Development And Test Results for a Vision-Based Approach to AVCS[1]

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ABSTRACT

To improve ground transportation, the United States began a program called the Intelligent Vehicle / Highway Systems (IVHS), sometimes called Smart Cars / Smart Roads. One of five IVHS components, the Advanced Vehicle Control Systems (AVCS), envisions autonomous vehicles that drive themselves, following their lane and avoiding other vehicles, all the while receiving routing and road information from an automatic traffic surveillance and planning system. Potentially, computer vision can fulfill many of the sensory requirements of mobility and traffic monitoring.

This paper presents the vision-based technology for AVCS developed at the National Institute of Standards and Technology (NIST). A testbed vehicle has demonstrated autonomous road following on a test course and on a highway at speeds of up to 90 km/hour under various weather and outdoor light conditions. This paper describes the latest highway tests, the algorithm development for autonomous vision-based car following, and the traffic monitoring system.

1. INTRODUCTION

The Intelligent Vehicle/ Highway Systems (IVHS) program is a major initiative of government, industry, and academia to apply advanced technology to the operation of the Nation's surface transportation systems in order to improve mobility, transportation productivity, enhance safety, maximize the use of existing transportation facilities, conserve energy resources, and reduce adverse environmental effects. The IVHS program consists of the following five broad, interrelated components: 1. Advanced Traffic Management Systems (ATMS); 2. Advanced Traveler Information Systems (ATIS); 3. Commercial Vehicle Operations (CVO); 4. Advanced Public Transportation Systems (APTS); 5. Advanced Vehicle Control Systems (AVCS).

The topic of this paper falls within the fifth IVHS component, Advanced Vehicle Control Systems. AVCS employ advanced sensor and control technologies to assist the driver in responding to the immediate environment on the roadway. AVCS will develop in an evolutionary manner, seeking first to enhance the driver's perceptions of his or her immediate environment. The long term AVCS will provide fully automated vehicle/highway systems replacing the driver functions. Full scale deployment of AVCS systems offer dramatic benefits, such as vastly increased highway capacity through the use of tightly packed automated vehicles traveling at freeway speeds, and increased safety by reducing the potential for driver error [1].

The need for autonomous vehicle lateral control (steering) and longitudinal control (braking and throttle) on future automated highways is described in the AVCS program plans [2]. It is envisioned that future automated highways may contain roadside and aerial traffic surveillance systems and advanced traffic management systems with the ability to track and even control individual or groups of vehicles in order to synchronize and coordinate their motion for various automated driving scenarios.

The California PATH program has already demonstrated platooning of vehicles using microwave range detectors mounted on the front of the test vehicles [3,4]. In addition, in order to improve

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response times needed for close proximity driving, each vehicle measures its acceleration and transmits the measurements to the vehicles directly behind it. This approach could be combined with their approach for autonomous vehicle lateral control using buried magnets in the road to achieve fully automated platooning.

The use of vision-based perception techniques for autonomous driving are being investigated in many programs in the United States as well as in other countries. A recent survey of these techniques is presented in [5]. Use of machine vision as a primary sensor has promise in that the infrastructure impact is minimized relative to other approaches. If such a low infrastructure impact approach could be implemented safely and affordably, then deployment, operations, and maintenance of AHS systems would be greatly simplified, increasing the viability of the overall concept, and facilitating rapid expansion of automated travel to the entire road network in future generation systems [6].

Over the past five years, NIST has been conducting cooperative research and development in vision-based vehicle mobility control. This paper describes this research and the viability of using vision to fill the long-term needs of AVCS. The initial work was in the development, integration, and demonstration of vision processing and control algorithms needed for autonomous road following (vehicle lateral control using lane markings), autonomous car following (vehicle lateral and longitudinal control for platooning) and the assembly and demonstration of an automatic vision-based surveillance system. Such a system could eventually be used as part of a higher level remote traffic control system for providing real-time traffic information, and coordinating lateral and longitudinal control of vehicles or groups of vehicles on instrumented highways.

2. CONTROL APPROACH

Testbed and support vehicles

The project utilizes a NIST testbed vehicle, a HMMWV, which was developed by NIST in cooperation with the U.S. Army Research Lab as part of the DOD's Unmanned Ground Vehicles program [7,8]. Figure 1 is a photograph of the testbed vehicle. The vehicle controller drives motors for steering, brake, throttle, transmission, transfer case, and park brake and monitors the dashboard sensors such as speed, RPM, and temperature. Prior to this project, the instrumented vehicle, which has a NIST Real-time Control System (RCS), had two modes of operation: Teleoperation mode - where an operator remotely controls the vehicle over an RF communications network; and Autonomous Mode called "retro-traverse" [9] - where the control system uses an inertial navigation system (INS) to steer the vehicle along a pre-recorded path. NIST replaced the human teleoperator control functions with intelligent vision processing elements in order to achieve autonomous, visually guided road following. The Department of Defense (DOD) made the vehicle available to NIST and DOT for this project.

Figure 1. Testbed vehicle followed by support van

A mobile computing and communications van was prepared to support the NIST AVCS development work [10]. This instrumented van serves two purposes. It houses the required computing systems in support of lane following on public roadways. The van also serves as a lead vehicle for car following algorithm development. In addition, the van houses the necessary development support hardware for these activities.

In typical operational scenarios, video imagery is gathered by a camera on the HMMWV and is sent by a microwave link to the chase van. The image information is processed in the van. Vehicle control commands are computed and then sent back to the HMMWV control computer via an RF data link. Although the ultimate goal is to mount all vision processing and vehicle mobility controller real-time computational resources on the test vehicle, a portable development and performance evaluation facility will still be necessary.

The equipment in the support van includes, communications systems, computing systems, racks, seating, power generators, and cooling. The computing system includes a PIPE (a low level vision processor), two Sun SPACRC2 workstations and a VME system. The Sun SPARC2 workstations are used as development stations, while the processors in the VME system perform vision processing functions using the extracted edge data from PIPE. A set of video monitors displays raw and processed video imagery to the operators. The communication system provides video and data links between the van and theHMMWV. Communication capabilities include two microwave video channels with audio subchannels, an RF low latency serial link, and capability for additional serial channels and an ethernet link. Figures 1 and 2 are photographs of the mobile lab vehicle.

Figure 2. Mobile Lab Interior.

Control Architecture

The implementation of the vision-based vehicle lateral control functions was performed in the framework of the RCS reference model architecture for an intelligent vehicle control system [7,8]. The reference model describes which functions are to be performed by the various controller components and organizes them using a consistent set of guidelines. Modules in the hierarchy include Sensor Processing (SP), World Modeling (WM) and Task Decomposition (TD). The roles of these submodules are described in [11].

The highest level of control for an individual vehicle, the Task level module, executes mission tasks phrased in symbolic terms, such as: Drive to exit 11 on I-270. A vehicle may be equipped with several subsystems, such as navigation, perception, and mission modules, which are directed by the Task level to achieve certain phases of the task.

The implementation for the U.S. Army Research Lab uses the lower two levels of the reference model architecture, Prim and Servo, to perform the mission elements. This included an automatic mode of operation called, Retro-traverse. In this mode, the operator teaches the vehicle a path during teleoperation which the vehicle automatically retraces on command from the operator. Vehicle navigation sensor data (position, velocity and acceleration) is processed and used to update the WM in the lowest level of the Navigation Subsystem and used to provide data to the WM in the Mobility Subsystem for steering the vehicle.

Extensions to the control system were necessary for implementing the AVCS autonomous road following function for the driving task [12]. The architecture developed for the initial development phase used the lower two levels of the generic vehicle control system. See Figure 3. The vision processing system used a model of the lane edges to assist in the prediction and tracking of the lane on the road. The computed coordinates of the center of the lane are then used to steer the vehicle, in a similar fashion to Retro-traverse.

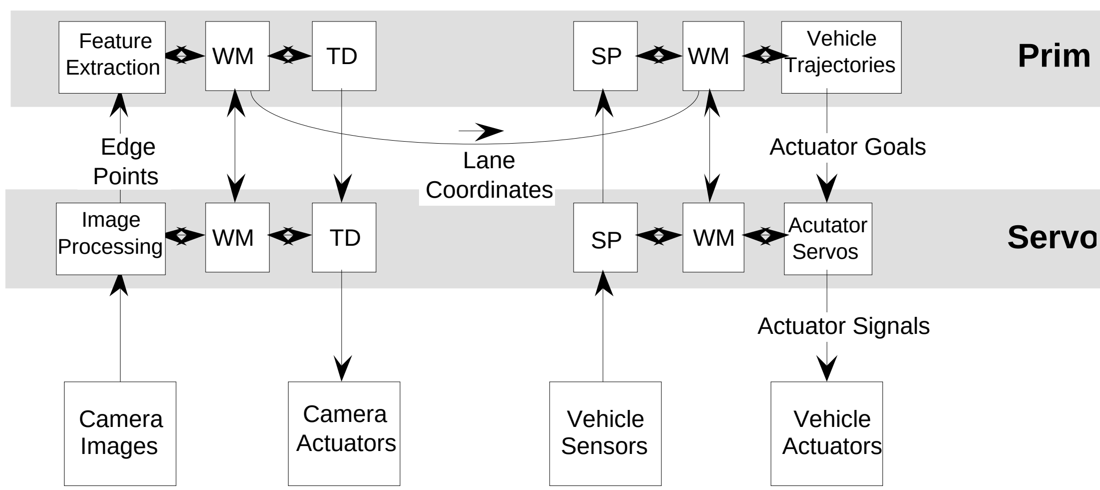

Figure 3. Control System Architecture for AVCS Autonomous Road Following

Our next phase of autonomous operation, car following and collision avoidance, requires the implementation of the next higher level of the control system, Emove. In this case the control system uses the visual surface features of the rear of the lead vehicle for lateral/longitudinal control in order to perform platooning. Eventually, the performance of higher level tasks, such as: obstacle recognition/avoidance and route planning, will require further extensions to the Emove and implementation of the Task levels of the architecture. An autonomous traffic surveillance and monitoring system would have a similar control structure that would provide routing and road information to the vehicle controller. The following three sections provide more details of NIST's work in road following, vehicle following, and traffic surveillance.

3. ROAD FOLLOWING

The controller tracks the painted stripes on the road and steers the vehicle along the center of the lane in the following steps. First, edges are extracted from the video image within a window of interest. Edges occur where the brightness of the image changes, such as where the image changes from a gray road to a white stripe. Then, the two quadratic curves that represent each lane boundary as it appears in the video image are updated. The system computes the coefficients of the curves using a recursive least square fit with exponential decay. Finally, the steering wheel angle that steers the vehicle along the center of the perceived lane is calculated.

Figure 4 shows the various scenes obtained when applying a window of interest to the road scene. The lateral position of the window of interest shifts in order to keep it centered on the road and its shape changes as a function of the predicted road curvature.

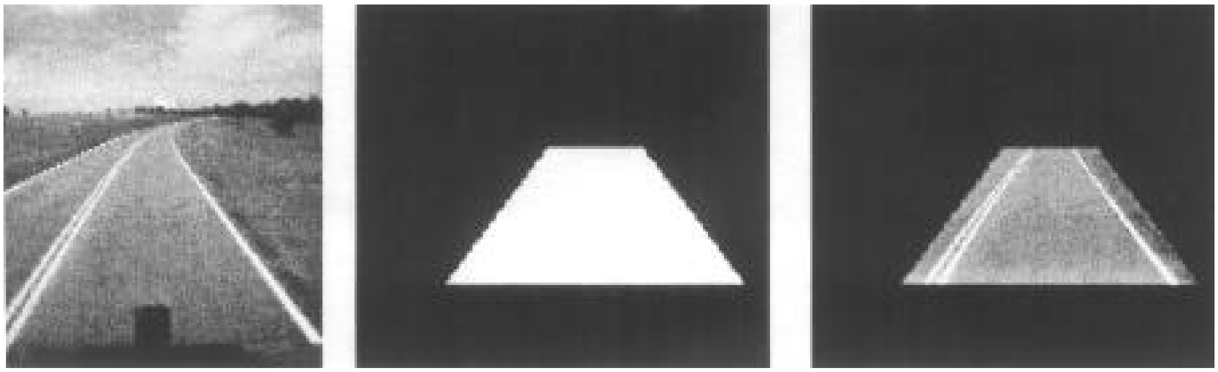

Figure 4. Road Scene, Window of Interest, Masked Road Scene.

The two models of the lane boundaries are related to each other using a road width constraint. Since road width remains relatively constant, the knowledge of road width can be used to strengthen the road model. The current road width is computed by taking the difference of the two lane marker models based on data from the latest image and averaging this measurement with previous ones. The computed road width can then be used in situations where an image provides very sparse edge data for one lane marker and relatively strong edge data from the other lane marker. When this happens, the model of the weak lane marker is reinforced by knowledge of its distance from the other lane marker. More details of the vision processing and control algorithms can be found in [13,14].

The vehicle controller computes a steering angle each vision cycle that steers the vehicle along the center or average of the two lane boundaries using the pure pursuit method [9,15]. This method calculates the position of the center of the lane at a set distance of 12 meters in front of the vehicle. A flat ground plane is assumed in the transformation from camera coordinates. The vehicle then steers to drive over this point. Figure 5 graphically depicts the computation of the turn radius from a goal point. The steering angle is set inversely proportional to the turn radius.

Unfortunately, computation and transmission delays cause problems such as instability at high speeds. Currently the total pipeline delay from when an image is taken until the steering wheel starts to move in response to that image is 0.3 seconds. (This pipeline delay is different than the processing rate, which at 15 Hz processes a new image every 0.067 seconds)

To account for the vehicle motion during the delay, the vehicle controller uses onboard navigation sensors. When a goal point is received, the vehicle controller recalls the vehicle's location when the video image was recorded and transform the goal point into the current vehicle frame. The modified goal point, turn radius and steering angle are repeatedly updated each control cycle as the vehicle drives down the road.

The Montgomery County DOT permitted NIST to test the instrumented vehicles on a public highway. During these tests, autonomous driving was maintained over several Kilometers (gaps in the lane markings at intersections prevented test runs of longer distances) and at speeds up to 90 Kph. The vehicle has also been driven on various tests courses under weather conditions ranging from ideal to heavy rain, and under various outdoor light conditions including night time with headlights on.

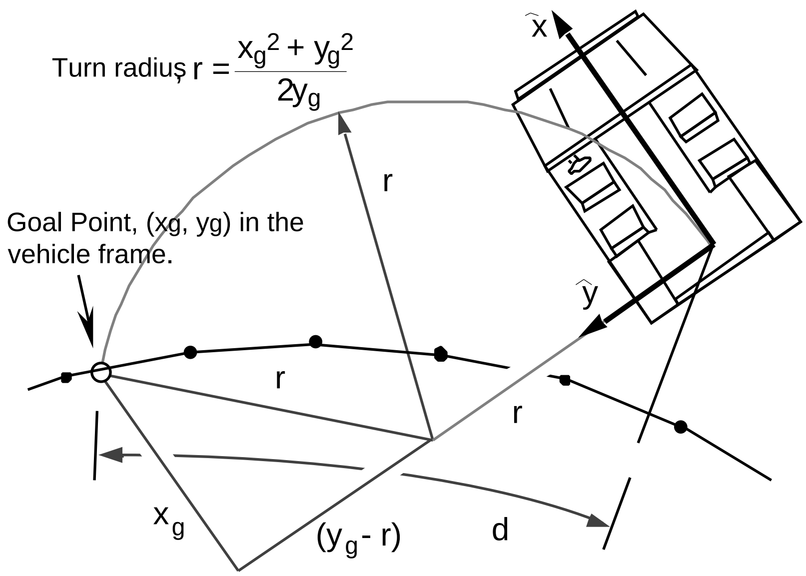

Figure 5. Pure Pursuit Steering

4. VISION-BASED VEHICLE FOLLOWING

In scenarios envisioned for automatic platooning of vehicles, a vision-based control system guides the vehicle to a lane which has a single vehicle or a platoon of vehicles to be followed. The vision-based control system would track the rear of the last vehicle and maintain a safe but very small following distance of two meters or less. The response of the vision-based vehicle longitudinal velocity control system could be further enhanced by using real-time acceleration and deceleration data transmitted from the lead vehicle. This cooperative scheme is similar to that used in the PATH approach [3,4]. To put this technology into actual operation, redundant sensors or the fusion of several different sensors may be necessary to achieve the reliable performance and safety needed for fully automated highway driving.

An approach to vision-based car following was developed and tested using video recorded sequences of scenes of a lead vehicle taken from the forward looking camera on the testbed vehicle while driving behind the lead vehicle [16].

This approach uses an object tracking method originally developed as part of NIST's participation in NASA's Flight Telerobotic Servicer project. This algorithm was originally designed to track the position and orientation of a moving 3-D part/object. In applying this method to car following, the system tracks the back of a vehicle or a target mounted on the back of the vehicle in much the same way it would track an entire object. Since orientation is approximately constant during car following, the algorithm estimates only the translation of the lead vehicle. Figure 6 shows the feature tracking method being tested on real data. The system demonstrated robust and reliable lead vehicle tracking for vehicle separations of up to 30 meters.

Figure 6. Vehicle tracking provides 3-D position.

5. AUTOMATIC TRAFFIC SURVEILLANCE

Practical automated highway systems will distribute the intelligent processing elements and advanced sensors between the instrumented vehicles and the highway infrastructure. The potential benefits of a highway equipped with advanced sensors are: (a), the information will extend the ranges and capabilities of vehicle on-board sensors; and (b), the information may be used by a high level traffic management system to coordinate vehicle interactions and thereby improve highway traffic flow and capacity. For example, an automatic vision-based highway surveillance system could perform the following functions: vehicle tracking, identification, incident detection, and atmospheric and roadway surface condition monitoring. This information would be used by trained traffic management personnel or automatic control systems to improve the performance and safety of automatic vehicle lateral and longitudinal control on automated highways. During fully automated operation, automatic low-level, high-bandwidth control (e.g., lane following, obstacle avoidance, etc) is still performed locally by each vehicle, but higher-level, low-bandwidth control (e.g., merging, passing, entering, exiting, etc.) is performed automatically by the traffic control center.

Unlike current automatic vision-based surveillance systems that detect vehicle presence in a manner similar to roadway-embedded loop detectors (i.e., only examine and process thin strip of roadway scene), advanced highway systems will require surveillance systems that can accurately track individual vehicle trajectories. Such systems will detect highway incidents more reliably and will be useful in preventing incidents and collisions. NIST is working with the Montgomery County, MD Traffic Management Unit to evaluate the effectiveness of vision systems that track individual vehicles. A prototype system is being assembled by NIST and the County which will initially evaluate an automatic target acquisition system developed by the DOD Army Research Laboratory for military applications [17]. This system is capable of detecting and tracking multiple moving vehicles on a highway section. Modifications are being made so that the system will generate statistical information such as traffic flow and density. This information will be fed into the County's Traffic Management Center. In the future, NIST and others will be able to evaluate various algorithms for vehicle tracking and incident detection on an actual roadway network.

6. CONCLUSIONS AND FUTURE DIRECTION

The goal of this work is to perform highway tests of NIST's preliminary version of a vision-based AVCS and to develop algorithms for autonomous vision-based car following. Autonomous vehicle lateral control (road following) was demonstrated on a Maryland highway at speeds up to 90 kph. A vision-based algorithm for autonomous car following was successfully tested in real-time using video recordings of a lead vehicle taken from the testbed vehicle. This model-based approach successfully maintained tracking of the lead vehicle on straight and curved sections of the roads and even through sharp right and left hand turns at intersections. Vehicle separation distance was varied between 3 meters and about 30 meters. Extracted translational information could be used for autonomous vehicle lateral control while the measured range and rate of change in range could be used for autonomous vehicle longitudinal control during platooning of vehicles.

The results clearly indicate that a vision-based approach to autonomous vehicle mobility control is a viable way of satisfying many of the technology needs of future automated highway systems envisioned for AVCS. With the initial technology developed by NIST, autonomous platooning of vehicles on existing non-instrumented infrastructure roads could be demonstrated this year. The testbed vehicle control system could be extended to use the measured lateral translational position of the lead vehicle for autonomous steering and the measured range and rate of change in range, to the lead vehicle, for autonomous control of the separation between the two vehicles. In addition, future work will focus on performance evaluation of autonomous road following on interstate type roads; development of additional vision processing and control schemes for autonomous road following to demonstrate reliable and robust performance; integration of a practical commercially available vision processing platform on the testbed vehicle; and vision-based obstacle detection and collision avoidance.

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