Team *ODY-ERA*

DARPA Urban Challenge

June 1, 2007

ODY-ERA: An Autonomous Urban Navigation System

www.geocities.com/odyera2007

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EXECUTIVE SUMMARY

"The best machine is the simplest one that works" – Albert Einstein

Team ODY-ERA presents a simple but effective method for realizing an unmanned, autonomous motor vehicle. We discuss its unique features and characteristics, and how they support the objectives of the DARPA Urban Challenge. Then we present our high-level architectural framework that allows for a robust and reliable design and implementation of the ODY-ERA vehicle, which operates safely and effectively in a city environment, in accordance with DARPA Urban Challenge rules.

We also present a description of our new approach to autonomous vehicle operation utilizing "Dottie", a machine vision system we have invented, which is highly sensitive and reliably determines the road to be traveled, centers the vehicle in the travel lane, identifies and avoids obstacles, and establishes right-of-way by analyzing traffic situations. This highly mathematical revolutionary approach will pave the future to vision sensing in mobile robotics. The focus of **Dottie** is on identifying and tracking clusters of points (or "dots") in the field of view, rather than on trying to identify the object itself. One of the key benefits that accrue from the "dot" technique is the significant reduction of the data storage and processing requirements by eliminating the need for pattern recognition. Another important aspect of **Dottie** is that it is a *passive* sensing system that does not emit electromagnetic signals, which are typically undesirable in a military environment. In addition, we claim that **Dottie** will replace the current sensing technologies and therefore simplify the overall operation of future autonomous vehicles.

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1. Abbreviations and Definitions

Ariadne	Team ODY-ERA's position-based, precision Ded Reckoning system.
Dottie	A novel machine vision system invented and developed by Team ODY-ERA for use in the Urban Challenge and other future applications.
CVT	Continuously Variable Transmission
GPS	Global Positioning System
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	**ODY**sseus-**ERA**tosthenes — An epic combination of elegant and efficient mechanical, navigational, numerical, and algorithmic concepts, implemented in the creation of an autonomous ground vehicle that is expected to be a worthy contender toward winning the Urban Challenge.
RC	Remote Control
RGB	Red-Green-Blue (space)
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

2. Introduction and Overview

Figure 1: *The 2007 Mercury Mariner Hybrid 4WD, ODY-ERA autonomous vehicle.*

After careful deliberation, our team has selected a vehicle platform that is most suitable for the Urban Challenge 2007 competition – a new 2007 Mercury Mariner Hybrid 4WD SUV (shown in Figure 1). Almost two years before the Urban Challenge was announced, one of the team ODY-ERA founders had proposed this type of vehicle for use in the previous Grand Challenge. Although the difficulty associated with this latest Challenge is at least an order of magnitude greater than the previous one, we feel that our choice of vehicle platform is best suited for the task. 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 computers 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.

While we have total understanding that the computers and software are of utmost importance in the development of this project, where we have painstakingly applied our comprehensive solutions, we first ensured that nothing is overlooked in the preparation of the mechanical aspects. 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 to be 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 most major 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 are 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. 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 – the same kind of controller that is used for steering control on the Mercury Mariner SUV. Commands for vehicle

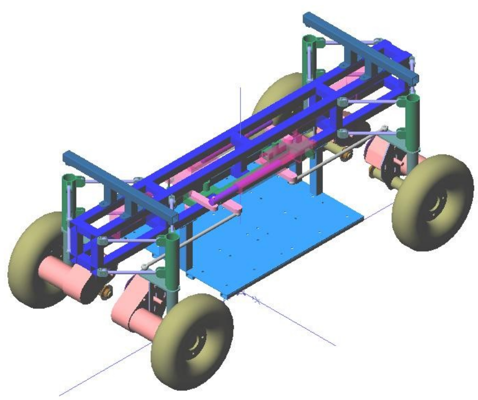

Figure 2: *CAD model of mini Ody-Era (mOE), a 1:3 scale autonomous vehicle.*

Figure 3: *mini Ody-Era (mOE), custom-made 1:3 scale autonomous vehicle.*

speed and steering are communicated to the RoboteQ via RS232 from a WindowsXP-based laptop PC. The autonomous software code processes RNDF 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 scaleable and can be readily adapted to any size 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.

3. Analysis and Design

3.1 Preparation for Creating ODY-ERA

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 30mph. 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

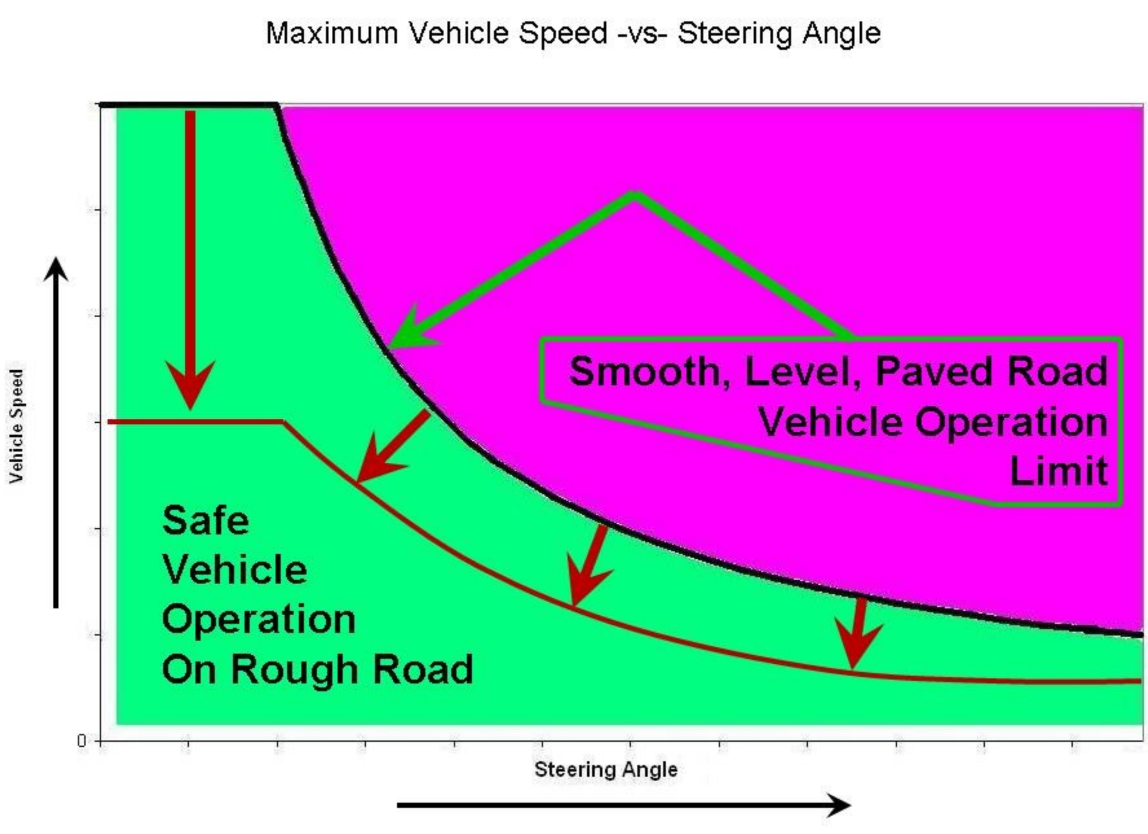

Figure 4: *ODY-ERA Speed -vs- Steering Angle Performance Envelope.*

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

3.2 Routing Calculation

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, 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 just a few seconds, along with creating a Ded 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. Distance calculations are made more efficiently by using the Haversine formula [2]. The Ded 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 to the vision system. The vision system, which is also supplemented by other sensors when applicable, considers the target speeds as its speed limits and de-rates them as necessary based on conditions. Sometimes, when vision does not adequately detect road roughness, input from the accelerometers at the un-sprung portion of the suspension in the proximity of the front wheels is used to further de-rate vehicle speed. A similar way of de-rating speed and modifying steering angle is done when other supplemental sensors provide conflicting information, based on a decision matrix that utilizes and solves such Sorites-style arguments [3]. Known deviations from the initial predictions are continually used to update the Ded Reckoning database.

When an unexpected roadblock is encountered, ODY-ERA executes a 3-point (180° CCW) turn, while the route to the remaining checkpoints is recalculated, and the Ded Reckoning database is updated. The typical 3-point turn takes less than a minute to execute. During this time, all of the re-routing calculations have been made and there is no need for further delay.

The low budget of team ODY-ERA and depleted personal "piggy banks" has forced the team to innovate and come up with straight-forward, simple and inexpensive solutions. Instead of an unaffordable high-end IMU, we have developed "Ariadne"; a low-cost, precision Ded Reckoning system. By not being able to afford 3D LMS and long-range radar, we opted to invent and develop a more effective solution of machine vision (Dottie), which is extremely accurate and can be readily implemented for the most part with low-cost USB webcams.

3.3 Ody-Era Autonomous System Architecture

The ODY-ERA mechatronic system was designed to be powered by the vehicle's existing electrical configuration. The main objectives of the design were safety (E-stop conformance, easy transition from autonomous to manual control of driving), low power consumption and 12Vdc power source. Figure 5 shows a block diagram of the ODY-ERA architecture. The system design is fail-safe and guarantees that E-stop will always bring the vehicle to a controlled stop –even if the ODY-ERA computer stops functioning, or if power is lost. The "Pause" function is implemented via the computer and software. Furthermore, the team-supplied E-stop receiver constantly queries the transmitter for a coded signal and if the vehicle is out of range, power to the throttle and brake controllers is interrupted, which results in clutch disengagement at the actuators and fail-safe mechanical application of the brakes to promptly halt the vehicle. The system allows for a quick and easy (on-demand) switchover from autonomous to manual control without necessitating hardware changeovers. During all autonomous testing, a person sitting in the driver's seat of the SUV can immediately take over control of the vehicle should the circumstances warrant it. In order to obviate the need for an auxiliary power system, ODY-ERA components have been selected so that the overall power consumption is minimized.

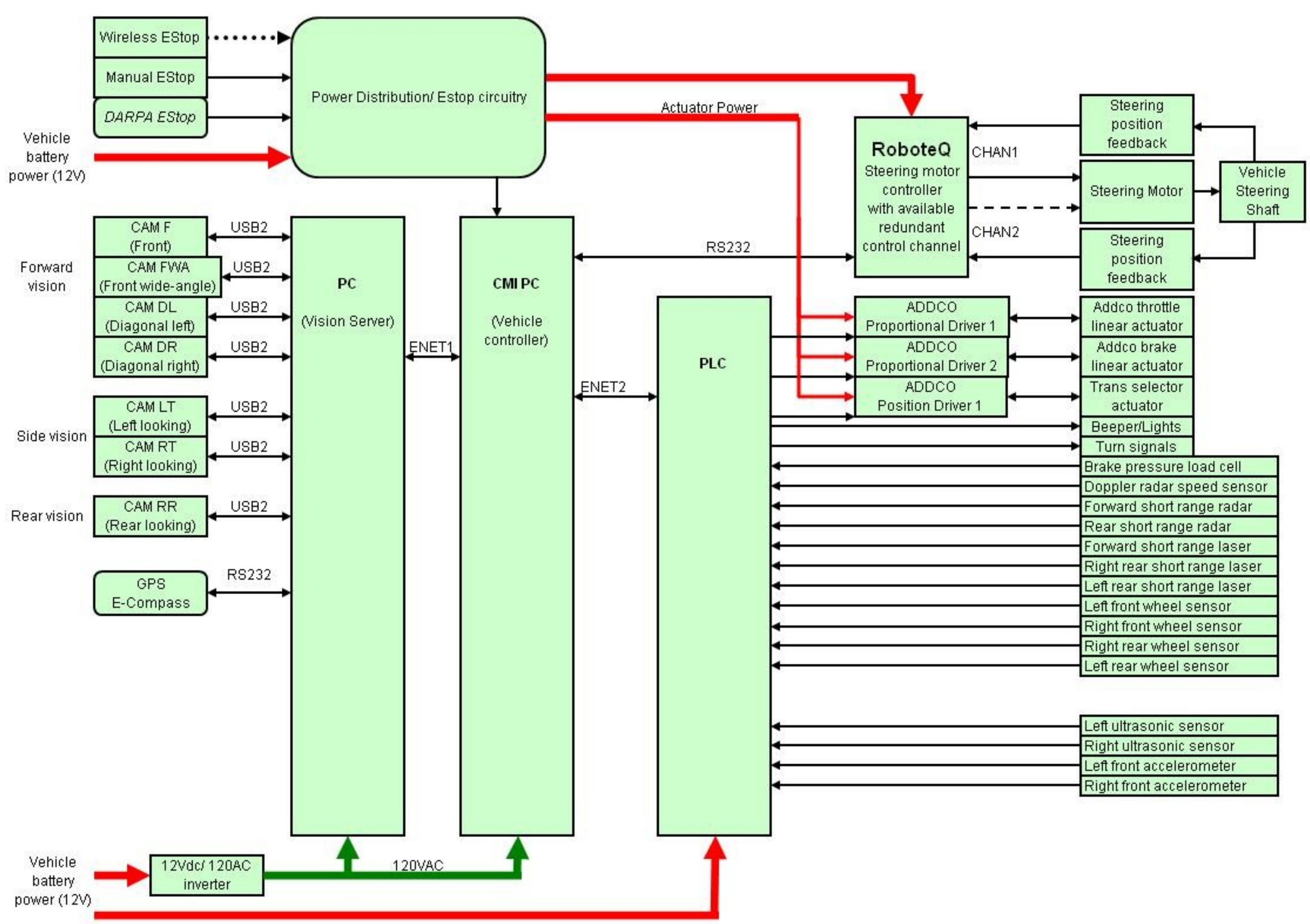

***Figure 5:** ODY-ERA Block Diagram of Autonomous System Architecture.*

4. Innovative Machine Vision

4.1 Introduction to Ody-Era Vision

A highly unique vision system has been developed as the primary sensor system for autonomous navigation, as will be described in this section.

From the military perspective, electromagnetic emissions from a vehicle should be avoided as far as possible, due to risk of vehicle detection in a hostile environment. This fundamental fact played a major role in determining that passive vision sensing should be the primary sensor system configuration for the Ody-Era vehicle.

Before going into any more details of the vision system, it should be noted that the current vision system can readily be adapted to the use of infrared imaging cameras. The algorithms used for vision processing are sufficiently generalized to make this transition with minimal changes. More details on these algorithms are provided later in this section.

The vision system for the Ody-Era vehicle consists of a suite of video cameras, mounted as sketched in Figure 6. Basically, this consists of two forward looking cameras, one of which has a "fish-eye" lens to capture a very wide field of view. Two additional forward-looking cameras are present, which are offset from the straight-ahead position by 50 degrees to the left and right. In the central section of the vehicle, two additional cameras are oriented about 110 degrees to the straight-ahead position. Lastly, a video camera with a fish-eye lens is pointed directly behind to enable rear vision capability.

These seven cameras enable the Ody-Era vehicle to have an almost 360 degree sweep of visibility, with only a few small blind spots. Each camera has a field of view of 50 degrees with the exception of the cameras with the fish-eye lens which is capable of a 150 degree field of view.

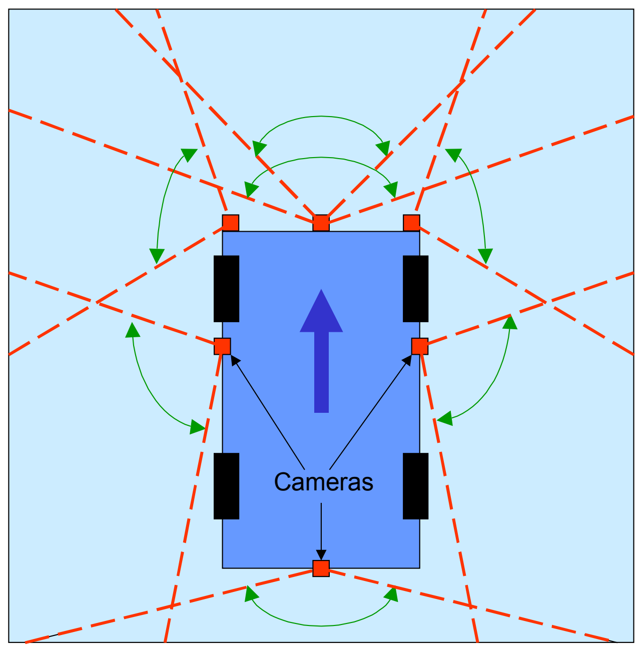

Figure 6: *Schematic showing the layout of cameras with overlapping field-of-views to ensure vision coverage around most of the vehicle. The location at the front center of the vehicle consists of both a regular as well as a 'fish-eye' lens camera.*

All cameras operate at either at 640x480 or at 320x240 resolution. The input consists of three color values for each pixel, one for each of the primary colors, in the 0 to 255 range for each color. This gives rise to a total number of color combinations of over 16 million (255 x 255 x

255) unique individual colors for each pixel. The total number of pixels per frame is either around 300,000 for the 640x480 video image or around 76,000 for the 320x240 image. This information is updated between 10 and 24 times per second from each camera. As can be seen from the above data, with all seven cameras simultaneously operating, the amount of information streaming into the vision processing unit is enormous.

4.2 Vision System Algorithms

The data streaming in real-time from the various on-board video-cameras is processed using sophisticated algorithms to interpret, analyze and control the vehicle. These algorithms form the core of the vision system and will be briefly described in the following paragraphs.

One of the fundamental differences between the Ody-Era vision system and other systems available today is that in the Ody-Era system, the emphasis is on determining the mathematical characteristics of the detected object, rather than its physical attributes. For example, the Ody-Era vision system does not care if the object blocking the road ahead is a traffic cone or a tank. All it cares about is the extent of the obstacle, its position relative to the Ody-Era vehicle and its velocity vector.

From the algorithm perspective, there is considerable advantage to be gained from this approach. Limited processing resources can be utilized much more optimally. A greatly simplified algorithm structure is another advantage, along with the inherent increase in reliability due to simplification of the overall system complexity.

It should be noted that the above approach has been successfully employed in the Ody-Era vehicle, as has been realized in the video demonstration submitted by the team.

The governing algorithms of the vision system are highly mathematical in nature. The fundamental basis of these algorithms is the existence of an imaginary field in front of the vehicle, which is disturbed by the presence of obstacles. For the purpose of basic visualization, this can be compared to an electromagnetic or gravitational field, but this simplification should not be generalized as there are significant differences.

This field simultaneously exists in two spaces, with a one-to-one translation between individual locations in these two spaces. The first space in which this field operates is that of the images generated by the individual video cameras and defined by the axes U and V. This is shown in Figure 7.

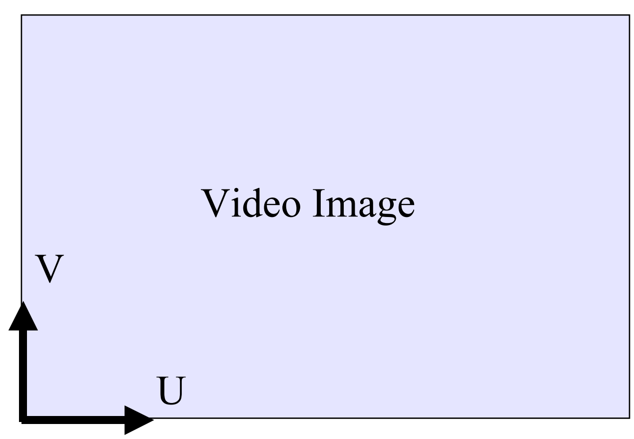

Figure 7: *Coordinate axes defining the space in which a 'field' is generated.*

The second space is the physical space in which the vehicle operates. This is illustrated in Figure 8. Note the use of the Eulerian coordinate system, wherein the coordinate system origin is attached to the vehicle.

Based on Figures 7 and 8, the field equations can be written as:

$$F_a = F_a(u, v, t) \quad (1)$$

and

$$F_b = F_b(x, y, z, t) \quad (2)$$

Where u, v are coordinates in the image frame, as shown in Figure 2, while x, y, z are coordinates in the vehicle reference frame shown in Figure 3. In both equations, 't' corresponds to time.

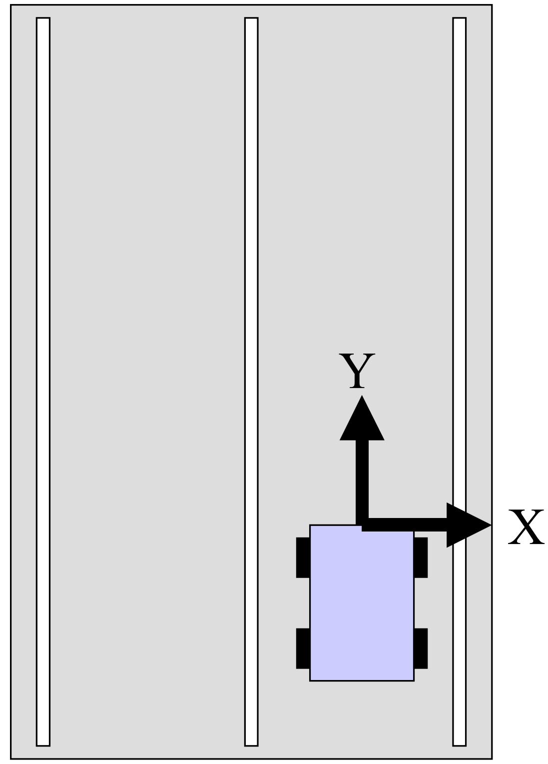

Figure 8: *Coordinate axes defining the physical space around the autonomous vehicle. The Z axis is out of the plane of the figure.*

The one-to-one mapping between the u-v and the x-y-z spaces can be represented by the matrix equation:

$$\mathbf{X} = \mathbf{M} * \mathbf{U} \quad (3)$$

where **X** and **U** are vectors consisting of components (x, y, z) and (u, v) respectively, and **M** is a transformation matrix. More information on the mathematical aspects of this section is available in references [6] and [7].

In the total absence of any obstacles or objects in the field of view, the field F_a assumes a constant value everywhere. However, the presence of objects distorts this field in the same manner as an electric charge distorts an electric field.

In the first step of the computations, the field F_a is determined utilizing detailed pixel color information as mapped in Red-Green-Blue (RGB) space. This three-dimensional RGB space conveniently permits the utilization of vector calculus in determining the time-dependent field F_a.

Once F_a is determined, potential obstacles are identified by the spatial gradients produced by their presence in the field. Mathematically, one can determine quantities dF_a/du and dF_a/dv, giving rise to the gradient vector:

$$\mathbf{F_a} = (dF_a/du)\mathbf{i} + (dF_a/dv)\mathbf{j} \quad (4)$$

High gradients correspond to potential obstacles when certain other conditions are satisfied, which are then marked in u-v space by means of 'dots', which are essentially dimensionless entities. These dots are then transferred to x-y-z space by means of the transformation matrix **M**, as described in Equation (3).

The results of the above transformation provide a spatial distribution of obstacles around the vehicle. This distribution is refreshed between 10 and 24 times per second, providing the autonomous navigation system with an extensive real-time situational awareness.

As can be inferred from the description, there are two key challenges in the above approach. The first of these is the derivation of the spatial field F_a and the second is the computation of the transformation matrix **M**. Due to the intensive technical nature of these two derivations, the detailed mathematical descriptions of these derivations far exceed the allowed length of this technical paper. It is currently intended that these derivations to be disclosed in technical papers at a later date.

4.3 Implementation of the Vision Algorithms

The algorithms described in the earlier section have been implemented and tested on various scales. A 1:48 scale model of a mock intersection was created which utilizes scale vehicles for added realism for testing the vision system (Figure 9). Note the presence of the 'vehicle' with a camera. In addition, a 1:3 scale prototype was fabricated and tests conducted with full autonomous navigation capabilities (Figure 3). A full scale vehicle has also been extensively tested in autonomous operation, as seen in the video demonstration that was submitted in April 2007 (Figure 1). All three scales of operation utilize exactly the same algorithms in the software so as to enable translation of results from tests conducted at one scale to another. Interestingly, the same camera has been utilized at all three scaling configurations, including the 1:48 configuration (camera visible in the lower center of Figure 9, identical to the one seen on the hood of the Ody-Era vehicle in Figure 1).

Figure 9: *The 1:48 scale model of an intersection being utilized for algorithm verification purposes.*

The algorithms as described in the previous section can now be illustrated using the 1:3 scaled prototype.

Figure 10 shows a frame extracted from the video input of the prototype vehicle, representing a typical 'roadway' encountered by the vision system during testing. Note that this roadway does not have any lane markings, thereby making it much harder to analyze than one that has clear lane markings.

The information contained in this frame is analyzed by the vision algorithms to construct the field defined by Equation (1). Spatial gradients of this field are then computed as defined by Equation (4). This is further processed to provide a set of 'dots' indicating limits of the roadway, as well as detecting any potential obstacles. Figure 11 shows the output from this stage of processing.

Figure 10: *Frame extracted from the video camera output for the 1:3 scale prototype, prior to any image processing.*

The 'dots' shown in Figure 11 are projected utilizing Equation (3) for determining the extent of the roadway ahead of the vehicle. This is shown in Figure 12. Depth perception is obtained to a distance of 50 feet in this case, which corresponds to a distance of 150 feet in an actual full-scale vehicle (moving objects have been detected at greater ranges utilizing time derivatives of the field F_a).

Figure 11: *'Dots' created by computing field gradients, as in Equation (4), followed by further processing to define the limits of the roadway.*

The resulting information provides a valuable map of obstacles in the immediate vicinity of the vehicle, based on which a desired trajectory (with corresponding desired velocities) is computed, which is then translated into steering and throttle/brake commands. The above process can be repeated as many as 10-24 times per second, enabling close tracking of other moving objects in the vicinity of the autonomous vehicle.

Figure 12: *Projection of 'dots' utilizing Equation (3) to obtain spatial depth perception.*

The system is capable of reliably detecting obstacles as small as a tennis ball at close range. It has been tested with various obstacles on the roadway utilizing the 1:3 scale prototype vehicle, including traffic cones, other vehicles, barricades, etc. With additional processing utilizing the time dependency of Equation (1), it is even possible to determine approximately the velocities of other moving vehicles. This capability is utilized at intersections, such as a four-way stop, to determine priority of passage through the intersection.

However, this system can, on rare occasions, produce false positive results, i.e., the system detects an object that that should really be of minor or no concern. In such cases, alternative sensor systems on board, such as the short-range radar or ultrasound sensors, can enable rapid clarification of the nature of the obstacle. It should be noted that the opposite case (not detecting objects of concern) has not occurred so far in all the extensive testing that has been conducted.

4.4 Vision System Summary

It should be noted that although the associated theory may appear abstract, it has been successfully implemented in a full-size vehicle, which met all the requirements of the video demonstration. As can be seen in that video, the vision algorithms described in this section provide very smooth and robust control of the vehicle.

Another very interesting aspect of this vision system is that since most of the expertise resides in the software, which essentially encapsulates algorithms that are not only highly mathematical but also highly efficient, the hardware cost is greatly minimized. For example, the demonstration in the video utilized hardware (including the video cameras, single controlling laptop, servo-controls, etc.) of less than $7000. In fact, some of the successful full-scale vehicle tests were conducted using only $50 web cams as the only image input devices at a 320 x 240 resolution.

Another advantage of the vision system is the scalability aspect, as demonstrated by the utilization of the entire system on a 1:48 scale, then on a 1:3 scale prototype, followed by the use on a full-scale vehicle. Almost no modifications were required other than changes to a few obvious parametric variables in order to obtain full functionality irrespective of scale. The utilization of the identical system on a 1:3 scale prototype as well as a full-sized vehicle clearly demonstrates the potential of this vision system in terms of transferability between vehicles of different sizes with minimal modifications.

In summary, the low-cost, high-degree of adaptability and scalability as well as the inherent robustness of the unique algorithms that constitute the vision system makes this a highly promising system for autonomous vehicles. The emphasis on passive sensing and minimal vehicle profile disruptions by sensing hardware also makes this system ideal for autonomous military vehicles.

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Acknowledgements

The authors would like to acknowledge the other ODY-ERA team members, all of whom have worked diligently and tirelessly to keep ODY-ERA competitive in the DARPA Urban Challenge. They are, alphabetically:

Mac Gray, Stavros Kritikos, Dennis Miller, Rob Siegfred, Mark Swain, and Ronald Webster.