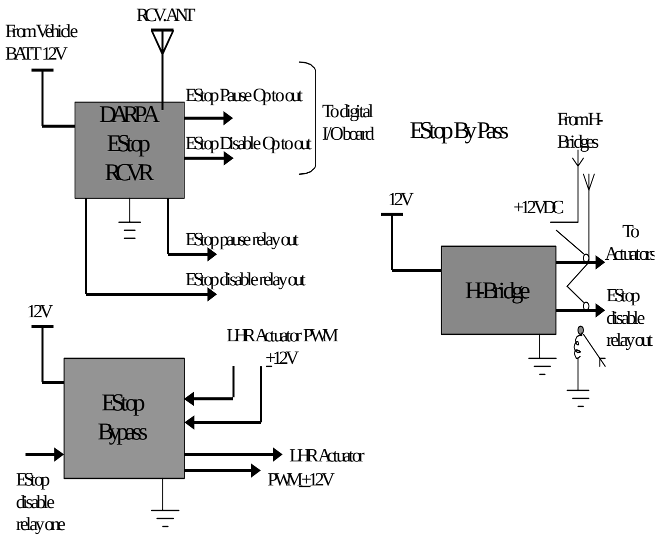

Figure 5 Emergency Control Subsystems

III. DRIVE-BY-WIRE SUBSYSTEM

CajunBot's Drive-by-Wire Subsystem enables the Automated Driver to control all vehicle motion. The primary interface to the vehicle is three points: left and right steering levers, and throttle. Two EMC Actu-Shift electric linear actuators drive the levers through a linkage mounted close to their pivot points. While the actuators have a travel of 2 ½”, they are capable of thrust in excess of 180 lb and employ a screw drive that enables them to lock in any position. The actuators each require 12VDC, 3-6A, and push or pull the plungers depending on the polarity of the driving voltage. In order to interface with the Automated Driver, the actuators use two components: a controller to convert serial data into low level direction and velocity signals, and a driver to convert the direction and velocity signals into high-power pulsed DC waveform to drive the actuators. For the controller on each actuator, a Parallax BASIC Stamp 2p24, essentially a low-power microcontroller programmable in simple BASIC commands, listens to its serial port for position commands. These commands are in the form of numeric values that tell the absolute position to which the actuator’s plunger should go and thus the lever. In order to do that, the stamp must have positional feedback from the actuator, that is, it must first determine where the plunger is in order to know in which direction to move it. This is a basic servomechanism. For this feedback, each actuator has a built-in 10K ohm linear taper potentiometer that gives a resistance proportionate to the position of the actuator’s plunger, with 0 ohm and 10K ohm being at the extremities of the actuator plunger’s travel. The BASIC Stamp contains a simplified A/D converter that is sufficient for dedicated single-channel use. It uses an external 0.1-microfarad metal film capacitor in conjunction with an external fixed resistor and the actuator’s potentiometer to form an RC timing circuit. The Stamp strobes the pin, charging the capacitor through the fixed resistor and measuring the discharge time through the potentiometer, the duration in which the capacitor voltage is sufficient to raise the pin. This is directly proportional to the potentiometer’s resistance and thus the plunger and lever position. This method has proven to be stable with its chief disadvantage being that the BASIC Stamp blocks for several milliseconds waiting for the capacitor to discharge during A/D conversion, preventing the Stamp from being able to receive new commands during that time. Moreover, this time is proportional to the analog value, making the delay variable between 5-50 ms. This could be abated by inserting a delay inversely proportional to the digital value, but the mechanism to do so would insert a delay of its own inherent in the instruction interpretation time. Using optimized code with manual subroutine calls and minimal I/O, the Stamp proved to be a serviceable and economical solution to the problem of receiving commands and controlling the actuators precisely using a closed loop.

To address the second issue, driving the actuators, two high-current “smart” H-bridges interface the Stamps with the actuators. Each H-bridge is capable of switching up to 30A and can vary velocity, braking, and acceleration of a motor using pulse width modulation. An H-bridge is a circuit that provides three usable outputs: zero voltage, positive supply voltage, and negative supply voltage. These possible outputs control the operation and direction of the actuator motor, controlling that of the lever. As added features, these H-bridges use high-speed, low resistance MOSFETs and built-in microcontrollers to provide additional useful capabilities: pulse width modulation, which controls motor speed and acceleration while maintaining a fairly constant torque by varying the duty cycle of a high-frequency, fixed voltage waveform fed to the motor, and dynamic braking, which halts the motor more quickly than simply de-energizing it by shorting the voltage generated by the motor, magnetically (dynamically) braking the motor. These H-bridges require no external discrete components and interface with the BASIC Stamps using a 2-wire synchronous serial interface called I2C, used in consumer electronics equipment to simplify communication among subsystems in more complex circuits.

The throttle control required less additional work due to its lower torque requirement and the ready availability of an integrated servo motor controller/driver with built-in serial communication capability. The motor used is a Hitec HS805BB ¼ scale high-torque hobby servo with a 1 ½” nylon horn (lever) attached to its shaft. A hobby servo has the convenient capability of receiving a low-level pulse width modulated signal and, through built in feedback closed loop control, positioning the shaft precisely at a given position proportional to the pulse width. This allows ready interfacing with virtually any microcontroller having a digital output line. To drive the throttle, a simple stiff wire pulls on the engine’s throttle valve, allowing the engine vacuum to help return the valve to its idle position when the servo returns. This method of linkage has the added advantage of letting the engine go into idle if the servo should become de-energized in the event of a power failure. The controller has a serial interface that receives numeric position commands from the Automated Driver and sends the PWM control signals to the throttle servo. It is capable of driving additional servos independently.

Signals on CajunBot consist of a pair of strobes on top, a siren, and left, right, and brake lamps, which are of the LED type for reduced current draw. These signals require driver circuitry to switch them on and off. The driver circuitry consists of a microcontroller-based digital I/O multi purpose board (PIC I/O) that accepts serial data from the PC and monitors and controls up to 12 digital I/O lines (0/5V TTL signal levels). A ULN2003A Darlington array accepts the TTL output lines for 1) the siren and strobes, 2) left and 3) right turn signals, and 4) brake lights and drives relays to switch 12VDC for each. Two input lines monitor the E-stop pause and disable outputs and are readable by the PC. Thus, the custom steering actuator controller/driver, throttle control, and signal control circuits together make up the drive-by-wire computer interface to the MAX IV ATV.

IV. SENSING SUBSYSTEM

CajunBot's sensing subsystem enables the Automated Driver to determine its own location to within 10cm and its orientation, i.e., roll, pitch, and heading and to determine absolute locations of returns (reflections) from the laser measurement system. The laser measurement system is a Sick model LMS221 outdoor unit, resistant to the elements.

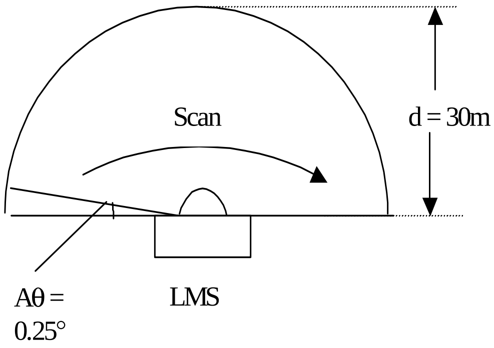

Figure 6 Top view showing LMS scan pattern

The LMS scans at a rate of 75 Hz in a 180-degree arc with a maximum measurable distance of approximately 30m in broad daylight on white cardboard. Its method of scanning may be found in [reference Sick technical manual]. Concisely, it uses a rapidly spinning mirror to sweep a laser across a plane while pulsing the laser and measuring the time of flight of the laser, inferring distance based on the average speed of light in air. The LMS is capable of scanning in 0.25 degree increments, which at 30m would give a resolution of 30m * $\tan^{-1}$(0.25 degrees) or about 13 cm by approximating the sections as right triangles. Software in the Automated Driver converts these polar measurements (azimuth, distance) to rectangular measurements and places them in a global coordinate system by using the relative position of the LMS on the vehicle to the GPS antennae and the measured position of the vehicle, superimposing an echo on the global coordinate system with the vehicle. Thus the Automated Driver subsystem keeps track of returns in a global rectangular coordinate system using the polar returns from the LMS, enabling the algorithm that detects and avoids obstacles to use the same coordinate system as the navigation algorithm.

The navigation sensors consist of the Applanix POS MV 320 inertial navigation system and an attached supplemental receiver to pick up correction signals from a subscription service for 10cm GPS accuracy. The POS MV 320 consists of a differential GPS receiver whose antennae are spaced 2m apart along the long axis of the vehicle a supplemental correction signal receiver/antenna integrated unit (C-Nav) in the center of the line between the differential antennae, and an inertial measurement unit placed along the same center line as close to the sensors as practical and still protect the unit. The IMU is a ring laser gyro that detects acceleration in any axis and rotation about any axis and is used to supplement the DGPS signal to give orientation and heading to the Automated Driver subsystem as well as position. The position and heading measurements allow the Automated Driver to navigate to a waypoint, and the orientation measurements are used to transform the locations of echoes from the LMS into global coordinates for obstacle detection and avoidance.

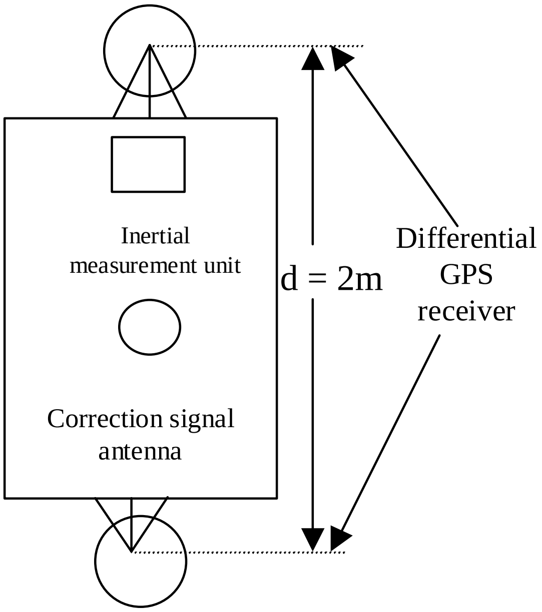

Figure 7 GPS Antenna Placements

V. LESSONS LEARNED AND FUTURE WORK

Working on CajunBot, as with any robotics work, has brought together knowledge from artificial intelligence, software engineering, electrical and computer engineering, and mechanical engineering. With respect to design and integration of sensor and control subsystems into an autonomous ground vehicle, the project required designing a practical autonomous guidance system with sufficient separation of subsystems to enable the sensors and controls to be replaced without affecting the entire system significantly. For this, the embedded systems, i.e., the microcontrollers, needed to provide a generalized interface consisting of commands and returned data that were abstractions of physical quantities, such as distance or resistance. Furthermore, care was taken to make the E-power subsystem simple yet cost-effective by using mostly off-the-shelf electronics.

To make the drive-by-wire system less costly, relatively low-cost linear actuators and a servo motor provided the steering and throttle control, which custom work was still required to proved closed-loop computer controls for the steering actuators.

The choice of sensors was practical yet forward-looking. The LMS used is ruggedized for use outdoors and provides the longest range and widest field of view in its cost class. The POS MV is a marine unit that was available for loan by a local company as was the C-Nav, and their performance was adequate although more work has yet to be done to synchronize the LMS data and position data more precisely to a global clock, and a supplemental altimeter would indicate change in relative altitude more precisely than GPS due to inherent limitations in GPS.

In order to improve drive-by-wire performance, two things may be done: 1) add feedback as to the change in heading that occurs when the Automated Driver attempts to steer the bot, 2) utilize more expensive, faster linear actuators, already under test, and a faster motor control microcontroller with efficient A/D conversion, dual channel inputs, multitasking capability via interrupts, and a hardware serial interface (UART), all for increased responsiveness of the steering controls. The drivers themselves, i.e., H-bridges, would need to be changed as experiments with the new actuators indicate that using a different PWM carrier frequency would increase efficiency.

The E-power subsystem 12VDC and 5VDC regulated outputs may be changed to more efficient switching power supplies capable of delivering higher power outputs than regulated power supplies from a smaller footprint unit, though these units are more costly than their regulated counterparts. An alternative to the separate controllers for signal, steering, and speed control is to use a PXI chassis with a DAQ board for digital and analog I/O and an off the shelf three channel motion control board for the actuators and throttle coupled with matched software for motion planning and logic. The drawbacks to this alternative are that it is more expensive than the existing solution and that compatibility with the existing sets of actuators is uncertain in terms of power output maximums on the motion control board, and compatibility of the feedback mechanisms (both optical/encoder and potentiometer on the new set), those these issues are expected to be research to determine this alternative's feasibility. Other improvements include getting reliable data transfer from the LMS at its maximum data rate, which requires special hardware (RS-422 high-speed interface) that as of this writing has compatibility issues with the Automated Driver software requiring a lower data rate to be used, and synchronizing and combining the output of a second LMS mounted either tilted down at an angle or rotated orthogonal to the existing LMS for vertical slope measurements for increased terrain awareness.

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REFERENCES

[1] Sick, "LMS Technical Documentation".

Figure 8 CajunBot