PrincetonUniversity

PROSPECT ELEVEN

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Technical Paper

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Abstract

Described is a low-cost approach to the problem of autonomous vehicle design using a single stereo camera and unified behavior control. Passive sensing offers advantages in both a military context, where undetectable sensors are crucial for effective operation and in a civilian context, in which multiple autonomous vehicles must not interfere with one another. Proposed is a novel reactive controller that operates on the principle that an effective decision can only be made in the presence of all available data. The unified behavior paradigm removes the need to arbitrate between multiple desired behaviors.

Introduction

The Princeton University team consists of a dedicated team of enrolled full-time undergraduate students, one graduate research assistant and several advising faculty. The vehicle is a silver crew-cab pickup truck dubbed "Prospect Eleven." The team has benefited from the hard work of: Anand Atreya '07, Bryan Cattle '07, Daniel Chiou '05, Kamil Choudhury '06, Brendan Collins '08, Ben Essenburg '05, Gordon Franken '08, Josh Herbach '08, Jeffrey Jones *05, Andrew Klaber '05, Michael Pasqual '05, Andrew Saxe '08, Scott Schiffres '06, and the unwavering support and guidance of Professor Alain Kornhauser of the Department of Operations Research and Financial Engineering and the assistance of Professors Sanjeev Kulkarni, Bradley Dickenson, and Stewart Schwartz of the Department of Electrical Engineering, and Professor Szymon Rusinkiewicz of the Department of Computer Science. Underclassmen have participated as either summer interns and/or on an extra-curricular basis, while upperclassmen have received independent research or senior thesis credit for their research contribution to the project. The one Graduate Assistant contributed as part oh his graduate research requirement. Faculty participation was only as research advisors. No professional staff was utilized.

Vehicle Description

Prospect Eleven is a stock 2005 GMC Canyon, modified for autonomous operation. Aftermarket add-ons include skid plates and a brush guard. The vehicle’s suspension and wheels remain stock. It has a wheelbase of 3.2 meters, and a turning radius of 13 meters. The back seats were removed to provide space for vehicle control systems, but the front seats were left intact. Prospect Eleven remains fully human-drivable.

Hardware Framework

Brakes are controlled by mechanical actuation. Two independent braking modules both connect to the brake pedal via Teflon-sheathed cables. A custom-made linear actuator applies or releases the brakes during normal vehicle operation using a DC motor. A tension sensor coupled with the vehicle’s brake activity sensor provides the necessary information for closed-loop control. The other braking module is a fail-safe emergency braking unit. A pneumatic piston applies over two-hundred pounds of force to the brake pedal. A positive signal from the DARPA-provided emergency-stop system is required to release the emergency brake and allow normal movement of the vehicle. The emergency brake’s pneumatic system is setup such that any failure of the Prospect Eleven’s software or hardware will result in an emergency brake application.

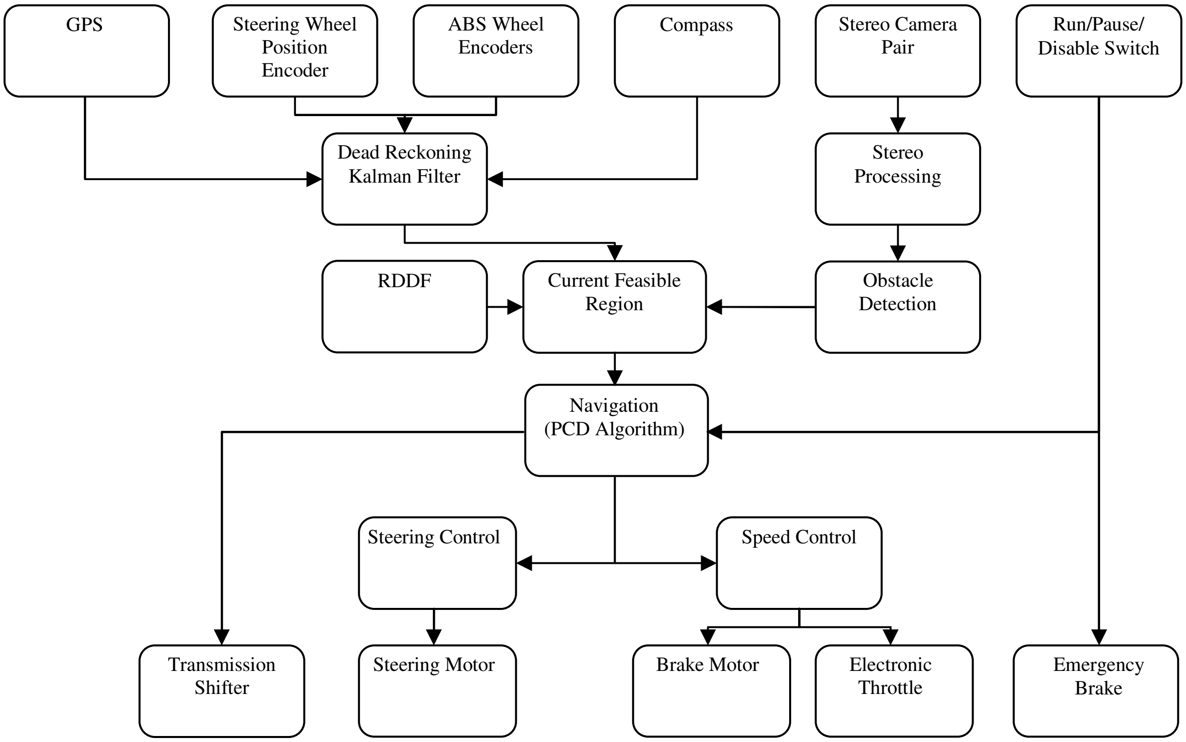
Steering control is achieved by a direct gear connection between the steering wheel and a DC motor. An optical digital position encoder is used for precise position feedback. Both of the DC motors (steering and brake) are activated by a RoboteQ AX2500 motor controller. Throttle control is achieved through direct interaction with the Canyon’s electronic accelerator pedal.

The Canyon’s alternator, backed by three standard 12V AGM batteries, provides all of the power for Prospect Eleven. All electronics are powered from this 12V system, with the computers and other AC-powered items running off a 2000 Watt inverter.

All of the modifications to Prospect Eleven were made with the intention of leaving the vehicle entirely human-drivable. Three dashboard-mounted switches cut power to computer controlled devices and allow for full human control. A manual override is necessary to keep the fail-safe emergency brake from activating upon autonomous shut-down.

Software Framework

Two commercially available computers perform all computations. One, named Santiago, is based on an Intel Pentium 4 processor and the other, called Prospero, and is based on an AMD Athlon 64 processor. The vision processing and obstacle detection algorithms are written in C++ and run on Prospero, due to its strong ability to handle such computations. The drive-by-wire, data acquisition and decision making control systems run on Santiago, whose processor was selected due to its "HyperThreading" capabilities, which provides an improved foundation for our multithreaded software architecture.



The software framework was designed with the goals of flexibility, productivity, and reliability in mind. The system is composed of a number of standalone components that interact with each other through direct communication as well as event-based signaling. In addition to significantly reducing complexity, this component-based and event-based architecture makes system monitoring very easy, as a great deal of system reliability is achieved simply through the addition of another "watchdog" component, whose sole job is to monitor the functioning of the other system components.

Localization

A Trimble DGPS unit (using WAAS) provides position data at 1Hz with 1 meter RMS error. A CoPilot GPS unit is used as a backup receiver. Dead reckoning, based on front-wheel ABS sensors and steering wheel position, interpolates position between GPS updates and during GPS outages. A Kalman filter optimally combines the two measurements each time a GPS position is received. In trials, dead reckoning was accurate enough to navigate an entire 200 meter course successfully. Parameter estimation techniques allow Prospect Eleven to continually adjust for changes in the car's state equations. As dead reckoning relies on accurate rotation data from non-slipping wheels, four wheel drive cannot be used unless absolutely necessary.

The vehicle navigates without the use of map data, but relies on ordered GPS control points.

Sensing

Prospect Eleven uses only one sensor for obstacle and lane detection—a Point Grey Bumblebee stereo camera mounted on the hood of the vehicle. Obstacles can be reliably detected at 50ft, with a horizontal field of view of 70°. Obstacles below 30cm in height are generally not detected until they are very close, due to the limits of the stereo image. The detection algorithm searches for deviation from a dynamically-computed ground plane. Stereo

vision has clear advantages over LIDAR in rain as light rain will not affect image quality unless it collects directly on the lens. In addition, water or other obstructions on the lenses produce holes in the depth image that will preclude detection in these areas but will not generate false positives.

The camera is encased in a custom-built enclosure that provides protection for the stereo system and active adaptation to the environment. Optical filters are mounted in front of the lenses to compensate for high light levels. The stereo vision system has the ability to operate in direct sunlight through the implementation of a moveable "blind spot." A layer of abrasion-resistant Lexan provides additional protection. Two blower fans supply a stream of high-pressure air to deflect dust and small particles away from the camera enclosure.

Detected obstacles in each stereo frame are sent to the command computer for tracking. The tracking system stores obstacles as discrete objects relative to the car's position. Using recent estimates of the car's motion, each new obstacle is matched to the predicted locations of previous obstacles. Matches are filtered for increased accuracy.

Lane localization also relies on processing the stereo depth image. Using essentially the same algorithm as obstacle detection, Prospect Eleven can locate berms, foliage, and drop-offs bordering the track. The detection algorithm relies upon the continuity of road edges to increase the sensitivity of detection. Unfortunately, distinctions between mostly flat terrains are lost, so stereo detection can not perceive much difference between rocky terrain and flat terrain.

Vehicle Control

Every twentieth of a second, Prospect Eleven fuses the relative position of obstacles with the surrounding RDDF course using the current best estimate of the car's state. This snapshot of the vehicle's surroundings provides a complete picture of the instantaneous feasible region around the car. A Projection-Constrained Decision (PCD) algorithm, termed "Point, Click & Drive", operates on this representation, producing a desired steering angle and desired speed. In the absence of obstacles, the PCD algorithm performs identically to a proportional navigation guidance-based control system, tracking a point along the course centerline. This behavior allows for smooth and quick convergence onto the course from any vehicle orientation and position.

When the projected path is blocked, the PCD algorithm selects the most attractive heading for the car to travel in and then chooses an angle that will bring the car to that heading in time to avoid obstacles, remain in lane boundaries, and remain in course boundaries. The attractiveness of a heading is a function of the proximity to infeasible regions, and the distance it progresses along the course before reaching an obstruction. Because the controller does not path-plan, there exist terrain conditions it cannot navigate. The algorithm is capable of avoiding obstacles while returning to the course from out of bounds. By putting all available information into one representation, the navigation system avoids typical pitfalls of behavior-based controllers. Instead of arbitrating between following the GPS path and avoiding an obstacle, the PCD algorithm selects a command that does both simultaneously.

The desired speed is a function of the distance to the edge of the feasible region along the car's current heading, the curvature of the course, and the lateral position of obstacles. Of course, Prospect Eleven will never attempt to reach a speed greater than the course speed limit.

Safety

Prospect Eleven has no modifications to the fuel or ignition systems aside from electronic relays to allow for full system disabling. As such, the propulsion systems have the same safety standards as consumer vehicles. As a precaution, a fire extinguisher is carried on-board. Four easily accessible emergency stop buttons, externally mounted over each wheel, will induce a full disable in Prospect Eleven.

Testing

Prospect Eleven has been tested at Princeton University as well as at off-site locations. Fields in and around Princeton provide hills and tree-lined dirt roads. Testing has also been conducted at Tom Haine's pick-your-own blueberry farm, which includes narrow roads, berms, and extensive foliage.

Testing in the Princeton area has enabled the fine-tuning of the control and obstacle detection algorithms. The blueberry farm test site was particularly instructive with respect to lane detection and precise vehicle control.

Source of Funds

Prospect Eleven was fortunate to receive product donations from several companies. Rick Spina ’85 helped obtain a salvaged vehicle from General Motors. Trimble Navigation and ALK Technologies donated GPS receivers. Otherwise, all student summer salaries, graduate student support and equipment was purchased using University endowment funds from the CSX Transportation Research Fund, the Lion Transportation Senior Thesis Fund, and the Kornhauser-Gervasio Graduate Fellowship. The team is also indebted to the generosity of the parents of the undergraduate researchers and Eric Huber.

Conclusion

Prospect Eleven is capable of reliably avoiding obstacles higher than 30cm off the ground, navigating through narrow gates, and tracking a GPS course at high speeds. The results of our obstacle and lane detection scheme indicate that stereo processing is a practical and viable alternative to active sensing that may soon find its way into general use. In addition, we have demonstrated how a small number of simple yet elegant algorithms can control an autonomous vehicle. Furthermore, if stereo processing is performed on an ASIC, a capable autonomous vehicle using only one standard computer is quite feasible. This lightweight scheme derives its capability from its unified control framework in which all information is fused into a single representation.

Student Research Papers

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