

Low-Cost Autonomous Vehicles for Urban Environments

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ABSTRACT

Despite the rapid progress in the development of autonomous vehicles, as seen in the DARPA Urban Challenge 2007, there has been very little emphasis on minimizing costs. Some teams spent upward of \$10 million in developmental expenses. The cost factor is very important as it is the primary driver leading to the commercialization of autonomous technology. With this fact in mind, an alternative approach has been emphasized here, wherein a fully autonomous vehicle designed for urban environments has been developed and tested for under \$20,000 in hardware costs. Moreover, this vehicle passed several rounds of elimination to participate in the semi-finals of the DARPA Urban Challenge at Victorville, California, in November 2007.

OVERVIEW

While there has been considerable development in the area of autonomous vehicles in recent years, the emphasis on low cost solutions has been neglected. As seen in the DARPA Urban Challenge held in November 2007, some of the teams had spent in excess of ten million dollars on their vehicles. Commercialization of autonomous vehicle technology however demands that cost issues remain at the forefront. This paper describes an autonomous vehicle system with less than \$20,000 of hardware on board that has been extensively field-tested and which participated in the concluding rounds of the recent DARPA Urban Challenge.

The primary drivers of a low-cost solution to autonomous urban navigation are the use of low-cost commercial hardware along with their interfacing with software containing

sophisticated algorithms able to maximize the utilization of the associated hardware. These algorithms are intensively mathematical, often employing closed-form solutions, to not only interface with relatively simple sensors but also to simplify computations so that a single desktop PC is sufficient to handle all aspects of vehicle control.

One example of this pairing of simple hardware and sophisticated software is in the vision system, which is the primary sensor system developed for our autonomous vehicle. The vision system hardware utilizes several \$50 webcams that provide all the necessary input. To reduce computational requirements, all cameras operate in the 320 x 240 pixel resolution only. Vision algorithms were created to simultaneously process multiple camera data and utilize these to obtain a real-time 3-D visualization of the surrounding spatial environment. Moreover, the computational efficiency of these algorithms permitted the use of a single desktop PC along with the flexibility of using Visual Basic 6 as the programming language.

Another such example is in the brake and throttle control where simple linear actuators are connected to the transmission shifter, accelerator and brake pedals of the vehicle, and are integrated in a manner that provides fail-safe operation via mechanical means. In the event that pre-set driving parameters are exceeded, or any type of power failure occurs, the vehicle will always come to a quick stop. These actuators are controlled by special algorithms employing closed-form equations to provide real-time dynamic control of the vehicle based on just the actual and desired velocities as input. Another critical innovation employed in the vehicle is the creation of a virtual Inertial Measurement Unit (IMU) which utilizes existing vehicle sensors and special algorithms,

thereby eliminating the need for purchasing very expensive IMU hardware.

The research and developmental activity that preceded the testing of the full-size autonomous vehicle also feature many innovative low-cost solutions. Chief among these is the extensive use of scale models to develop critical vision algorithms that form the core of the vehicle control system. Initial development occurred with 1:48 scale static models. Algorithms that passed this stage were encoded into a specially fabricated 1:3 scale self-propelled autonomous vehicle and tested for dynamic validation with other 1:3 scale traffic vehicles. Only when the algorithms passed these two stages were they tested on the full-size vehicle, which not only saved considerably on the cost of testing, but also significantly lowered the risk factor for damage or injury at the full-size vehicle level. Despite the inherently high risk of testing a newly developed autonomous vehicle, no person or property suffered even a minor scratch throughout this endeavor that lasted well over one year. This can be attributed to strict adherence to proper safety procedures by all participants, and the innovative fail-safe designs that were implemented.

There are two other significant advantages of our system. The first of these is that it is ideal for military applications because it utilizes a passive vision system as the primary sensor system. Unlike other vehicles that employ a number of radars which greatly increases their electromagnetic signature, our vehicle is not only passive but, due to the small size of the cameras, presents a very low physical profile. The other advantage of our system is in the ease with which it can be converted from fully autonomous to fully manual control. This can be accomplished in seconds because the special design of the actuator assembly enables manual override without the need for any removal of actuator hardware. A safety driver during autonomous testing (which was always performed in approved off-road locations) could take over control of the vehicle at any instant, immediately – without the need of pushing any switches or levers to transition from autonomous to human operation.

In summary, a versatile low-cost autonomous vehicle system suited for navigation in urban environments is presented here, which has been extensively field-tested and which also successfully participated in the DARPA Urban Challenge in 2007.

DEFINITIONS

Ariadne

Team ODY-ERA's position-based, precision Dead Reckoning system.

Cyclops

A novel machine vision system invented and developed by Team ODY-ERA for use in the Urban Challenge and other future applications. Appropriately named after the primordial race of one-eyed giants from Greek mythology, the ODY-ERA vision system primarily uses only a single forward-looking camera.

CVT

Continuously Variable Transmission

GPS

Global Positioning System

Hanuman

The integrated system of sensors and software that controls our autonomous vehicle, named after the legendary warrior Hanuman from the ancient Indian epic - the Ramayana. Known for his immense strength, unflinching loyalty and the ability to effortlessly travel to any place at any time and under any conditions, Hanuman embodies the very qualities we seek in our autonomous vehicle.

IMU

Inertial Measurement Unit

IR

Infra-Red

LMS

Laser Measuring System (also known as LIDAR)

MDF

Mission Data File, a file format defined by DARPA for use in the Urban Challenge.

ODY-ERA

ODYsseus-ERAtosthenes — An epic combination of elegant and efficient mechanical, navigational, numerical, and algorithmic concepts, implemented in the creation of an autonomous ground vehicle. Odysseus and Eratosthenes represent two giant figures from Antiquity on whose shoulders we are standing.

RC

Remote Control

RNDF

Route Network Definition File, a file format defined by DARPA for use in the Urban Challenge.

SUV

Sport Utility Vehicle

USB

Universal Serial Bus

HARDWARE

After careful deliberation, a vehicle platform that was considered to be best suited for the Urban Challenge 2007 competition – a new 2008 Mercury Mariner Hybrid 4WD SUV (shown in Figure 1) – was selected. The first and most important consideration is that this vehicle meets DARPA Urban Challenge specifications. The combination of an electric motor and a gasoline engine for propulsion coupled to a CVT results in smooth operation and requires minimal modifications. Its electrical system can be utilized to draw up to 1200W to power the ODY-ERA computer and autonomous vehicle control systems. Furthermore, the engine will cycle on and off automatically while on “Pause” during a mission, as needed to maintain a controlled climate in the cabin and proper levels of electrical power to the equipment.



Figure 1: The 2008 Mercury Mariner Hybrid 4WD, ODY-ERA autonomous vehicle.

Even though computers and software are of utmost importance in the development of this project, the mechanical aspects have also been given thorough consideration. As a matter of fact, it is the synergistic effects from several proven mechanical innovations we have already developed that enabled us to bring an elegantly simple autonomous solution to this competition. Using our experiences from building a custom robotic vehicle, called “Conestoga-Bot”, which advanced in the quarterfinals of the Grand Challenge 2005 (for the most part due to the merits of its physical capabilities), we implemented several vehicle control features we had already developed to the Mercury Mariner Hybrid SUV, as part of its transformation into ODY-ERA. One of these is our precision closed-loop, servo-controlled steering system we have implemented, while retaining all stock electric-steering components of the Mercury Mariner. Three other innovative features we had designed for the Conestoga-Bot and reused on ODY-ERA are the unobtrusive gear-

selector, throttle, and brake control sub-systems that provide fail-safe autonomous operation when used with our E-stop, or the E-stop that is provided by DARPA. Furthermore, these systems allow for immediate, unencumbered transition from manual to autonomous vehicle operation and vice versa. During testing and development, a safety person sitting in the driver’s seat can instantly take control of the vehicle at any time, as needed. All of the vehicle’s original safety restraints and airbags remain intact and offer security to the occupant(s) while testing, as was intended by the manufacturer for regular road use.

The largest problem associated with this program is the inherently dangerous nature of having a 2-ton vehicle operating autonomously during its development. Since safety is the number one priority of Team ODY-ERA, considerable effort has been directed toward mitigating all circumstances that can pose a threat to the personal well-being of crew and others and/or to property. While our meticulous approach has resulted in affording ample security to persons in the vicinity and to the occupant(s) of the ODY-ERA vehicle while testing, our initial development of algorithms and software is previously validated with small-scale models. For example, vision algorithms are at first developed using still pictures. Then a 1:48 scale model of roadway, intersection and Matchbox-style cars are used along with a computer and video cameras to confirm the desired results. Once satisfactory results are obtained, the next step is to conduct autonomous testing with “mOE” (mini ODY-ERA) — a 1:3 scale vehicle we have specifically designed and built to reduce exposure and thus enhance safety, as seen in Figures 2 and 3.

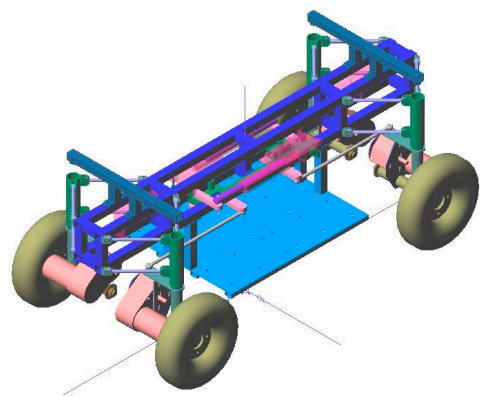


Figure 2: CAD model of mini ODY-ERA (mOE), a 1:3 scale autonomous vehicle.

This vehicle is powered by two 12Vdc utility vehicle batteries that drive four DC motors, one at each wheel. Steering and propulsion are controlled by a RoboteQ AX2850. Commands for vehicle speed and steering are communicated to the RoboteQ via RS232 from a WindowsXP-based laptop PC. The autonomous software code processes RNDP and MDF

files, along with data from GPS, E-compass, video cameras, and other sensors. In addition to the benefits gained in terms of increased safety of our program by small-scale testing, we have proven that our approach in developing an autonomous ground vehicle system is scalable and can be readily adapted to any size vehicle.



Figure 3: Mini ODY-ERA (mOE), custom-made 1:3 scale autonomous vehicle.

As a matter of fact, we naturally find that if a certain version of the code works satisfactorily with mOE, we end up with better, more precise results when we scale up to run the full-size ODY-ERA vehicle. This is due to the fact that the GPS uncertainty is the same whether you are operating on a (1:3 scale) 5ft wide lane or a (full scale) 15ft wide lane.

MECHANICAL EVALUATIONS

Prior to installing any of the systems for autonomous operation to the Mercury Mariner SUV, vehicle testing was conducted in large vacant paved and unpaved areas, such as parking lots and farms, with level and inclined terrain. Extensive data was gathered by using accelerometers, where the performance envelope of the vehicle was determined in terms of throttle, braking, and cornering response for speeds of up to 30 mph. Data was also collected on wheel position with respect to distance traveled while going straight and at several different steering angles. It was then reduced into tabular form and closed-form equations for more efficient programming. This information was later used for calibration and to define competitive, but safe limits of autonomous vehicle operation. As an example, maximum vehicle speed was defined with respect to steering angle for various conditions, as shown in Figure 4. A threshold limit curve is

defined for smooth and level paved road, as shown, which will never be exceeded – even though it includes a generous factor of safety.

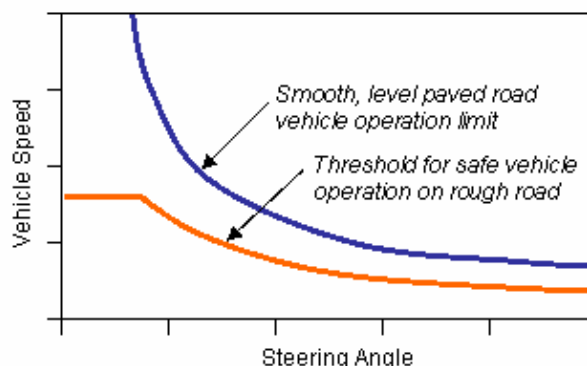


Figure 4: Speed-versus-steering performance envelope.

Similar curves were defined for increasingly worse conditions and have also been included in the algorithms for further de-rating (limiting) allowable combinations of vehicle speeds/steering angles. This performance envelope of the vehicle is used extensively in combination with routing algorithms for predicting the target speed of the vehicle throughout a mission.

ROUTING ALGORITHMS

Determination of the most optimum route within the RNDF for any given mission is accomplished by a specially developed variation of Dijkstra's Algorithm [1] with additional considerations embedded. All potential routes are considered between two checkpoints, and then weighted penalty-functions are used to calculate the quickest route. Distinct penalty-functions are assigned for crossing 4-way-stop intersections, merging into thru traffic, speed limits, turns at intersections, etc. By considering all these factors in the routing calculations, oftentimes the shortest route is not the quickest. Once a roadblock is encountered, the blocked section can be avoided from either side for the remainder of a mission.

A typical urban route that is about 10 miles long is calculated in a fraction of a second, along with creating a Dead Reckoning database that includes heading and true position at 1ft intervals with target vehicle speed, target steering angle, and elapsed time (ET) at each interval. The Dead Reckoning predictions are based on vehicle calibration, performance envelope, calculated road curvature, and penalty functions – assuming smooth and level paved road. This information is available in real-time and is used in conjunction with the vision system. The vision system, which is also supplemented by other sensors when applicable, considers the target speeds