VISTA – Vehicles with Intelligent Systems for Transport Automation

Final Report 473(b)

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16. Abstract –

This project report documents the work performed on the *Research Program on Vehicles with Intelligent Systems for Transport Automation (VISTA).* This effort, to develop and demonstrate a control architecture for Intelligent Vehicles that is deployable within the next 5 to 10 years, was funded by the Arizona State Legislature and administered by the Arizona Department of Transportation (ADOT). In particular, the research team investigated the following "new" concepts as far as AHS and Intelligent Vehicles are concerned:

1. The use of a hierarchical control structure that requires less frequent, and less spatially dense, communication between the traffic operations center and the vehicles, and requires less computational effort for lateral and longitudinal control of the vehicle on the highway; and
2. The use of cheaper sensor technology for establishing vehicle position and implementing feedback control.

It was concluded from this project that the technology is ready for affordable intelligent autonomous vehicles. The control of those vehicles is robust and reliable, and requires minimal and affordable additional highway infrastructure. It is anticipated that using intelligent vehicles would increase air quality and decrease energy consumption. Potential legal issues would be major obstacles to the public use of such vehicles. However, the technology developed in this project may be utilized in many specialized applications or restricted environments.

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VEHICLES WITH INTELLIGENT SYSTEMS FOR TRANSPORT AUTOMATION

FINAL REPORT

Submitted to the

Arizona Department of Transportation

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Research Program on Vehicles with Intelligent Systems for Transport Automation (VISTA)

EXECUTIVE SUMMARY

This report documents the work performed on the project *Research Program on Vehicles with Intelligent Systems for Transport Automation* (VISTA). This effort, to develop and demonstrate a control architecture for Intelligent Vehicles that is deployable within the next 5 to 10 years, was funded by the Arizona State Legislature and administered by the Arizona Department of Transportation (ADOT). Essentially, the scope of this VISTA Project was to:

1. Develop a Prototype Autonomous Vehicle - the VISTA Vehicle - which was done using a 1989 Chevrolet Celebrity during November 1998 – March 1999.

2. Demonstrate the VISTA Vehicle on State Route 51 in Phoenix - which was performed on April 27-28, 1999.

3. Conduct further research of the VISTA Vehicle – which was performed from May 1999 to June 2000.

The project's research team demonstrated proofs of concept for the following three new technologies for automated vehicle driving:

- Calibration-based Vehicle Control: Traditionally, vehicle control is achieved through continuous guidance provided by markers or sensors distributed densely along a highway (e.g., magnet nails every meter). In calibration-based vehicle control, in-vehicle sensors are used to guide a vehicle and those sensors are calibrated periodically through calibration bases sparsely distributed along the highway (e.g., barcodes every few miles). This method could reduce significantly the cost of constructing and maintaining sensors on the roadway.

- Long-Range Vehicle Trajectory Planning and Optimization: Guidance-based control provides only short-range road information to vehicles. Using calibration-based vehicle control, we can preview long-range road curvature and other information at calibration bases, and therefore will be able to plan and optimize vehicle trajectory for a long distance. This will not only increase the traffic throughput, driving safety and efficiency, but it could also reduce energy consumption and air pollution (by planning more efficient trajectories).

- Distributed Hierarchical Agent Programming Control: Instead of the traditional functional decomposition into sensing, planning and executing, vehicle control systems are decomposed into hierarchically organized special-purpose task-achieving modules, called agent programs. Fuzzy logic-based driving agent programs (from human driving behaviors) are used for many modules. This method makes vehicle control systems demand less computation power, easy to design, and more efficient and reliable.

It was concluded from this project that the technology is ready for affordable intelligent autonomous vehicles. The control of those vehicles is robust and reliable, and requires minimal and affordable additional highway infrastructure. It is anticipated that using intelligent vehicles would increase air quality and decrease energy consumption. Potential legal issues would be major obstacles to the public use of such vehicles. However, the technology developed in this project could be utilized in many specialized applications or restricted environments.

This VISTA research program complements the University of Arizona's recent project *Systems Analysis of Tucson-Phoenix Intelligent Lanes,* which is Project H in the ATLAS (Advanced Traffic and Logistics Algorithms and Systems) Program. That research was sponsored by the University and the U.S. Department of Transportation through ADOT.

PREFACE

The Vehicles with Intelligent Systems for Transport Automation (VISTA) project was directed by three principal investigators: Professors Fei-Yue Wang and Pitu Mirchandani of the ATLAS Center and the Systems and Industrial Engineering Department at the University of Arizona, and Professor C. Y. Kuo of the Mechanical and Aerospace Engineering Department of Arizona State University.

The VISTA Project was funded by the Arizona State Legislature and was administered by the Arizona Department of Transportation. The authors wish to acknowledge the very significant input provided by Mr. Dave W. Bruggeman, Director of Traffic Engineering and ITS Design of BRW Inc.

In addition, sixteen student research assistants, including eleven graduate students, two undergraduate students, and three visiting scholars were supported by the project and/or had contributed to the project. The graduate students were Yuetong Lin, Yijia Xu, Pingzhong Li, Sundar Kuppuswamy, Wenji Liu, Yanqing Gao, Darko Babic, Long Wu, Jeff Neibauer, Robert Dunn, and Ziyu Huang, the undergraduate students are Christopher Yeo and Michael Do, and the visiting scholars are Nan Tan, Wenji Liu, and Quihe Qin.

Last, but not least, the authors appreciate the inputs of the VISTA / ATLAS Technical Advisory Committee: Alan Hansen, Federal Highway Administration, Phoenix, Arizona; Tim Wolfe, ADOT Technology Group; Joe O'Neill, ADOT Equipment Services; David Hunt, ADOT TTG/CVO Projects; John Harper, ADOT Flagstaff Maintenance District; Perry Powell, ADOT Phoenix Construction District; and Matt Burdick, of the ADOT Community Relations Office.

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Arizona Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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Given the continuously increasing traffic congestion on the national highways, one approach to mitigate the delays and safety problems associated with this congestion is the introduction of Intelligent Vehicles and Automated Highway Systems (AHS). Over the last few years, the United States Department of Transportation (USDOT) has expended significant resources and effort into feasibility studies of AHS, and the development of concepts, architecture, and technologies for AHS. Specifically, the USDOT conducted a feasibility study, and the National Automated Highway System Consortium (NAHSC) was formed to refine promising concepts and move toward deployment. The consortium consisted of public agencies including FHWA, California DOT, and others, and private companies such as General Motors, Motorola, and Hughes.

In August 1997, the NAHSC presented its first public demonstration of AHS in San Diego, California. This proof of technical feasibility demonstration was requested by the United States Congress in the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) legislation, which read in part:

> "*The Secretary of Transportation shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed ... The goal of this program is to have the first fully automated roadway or an automated test track in operation by 1997.*"

It has been realized that a one-step deployment of AHS is both impractical and extremely expensive. Thus, the emphasis has shifted to the development of technologies that can be incrementally introduced and tested which would be beneficial now, but fully beneficial when a complete AHS is employed, where platoons of vehicles will travel from point to point at very high speeds with little or no interactions with the drivers (unless they are getting on or off the AHS). An example of such a technology is Adaptive Cruise Control (ACC). This allows a vehicle to follow another vehicle with a very short headway, where the following vehicle will automatically accelerate or slow down when the leading vehicle does so. In the United States, ACC is being developed as an option in high-end cars; it is already available as an option in some cars in Japan and Europe.

Another incremental deployment technology is the "Intelligent Vehicle," or IV. The idea here is to put as much intelligence in the car as possible so that it is semi-autonomous, requiring very little instruction or interaction from the driver of the vehicle. At a minimum, an intelligent vehicle will need ACC, a mechanism to sense its position, and a mechanism that provides feedback for control after the position has been validated. There are two major university research programs for the study, research and development of AHS and Intelligent Vehicles. One is at Carnegie Mellon University (CMU), where the Intelligent Vehicle uses machine vision to sense its position with respect to marked lines on the pavement. The other is at the PATH Center at the University of California at Berkeley. The PATH vehicle (Partners for Advanced Transit and Highways) uses feedback from magnetic lane markers to sense the vehicle's position with respect to the AHS lane being used.

The most costly aspect in the deployment of AHS is the infrastructure. Protected lanes need to be constructed, mechanisms for entering and exiting the lanes (at a few points) need to be implemented, communication/electronic equipment must be installed for continuous monitoring of the vehicles in the lanes and, if required, for mechanizing the strategies for coordinating the control of the vehicles.

Fortunately for Arizona, there is a "window of opportunity" where planned infrastructure expenditures may be used, with some additional funding from USDOT, the Arizona Department of Transportation (ADOT), and private entities, to construct "Intelligent Lanes" between Phoenix and Tucson. Considering the traffic forecasts into year 2020, ADOT has identified the need for a third lane of Interstate 10 between the two cities by the year 2005, and a fourth lane by the year 2020 [1]. Thus, whether or not intelligent vehicles are deployed, it is extremely likely that ADOT will have planned expenditures to build one or two more additional lanes between Phoenix and Tucson.

When construction of additional lanes is considered, it has been shown by the VISTA research team [2] that deployment of intelligent vehicles is both feasible and beneficial if communications and electronics infrastructure can be included in this construction with minimal additional cost. In fact, the 1997 study by BRW proposes a six-phase, three-track approach that addresses both the need to increase capacity of the Phoenix-Tucson corridor and the development and deployment of intelligent vehicles if deemed necessary. Track 1 is aimed at providing incentives for drivers to use equipment that will enable intelligent vehicle operations (e.g., ACC); Track 2 involves the installation of communication/electronics infrastructure to communicate with the intelligent vehicles (e.g., monitoring of individual cars in the intelligent lanes); and Track 3 is to integrate the intelligent vehicle with the intelligent infrastructure and to operationalize the AHS.

BRW proposes a phased approach to the implementation, with full operational testing of developed intelligent vehicles, technologies and products taking place by the year 2009, and having exclusive lanes for intelligent vehicles by the year 2020 (in anticipation that a large number of them will be operating by then). The reader is referred to the BRW study for a proposed implementation schedule and plan.

Although BRW discusses various options for the technologies that may be used for the Phoenix-Tucson corridor, it does not recommend any specific technology that will be most suitable for this purpose. In fact, the three major issues in the choice of the technology are that:

- "Intelligence" in the vehicle must be affordable by a large segment of the population.
- The infrastructure should be initially usable by conventional vehicles.
- The additional agency (USDOT / ADOT) cost for equipping the infrastructure must not be so prohibitive, that the intelligent vehicles are not cost-effective.

These considerations led the VISTA research team (Vehicles with Intelligent Systems for Transport Automation) to investigate new technologies and concepts that can address the above issues. In particular, the research team investigated the following "new" concepts as far as AHS and Intelligent Vehicles are concerned:

1. The use of a hierarchical control structure that requires less frequent, and less spatially dense, communication between the traffic operations center (TOC) and the vehicles, and requires less computational effort for lateral and longitudinal control of the vehicle on the highway; and

2. The use of cheaper sensor technology for establishing vehicle position and implementing feedback control.

II. THE PROJECT OBJECTIVES

In 1998, based on the above background, the Arizona Department of Transportation established a research program in Intelligent Vehicles and Automated Highway Systems, which will be referred to in the sequel as the VISTA Program. This program was funded by an appropriation from the Arizona State Legislature. The principal investigators (PIs) of the VISTA Program were Professors Wang and Mirchandani from the University of Arizona (UA), and Professor Kuo from Arizona State University (ASU).

The VISTA Program was charged to:

- Conduct a preliminary analysis of alternatives for an intelligent vehicle corridor between Tucson and Phoenix.
- Develop one or more technologies for demonstration of the alternatives.
- Propose further design and development of a recommended alternative.
- Seek partnerships and collaborations for future research and projects.

To accomplish those goals, the following were identified for investigation:

1. **Demonstration Vehicle:** *VISTA*'s demonstration vehicle was to be equipped with advanced sensors and computer-based control systems. In addition, to execute the commands for longitudinal control, it was to have actuators for vehicle acceleration and deceleration. For lateral control, rotation of the steering wheel was to be handled by the on-board control computer.

2. **Fuzzy Control Technologies:** The performance of current longitudinal and lateral control technologies depends on the availability of accurate dynamic models of vehicles. However, it is well known that a universal dynamic model for automobiles is probably not feasible. Furthermore, due to the complex and time-varying nature of dynamic properties of an ordinary automobile, its control system must deal with a strongly nonlinear process in the presence of disturbances such as obstacles and ambiguous information coming from the sensors. It is well known that linear control theory lacks a proper paradigm for modeling such a complex system. This is especially true for the lateral control problem. Therefore,

innovative control methods that do not require an accurate model of vehicle dynamics and yet provide adequate or even optimal performance for different driving conditions were to be investigated. Realizing that a person can drive a vehicle with great skill but without knowing anything about the vehicle's analytical dynamic model, the research team's goal was to design a control system that can mimic a human driving agent (but must have faster response to changes in driving conditions).

For this purpose, the research team was to develop and test a fuzzy logic-based control design for both longitudinal and lateral controls. Over the last six years, the members of the research team have demonstrated successfully that rule-based fuzzy control methods, which can easily incorporate heuristics and human skills in control design, can be used to control complex systems without utilizing explicit models of system dynamics. For example, using fuzzy control, they have developed a control system for a heavy-duty wheel loader to autonomously dig in difficult mining environments. This system was built using fuzzy control rules that mimic actions taken by a skilled human operator in similar situations. Test results on a Caterpillar 980G Wheel Loader have been very successful, showing performances better than other control technologies tested. The same techniques were to be applied to automated vehicle driving (use of fuzzy logic to drive vehicles on well-defined lanes may be easier than for digging in unstructured and changing mining environments, since there is an abundance of human automobile driving experience).

3. **Hierarchical Control System:** Traditional control system designs for vehicle systems have been based on a framework of functional decomposition into “sensing,” “planning” and “executing” components. Such a framework normally demands a significant overhead in terms of computational effort, communication time, and decision-making capability. Within this framework, even a very simple task has to be processed through a full range of operational activities.

   An agent-based method, however, takes a different approach by decomposing a control problem into special-purpose task-achieving programs. Usually, these programs are coupled directly to sensory information and can be constructed using simple computations with minimal memory needs, and may be implemented with inexpensive and simple hardware. Such an approach has been studied extensively and applied successfully for mobile robotic control systems.

The research team's proposed vehicle control was to be based on a set of simple and specific task-achieving agent programs for sensing and actuation using fuzzy logic. Each agent program is described by a set of fuzzy decision rules and fuzzy linguistic variables. In this way, the process of converting human skills and experience for different driving conditions into microprocessor-based control algorithms is greatly facilitated.

Examples of specific agent programs include *line-follower, frontal-collision avoider, distance-follower*, etc. In order to achieve coherent vehicle operation, these agent programs must be integrated. To this end, the system control architecture for automated vehicle driving was to be constructed according to the hierarchical structure developed for intelligent machines [3] and robotic mining vehicles for lunar mining [4]. In this structure the agent programs are arranged in two hierarchical levels: *agent coordination* (for path planning), and *agent execution* (for trajectory control). This hierarchical structure is well suited for integrating sensory information acquisition with task control functions required of intelligent vehicles.

III. THE PROJECT RESULTS

To achieve the research goals outlined above, the following tasks had been proposed and completed in the VISTA Program:

Task 1: *Obtain and Enhance a Demonstration Vehicle*
Task 2: *Develop Longitudinal and Lateral Control Systems*
Task 3: *Demonstrate Intelligent Vehicle Concepts*
Task 4: *Compare and Evaluate Available Intelligent Vehicle Technologies*
Task 5: *Seek Partnerships for Research and Development Collaborations*

Task 1: Obtain and Enhance a Demonstration Vehicle

To emphasize the deployability of VISTA's intelligent vehicle and automated highway system concepts, a demonstration vehicle, herein called the VISTA Vehicle, was developed. It consisted of a 1989 Chevrolet Celebrity car leased to UA from ADOT's fleet, and equipped and modified as described below. The selection of this type of car was based on (1) the size of engine chamber - so that enough open space is available to accommodate various actuators and systems required for the modification, and (2) availability of interior space for both the control/computer hardware and 3 - 4 passengers.

Four major hardware modifications were made on the selected vehicle:

1. Some electronic circuit design and rewiring was done so that an on-board control computer can operate the adaptive cruise control system.
2. A servomotor was coupled to the steering mechanism so that a control system can steer the vehicle.
3. A servomotor was coupled to the throttle mechanism so that the control system can regulate the vehicle's acceleration.
4. An actuator was installed to control the braking action.

At the beginning of the project, the VISTA research team visited both the University of California (i.e., the PATH Project) and Carnegie Mellon University to investigate how these research groups modified their "off-the-shelf" cars to make them into intelligent vehicles. The pictures in Figures 1-5 show the VISTA vehicle, the layout of equipment that makes it "intelligent", and the hardware.

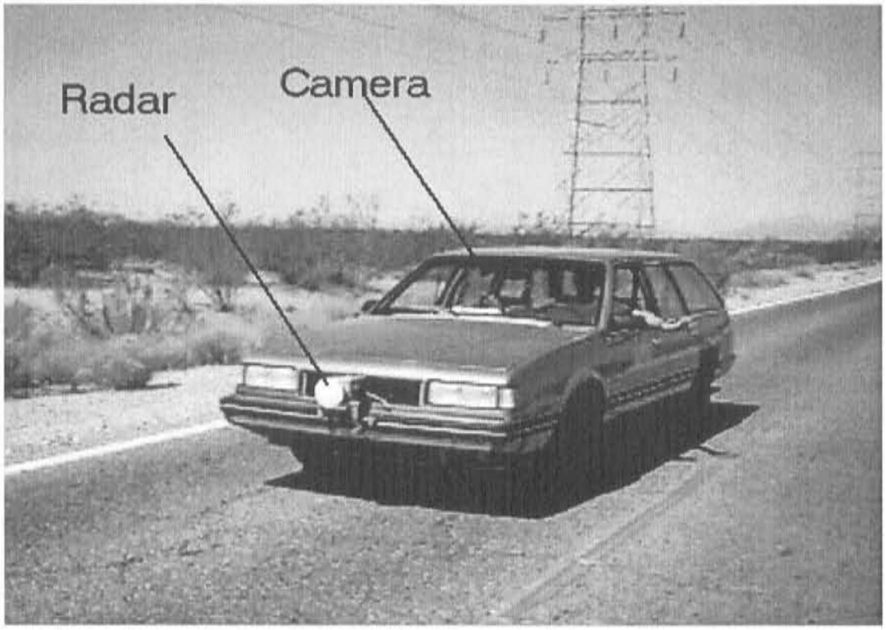

Figure 1: The VISTA Vehicle

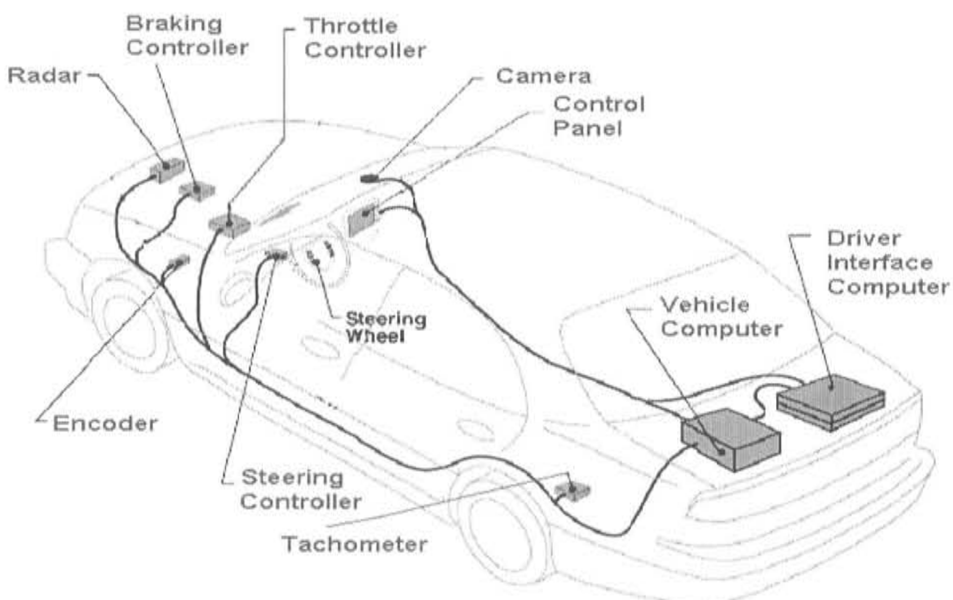

Figure 2: The VISTA Vehicle Hardware

Figure 3: The Camera and its Processor

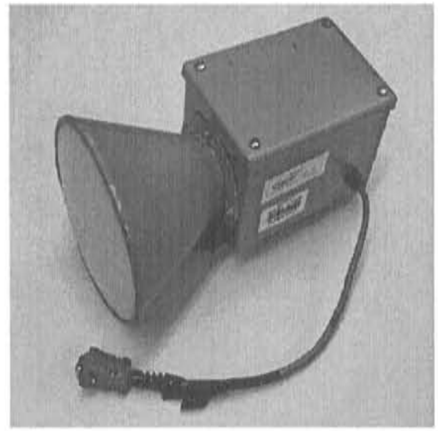

Figure 4: The Radar Sensor

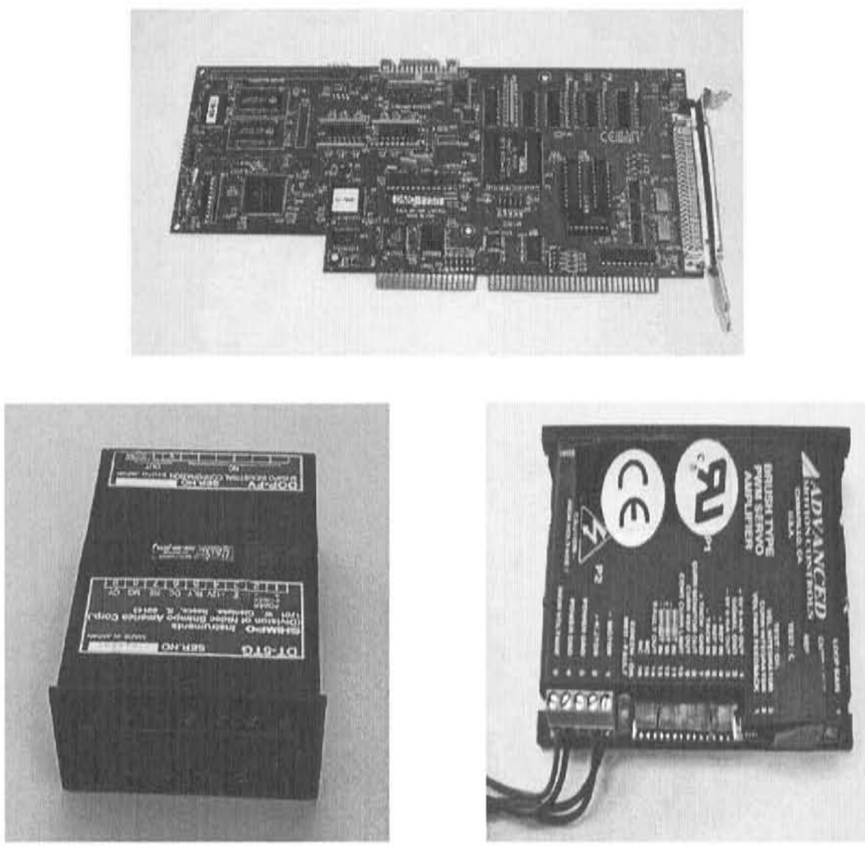

Figure 5: The Control Board, Amplifier, and Display

Task 2: Develop Longitudinal and Lateral Control Systems

The VISTA team used fuzzy control theory and the team's recent R&D results on fuzzy logic to develop and evaluate control programs for:

- long-range path planning,
- radar-based headway maintenance,
- radar-based road following; and,
- close vehicle following (platooning).

Each of the above control programs consisted of a set of fuzzy rules which organize basic longitudinal and lateral vehicle commands. Many of these fuzzy control rules were obtained directly from human driving behavior. Since fuzzy control rules use linguistic terms such as "if the distance between the two vehicle is little large, then increase the speed a little bit," the human driving skills and experiences can be easily converted into fuzzy control programs. At the first, a non-adaptive fuzzy technology was used. Later, the research team used a neuro-fuzzy method to add learning capability into the fuzzy control programs, to improve performance for specific vehicle and road conditions. Figure 6 shows the control structure of the VISTA Control System:

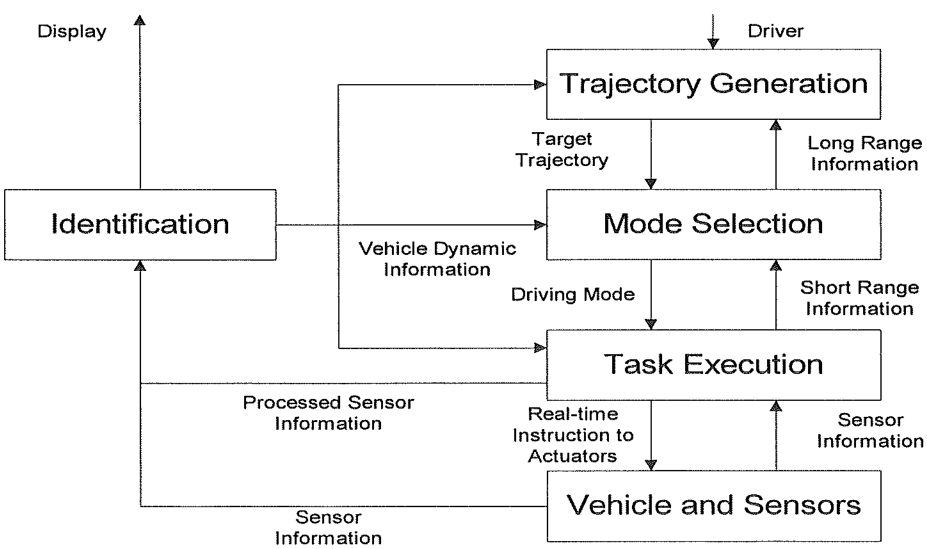

Figure 6: Hierarchical Structure of the VISTA Control System

Task 3: Demonstrate Intelligent Vehicle Concepts

On March 22, 1999, the VISTA team successfully demonstrated the longitudinal control of the VISTA vehicle to its Technical Advisory Committee at an Arizona State University parking lot in Tempe. Figure 7 shows the platooning function demonstration.

Figure 7: Demonstration of Longitudinal Control of VISTA Car at ASU [March, 1999]

On April 27-28,1999, the VISTA team successfully demonstrated the longitudinal and lateral controls of the VISTA vehicle to the public, the media and ADOT on the Squaw Peak Freeway (State Route 51) in Phoenix. Figures 8 and 9 show the demonstration.

Figure 8: Demonstration of Autonomous Control of VISTA Car on State Route 51 (April 27, 1999)

Figure 9: Demonstration of Autonomous Control of VISTA Car
on State Route 51 (April 27, 1999)

Task 4: Compare and Evaluate Available Intelligent Vehicle Technologies

Based on literature reviews, studies, field tests, and demonstrations of the various technologies for sensor and control technologies for intelligent vehicles, the research team concluded that the following new technologies and concepts have a high potential for successful implementation:

- Calibration-based Vehicle Control (used in the VISTA vehicle, instead of Guidance-based Vehicle Control used in PATH and CMU vehicles). This reduces cost of constructing and maintaining sensors on the road.

- Trajectory Planning and Optimization based on the long-range information on road geometry and geography. In addition to planned increase in traffic throughput, driving safety, and lower requirements on computation power, this could reduce energy consumption and air pollution (by planning more efficient trajectories).

- Distributed Hierarchical Agent-based Control, instead of the traditional functional decomposition into sensing, planning and executing. Vehicle control systems are decomposed into hierarchically organized special-purpose task-achieving modules, called *agent programs*. Fuzzy logic-based driving agent programs (from human driving behaviors) are used for many modules.

Task 5: Seek Partnerships for Research and Development Collaborations

Currently, members of the VISTA team are in the process of negotiating with the following two groups for the continuation of research and application of the new technologies and concepts developed in the VISTA project:

1. Intelligent Technology International, Inc., (ITI). ITI has proposed a new "Road to Zero Fatalities" Project to USDOT on the use of Differential Global Positioning Satellites and digital maps to warn vehicles before they leave a lane, thus making driving safer. The VISTA team is setting up a collaboration with them, and with other private and public sector partners, to develop the digital maps and to investigate the applicability of the VISTA architectures.

2. The First Automotive Work (FAW) of China. The VISTA team is seeking support from FAW for conducting a similar project in China.

Conclusions

From the VISTA project, we can conclude that the technology is ready for affordable intelligent autonomous vehicles that can be deployed in the next 5 to 10 years. The control system of those vehicles is robust and reliable, and it requires minimal and affordable additional highway infrastructure. It is also anticipated that using intelligent vehicles would increase air quality and decrease energy consumption. Potential legal issues would be major obstacles to the public use of such vehicles. However, the technology developed in this project could be utilized in many specialized applications or restricted environments.

IV. VISTA RESEARCH PROJECTS BY GRADUATE STUDENTS

Being a university-based program, one of the major goals of the VISTA program was to introduce research and teaching components related to *intelligent transportation systems* in the engineering curricula. A major success of the program was the energetic and enthusiastic participation by graduate students at UA and ASU. The following students and visiting scholars had been supported by and/or had contributed to the VISTA project:

1. Yuetong Lin
2. Yijia Xu
3. Pingzhong Li
4. Sundar Kuppuswamy
5. Nan Tan
6. Wenji Liu
7. Yanqing Gao
8. Darko Babic
9. Wenji Wu
10. Long Wu
11. Jeff Neibauer
12. Quihe Qin
13. Robert Dunn
14. Ziyu Huang
15. Christopher Yeo
16. Michael Do

Among them, the following six graduate students wrote their Master of Science thesis/project based on research related to the VISTA project:

1. **Ziyu Huang, Spring 1999.**
   Report Title: *Longitudinal Control of Intelligent Vehicle using Fuzzy Control and Genetic Algorithms*

2. **Pingzhong Li, Summer 1999.**
   Report Title: *Nonlinear Parameter Identification based on Gradient method and Genetic Algorithms and its Application to Intelligent Vehicles*

3. **Robert C. Dunn, Summer 1999.**
   Report Title: *Comparison of Guidance Methods for Vehicles with Intelligent Systems for Transport Automation (VISTA) Project*

4. **Jeff R Neibauer, Fall 1999.**
   Report Title: *Development of a High-Fidelity Six Degree-of-Freedom Simulation in Support of the VISTA Project*

5. **Long Wu, Fall 1999.**

   Report Title: *Supervised Learning of Longitudinal Driving Behavior for Intelligent Vehicles using Neuro-Fuzzy Networks: Initial Experimental Results*

(Note: A paper based on the above report has been published in the *International Journal of Intelligent Control and Systems*, Vol.3, No.4, pp.443-464, 1999.)

6. **Sundar Kuppuswamy, Summer 2000.**

   Report Title: *Analysis of Benefits, Costs, and Market for VISTA Vehicles*

The following student will complete his research report based his work in VISTA Project:

Yuetong Lin, Fall 2000.

Report Title: *Investigation of Implementing Adaptive Driving Systems for Intelligent Vehicles using Neuro-Fuzzy Networks*

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