RUN-OFF-ROAD COLLISION AVOIDANCE USING IVHS COUNTERMEASURES

TASK 5 REPORT: TECHNOLOGY STATE-OF-THE-ART REVIEW

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where SVRD crashes are a frequent occurrence. The latter system a laser scanner under development by Aerometrics and supported by NHTSA, was not available for the SVRD project. Consequently, two CMU lateral position measurement systems were evaluated during Phase I. These CMU systems are ALVINN and RALPH. Both were described in the Task 3 report of Phase I.

Continuing where the Phase I technology assessment stopped, the CMU project team selected four general CAS functional areas for review during Phase II. These include: (1) noncooperative and cooperative lateral position monitoring systems, (2) vehicle state monitoring systems, (3) in-vehicle fiction detection systems, and (4) infrastructure hazard detection systems. The first category was further divided according to the following subcategories: (1 - 1) multi function prototype vehicles with SVRD capabilities, (l-2) edge detection/lane following (in-vehicle methods), and (l-3) edge detection/lane following (infrastructure-based). The first subcategory included several papers that describe prototype vehicles with in-vehicle CASs, which address several crash types in a prioritized manner, while the other two categories address single function systems pertaining strictly to SVRD applications. Inclusion of the first subcategory concerning multi functional CASs sets the stage for the integration of SVRD countermeasures with other countermeasure systems that will likely evolve in the quest for commercially viable systems of the future. Such integration has already been achieved in European prototype vehicles.

Driver state monitoring was not reviewed since it is being investigated in other NHTSA programs, which include Driver Status/Performance Monitoring and Direct Psychological Monitoring of Driver Alertness and Attention Focus.

Multifunction Prototype Vehicles with SVRD Capabilities: The paper by Alloum (1993) describes a multi purpose CAS prototype vehicle that was developed by the French team, consisting of the Renault Corporation, PSA Peugeot-Citroen and others working in the European Prometheus (PROgram for a European Traffic and with Highest Efficiency and Unprecedented Safety) program. This prototype is designed to provide driver assistance with the issuance of information about the safety of certain maneuvers, such as lane following, lane changing and obstacle detection. At no point does the system take over control of the vehicle. This paper emphasizes the importance of the “time treatment” of the data needed to assess the vehicle behavior and its environment. There is an inherent trade-off between the accuracy associated with a lot of data versus the additional computational time required to process a large data volume, as well as added cost.

With the support of the Prometheus program, there are three separate German prototype vehicles, which provide multi functional collision avoidance systems and were developed under the leadership of the Armed Forces School (Universitaet der Bundeswehr), Daimler-Benz, and the Fraunhofer Institute (Fraunhofer Institut fuer Information und Datenverarbeitung). All three prototypes are very dependent on the use of video cameras to provide real-time information about the environment surrounding the prototype vehicle (e.g., lane edges, other vehicle, roadside objects, pedestrians, and road signs).

The prototype vehicle (Dickmanns, 1994) from the Armed Forces School has the ability to perform many of the functional requirements needed by a countermeasure system to address SVRD crashes. In many respects, this vehicle resembles the prototype vehicle engineered by Daimler-Benz (Ulmer, 1994). The latter vehicle has also been reviewed as part of this literature assessment. Areas of commonality between these two German vehicles include reliance on machine vision and use of considerable software integration to realize a multi-functional collision avoidance system.

There are, however, some significant differences between these prototype vehicles. The engineering approach invoked by the Armed Forces School seeks to minimize the number of video cameras needed to monitor the environment about the subject vehicle. For example, the Daimler-Benz vehicle currently requires 18, fixed-mounted cameras, whereas the Armed Forces School prototype needs only eight cameras, mounted on platforms with two degrees of freedom (azimuth and elevation). A smaller number of cameras can be realized by utilizing them in a saccadic gazing fashion in the same manner that humans perform visual scanning by eye and head movements, according to the Armed Forces School.

A derivative product from the Daimler-Benz prototype research is the steering assistant (Franke, 1994) that relieves the driver of the necessity of making small amplitude steering wheel adjustments on both straight and curved highway segments. Although the driver is in complete control at all times, the steering assistant provides increased driving comfort as indicated by driving experiments conducted at the Dairnler-Benz simulator in Berlin. The technologies and system configuration of this driving assistant are similar to the prototype vehicle developed by CMU for use on the SVRD program. However, in the SVRD program an in-vehicle warning is issued if “normal” lane keeping is exceeded, whereas the steering assistant provides constant, small-scale steering corrections.

The paper by Struck (1994) describes an in-vehicle, electronic system to detect the presence of an intersection, as well as to develop and follow a trajectory through it without driver intervention. Such a capability would be useful for the SVRD program, where digital maps and GPS (Global Position Sensors) could provide information about the location of an impending curve, the radius of curvature and the real-time distance between the subject vehicle and the entrance to the curve. Working closely with Daimler-Benz on the Prometheus project, the Fraunhofer Institute developed this autonomous maneuvering system by combining computer vision and navigational information. The latter data is derived from a ***Travel Pilot(R)*** from the Robert Bosch company.

Edge Detection/ Lane Following (In-Vehicle Methods): The work described in the paper by Behringer (1995) of the Armed Forces School is based on the use of a forward-looking video system to determine the orientation of the subject vehicle within a lane, detect obstacles in its path and also measure the radius of curvature of the roadway ahead. Once a dangerous situation is detected, the system issues an in-vehicle alert. One of the primary reasons for reviewing this paper is due to modeling the radius of curvature, which is utilized in one of the algorithms of the SVRD program.

The approach developed by the Armed Forces School is object oriented and utilizes recursive estimation of the state vector of objects, which includes the subject vehicle, as well as other vehicles and roadside appurtenances. A 4D (3D space + time) method is used to model each object so that the state vectors are estimated by Kalman filtering for circumstances involving horizontal curvature. Included in the process are the statistics of system and measurement noise.

The Daimler-Benz prototype vehicle (previously discussed in the paper by Ulmer) is equipped with 18 video cameras in order to monitor the state of the environment external to it. Described in the paper by Reichert (1994) is method of representing this sensor data by means of a dynamic risk map. The latter is essentially a three dimensional, topographical plot where the horizontal plane is defined by the x-y axes (i.e., the roadway) and the vertical axis (i.e., z axis) is related to the level of risk associated with an object within range of the subject vehicle's sensors. Reichert describes an analytical approach to convert measured sensor data (e.g., range and velocity of other vehicles and objects) from the vehicle's environments into scalar potentials (i.e., a risk map) associated with objects under sensor surveillance and tracking. These potentials can be used to calculate control signals to be applied to actuators of the subject vehicle or to be utilized first for in-vehicle warnings if there is sufficient time for a driver response.

The primary application addressed in the paper by Choi (1995) is super cruise control, namely the functions of autonomous intelligent cruise control combined with autonomous road following and steering. Autonomous intelligent cruise control has the usual definition of maintaining a constant vehicle speed of the subject vehicle when no car is in front of it and then switching over to maintaining constant distance when there is a lead vehicle. In the opinion of Choi neither vision algorithms nor neural based algorithms individually are sufficiently robust to provide adequate super cruise control performance. They present a hybrid approach, which combines the best features of both vision and neural networks image processing algorithms.

The lane recognition/vehicle location system of Suzuki (1992) uses a CCD video camera, a frame memory, PC, monitor, and four transputers. The latter perform the operation of thresholdiig the imagery, applying Hough transforms to fit numerical white line data to a straight line (i.e., both left and right lane lines), and lane recognition. The final result is that the numerical data is transformed into line imagery, which is superimposed on the original video image. The system is also able to predict the location of a lane line even if one is temporarily missing. This capability is based on the fact that the width and the height of a triangle (i.e., the road as it extends into the foreground) are constant for the same lane. Coordinates for two apexes can be calculated if one apex is known.

In cases where roadway makers are not present or when color video imagery is not available, texture in the imagery may be a useful feature to distinguish (i.e., segment) road lane and background pixels (Zhang, 1994). In his approach, Zhang characterizes texture by it's orientation field and from it the covariance matrix of the gray value changes in an image is estimated. Each point in this orientation field is a vector with two components: the local orientation and the strength of the texture anisotrophy. Both gray value changes and their covariances are calculated by using filters. Under the assumption that roads lie in a plane, Zhang proposed an approach that estimates a relative optimal filter scale at each point from the projection parameters of a calibrated camera

Edge Detection/Lane Following (infrastructure-Based): Unlike SVRD program, which uses in-vehicle video camera technology to measure lateral excursions of a vehicle, the PATH project (Partners for Advanced Transit and Highways) utilizes an infrastructure approach to determine the lateral vehicular location (Shladover, 1992). This infrastructure approach is based upon permanent magnetic markers, which are embedded in the lane center at regular intervals. The field of these magnetic markers is measured by a Hall-effect magnetometer located on the vehicle under the front bumper. The paper by Shladover was selected for review because (1) the PATH program represents a "bench mark" regarding the capability of infrastructure-based approaches and (2) the lateral control accomplishments of this program may become an important part of the automated highway system (MIS). Vehicles operating in an AHS environment would be subject to lateral control, as well as longitudinal control, and would, therefore, avoid SVRD crashes.

Complimenting the work done in the PATH program, the paper by Ohnishi (1992) describes a test track to evaluate vehicle performance under rough road conditions for extended periods of time. In order to create a sense of realism, vehicles under test have on-board electronic control units to generate actual driving patterns by means of fuzzy control. The test track has a traffic control system to allow evaluation of multiple vehicles simultaneously. Control of the track is achieved by guidance cables (rather than magnetic markers as in the PATH program) that are positioned on both sides of each lane. There are twenty four loop antennas for road-to-vehicle communications and are also positioned on the main line. Two antennas are located at the enter/exit lane.

In order to counter weather effects, which may impact vision-based sensors, Stauffer (1995) has proposed the use of a two-axis magnetometer on a vehicle to sense the magnetic field from a tape, which is aligned along the center line of a lane instead of magnetic markers or electric cables. The magnitude of the measured field is proportional to the lateral distance between the tape and the magnetometer. It assumed that the sensor height is held approximately constant and that orienting the magnetic axis of the tape in the vertical direction will minimize cross coupling errors between the horizontal and vertical channels of the magnetometer. The ambient field of the earth is eliminated by electronic filtering.

Tire Pressure Measurement: Tire blow out, typically caused by under inflation, is one of the primary causes of vehicle mechanical failure regarding SVRD crashes. The paper by Wallentowicz (1990) was chosen because it provides an overview of several tire monitoring approaches. He indicated that tires are frequently driven at pressures below the recommended operating level, which has a bearing on the countermeasure performance for SVRD crash avoidance. According to the work on Phase I of this project, the countermeasure response was based partly on the "last chance to act" which was the last point in time when a vehicle could be maneuvered back to its original position in the lane center after deviating from its "normal" trajectory." This "last chance to act" is partly dependent on the response of the tires and ma affect the threshold settings of the SVRD countermeasures.

Measurement of Roadway Surface Conditions (In-vehicle Systems): The importance of the paper by Cremona (1994) to the SVRD crash avoidance project is due to an in-vehicle radar system that was designed to measure both vehicle ground speed and the condition of the road surface ahead of the vehicle. Knowing roadway surface states, especially in a preview mode, may provide more reliable lateral and longitudinal vehicle control Both vehicle speed and roadway condition were obtained by first determining the power density spectrum of the reflected radar beam. This spectrum has an array of lines (i.e., intensity versus radar frequency), whose pattern is indicative of the roadway surface. Since the spectral lines are Doppler shifted due to the relative velocity between the road and the vehicle, the vehicle speed can be obtained by measuring the shift of a spectral line, where the shift is proportional to the vehicle speed.

The optical system discussed in the paper by Yoda (1995) for measuring road surface conditions consists of an array of light emitting diodes (LED) whose beams are directed nearly perpendicularly to the road surface. After reflection from this surface, the return beams pass thru an objective lens, a collimating lens and then through a spatial filter (i.e., a grating with periodic openings), which performs a Fourier transform on the return beam. The LEDs and other optics are part of an electro-optical system, which is mounted on a vehicle to measure pavement conditions in real-time. The pattern of the Fourier transform has been characterized by Yoda in terms of two indices, which, when plotted on a graph, provide clusters of data points. Each cluster corresponds to a particular pavement condition (e.g., dry, wet, snow covered, etc.).

Hazard Detection and Warning Systems (Infrastructure-Based): There is a requirement for sensors to measure roadway surface conditions and to broadcast that information to motorists in advance of the actual roadway area, which may be effected by water, snow and ice. Such information could be used by an in-vehicle SVRD countermeasure system to determine braking distances for road surfaces with reduced coefficients of fiction and to define safe entry speeds to roads with horizontal curvature. Vendor literature of systems that have this capability was reviewed.

Summary: There does not appear to be any complete SVRD countermeasures in the commercial market, although there are several, multifunction prototype vehicles with SVRD capabilities. There are component technologies that are commercially available (e.g., tire pressure monitoring systems or infrastructure-based pavement monitoring systems), as well as subsystems for image processing of lane edges and object detection.

According to the reviewed papers the European systems are the most advanced in terms of providing collision avoidance systems that address multiple crash scenarios, including SVRD crashes, in a prioritized manner. Under the German Prometheus Program three such prototype vehicles have been designed and developed by Daimler-Benz, the Armed Forces School and the Fraunhofer Institute. The French have engineered a similar, advanced prototype vehicle as part of their participation in the Prometheus Program. All of these systems rely heavily on the use of in-***vehicle*** video cameras to acquire data about the state of the environment surrounding the subject vehicle. The use of video cameras is predicated on the necessity of being able to measure this environment with a high degree of spatial resolution (e.g., determining lane edges/curvature reading road signs, etc.), which other technologies, such as radar, can not provide. However, video cameras have performance limitations due to weather conditions (e.g, rain, fog, snow) and illumination conditions. Shadows and specular reflections from puddles may also cause difficulties for some systems.

It should be noted that the European Prometheus Program for crash avoidance systems started in the mid 1980s, at a time when GPS (Global Position System) and digital maps were not a commercial reality, which is no longer true today. Given the availability of these latter technologies, the reliance on video technology can be reduced by embedding the location of entrances and exits to curved roads, proper entry speeds at these entrances, locations of signs with speed restrictions, as well as intersection locations in digital maps. The use of GPS and digital maps for SVRD applications may be accelerated by their commercial use in other smart highway areas, such as Advanced Traveler Information Systems (ATIS), which utilize these technologies for navigational purposes.

Multifunction Prototype Vehicles with SVRD Capabilities

Alloum, A., El-Eter, B., Rombaut, M., ***Dynamic data management in the ProLab II driving assistance system,*** **In Proceedings of the Inteliigent Vehicles 93 Symposium (pp. 84-87), Tokyo, Japan, July 14-l6, 1993, Sponsored by the IEEE electronics Society.**

Topic: Prototype Vehicle for Driver Assistance - French Research and Development (Heudiasyc-URA, Universite de technologie de Comiegne, France)

Summary:

The French team consisting of the Renault Corporation, PSA Peugeot-Citroen, along with other members of ProArt-France (a sub group of the European Prometheus Eureka project) group, have developed a first generation prototype vehicle (ProLab I) and as of 1993 were embarking upon a second generation prototype vehicle, namely ProLab II. This team effort is part of the European Prometheus (PROgram for a European Traffic and with Highest Efficiency and Unprecedented Safety) program. Both prototypes are designed to provide driver assistance with the issuance of information about the safety of certain maneuvers, such as lane following, lane changing and obstacle detection. At no point does the system take over control of the vehicle.

This paper was reviewed in the context of the single-vehicle-roadway-departure (SVRD) program, which requires a lane tracking function to determine when the driver has exceeded his/her normal lane keeping. The reviewed paper describes a system with not only lane tracking, but includes several other functions, which are integrated within a total system. Thus, this paper was chosen for review according to the immediate needs of the SVRD program, but also with an eye to the future when other crash avoidance countermeasure systems may be fused into a comprehensive collision avoidance system.

This paper emphasizes the importance of the “time treatment” of the data needed to assess the vehicle behavior and its environment. There is an inherent trade-off between the accuracy associated with a lot of data versus the additional computational time required to process a large data volume, as well as added cost. In an effort to optimize this trade between too much and too little data., the dynamic data manager, the primary topic of this paper, was conceived as an important interface between lower level sensor processing functions and higher level information-extraction modules.

The ProLab vehicle is designed to perform under a limited number of contexts. These are major highways without obstacles, main roads, where obstacles could have the same or opposite direction as the subject vehicle, highway entrances and exits and cross roads, which could involve pedestrian crossings and stop lines (i.e., the paper talks about stop “bands”).

Figure 1 provides a downward view of the ProLab vehicle showing the position of several video cameras mounted on the subject vehicle to monitor its environment.. In the reviewed paper these instruments are referred to as exteroceptive sensors to distinguish them from body motion (i.e., proprioceptive) sensors, which are also positioned on the vehicle. These proprioceptive devices include lateral, longitudinal, and yaw rate sensors, as well as steering, brake pressure and accelerator sensors, as indicated in Fig. 2.

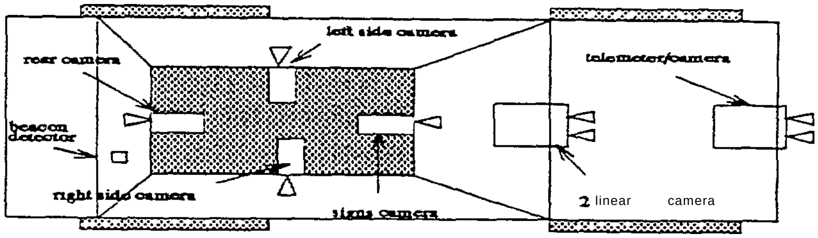


Figure 1: The Prototype Ezteroceptive Sensors

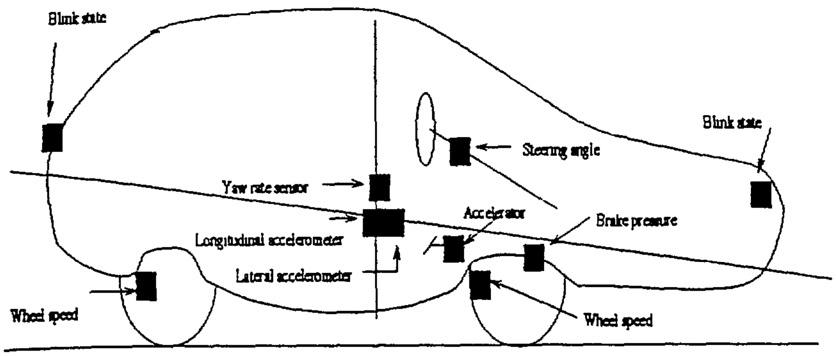


Figure 2: The Prototype Proprioceptive Sensors

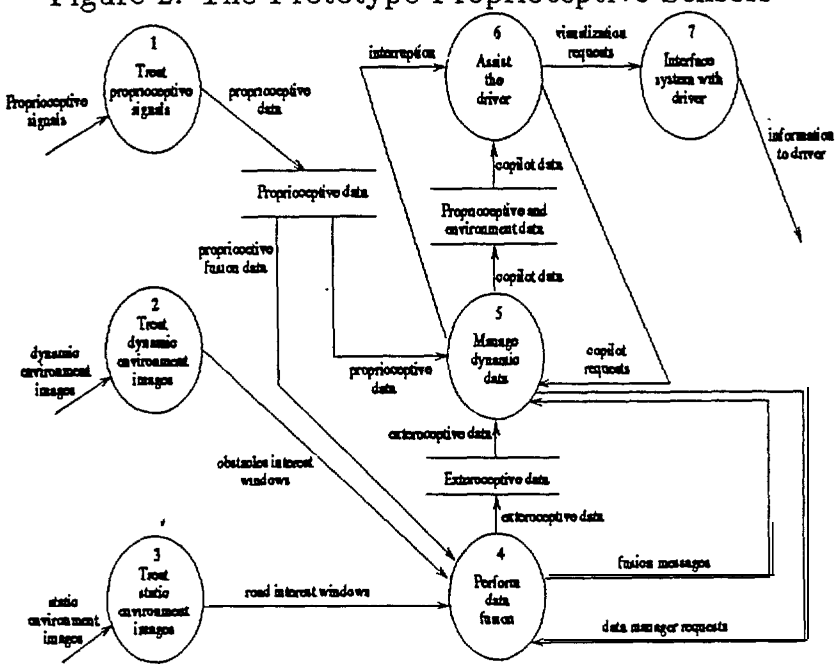


Figure 3: The ProLab II Requirements Model

The environmental sensors include: a camera coupled to a laser “telemeter” (i.e, presumably a laser radar) for detecting and identifying obstacles in front of the subject vehicle; and two linear cameras on the roof to detect and identify pedestrians and animals. (A linear camera typically refers to a camera that produces a single scan line image, istead of a 2D image). A stereo camera could be a logical choice because it can provide range information regarding pedestrians and obstacles. There are two other cameras to detect lateral obstacles; a rear camera to determine the presence of obstacles in that direction, as well as a camera to detect and identify road signs, in addition to providing information about the orientation of the subject vehicle with respect to the roadway. The top part of Fig 1 also indicates a beacon detector, mounted on the rear of the subject vehicle.

Figure 3 illustrates the data flow in the ProLab vehicle. The flow is designated according to process numbers, where, for example, processes l-3 treat the environmental and body motion sensor data. Notice that the former is divided according to static (e.g., current lane number and position of the subject vehicle with respect to the “route axis”) and dynamic data (e.g., other vehicles). From the context of the paper, the route axis means a route specification. [This capability would imply a navigational system which has a GPS (Global Position Sensor) receiver and a digital roadway data base]. Process 4 is responsible for data fusion, process 5 is the interface between the previously mentioned module and the next higher one, namely the copilot, which performs a situations diagnosis. The final module in this data processing chain is the person-machine interface, which informs the driver about decisions reached by the copilot.

The paper makes a distinction between sensed and computed data. For example, the former involves all the data emanating form the environmental and body motion sensors, while the latter includes data regarding obstacles in blind zones (i.e., time to disappear into and re-appear from), time dating of environmental/body motion data, desired cruising speed, required time/distance for the execution of maneuvers, and braking levels.

The paper refers to the mean age of data as the blink states, which are part of the input supplied to the copilot. It is noted that several tasks are executed on different processors, each with different clock frequencies and computational times. This circumstance introduces a “data elaboration time,” which is the sum of all the execution times, regarding, for example, the perception module data acquisition times to the sensor fusion times. The ProLab system considers a mean value of this elaboration time.

In this reviewed paper a case is made for the necessity of having a middle level function to manage and transform data coming from a lower level and then continuing to the higher level for diagnosis. This middle level function, called a dynamic data manager (DDM), operates in both controlled and continuous modes. The former involves activation of processing functions only when necessary, while the latter provides periodic updating. For example in the detection mode, the DDM supplies the measured position of the nearest vehicle and pedestrian obstacle, as well as the position of an announced narrowing or road works, if any, in either case. In a continuous mode, the DDM requests that a particular obstacle be tracked until further notice. In this case, the position and velocity updates are supplied at a frequency higher than that of the detection mode.

Finally, the paper defines a punctual focusing mode, where information is supplied to the copilot only once.

"Since some perception modules are controlled, the DDM activates or inactivates them according to the context and to the copilot requirements. Other requests are made to ask for obstacle attributes or for the static environmental state Asking for an obstacle attribute needs a focus mode of the sensors involved in the elaboration of the needed information. The focus mode could be punctual or continuous. The perception mode replies by updating the shared data zone. A request about the static environment could be made by asking the question: is there any special direction sign on the road? The perception module gives the direction sign code, if any and its relative position."

Key Findings:

Applications: The primary application is providing assistance to the driver by informing him/her about the driving situation and providing advice about possible maneuvers.

Specifications: There are few numerical specifications in the reviewed paper. However, the ProLab prototype vehicle is designed to function in certain contexts, such as major highways, main roads, entrance/exit ramps and crossroads.

Some specifications were provided in the context of developing the software for ProLab II. According to the reviewed paper, " A hierarchial internal structure of the system is necessary, with a real time kernel at the lowest level. That allows multitasking, pre-emptive scheduling, fast and flexible intertask communications and synchronization, as well as bounded performance. We chose the WindVxWorks (C) as a real-time environment, which has several benefits like a minimized pre-emptive latency, an interesting configurability, a useful kernel extensibility, multi processing facilities and optimized response times. The Software Through Pictures (C) tool (STP) permits the implementation of the SART real-time systems specification. Graphical editors are supplied to edit hierarchial data flow diagrams and diagrams consistency checking is possible."

Other specifications pertain to the vehicle dynamical models embedded in the ProLab II software. For example, the model accounts for the vehicle degrees of freedom, such as movement along the lateral, longitudinal, yaw and roll axes. Also taken into account are side slip angles and wheel road adherence. The vehicle dynamical model can be adapted (i.e., decomposed into two sub models, one for lateral movement, the other for longitudinal motion) according to the needs of a particular vehicle maneuver. In the case of lane changing, a lateral vehicle dynamical model would be needed, while a much simpler longitudinal model would be used for, say, intelligent cruise control applications.

Cost: N/A

Maturity: N/A

Safety: Although there is not an abundance of data in the reviewed paper, some simulation results were presented by computing the bounds associated with vehicle “security”(i.e, vehicle dynamical stability). The simulations were related to both smooth and rough lane changes by using “pole place” techniques (i.e., presumably by simulating a vehicle maneuvering around cone shaped objects placed at regular intervals). Results of the simulation were presented in terms of rear/front slide slip, lateral movement error and yaw error.

Reliability: N/A

Availability: N/A.

Acceptance: N/A

Technical Feasibility/Deployability: From reading this paper it is reasonable to assume that some standard hardware components are utilized, such as body motion sensors and video cameras. However, the critical element linking the environmental sensory data with the man-machine interface is the integrated software that was developed by the French team. Some of these integration functions include interfacing (e.g., perception and copilot interfacing), data dating and data estimation.

Dickmanns, E. D., Eehringer, R, Dickmanns, D., Hildebrandt, T., Maurer, M., Thomanek, F., Schielen, J., *The seeing passenger car "VaMoRs-P,* In Proceedings of the Intelligent Vehicles 1994 Symposium (pp 68-73, Paris France, October 24-26, 1994, sponsored by the IEEE Industrial Electronic Society.

Topic: Prototype Vehicle for Collision Avoidance - German Research and Development (Armed Forces School, Munich)

Summary:

The prototype vehicle described in this paper has the ability to perform many of the functional requirements needed by a countermeasure system to address single-vehicle-roadway departure (SVRD) crashes. In many respects, this vehicle, designed and built by the Armed Forces School, resembles the prototype vehicle engineered by Daimler-Benz (Both groups are members of the same Prometheus team). The latter vehicle has also been reviewed as part of this literature assessment. Areas of commonality between these two vehicles include reliance on machine vision and use of considerable software integration to realize a multi-functional collision avoidance system. The multi fimctionai nature of this prototype has the ability to make a prioritized response based on the need to avoid SVRD incidents while avoiding other potential crash scenarios in the course of performing run-off-road avoidance maneuvers.

There are, however, some significant differences between prototype vehicles. The engineering approach invoked by the Armed Forces School seeks to minimize the number of video cameras needed to monitor the environment about the subject vehicle. For example, in the above referenced paper, it is noted that the Daimler-Benz vehicle currently requires 18, fixed-mounted cameras, whereas the Armed Forces School prototype needs only eight cameras, mounted on platforms with two degrees of freedom (azimuth and elevation). A smaller number of cameras can be realized by utilizing them in a saccadic gazing fashion in the same manner that humans perform visual scanning by eye and head movements, according to the Armed Forces School.

Also provided in the above referenced paper is a top level summary of the sensor/decision making architecture, which includes three processing layers. See Fig. 1. At the lowest level there is a direct feed back or reflex-like behavior, the middle level pertains to mode selection of rule-based actions, while the top level involves situation assessment, goal oriented action planning and adaptations. This top level exercises an influence on the lower modules, such as rule selection monitoring, feed forward programs and feedback control laws. See Fig. 2.

The first such layer involves reflex-like behavior and includes the sensor, state estimator and a set of feedback control laws, which are applied to the vehicle actuators. The state vector *feedback* is designed for optimal performance for linear systems and quadratic goal functions. A four-dimensional approach to vision provides the state variables needed for this approach. According to this paper, the four dimensions refer to the three spatial coordinates plus a time variable. This lowest processing level is applicable for lane keeping and convoying (i.e., applications that require

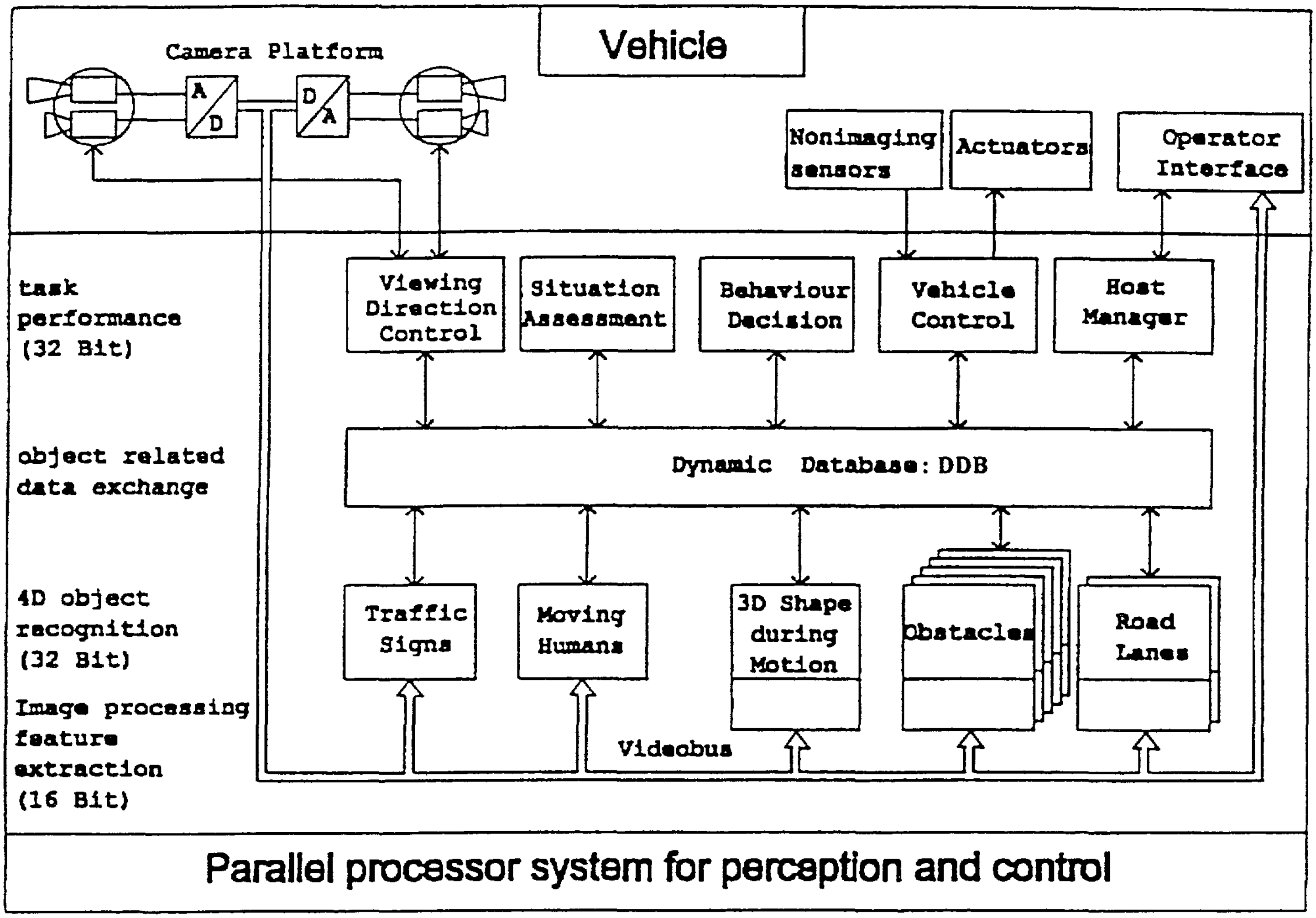
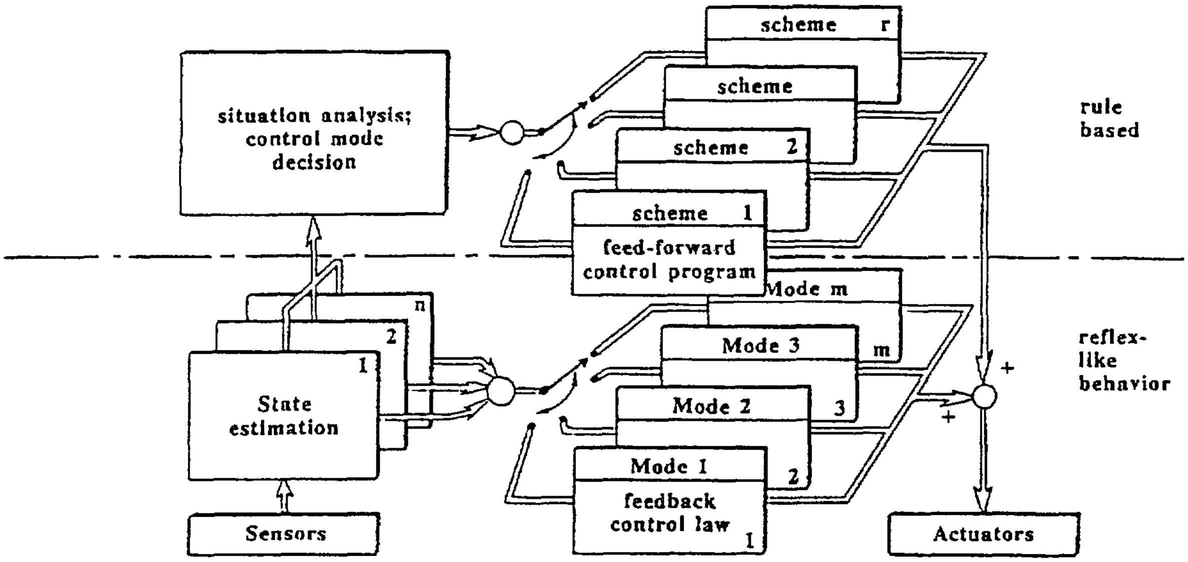
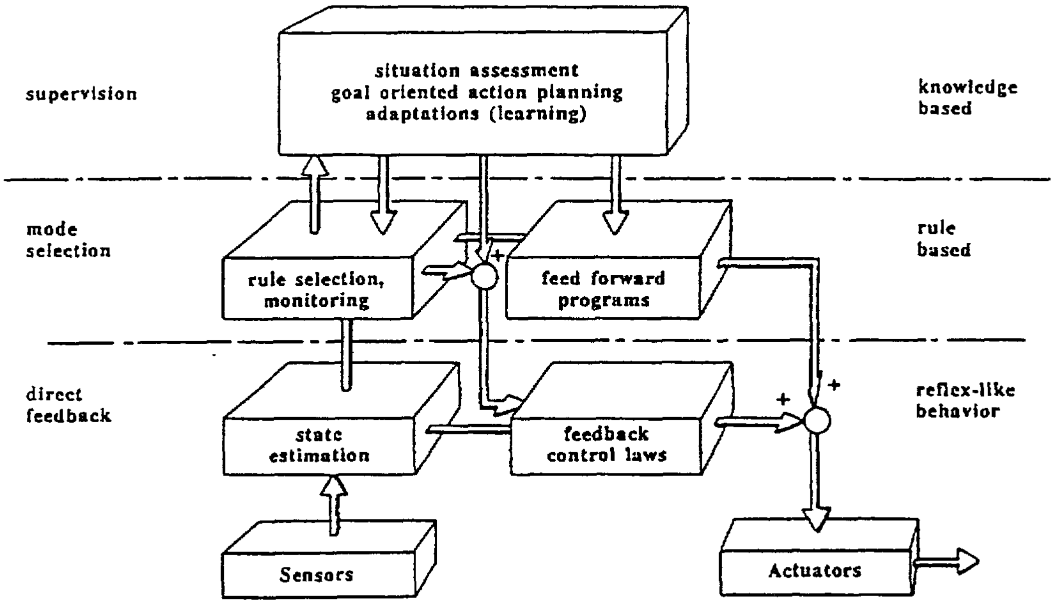


Figure 1. Overall object - oriented system architecture



a) Selectable continous state feedback superimposed by event-triggered feed-forward



b) Three-layered scheme based on a)

Figure 2. Situation dependent, intelligent control with knowledge based mode switching

fast reaction times)

The next higher processing level treats more complicated circumstances involving, for example, obstacles in the lane of the subject vehicle and a resulting lane change, avoidance maneuver. According to the above paper, “a feed forward generic control time history may be called up with a proper set of parameters , which are known to steer the vehicle safely into the neighboring lane; this maneuver may be achieved by applying simple rules to a data set composed of the relative states of several other objects ” This middle layer represents “rule-based behavior triggered by special events recognized through vision. The transition from free-lane cruising to convoy driving when running up to a slower vehicle in front is another typical event-triggered behavioral component.”

Key Findings:

Applications: Obstacle detection, road detection/tracking and lane changing are applications mentioned in the above referenced paper.

Specifications: Two transputers (a T222 and a T805) are used to detect up to five objects in four video cycles (80 milliseconds). “Object detection . ..is achieved in 26 vertical search windows covering about a third of the image every 80 ms with gradient masks of size 9 by 3. Up to 180 edges may result which are grouped into 20 contours; From these, up to five objects are extracted, each characterized by 18 attributes.”

Also mentioned was the need for driving at higher speeds. Therefore, the viewing distance should be increased up to 200 meters, possibly using trifocal vision, according to the Armed Forces School. A two hundred meter viewing range might be considered a significant “stretch” since many research papers stemming from the vehicle control literature cite 100 meters as a typical maximum range. In this reviewer’s opinion, a range of 200 meters may be quite challenging in view of the additional roadside “clutter” that will be captured by the sensor field-of-view

According to the above referenced paper, it is necessary to recognize roadway curvature as early as possible in order to sustain high speed driving. Since measurement of roadway curvature is essential, “a piecewise curvature model according to the rules used for construction of high speed roads is being substituted for the simple (time-varying) sliding model used up to now; this will also simplify the handling of changing lanes as they occur at entries and exits of highways. This more general model can, later on, be easily expanded for road forkings and general road crossings.”

Cost: N/A

Maturity: This subject was addressed in the following context: “The new generation of microprocessors becoming available over the next months will allow to further increase system capabilities over the next years while simultaneously shrinking both volume and power consumption of the system. Both the perception subsystem and the overall system architecture are becoming more powerful, which is a good indication of the systems becoming more mature. However, it should not be overlooked that in order to achieve robust performance approaching the performance level expected from human drivers there is still a long way to go.”

Safety: N/A

Reliability: N/A

Availability: The vehicle discussed in the above referenced paper is a prototype design and built by the Armed Forces School and, therefore, is not available.

Acceptance: N/A

Technical Feasibility/ Deployability: These categories have been demonstrated in that both prototype vans from the Armed Forces School and the prototype from Daimler-Benz have been driven autonomously on 3000 km of public roads between 1992 and 1994 at speeds up to 80 km/hr. Commercially available hardware is used for the video cameras, body motion sensors and the computer electronics. Special hardware was designed for the camera platforms, which must perform precision pointing and tracking. Key to the design of this prototype was the development of specialized software for image processing feature extraction, object-related data exchange and task performance.

Ulmer, *B.*, (1994). ***VITA II - active collision avoidance in real traffic.*** **In Proceedings of the Inteiligent Vehicles 1994 Symposium (pp l-6). Paris, France, October 24-26, 1994, Sponsored by The IEEE Industriai Electronic Society.**

Topic: Prototype Vehicle for Collision Avoidance - German Research and Development (Daimler-Benz, Stuttgart)

Summary:

The Daimler-Benz prototype vehicle described in this paper provides several, integrated, in-vehicle countermeasures, including one for single-vehicle-roadway-departure (SVRD) collisions. Based on machine vision, image processing and artificial intelligence interpretation of sensor data, this prototype can support several counter measure functional goals established during phase 1 of the SVRD Specification Development Program sponsored by the National Highway Traffic Safety Administration (NHTSA).

Daimler-Benz has been developing video-based prototype vehicles for automated driving since 1985. The first such prototype was VITA I, which performed the following functions: lane keeping, intersection recognition, convoy driving, stopping for obstacles and supervised lane changes. This vehicle, a Mercedes van, was demonstrated at the Prometheus board meeting in 1991. The second prototype is VITA II, a Mercedes S-class vehicle, has an expanded set of capabilities: lane/speed/distance keeping, lane changing/overtaking, collision avoidance, intersection recognition and traffic sign identification. The computer equipment, power supplies, and air conditioning of VITA II has been scaled down to fit in the trunk of the S-class vehicle.

Funding for the development of the Daimler-Benz VITA prototype vehicles is derived from the European Prometheus program. There are several team members supporting Daimler-Benz and include the Armed Forces School [Universitat der Bundeswehr] in Munich, University of Bochum, the University of Koblenz and the Fraunhofer-Institut fuer Information und Datenverarbeitung (data processing).

The Armed Forces School, a major contributor, has been involved with the following subtasks related to VITA: automatic recognition of vehicles from behind, road/subject vehicle state recognition, vision for intelligent vehicles, multiple object recognition, scene interpretation, camera platforms and knowledge-base driver monitoring (DAISEY). From a number of published papers, it is known that the Fraunhofer Institute provided expertise in: driver's warning assistant for intersections, interaction between digital road map systems and trinocular autonomous driving, obstacle detection by real-time optical flow and texture-based segmentation of road images.

The VITA II prototype vehicle is completely self contained and does not require additional modifications to the infrastructure. See Figs 1 and 3 from the reviewed paper. The only dependence on the latter is based on the need to key on already existing roadway/intersection markings and highway signs. VITA II relies exclusively on video cameras and has: 4 lateral, black and white vision systems (each lateral camera is a three lens stereo camera with two such cameras per side), 4 front-looking color cameras and two rearward viewing cameras. There are also two cameras, configured in a stereo mode, outfitted on the front bumper. These bumper cameras can detect a swerving vehicle immediately in front of the vehicle for the application of emergency braking.

With this many cameras (i.e., 18), most of the surrounding field of the vehicle can be monitored. Blind spots are treated by calculating time estimates (using Kalman filtering) when another vehicle is expected to emerge fiom a blind zone based on its last appearance in a monitored zone, as well as the other vehicle's speed. This capability is useful for lane change/merge applications.

VITA II relies exclusively on video-based technology because only the latter is capable of providing the spatial resolution needed to read road signs and discern lane markings. The use of a video system does not require a communication license and does not generate electromagnetic interference between vehicles equipped with this technology. However, video systems have limited usefulness during marginal ambient lighting conditions, night time, or periods of adverse weather.

An infrared camera may be a possible alternative to video cameras, except that infrared cameras may not have sufficient spatial resolution and may be unable to read road signs because there will be little temperature diierence between the body of the sign and its lettering. Unlike video cameras, which measure light reflected from objects and the background, infrared cameras generate imagery based on temperature differences within that imagery. If there are no significant temperature differences (i.e., within the sensitivity range of a particular infrared camera) between an object and its background, the object will not be observed.

Key Findings:

Applications :The primary purpose of VITA II is autonomous driving, although it has been modified to function as a driver's assistant. This modification, provided by one of the Daimler-Benz team members (the Armed Forces School), is a modular computer program, called DAISEY.

Specifications: The above referenced article does not provide many numerical specifications per se, but does outline the top level details of the VITA II prototype. VITA II is equipped with vision sensors, application computers, vehicle computers, actuating systems, monitors and user interfaces. It is powered by a 1500 watt generator, which is temperature controlled by air conditioning. For computational support, VITA II has two principal computers: one to control the vehicle (e.g., steering, throttle and braking) and the other to control the video cameras and provide processing functions, such as road sign recognition.

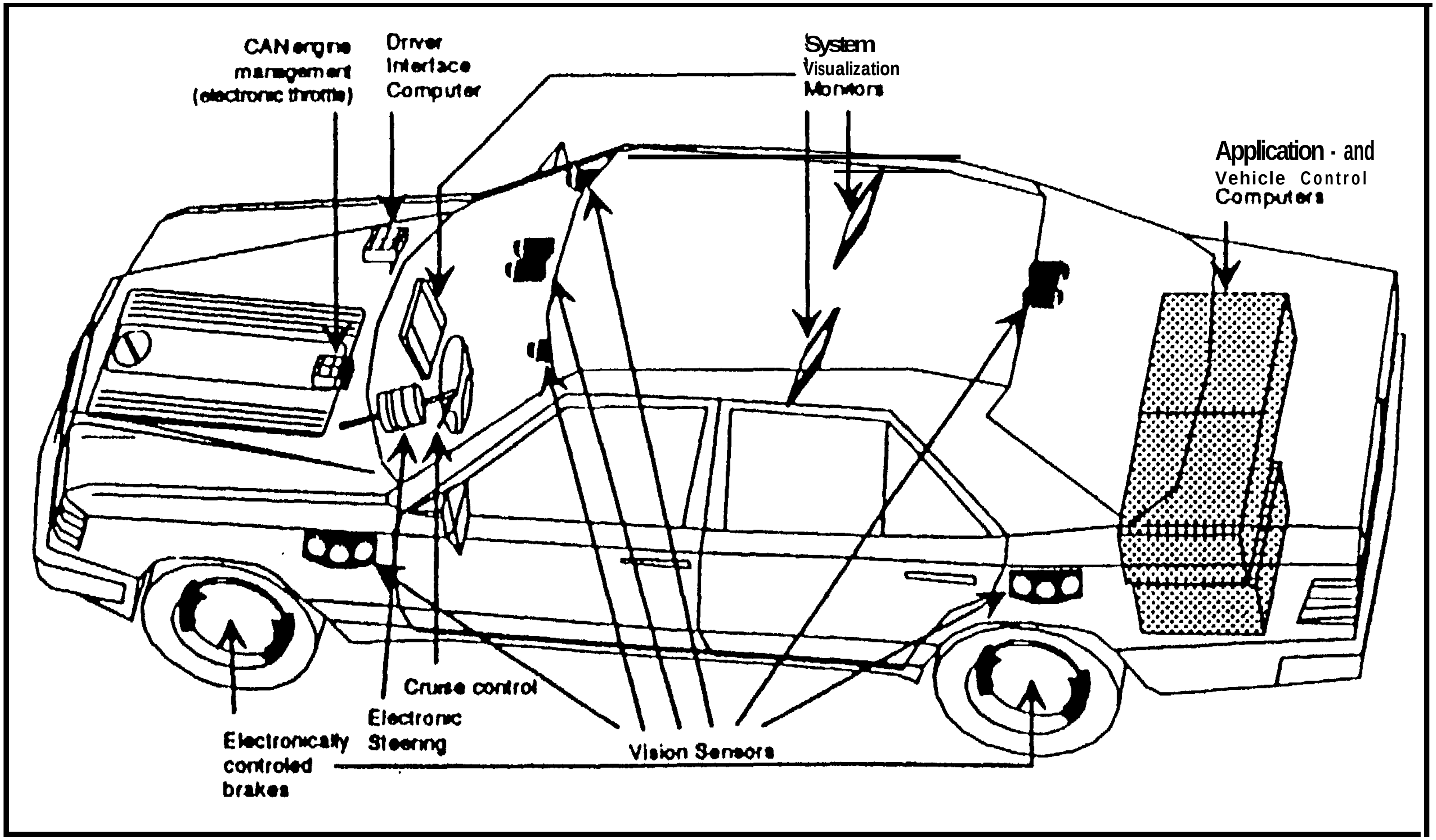


Fig.1: Autonomous passenger car VITA II

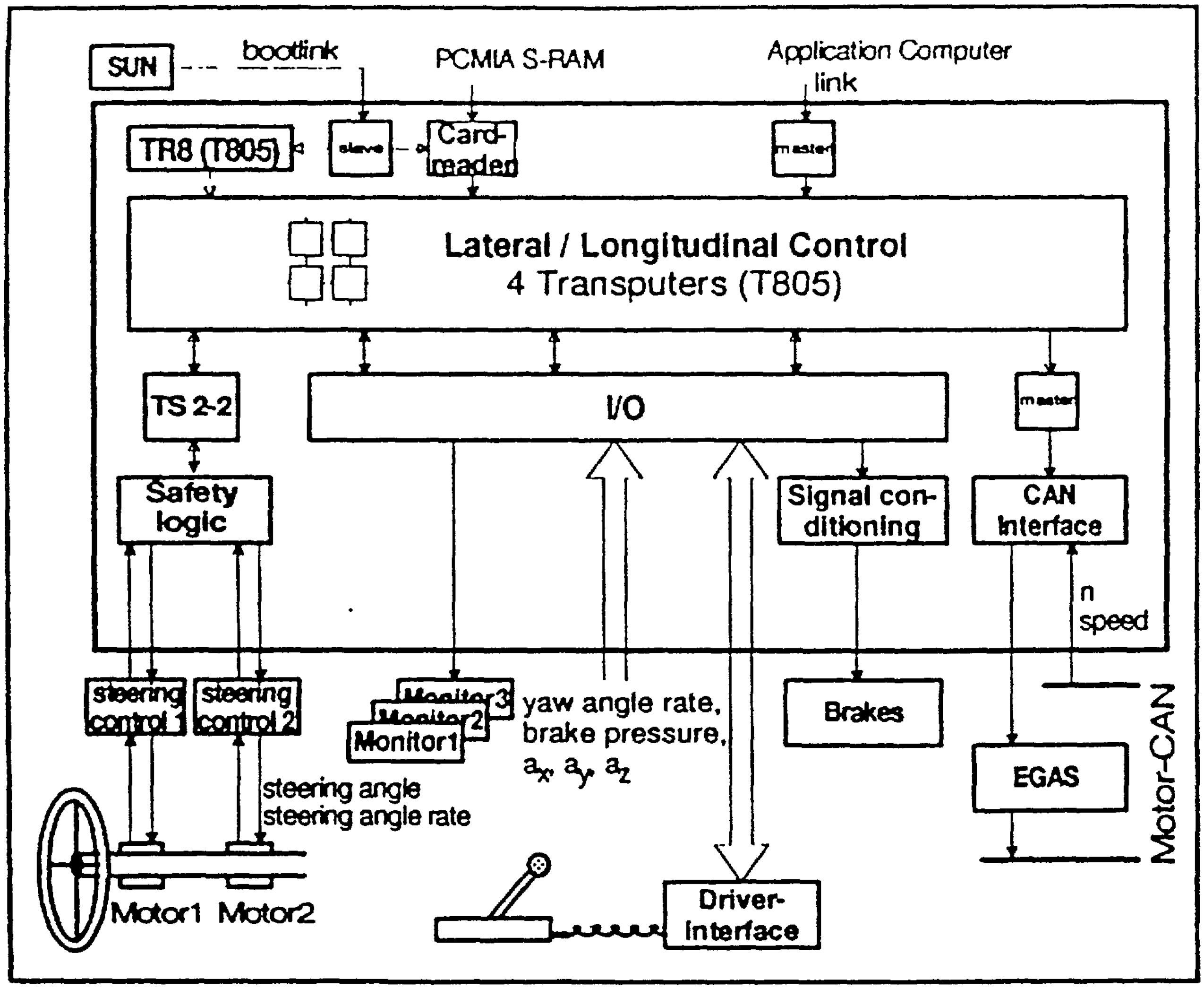


Fig.3: Vehicle computer

VITA II has body motion sensors to measure lateral/longitudinal acceleration, incremental and absolute steering angle, operational temperature, brake pressure, orthogonal acceleration for normalization, yaw angle rate, vehicle speed and engine revolutions.

Collision avoidance in VITA II is governed by two modules: planning and decision. Operation of the latter functions depend upon data, such as desired speed, desired vehicle and driver behavior, location and speed of other objects, traffic sign information, and lane geometry information. There are two basic approaches undertaken in VITA II for the development of collision avoidance algorithms. These are the potential field and the state transition methods

The potential field method (reviewed in this report) of determining 1ateral/longitudinal control signals for vehicle control is analogous to the classical mechanical procedure of calculating a vector force by applying a negative gradient to a scalar field. In the case of the potential field method, the technique relies on the calculation of scalar potentials(i.e., risk fields) associated with roadway objects. Given these potentials, a gradient operator is applied to each in order to determine associated lateral/longitudinal acceleration vectors. These vectors are then combined with a navigational (i.e., an end-point goal) vector in order to apply appropriate control signals to the actuators of the subject vehicle, thereby maneuvering it around obstacles and still steering in the direction of the goal.

In the state transition method, all possible traffic situations are represented. This method utilizes prototypical control concepts, such as lane change and car following, whereas there is a continuous application actuator signals in the potential field method.

Cost: This subject was not addressed. One could assume that part of the ultimate commercial viability of VITA II would be dependent on reducing the cost due to the many video cameras, computers, power supply and air conditioning. One method for cost reduction is now being considered by the Armed Forces School in Munich. Their approach involves fewer cameras by utilizing them in a saccadic gazing manner (i.e., a rapid jerky motion from one fixation point to another). The Armed Forces School prototype is reviewed in this report.

Maturity: This topic was not addressed. However, Daimler-Benz has been developing autonomous, prototype vehicles since the mid 1980s. One can therefore, presume that VITA II, a second generation experimental vehicle, possesses a high level of maturity as a prototype.

Safety: This subject was not addressed in numerical terms (e.g. number of accidents prevented, reduction in the number of near misses). However, the functional capability of VITA II addresses safety in terms of lane keeping, obstacle avoidance, etc.

Reliability: N/A

Availability: N/A

Acceptance: N/A

Technical Feasibility/Deployability: the prototype from Daimler-Benz has been driven autonomously for thousands of kilometers on public roads. Commercially available hardware was used for the video cameras, body motion sensors and the computer electronics. Critical for the design of VITA II was the development of specialized software for image processing feature extraction, object-related data exchange and task performance.

Franke, U., Mehring, Suissa, A., Hahn, S., ***The Daimler-Benz steering assistant- a spin-off from autonomous driving,*** **in Proceedings of the Inteiligent Vehicles 94 Symposium, (pp 120- 124), Paris, France, October *24*, 1994, Sponsored** by **the IEEE Electronic Society.**

Topic: Prototype system to provide steering assistance as a link between manual and autonomous driving - German Research and Development (Daimler-Benz, Stuttgart, Germany)

Summary:

The Daimler-Benz steering assistant relieves the driver of the necessity of making small amplitude steering wheel adjustments on both straight and curved highway segments. Although the driver is in complete control at all times, the steering assistant provides increased driving comfort as indicated by driving experiments conducted at the Daimler-Benz simulator in Berlin. The technologies and system configuration of this driving assistant are similar to the prototype vehicle developed by Carnegie Mellon University (CMU) for use on the Single-Vehicle-Roadway-Departure (SVRD) program. However, in the SVRD program the immediate purpose of the crash avoidance system is to provide an in-vehicle warning if the driver deviates excessively from his/her normal lane keeping. Another purpose of the SVRD countermeasure system may be to exert some degree of control over the vehicle in situations where the driver cannot react fast enough. Thus, in most cases the SVRD will provide an in-vehicle warning, rather than generate small amplitude steering corrections.

Development of the steering assistant was preceded by work in lateral vehicle guidance that began with optical methods in 1986. This early work resulted in autonomous vehicle guidance using video cameras and image processing to extract roadway features (e.g., road edge, radius of curvature), which served as input to an in-vehicle computer algorithm to generate actuator control signals. The resultant prototype system is called OSCAR, which uses commercially available transputer hardware built into the trunk of a station wagon (MB 300TE).

The steering assistant employs a monochrome CCD camera, whose view is in the forward direction. The camera imagery is processed to provide lateral offset, yaw angle relative to the road axis, curvature of the road, the clothoid parameter (describes rate of road curvature change), road width and tilt angle of the camera. See Fig. 2 from the reviewed paper for a top level schematic of the steering assistant.

It is interesting to speculate about the lateral control algorithm(s) used by the steering assistant given the above parameters obtained from image processing. Some of these are the same parameters currently used (as of May 1996) in the SVRD program. For example, the SVRD project uses two algorithms to determine lateral excursions: the time-to-trajectory divergence (TTD) and the time-to-line crossing (TLC). The TTD algorithm uses the following sensor measurements: radius of road curvature, radius of curvature associated with the current arc of the driver's trajectory, and the vehicle speed. Used as input to the TLC algorithm are the yaw rate,

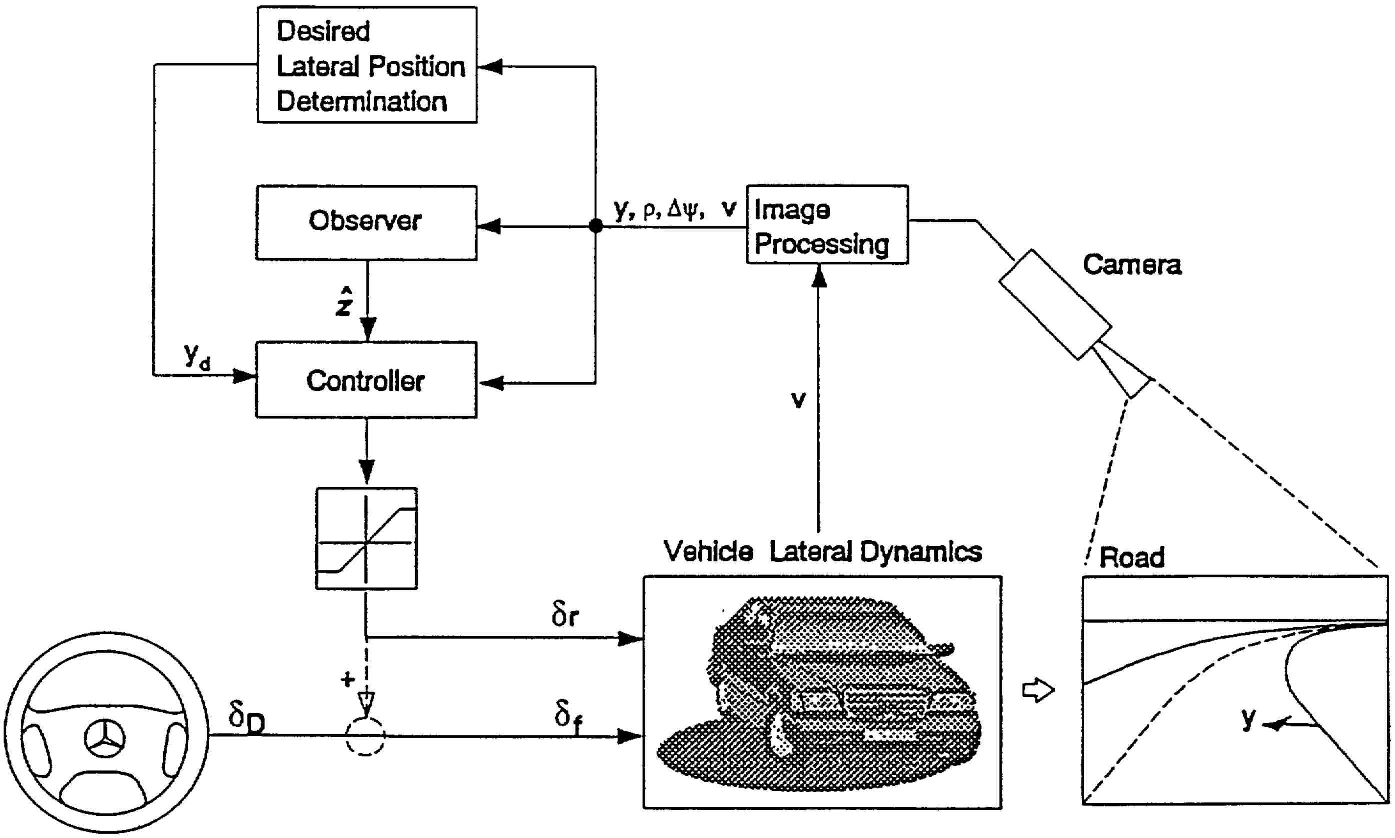


Figure 2: Concept of the DB Steering Assistant. From image processing via observer and controller an additional correcting steering angle is derived and put to the steering rod.

longitudinal speed of the vehicle and distance between the edge of the road as well as its first derivative. Not used in either of these algorithms is the clothoid parameter.

Also supporting the steering assistant is a function called the "observer," which receives input from the image processing output, according to Fig. 2 of this paper. However, in the text of the paper, it is noted that the "observer estimates current disturbances z, which cannot be measured from the cameras image (e.g., road inclination to one side that caused change in the vehicle's position or orientation). With this additional information the controller can take over the fine tuning by adding a correcting steering angle to the driver's command." However, there seems to be some confusion about the source of input to the "observer."

Key Findings:

Applications: The prototype control system described in this paper generates fine tune steering corrections to reduce driver workload and make possible future roadways with smaller widths due to the reduction of lateral excursions with the use of this system.

Specifications: Several performance parameters were cited in this paper. The controller has an accuracy of +/- 10 cm (at static steering positions). The authors said that this was a compromise between driving comfort and controller safety limits, although it was noted that "heavy environmental disturbances" resulted in 30 cm lateral deviations. The figure of +/- 10 cm is consistent with the performance of the Carnegie Mellon vehicle used on the SVRD program.

The steering wheel corrections are +/- 0.25 degrees at the vehicle wheels and corresponds to +/- 4 degrees at the steering wheel. Driver performance was improved at speeds up to 160 km/hr.

Cost: N/A

Maturity: In some respects the steering assistant is a partially mature system in that it was preceded by prior work starting in 1986, uses commercially available hardware and has under gone some testing as of 1994. Additional testing across a broad range of the driving population (e.g., young, old drivers) is required, especially during adverse weather and low light level conditions.

Safety: N/A

Reliability: See comments under Maturity

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: Given the preliminary success determined from driving simulator experiments, this prototype steering assistant has demonstrated some potential for reducing driver workload. Its technical feasibility is not an issue per se, except that the steering assistant will require some re-engineering to make it cost effective.

Struck, G., Geissler, J., Laubenstein, F., Nagel, *H.*, Siegle, *G.*, *Multi-camera vision-based autonomous maneuvering at road intersections,* In Proceedings of the Intelligent Vehicles 1994 Symposium (pp 189-194), Paris France, October 24-26, 1994, sponsored by the IEEE Industrial Electronic Society.

Topic: Use of video cameras and digital maps for autonomous driving and intersection negotiation - German Research and Development (Fraunhofer-Institut fuer Informations und Datenverarbeitung, Karlsruhe)

Summary:

This paper describes an in-vehicle, electronic system to detect the presence of an intersection, as well as to develop and follow a trajectory through it without driver intervention. Such a capability would be useful for the Single-Vehicle-Roadway-Departure (SVRD) program, where digital maps and GPS (Global Position Sensors) could provide information about the location of an impending curve, the radius of curvature and the real-time distance between the subject vehicle and the entrance to the curve. The motivation to engineer this system stems from the German philosophy that "the ability to guide a vehicle automatically on a road network is regarded as a desirable goal by itself as well as an immediate objective towards a competent driver support system."

Working closely with Daimler-Benz on the Prometheus project, the Fraunhofer Institute has developed an autonomous maneuvering system by combining computer vision and navigational information. The latter data is derived from a ***Travel Pilot(R)*** from the Robert Bosch company. Presumably the ***Travel Pilot(R)*** has a Global Position Sensor(GPS), although this reviewed paper did not explicitly mention it.

Figure 1 illustrates several subsystems and their relationship to each other. For example, in addition to supplying the digital map, the ***Travel Pilot(R)*** provides continuous updates on the position of the subject vehicle and its orientation relative to the map. The driver inputs his/her destination request to a PC so that the system plans the route before starting the vehicle. The data transferred between the PC and the central computer includes vehicle speed, curvature of the upcoming roadway, angle between the vehicle and the road, distance to the next intersection, turning angle at the intersection, type of intersection, and the distance to the destination point.

As of 1994, three video cameras were used and located behind the front windshield. The central camera is bored-sighted along the longitudinal axis of the subject vehicle. Each camera has a 60 degree viewing angle. The other two cameras on either side of the central camera are capable of being panned with an angle of 35 degrees to the left and right. Information from the digital map is used to automatically select the optimal field of view during each phase of a turning maneuver.

There are two basic image processing tasks, namely surveillance and tracking. The reviewed paper refers to the surveillance task in terms of a ***Watch Module,*** which detects road borders and intersections. The ***Travel Pilot(R)*** provides information about the road orientation. As of 1994 the road-junction model utilized a gap in the boundary of the lane being followed in order to locate an

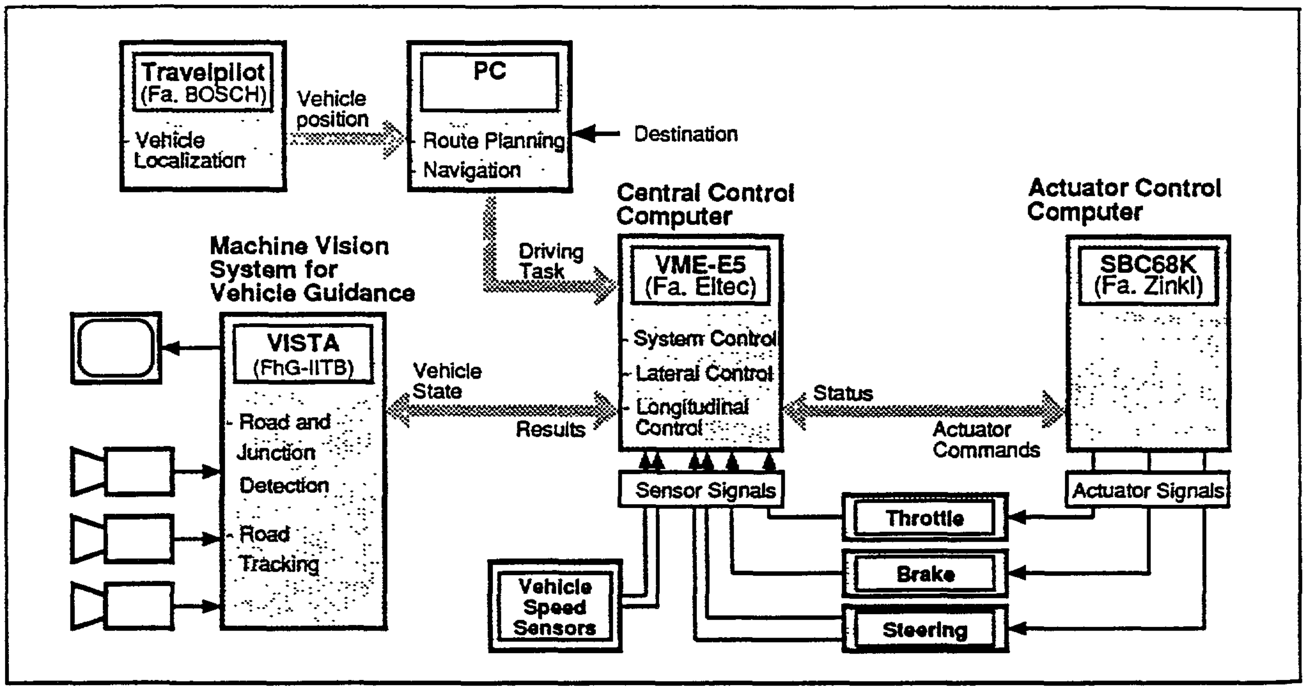


Fig. 1: The current System Configuration of the IITB's first Experimental Vehicle (MB609D)

intersection. Tracking of road borders is accomplished by a vehicle dynamical model and a road model. The latter mode1 involves the lateral distance from the right border of the road, the angle between the vehicle and the lane, the lane width and its curvature. Additional inputs are vehicle speed and steering angle.

The reviewed paper described additional steps for negotiating an intersection. In the case of a left turning maneuver at a T junction, the following procedures are followed. By tracking the left and right boundaries, the subject vehicle is automatically guided. Enabling the ***Watch Module*** starts the search for an intersection and is updated at a rate of 2 Hz. "Using the images from the appropriate (here leftward bound) camera, the Tracking Module starts to track this leading straight line independently with a faster repetition rate of about 8 Hz. A turning-off trajectory with the turning angle is derived from the digital maps updated with the same rate. As the vehicle follows this constantly updated trajectory, the image source is automatically switched back to the center camera as soon as the turning vehicle has approached the goal orientation with a predefined tolerance."

Key Findings:

Applications: Highway exits, lane tracking and roundabouts are the areas of interest. The technology employed by this system may be most useful for the NHTSA specification development program regarding intersection crash avoidance.

Specifications: A detailed list of specifications was not provided, except some particular parameters already cited above.

Cost: The cost of the entire system was not mentioned. It could be inferred that the ***Travel Pilot(R)*** by Robert Bosch is commercially available.

Maturity: N/A.

Safety: No specific quantification of overall safety performance was given. It should be mentioned that the system performance was first evaluated using off-road sites.. As of 1994 additional testing had been done on public roads that were temporally blocked from public use.

Reliability: According to the reviewed paper, some additional work is needed to handle road tracking of two consecutive narrow curves with opposite radii of curvature.

Availability: Since the overall system is a prototype, it is assumed to be not available. The ***Travel Pilot (R)*** may be a commercial product.

Acceptance: N/A

Technical Feasibility/Deployability: The prototype described in this paper ranks highly in both of these categories as demonstrated by field testing at the time of publication.

Systems Edge Detection/ Lane Following (In-Vehicle Methods)

Behringer, R, ***Detection of & continuities of road curvature change by GLR,*** **In Proceedings of the Intelligent Vehicles 95 Symposium, (pp 78-83), Detroit, MI, September 25-26, 1995, Sponsored by the IEEE Electronic Society.**

Topic: An update of a state vector is processed using a new approach for spatial segmentation of a curved road based on a video camera installed in a passenger vehicle. - German Research and Development (Armed Forces School, Munich, Germany)

Summary:

The work described in this paper is based on the use of a forward-looking video system to determine the orientation of the subject vehicle within a lane, detect obstacles in its path and also measure the radius of curvature of the roadway ahead. The latter feature is of interest to the single-vehicle-roadway departure (SVRD) program. In the SVRD project, two video cameras and a computer, located onboard the prototype vehicle developed by Carnegie Mellon University (CMU), use two algorithms to measure lateral deviations of the vehicle. One of the algorithms compares the roadway radius of curvature (by processing video imagery from a forward looking camera) with the radius of curvature assumed by the driver's trajectory. The other algorithm utilizes a downward looking camera to measure the distance between the edge of the vehicle and a painted line delineating the road.

The primary purpose of this system in the reviewed paper is to provide driver alerts, although the author indicated that a good test of this system is to permit autonomous driving. Tests over several thousand kilometers have been conducted in a prototype vehicle labeled, VaMP (the translation of this pneumonic into English is: prototype for autonomous mobility and image-computing vehicle).

The approach developed by the Armed Forces School is object oriented and utilizes recursive estimation of the state vector of objects, which includes the subject vehicle, as well as other vehicles and roadside appurtenances. A 4D (3D space + time) method is used to model each object so that the state vectors are estimated by Kalman filtering for circumstances involving horizontal curvature. Included in the process are the statistics of system and measurement noise. Figure 1 from the reviewed paper illustrates the 4D approach to dynamic vision conceived by the Armed Forces School.

The author made the following comments about the model for horizontal curvature. "A road usually consists of segments of constant curvature C or constant curvature change rate C 1. For applying the above approach to estimation of road curvature, there has to be a dynamical model for the spatio-temporal change of the curvature. This model is given by assuming a linear change of the curvature C(1) with the traveled arc length 1 within a segment Ls of the road according to eq. 1, which leads to the shape of the clothoid in the horizontal road plane. The transition

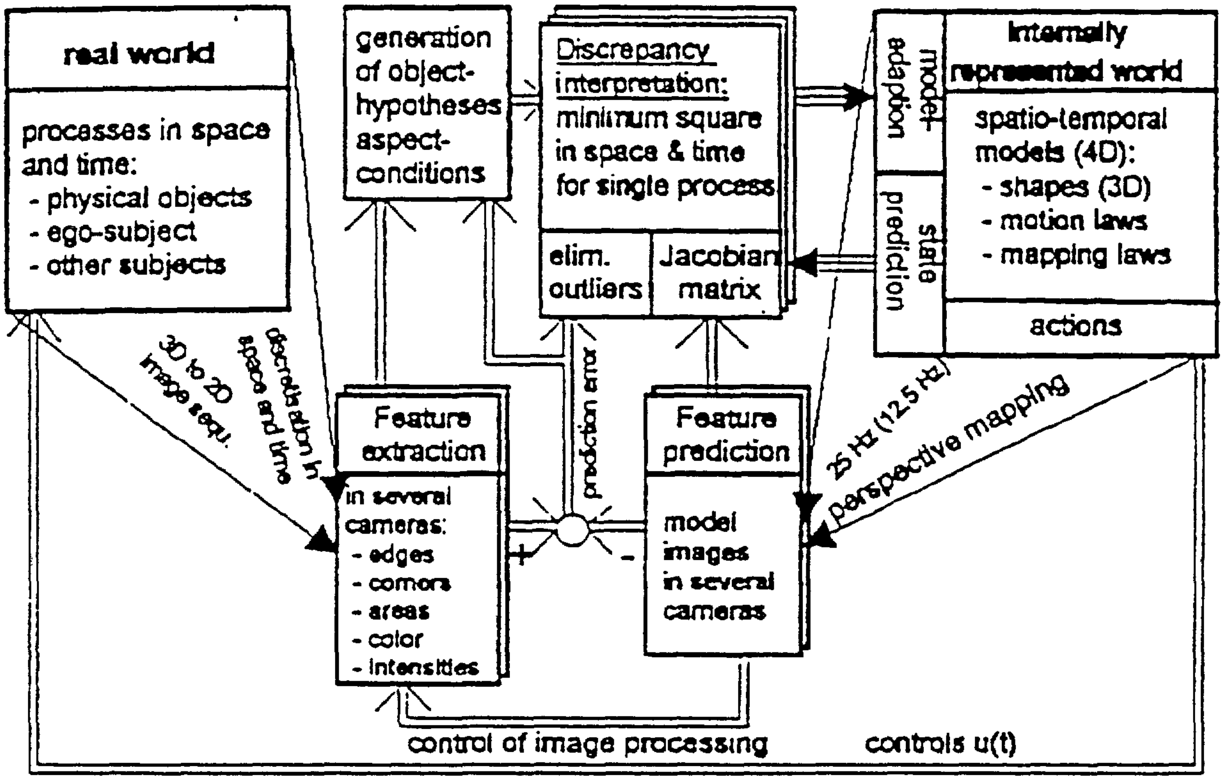


Figure 1: The 4D approach to dynamic vision

between such segments contains jumps in the curvature parameter C I, even when the curvature parameter C(1) is steady across the segment transitions

$$Cs(1) = C0,s + Cl,s * 1 \qquad LO < 1 < LO + Ls \qquad (1)$$

This problem has been avoided by modeling a smooth transition of the curvature by introducing an averaged curvature model.. .The average curvature parameters of this segment are assumed to be time-independent and to change depending on the vehicle speed v(t). Therefore, the road curvature can be described by a set of differential equations forming a dynamical model.. .A Generalized Likelihood Ratio (GLR) method can be applied to detect jumps of the clothoid parameter C 1."

Key Findings:

Applications: The primary topic of this paper concerns an improvement of an algorithm for road detection and tracking.

Specifications: The test vehicle is a Mercedes 500 SEL passenger car, and has been driven autonomously at speeds up to 130 km/hr. Driving performance includes maintaining the center lane position, avoiding collisions with other vehicles and overtaking other, more slowly moving vehicles. Equipment on the vehicle includes two CCD cameras in front looking forward and two cameras in the rear. Each camera has a different bifocal lens in the ratio of 1:3. Each set of two cameras is mounted on a specially engineered platform to provide saccadic gaze control.

The computer system consists of 60 transputers, which are partitioned into groups according to functional requirements, such as communication, image processing and object modules. Basic image processing is achieved by an edge extraction module, which uses mask correlation in specified areas of the image. "These algorithms run on 16 bit transputers T-222 and are synchronized by the video sync signal. Results are sent to multiplexer processors, which perform data selection and parameter adaptation for image processing control. Recursive estimation is performed on a singie 32 bit transputer T-805. From here, the estimated state vector is sent to the Dynamic Data Base (DDB) module, where it can be accessed from other modules in the system. "

Cost: N/A

Maturity: N/A

Safety: N/A

Reliability: N/A

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: “It has been shown that it is possible to detect changes of road curvature by a spatial recursive estimation process, derived from the Kalman filter, The segmentation into road segments with constant curvature Cl can be done by applying a jump detector derived from GLR methods. This approach seems promising for a recovery of other spatial properties, when the spatial property state vector X can be written as a piecewise steady function.. .”

Reichert, D., Schick, ***J., Collision avoidance in dynamic environments applied to autonomous vehicle guidance on the motorway,*** **In Proceedings of the Intelligent Vehicles 1994 Symposium (pp 74-78), Paris France, October 24-26, 1994, sponsored by the IEEE Industrial Electronic Society.**

Topic: Use of Scalar Potentials to Represent Roadway Obstacles for Automatic Vehicle Guidance to Avoid Collisions - German Research and Development (Daimler-Benz, Stuttgart)

Summary:

The Single-Vehicle-Roadway-Departure (SVRD) crash avoidance specification development program requires a countermeasure system to determine the edge of the roadway and provide a warning or possibly an automated control function to avoid such a departure. This requirement is addressed by the above referenced paper, which describes a concept to convert measured sensor data (e.g., range and velocity of other vehicles and objects) from complex environments into scalar potentials associated with objects under sensor surveillance and tracking. These potentials can be then used to calculate control signals to be applied to actuators of the subject vehicle. The actuators could provide either partial or full vehicle control, depending on the time available before impact. Alternatively, the same control signals could be first utilized for in-vehicle warnings if there is sufficient time for a driver response. This scalar potential methodology may be suitable for applications related to SVRD, intersection, rear-end and lane change/merge crash avoidance.

The Daimler-Benz prototype vehicle VITA II (discussed in this review series of German systems) is equipped with 18 video cameras in order to monitor the state of the environment external to it. Described in the above paper by Reichert et. al. is method of representing this sensor data by means of a dynamic risk map. The latter is essentially a three dimensional, topographical plot where the horizontal plane is defined by the x-y axes (i.e., the roadway) and the vertical axis (i.e., z axis) is related to the level of risk associated with an object within range of the subject vehicle's sensors. See Fig. 2 from the reviewed paper.

In analogy with electric scalar potentials, the topology of the risk map is distinguished by peaks and valleys. The peaks are co-located with obstacles to be avoided, while the valleys represent collision-free paths to be followed. The subject vehicle is, therefore, treated as a charged particle, which undergoes an increasing magnitude of repulsion as the subject vehicle nears a dangerous object. This "electrical" force, acting between an obstacle to be avoided and the subject vehicle, is calculated by taking the spatial derivative of each scalar potential and summing all the resulting forces (i.e., a total repulsive force acting on the subject vehicle).

The total repulsive force is combined with an "attractive" force, which defines the ultimate path goal of the subject vehicle (i.e., remaining on the road, where the goal could be a point at a predefined distance ahead of the subject vehicle) The result of this vector summation is converted into lateral and longitudinal accelerations to be generated by actuators on the subject vehicle

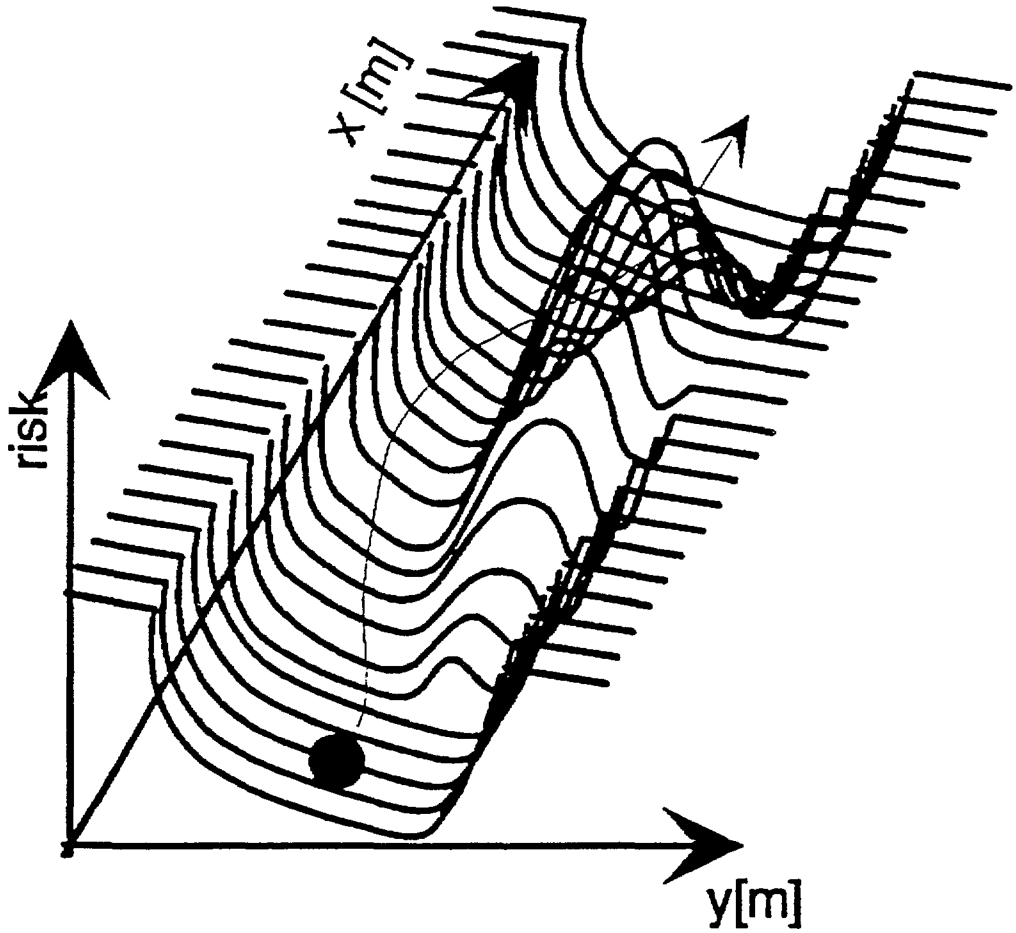


Figure *2: This potential field shows a simple traffic scenario with an obstacle ahead and a road with* ***two*** *lanes. The forces generated by the electric field guide the vehicle along the indicated trajectory.*

in order to maneuver the subject vehicle along a collision-free path, which is biased in the direction of vehicle's navigational goal.

In addition to the conversion of visual sensor data into associated risk potentials, other factors are also taken into account. The latter include a driver model for a specific driver, vehicle dynamical model and use of traffic sign information. The driver model is sufficiently adaptable so that different drivers may be represented.

This approach, used by Daimler-Benz, is based on the artificial potential field method, which has been developed by workers in the robotics community (see references at the end of this review). Workers at Daimler-Benz have adopted the theoretical frame work by Krogh and Thorpe (1986).

The method of defining the scalar field associated with an obstacle is summarized below based on an explanation due to Krogh (1984). For simplicity, assume a one dimensional motion such that the subject vehicle is traveling along the x-axis with a speed v and is heading toward a wall, which is a distance d away at some initial time. If the maximum deceleration of the subject vehicle is a, then it can stop in a minimum time oft: t = v/a. Conversely, if an acceleration of less than a is applied, say A, then the subject vehicle can attain zero speed over a distance d in a maximum avoidance time T: T = 2d/v. The reserve time is defined to be (T -t) and ***its reciprocal is the generalized potential field to which a spatial gradient can be appiiedfor calculation of the repulsive force.***

From this definition of the potential field, it can be seen that the potential becomes infinite when T = t and is zero when the velocity is zero. Thus, ***both*** the distance (i.e., between subject vehicle and obstacle), as well as the velocity of the subject vehicle are considered, so that the magnitude of the resulting potential field will be affected accordingly. This method can be extended to three dimensions by using vector quantities for velocities and distances and resolving their components along directions that are parallel and perpendicular with respect to the obstacle.

The potential field method may be suitable for treating the SVRD crash problem by representing the edge of the road as an obstacle (with its associated potential function) to be avoided. If one assumes the availability of sufficient sensor information (e.g., edge of the road, other vehicles, etc.), then the potential field methodology could provide a representation of these objects and rate them according to the risk factors related to approaching velocity and relative distance. The potential field algorithm could be extended so that in-vehicle warnings could be provided in cases where only moderate probability of a crash is likely based on the use of a risk "threshold." For circumstances where the risk exceeds the chosen threshold, then the potential field method can determine the required lateral/longitudinal decelerations to be applied by the subject vehicle actuators when there is no longer time to account for driver reaction. The latter quantity would be known presumably because, according to the German embodiment of the potential field method, there is provision for an explicit driver model.

Key Findings:

Applications: This topic concerns the determination of a collision-free path for vehicles operating in a highway environment.

Specifications: N/A.

Cost: N/A

Maturity: N/A.

Safety: N/A

Reliability: N/A

Availability: N/A

Acceptance: N/A

Technical Feasibility/Deployability: "The method described above has been implemented on a PC and on a transputer system. First results are taken from a simulation environment. In this environment the autonomous vehicle demonstrated accurate behavior. Apart from lane keeping, distance keeping, and overtaking, it solved dangerous situations caused by maneuvers of the vehicle."

"With the help of some simplifications made on the complex theoretical model the system is running on PC in real time. This was achieved by reducing the potential field to a set of peaks. The loss of exactness was tolerable for simulations."

References:

1. Krogh, B., **A** generalized potential field approach to obstacle avoidance control, Robotics Research Conference Papers, Robotics International of SME, Dearborn, MI, 1984

2. Krogh, B., Thorpe, C., Integrated path planning and dynamic steering control for autonomous vehicles, Proceedings of the IEEE International conference on Robotics and Automation, 1986

Choi, D.-H., **Oh, S.-Y., Kim, K.-I.,** ***Fitness-based modular sisuosteering architecture for super cruise control of automobiles,*** **In Proceedings of the Intelligent Vehicles 95 Symposium, (pp 170-175), Detroit, MI, September 25-26, 1995, Sponsored by the IEEE Electronic Society.**

Topic: Hybrid approach using both vision algorithms and neural networks for steering control

Summary: The primary application addressed in this paper is what the authors define as super cruise control, namely the functions of autonomous intelligent cruise control combined with autonomous road following and steering. Autonomous intelligent cruise control has the usual definition of maintaining a constant vehicle speed of the subject vehicle when no car is in front of it and then switching over to maintaining constant distance when there is a lead vehicle.

In the opinion of the authors neither vision algorithms nor neural based algorithms individually are sufficiently robust to provide adequate super cruise control performance. They present a hybrid approach, which combines the best features of both vision and neural networks image processing algorithms.

The concept of a hybrid approach may have interesting consequences for the single-vehicle-roadway-departure (SVRD) program. In the case of this program, the prototype vehicle engineered by Carnegie Mellon University (CMU) employs both forward and downward looking video cameras. The image processing in the look-ahead camera utilizes an algorithm called RALPH (Rapidly Adapting Position Lateral Handler), and was developed by CMU. For lane following applications RALPH performs well with a mean location accuracy from 11.1 to 15.8 cm. The accuracy depends on the type of road and lighting conditions (i.e., day versus night). In the case of the forward looking video system, it is interesting to speculate about the possibility of fusing (i.e., meant in the sense of this reviewed paper) RALPH with other image processing algorithms to create an integrated collision avoidance system to address the prevention of SVRD and other crash types (e.g., intersection crashes).

“In this paper, a different kind of modular architecture has been developed for road following. The system consists of several expert modules each of which generates its own output from the input using independent features and roles. First, the constituent modules are based on simple vision processing algorithms as well as neural net algorithms in that a bottom line stability is achieved by using the simple vision algorithms while more difficult situations are more effectively handled by the neural net algorithm. Use of the vision modules for simple input situations also allow to reduce the amount of training data for the neural net which then handles only difficult class of road scenes.”

“It (i.e., the modular system) consists of three distinct expert modules each acting on the same input image (See Fig. 2 from the reviewed paper). The edge module produces the steering command (S) by extracting edges from the road scene and the color module extracts them from color information of the lanes. The neural net module, however, generates the command by mimicking human drivers. In addition to the expert steering command, each module also

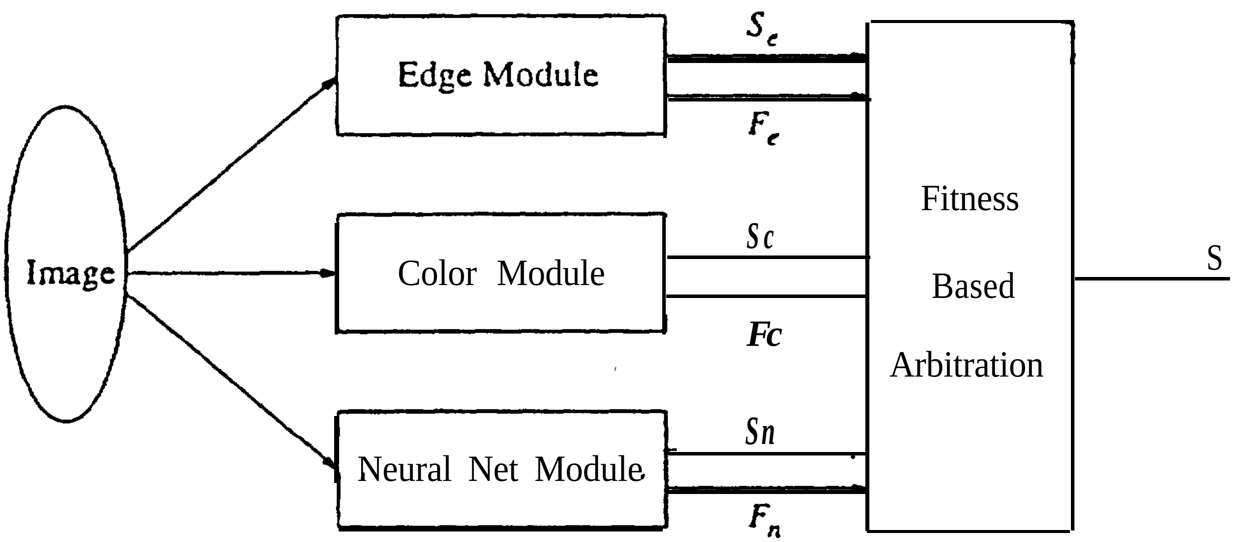


Fig. 2. Fitness-Based Visuosteering Modular Architecture

generates its own fitness (F) value that indicates the degree of expertise each module has for the input road scene at hand judged from its own experience."

Key Findings:

Applications: hybrid image processing architecture for autonomous driving or lane following.

Specifications: "Real driving experiments were carried out by driving the PRV II (a prototype vehicle) . ..using the proposed modular architecture. The edge or color modules can be run at 10 Hz while the modular architecture run at 5 Hz on an IBM PC 486. The neural network has been trained on-the-fly with real-time driving data in this experiment though it could have been trained off-line (with.or without fine tuning) with human driving data for later use on-line. The time saving in modular architecture is possible because the intermediate results in one module could also be used in other modules.

The low fitness values for the edge or color modules at the intersection are readily observed meaning that either of these modules alone would have driven the car off the road. On the other hand, with the modular scheme, the vehicle was able to run smoothly all along the path including two intersections at 30 km/hr on the average. It is important to note that cracks and shadows could also generate error in the edge or color modules. Finally, the proposed architecture also drove the van along the path at the average velocity of 45 km/hr with a maximum instantaneous velocity of over 60 km/hr."

Cost: N/A

Maturity: N/A

Safety: N/A

Reliability: N/A

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: "Future work includes a possible usage of fuzzy rules to the fitness evaluation stage instead of the fixed rule being used currently. Another topic of research is how to filter the steering command signals for smooth driving of the SSC (i.e., super cruise control). Also, a 2-D road modeling will facilitate generating even smoother commands due to the road prediction capability."

Suzuki, A., Yasui, N., Nakano, N. Kaneko, M., *Lane recognition system for guiding autonomous vehicle*, In Proceedings of the Intelligent Vehicles 92 Symposium, (pp 196-201), Detroit, MI, July 29-July 1, 1992, Sponsored by the IEEE Electronic Society

Topic: Video camera/image processing system for lane recognition and vehicle location

Summary: This lane recognition/vehicle location system uses a CCD video camera, a frame memory, PC, monitor, and four transputers. The latter perform the operation of thresholding the imagery, applying Hough transforms to fit numerical white line data to a straight line (i.e., both left and right lane lines), and lane recognition. The final result is that the numerical data is transformed into line imagery, which is superimposed on the original video image. The system is also able to predict the location of a lane line even if one is temporarily missing. This capability is based on the fact that the width and the height of a triangle (i.e., the road as it extends into the foreground) are constant for the same lane. Coordinates for two apexes can be calculated if one apex is known.

Key Findings:

Applications: lane keeping and vehicle orientation with respect to its lane.

Specifications: The video imagery of the road consists of a gray scale with 373 x 238 pixels x 8 brightness levels. The amount of imagery to be processed is minimized by choosing a camera elevation angle to eliminate as much of the sky background as possible. At the time of publication the processing time for one frame was 100 ms. Future research will focus on improving the accuracy of the system for use during more difficult ambient conditions. See Fig. 1 for schematic diagram of the system. In this figure TP-A performs a thresholding operation, TP-L/R, a Hough transform on the left lane/right lanes, while TP-DG provides a lane recognition function.

Cost: N/A

Maturity: Although this system has undergone some field testing, it is, however, a prototype and requires further refinement, especially for adverse weather conditions and additional evaluation for a wide variety of drivers.

Safety: N/A

Reliability: The video camera and electronics were installed in a vehicle, which was driven under a variety of conditions (e.g., daytime/fine/cloudy, daytime/rainy; twilight/fine; night/fine/cloudy; night/rainy). Accuracy of lane recognition was based on whether or not the calculated line was within 5 pixels of the original lane image. Recognition accuracy is dependent on the prevailing illumination and weather conditions. The system was accurate 97% of the time during daytime(fine/cloudy), but dropped to 76% during daytime rainy

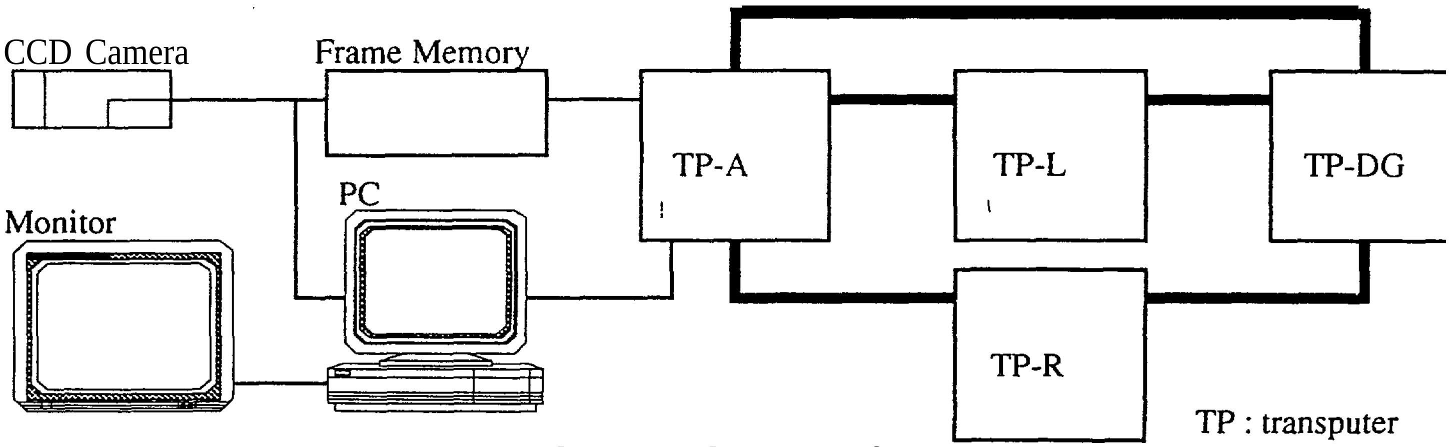


Fig. 1 Schematic diagram of system

conditions. This reduction is due to the fact that wet roads tend to reflect light into the video camera so that lane recognition becomes more difficult during the thresholding operation. Accuracy was 26% at twilight (fine), 98% at night (fine/cloudy), and 12% at night during rainy conditions. Twilight conditions were a problem because the sun angle was low and the road served as a good reflector of the sunlight. "It was also noted that the recognition of the location failed for several frames when the car crossed the white line. This occurred because the system could not identify the lane in which it belonged."

Availability: This is a prototype and is, therefore, not available.

Acceptance: N/A

Technical feasibility/deployability: This prototype has been engineered with off the shelf hardware and has demonstrated feasibility at the time of publication. The algorithms are well know, such as thresholding and the Hough transform. However, further improvements in performance for adverse weather conditions and additional testing are required.

Zhang, J. Nagel, H.-H., ***Texture-based segmentation of road images,*** **In Proceedings of the lntelligent Vehicles 1994 Symposium (pp 260-265) Paris, France, October 24-26, 1994, Sponsored by The IEEE industrial Electronic Society.**

Topic: Autonomous vehicle navigation based on location of road edges by differentiating roads and backgrounds by texture

Summary: In cases where roadway makers are not present or when color video imagery is not available, texture in the imagery may be a useful feature to distinguish (i.e., segment) road lane and background pixels. "In our approach, we characterize texture by it's orientation field and estimated from this the covariance matrix of the gray value changes in an image. Each point in this orientation field is a vector with two components: the local orientation and the strength of the texture anisotrophy. Both gray value changes and their covariances are calculated by using filters. Under the assumption that roads lie in a plane, we propose an approach that estimates a relative optimal filter scale at each point from the projection parameters of a calibrated camera."

Key Findings:

Applications: finding road edges for autonomous vehicle navigation and single-vehicle-roadway departure crash avoidance

Specifications: "We propose a new measure of the strength of the texture anisotrophy based on the eigenvalues of the covariance matrix of gray value changes. These two eigenvalues represent the gray value changes in both directions: along and across the texture orientation. The texture direction is related to the eigenvector orientations of this covariance matrix."

Cost: N/A

Maturity: N/A

Safety: N/A

Reliability: Experimentally it has been shown that, "although the gray value between the road surface and the environment appears very similarly, it can be clearly seen that the strength of the texture anisotrophy does show significant differences." This difference is highlighted in Figs. 3 (a), 3 (c), and 4 (b) from the reviewed paper. The original gray value image is illustrated in Fig. 3 (a). This image was processed by ***edge detection*** to delineate the roadway edge from the shouider in Fig. 4 (b), while in the result of ***texture-based*** image processing is shown in Fig. 3 (c). For this particular roadway/shoulder example, the results of the texture segmentation [Fig. 3 (c)] method provide a clearer depiction of this boundary compared to the edge detection approach where there is some edge ambiguity due to image processing artifacts in the roadway [Fig. 4 (b)].

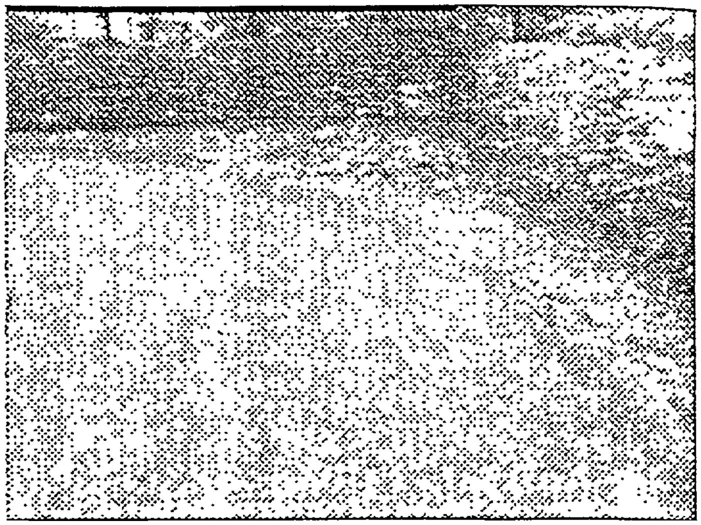


Fig. 3 (a) Grey value image

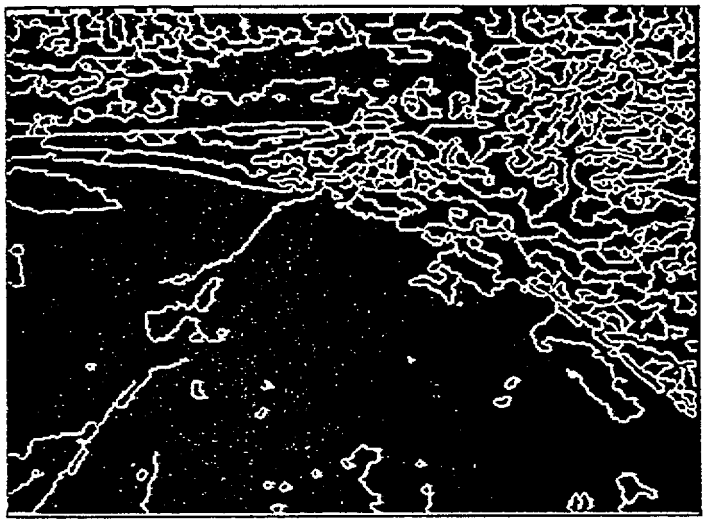


Fig. 4 (b) Contours detected *Fig. 3 (a).*

Figure *4: Road boundary detection using an edge-based method.*

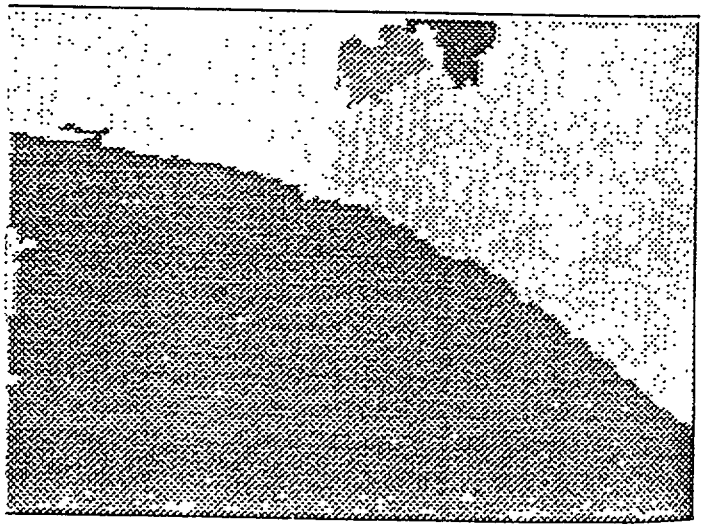


Fig. 3 (c) Segmentation result

Reliability (cont.). The best way to use this texture-based road detection is in combination with an edge-based technique. Such a hybrid system should be able to address situations neither could alone.

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: Image processing of roadway video with texture-based segmentation has been demonstrated. “The principle advantage of our method is its ability to segment the road images that cannot be characterized by color or contour.” However, the reviewed paper does not indicate the extent to which the described texture-based approach is effected by illumination, weather conditions or the amount of computational overhead needed for image processing, compared to other edge detection methods. Furthermore, the utility of this image processing method could be expanded by a modification, which avoids the assumption that the road lies in a plane.

Edge Detection/Lane Following (Infrastructure-Based)

Shladover, S., The California path program of IVHS research and its approach to vehicle highway automation, En Proceedings of the Intelligent Vehicles 92 Symposium, (pp 347-352), Detroit, MI, June 29-July 1, 1992, Sponsored by the IEEE Electronic Society.

Topic: Lateral vehicle control method based on infrastructure support

Summary: Established in 1986 by the Institute of Transportation Studies at Berkley, the mission of the Path (Partners for Advanced Transit and Highways) program is to apply advanced technologies for California's transportation system by performing related research . In addition to Advanced Traveler Information Systems (ATIS), Commercial Vehicle Operation (CVO), etc., the PATH program has performed considerable research in Advanced Vehicle Control Systems (AVCS), both for lateral and longitudinal applications. Much of this work is focussed on automated highway systems where vehicles would travel in platoon formations with close inter-vehicle spacing so that more vehicles could be accommodated in the longitudinal direction and would need smaller lane widths.

Unlike the Single-Vehicle-Roadway-Departure (SVRD) program, which uses in-vehicle video camera technology to measure lateral excursions of a vehicle, the PATH project utilizes an infrastructure approach to determine the lateral vehicular location. This infrastructure is based upon permanent magnetic markers, which are embedded in the lane center at regular intervals. The field of these magnetic markers is measured by a Hall-effect magnetometer located on the vehicle under the front bumper.

"The lateral control system is shown in schematic form in Figure 1. The lateral position error feedback signals from the magnetic sensors are combined with preview information about the road geometry to generate the steering commands. The preview information is encoded in the sequence of magnetic markers by alternating the magnet's polarity (so that each marker represents one bit in the sequence). Experiments have been performed with two different controllers, PID (proportional-integral-derivative) and FSLQ (frequency-shaped linear quadratic), both with and without the addition of preview information- A fuzzy rule-based controller is being designed and evaluated in simulation, so that it can later be tested on the vehicle as well."

Key Findings:

Applications: lateral vehicle control for automated highways and for SVRD crash avoidance.

Specifications: The vehicle remained with 5 cm of the lane center even when traversing a track with a 75 m radius of curvature at a speed of 50 km/hr. These conditions resulted in a steady lateral acceleration of 0.27 g, "which is relatively high by standards of normal freeway driving."

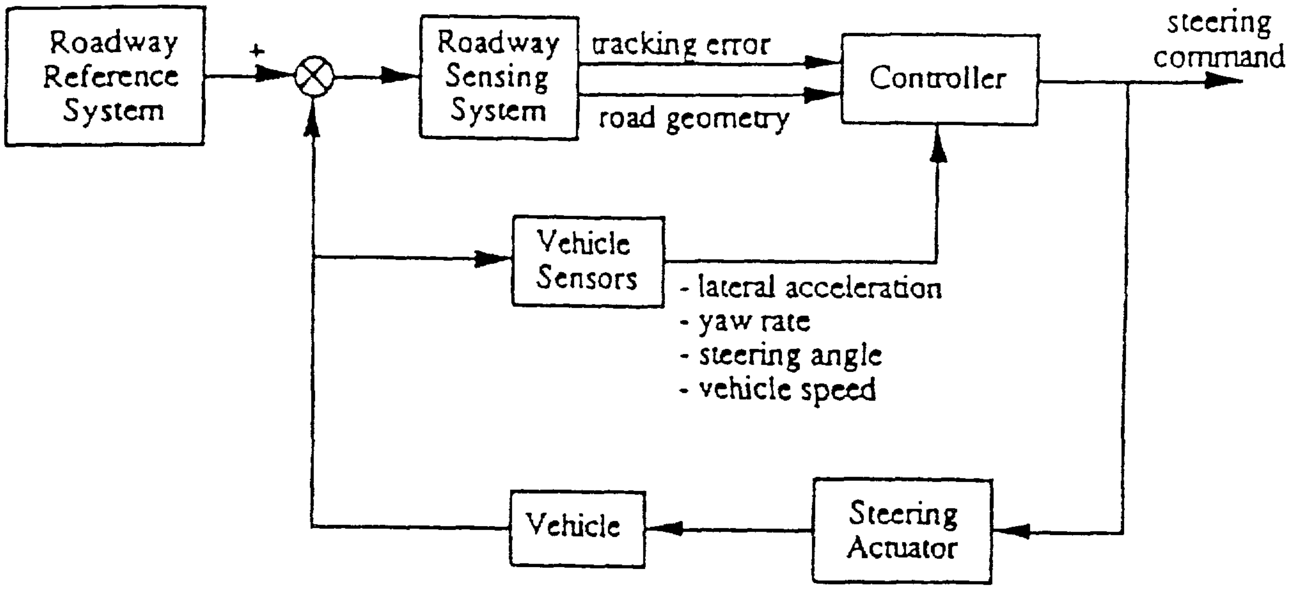


Figure 1. Lateral Control System Schematic.

Cost Ceramic magnetic markers cost approximately $1 each. “The cost of installing the magnets is likely to exceed the cost of the magnets themselves, but the installation process is expected to be well suited for robotic construction techniques that can keep the cost modest.”

Maturity: N/A

Safety: N/A

Reliability: “we are not aware of any other lateral control system for a road vehicle that has demonstrated a comparable combination of lane tracking accuracy and ride quality for conditions as demanding as this.”

Availability: N/A

Acceptance: see comments under reliability

Technical feasibility/deployability: The system has been proven to have technical feasibility under test track conditions. However, more extensive field testing is required. The deployability of such a system is somewhat problematic given the necessity to embed and maintain millions of magnetic markers in thousands of highway miles.

Ohnishi, K., Komura, J., Ishibashi, Y., ***Development of automatic driving system on rough road - realization of high reliable automatic driving system,*** **In Proceedings of the Intelligent Vehicles 92 Symposium, (pp 148- 163), Detroit, MI, June 29-July 1, 1992, Sponsored by the IEEE Electronic Society.**

Topic: Lateral and longitudinal infrastructure-based system for driverless vehicle testing on rough roads

Summary: The authors describe a test track to evaluate vehicle performance under rough road conditions for extended periods of time. In order to create a sense of realism, vehicles under test have on-board electronic control units to generate actual driving patterns by means of fuzzy control. The test track has a traffic control system to allow evaluation of multiple vehicles simultaneously.

The length of the test course is 676 meters and consists of an unpaved road. Control is achieved by guidance cables that are positioned on both sides of each lane, which is 4 meters in width. There are twenty four loop antennas for road-to-vehicle communications and are also laid on the main line. Two such antennas are located at the enter/exit lane. "Magnetic sensors installed at the front and rear portions of the vehicle detect the alternating magnetic fields generated by the guidance cables laid on both sides of the test course in order to calculate lateral displacements caused by fluctuation of the vehicle posture (pitching, rolling), which was the most serious problem of this method. The pickup coil configuration and the lateral displacement method have been optimized to allow the stable detection of lateral displacements even on rough roads."

Key Findings:

Applications: automatic, driverless testing of vehicles on rough roads

Specifications: Vehicle motion patterns are designed to closely resemble those of actual drivers. For example, specifications in this regard are: vehicle speed error is 3 km/hr, max; lateral displacement error is 0.5 meters, max. The measurement error in driving distance is 1 meter or less. The loop antenna induction radio is full duplex with 9600 bps so that bidirectional communication is possible at 100 km/hr. There are actuators for acceleration, braking, steering and shifting. See Fig. 3 from the reviewed paper for the configuration of the in-vehicle units.

Cost:

Maturity: N/A

Safety: Collision prevention control is accomplished by the fact that multiple vehicles under test are never in the same section of the course at the same time. Fail-safe features are: low speed driving mode (vehicle with a minor fault can continue driving), specified

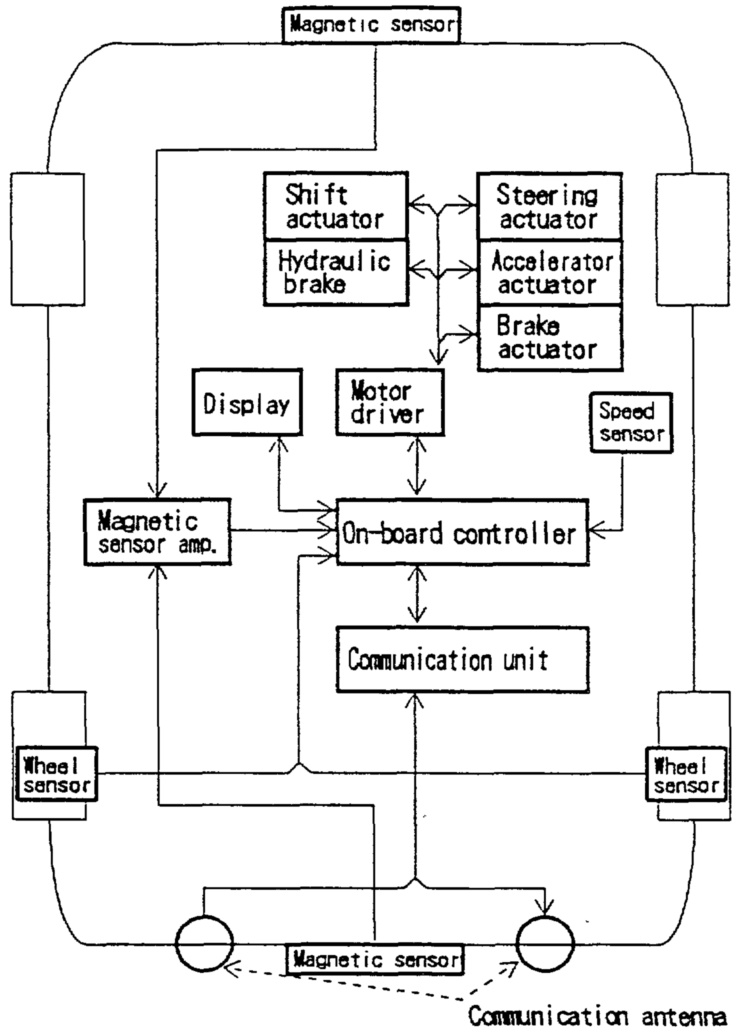


Fig. 3. Configuration of the on-board units

stop location mode (vehicle with a moderately serious fault continues to the nearest antenna and then stops), emergency stop mode (occurrence of a very serious fault causes the vehicle to stop immediately).

Reliability: Vehicle motion data from actual drivers and automatically driven vehicles was compared. “The frequency of the speed errors is lower for the automatic driving than the other, and the lateral displacement error of the former also satisfies the requirement of 0.5 meter difference from the target value.”

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: In a positive vein, the authors noted the following: “By application of the fuzzy control, the automatic driving is capable of attaining a similar steering pattern to that of the driver. .-According to the foregoing results, it was verified that the automatic driving was capable of evaluating vehicle durability under the same driving conditions as those driver operations. Finally, long distance driving test were carried out using the automatic driving vehicles to verify the durability, reliability and fail-safe features. Troubles, such as collision, non-controlled driving, course-out, etc. did not occur even once in the long distance driving. All faults created intentionally were detected, and the safety stop in the test was also confirmed.” As a negative aspect of this system it should be noted that that there is an increased difficulty of deployment and maintainance over magnetic markers due to the active nature of the buried cable. For example, a broken cable could be very problematic.

Stauffer, D., Barret, M., Demma, N., Dahlin, T., ***Magnetic lateral guidance sensors for automated highways,*** **SPIE Proceedings of Collision Avoidance and Automated Traffic Management Sensors, Philadelphia, PA, October 25-26, 1995, SPIE Vol. 2592, pp 138-149.**

Topic: Lateral guidance for vehicles provided by magnetic tape embedded in the highway

Summary: Some vehicle control approaches depend on in-vehicle machine vision systems to extract roadway references points, such as lane edges, for vehicle orientation. Technologies that rely on vision suffer from degraded performance during periods of adverse weather In order to counter weather effects, the authors have proposed the use of a two-axis magnetometer on the subject vehicle to sense the magnetic field from a tape, which is aligned along the center line of a lane. The magnitude of the measured field is proportional to the lateral distance between the tape and the magnetometer. It assumed that the sensor height is held approximately constant and that orienting the magnetic axis of the tape in the vertical direction will minimize cross coupling errors between the horizontal and vertical channels of the magnetometer. The ambient field of the earth is eliminated by electronic filtering.

Key Findings:

Applications: the primary application is lateral vehicle guidance, although preview information (e.g., radius of curvature of an approaching bend in the road) could be encoded in the tape.

Specifications: Figure 1 illustrates the placement of the magnetometer with respect to the magnetic marking tape. Shown in Fig. 2 is the orientation of the magnetic markers to achieve an alternating magnetic field for discrimination against the earth's ambient magnetic field. The sensor is a magneto resistive device that integrates four arms of a Wheatstone bridge on a silicon substrate and also includes planer metallized coils for resetting the sensor axis. The authors claim that the sensitivity of this instrument exceeds that of a Hall-effect magnetometer.

At the time of publication, several batches of different types of tapes had been developed, with 2 and 4 inch widths and a thickness of approximately 0.080 inches. The four inch tape provided a magnetic field of about 2 gauss at a distance of four inches above it and a field strength of approximately 7 milligauss at a distance of four feet. Road test have demonstrated that the tape is not readily demagnetized because it has a high coercivity, typically 3000-4000 oersteds

Cost: N/A

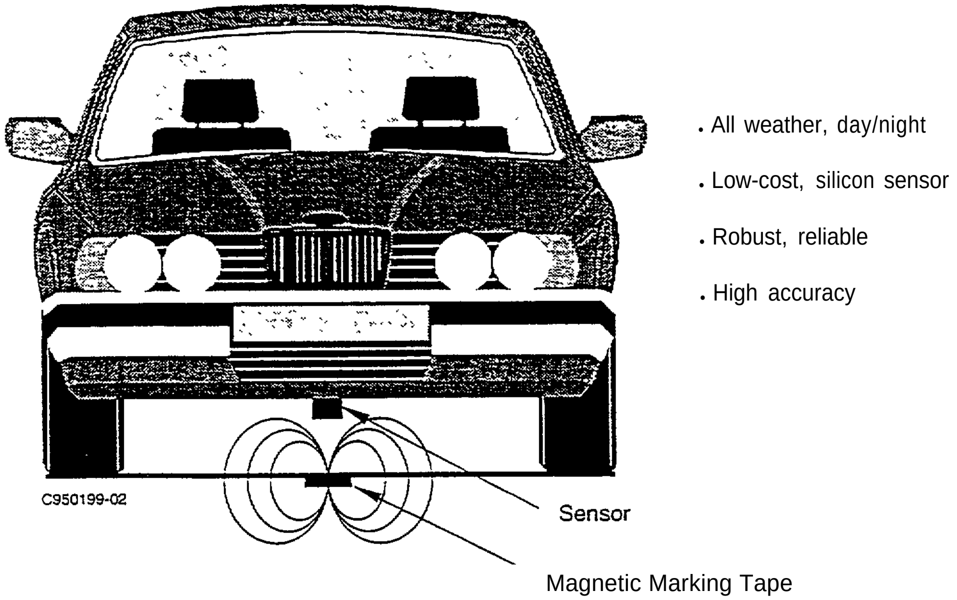


Figure l- Markers with field axis vertical provide determination of position in transverse plane.

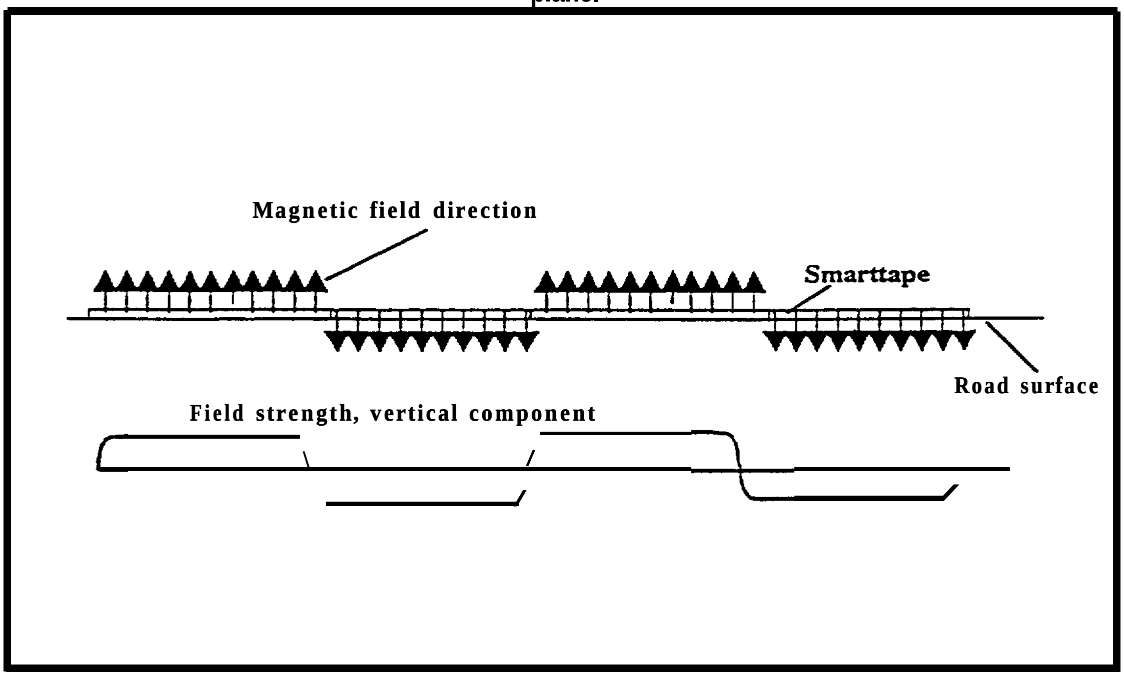


Figure 2- Alternating the field direction in a repetitive pattern allows discrimination against Earth's ambient magnetic fieId.

Maturity: This use of magnetic tape and a magnetometer is a relatively new concept that requires additional testing under a variety of weather conditions over long periods of time. Such test will help determine the permanency of the magnetic field and the adhesiveness of the tape to the roadway. It is this reviewer's understanding that the magnetic concept has been proposed for the guidance of snow plows in Minnesota. This application may provide useful data concerning the longevity of the magnetic lateral guidance concept

Safety. N/A

Reliability: N/A

Availability; Since this technique is still undergoing further development, it is not commercially available.

Acceptance: N/A

Technical feasibility/deployability: Initial field tests have confirmed the technical feasibility of this concept. However, additional test are needed to establish durability and accuracy over time. The deployability of magnetic tape would be increased if visually distinctive tape could be placed at the edges of a lane (rather than the middle, as illustrated in Fig. 1) and used to replace painted lane markings. It is known that the 3M company is investigating magnetic tape that would make this possible.

Tire Pressure Measurement

Wallentowitz, H., Riedl, H., Bruns, H., ***The Michelin-BMW tire pressure checking system The first active step towards the development of an active tire,*** **23 FISITA Conference-The Promise of a New Technology in the Automotive Industry, pp 799- 810, Torino, Italy, May 7-11, 1990**

Topic: Several tire pressure checking systems, including a system developed jointly by BMW and Michelin

Summary: A review of this paper was conducted because tire blow out, typically caused by under inflation, is one of the primary causes of vehicle failure related to single-vehicle-roadway departure (SVRD) crashes. This paper was chosen because it provides an overview of several tire monitoring approaches.

The authors indicate that tires are frequently driven at pressures below the recommended operating level. For example, "35% of all tires checked had a reduced pressure of more than 0.2 bar. Furthermore, 16% had an already dangerously reduced pressure of 0.5 bar." Operation at reduced pressures shortens tire life and has a negative impact on vehicle handling characteristics, especially during emergency maneuvers.

The latter consideration has a bearing on the countermeasure performance for SVRD crash avoidance. According to the work on Phase I of this project, the countermeasure response was based partly on the "last chance to act" which was the time when a vehicle could be maneuvered back to its original position in the lane center after deviating from its "normal" trajectory." This "last chance to act" is partly dependent on the response of the tires and effects the threshold settings for the SVRD countermeasures.

Tires tend to become heated due to the vertical flexing of tire as it is being driven. This heat from mechanical forces causes increased tire pressure due to the ideal gas law where temperature is proportional to pressure. Increased loading is translated into more flexing, and thus a pressure increase. Therefore, driving at higher speeds and with greater loading requires that tires should be inflated at higher levels to avoid flexing.

The authors reviewed several tire monitoring systems, which are listed in Table 1. From this table it can be seen that measured variables are pressure, pressure + temperature, oscillation characteristics, tire deflection and tire width. Due to the reasons cited above regarding causes for increased tire pressure, the authors are of the opinion that systems that measure only pressure and not the temperature are not effective tire monitoring devices. The table also differentiates tire monitoring system types, such as threshold, mechanical or electrical. Another important consideration involves operation of tire monitoring while a vehicle is at rest.

Tire Monitoring Systems

Measured Varialble	Manufacturer/Patent Owner	Name of System or Source	Threshold System	Analog System		Operation also when vehicle is stopped
				Mech. Sensors	Elect. Sensors	
Pressure	Concha	Electronic Tire Monitoring System	X			
Pressure	Nissan	TWD - III	8 pressure conditions			X
Pressure	Fuji Heavy Ind.	conf. manuscript	X			
Pressure +Temp.	Alligator/Doduco	Electronic Tire Pressure Monitor		X		
Pressure + Temp.	Bosch/Porsche	RKS- G/RDK	X			
Pressure + Temp.	BMW	DE 3029563C2				X
Pressure + Temp.	Imperial Clevite	Tire Tele	X			
Pressure + Temp	Labinal	Tire Control System				X
Pressure + Temp.	Michelin	MTM				X
Pressure + Temp.	Moto Meter	Tire Air Press.	X			
Pressure +Temp.	Schrader	Deflation Warning Device		X		
Oscillation Charact.	BMW/Daimler-Benz	No implementation systems known				
Tire Deflection	Continental	No implementation systems known				
Tire Width	Technomedia	No implementation systems known				

Key Findings:

Applications sensors for measuring tire parameters such as pressure, temperature + pressure, oscillation properties, deflection and width

Specifications: The authors reviewed five specific tire monitoring systems These are RKS-G, Tire Tele, TCS, MTM and TPC. Although operating principles were summarized, few specifications were provided. Several graphs were provided to illustrate the relationships between vehicle speed, temperature and pressure.

Cost: N/A

Maturity: From the description of the tire monitoring techniques in the reviewed paper, it is reasonable to assume that their maturity and reliability should be reasonably high compared to other, more complex systems reviewed in this report

Safety: N/A

Reliability: See comments under maturity.

Availability: At the time of this review the tire monitoring methods exit as prototypes and are not yet commercially available.

Acceptance: N/A

Technical feasibility/deployability: The authors discussed prospects for a so-called active tire, which relies on tire-monitoring and a means to actively change the tire pressure to accommodate loading, speed and driving comfort. “This means that a system with the following characteristics should be available:

1. The tire pressure corresponds continuously to the tire load that can be calculated from the loading condition and actual speed. In this connection the tire pressure is especially determined under consideration of driving comfort.

2. Influences on the tire pressure resulting from changing ambient conditions as for instance temperature of the ambient air and barometric pressure are automatically compensated.

3. In the case of leakages- these may be minor leakages in the filling valve or such ones caused by objects entered into the tire - additional air will be automatically pumped into the tire.”

Measurement of Roadway Surface Conditions (In-vehicle Systems)

Cremona, P., Kunert, M., Castine, F., ***Parametric Spectrum analysis for target characterization,*** **In Proceedings of the Intelligent Vehicles 94 Symposium, (pp 149-154), October 24-26, 1994, Paris, France, Sponsored by the IEEE Electronic Society.**

Topic: Radar to determine vehicle ground speed and classification of the roadway in front of the vehicle

Summary: The importance of this paper to the SVRD (Single-Vehicle-Roadway-Departure) crash avoidance project is that the authors have developed an in-vehicle radar system to measure both vehicle ground speed and the condition of the road surface ahead of the vehicle. Knowing these parameters, especially in a preview mode, would provide more reliable lateral and longitudinal vehicle control. Both of these parameters were obtained by first determining the power density spectrum of the reflected radar beam. This spectrum has an array of lines (i.e., intensity versus radar frequency), whose pattern is indicative of the roadway surface. Since the spectral lines are Doppler shifted due to the relative velocity between the road and the vehicle, the vehicle speed can be measured by measuring the shift of a spectral line, where the shift is proportional to the vehicle speed.

Analysis of the reflected radar data may be accomplished by several methods and is typically done by the Fast Fourier Transform (FFT). A Fourier transform is given by a series of sines and cosines (i.e., orthogonal functions), whose coefficients are calculated by the FFT technique. The magnitudes of the coefficients uniquely represent a particular return beam. The authors, however, elected to use another method called autoregressive (AR) parametric estimation to represent the spectral density of the reflected radar beam. The reason given by the authors for employing the autoregressive method is: "The biased estimates with poor resolution and high side lobe levels (especially found when short data records are evaluated), produced by the conventional spectrum analysis (e.g., the FFT), are overcome by using the parametric spectrum analysis. The AR method provides estimates with reduced bias, improved resolution, and no side lobes. Second, the AR modeling reduces the essence of large data samples to a small number of parameters with condensed information about the signal. So this method constitutes a suitable technique for pattern recognition because the resulting classification algorithm will require less computational effort with fewer, but more significant data inputs. Moreover, from these autoregressive parameters, we can create diierent sets of parameters containing the desired information, which can be used directly in a classification scheme."

Key Findings:

Applications: determination of vehicle ground speed and classification of a roadway in front of the subject vehicle.

Specifications: A radar beam with a 38 GHz center frequency and a frequency bandwidth of 600 MHZ was used in a homodyne receiver. The outgoing beam was a continuous wave with frequency modulation (FMCW.) There were two separate, identical antennas, one for transmission and one for reception. Each antenna was of the horn type and had an aperture of 14 deg x 14 deg. The averaged transmitted power was 20 milliwatts with rectangular polarization.

The authors point out that most radars for autonomous intelligent cruise control will utilize switched, multiple beams. It was suggested that one of these beams could be reserved for vehicle ground speed and roadway classification. For the work described in this review, the authors used a depression angle of 16 degrees (i.e., 84 degrees between the vertical to the ground and the center of the beam) in order to project the radar beam at some distance in front of the subject vehicle.

Cost: N/A

Maturity- N/A

Safety: N/A

Reliability. This topic is addressed in two parts, one concerned with ground speed measurements and the other with road surface characterization. Ground speed measurements were obtained by analyzing the radar data by means of different Doppler frequency estimation methods, including AR. Over a range of speeds from 3 1 km/hr to 107 km/hr, the AR method yielded the lowest variances of speed over ground. Accuracy was quoted in terms of variance, which was 0.267 km/hr (at a vehicle speed of 3 1 km/hr), 0.612 km/hr (at 50 km/hr), 0.507 km/hr (at 98 km/hr) and 1.367 km/hr (at 107 km/hr).

Road surface characterization is accomplished by first determining the spectral power density of the reflected radar beam for various road surfaces and conditions. These power spectral densities were reconstructed by means of the AR techniques using only 8 coefficients. The number eight was found to be the maximum number needed to reduce the variance in the ground speed measurement to a minimum value. Use of more than eight coefficients did not cause a further reduction in the ground speed variance. Spectra of known road surface roughnesses and wetness levels were acquired as references in order to compare them with other road surface conditions later.

The authors used two types of pavements, one slightly rough and another with a higher degree of surface roughness than the first pavement type. The amount of wetness was varied from at most slightly wet in the case of the first pavement type, up to considerable wetness for the rough roadway pavement. (The level of wetness was not quantified, nor was the degree of roughness). See Figs. 6 and 7 from this reviewed paper, that illustrate power density functions for wet and dry roads. There is a noticeable difference in the structure around the central peak, which varies according to pavement conditions.

Intermediate cases of wetness are distinguished by the degree to which their power density spectrum of the return wave resembles the power density spectra of a dry road surface. The degree to which they are similar is determined by a pattern classification technique

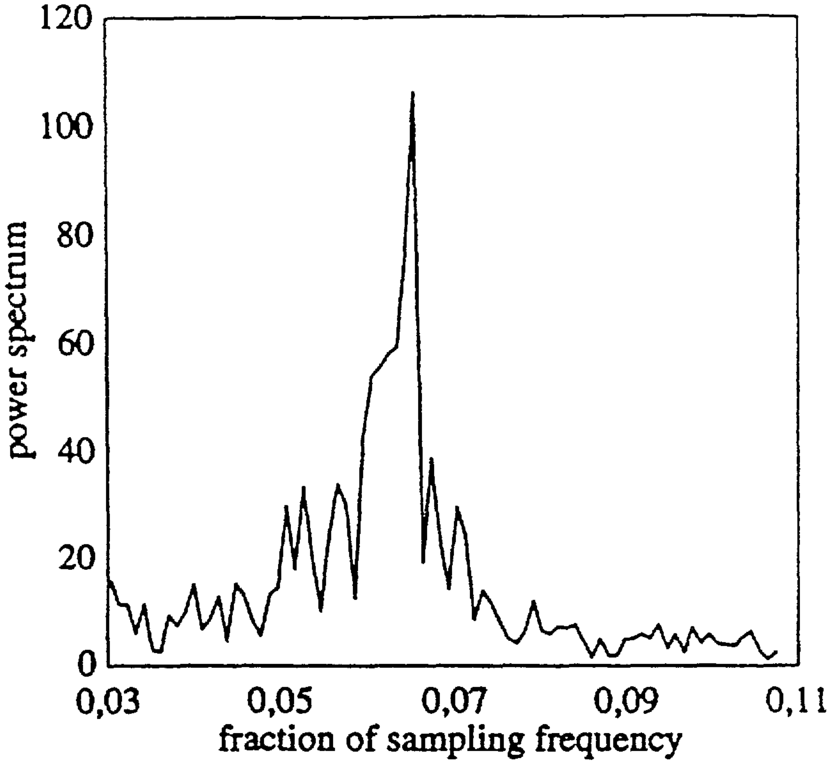


Figure 6 : typical wet road spectrum

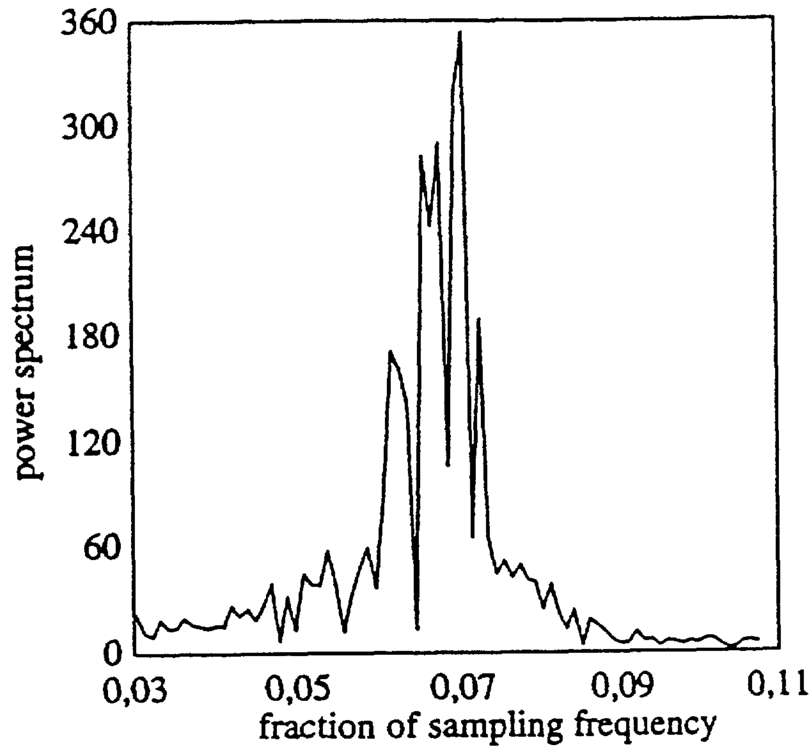


Figure 7 : typical dry road spectrum

using k-Nearest Neighbors (kNN) as determined by an appropriate distance metric, such as Euclidean, Mahalanobis, X^2, and Cepstral distances. Several blocks of radar data were subjected to these distance metrics to determine the k-Nearest Neighbors. Except for the Mahalanobis distance metric, the other metrics were inconsistent from one block of data to the next.

Availability: N/A

Acceptance: N/A

Technical feasibility/deployability: Generally, the results of this paper demonstrate the potential feasibility of classifying the return beam on the basis of road surface roughness and wetness ahead of the subject vehicle. However, more work is needed to enhance the reliability of this technique, perhaps by a neural network classification technique. Also, this technique should be tested on snow and icy road conditions. There is a constraint indicated by the authors where the results of classification are dependent on the speed of the subject vehicle and the frequency modulation slope of the FMCW beam. The latter parameter can probably be standardized so that it does not influence the classification process. However, the influence of vehicle speed on classification may be more problematic.

Yoda, S., Okabe, H., Takagi, J., Yamashita, T., ***Road surface recognition sensor using an optical spatial filter,*** **In Proceedings of the Intelligent Vehicles 95 Symposium, (pp 253-257), Detroit, USA, 1995, Sponsored by the IEEE Electronic Society.**

Topic: Optical system using a laser to measure ground speed and characterize road surface conditions

Summary: Both this paper, and another paper (Cremona 1995) presented in this review, offer the possibility of measuring the wetness of roadway surfaces. Real-time knowledge about such conditions would afford better lateral and longitudinal control of a vehicle to avoid single-vehicle-roadway-departure (SVRD) crashes.

The optical system discussed in this paper consists of an array of light emitting diodes whose beams are directed nearly perpendicularly to the road surface. After reflection from this surface, the return beams pass thru an objective lens, a collimating lens and then through a spatial filter (i.e., a grating with periodic openings), which performs a Fourier transform on the return beam. This transformed beam is split into two beams by a prism array. Each of these beams is detected by a PIN diode.

The magnitude of the ground speed influences the Doppler shift of the spectral lines in the Fourier transform. Measurement of the shift for one such spectral line yields the ground speed.

Effecting the pattern of the Fourier transform are the distribution of particle sizes in the roadway and the brightness of the intensity of the reflected beam. Two indices were defined by the authors that are related to the properties of the Fourier spectrum. The indices are formed by first measuring the area under the largest peak of the Fourier transform and the area under the low spatial frequency part of the spectrum. These areas are essentially the integrals of the Fourier intensity where the limits of the first integral (i.e., area under the spectral curve) are over the range of low spatial frequencies, while the limits of the second integral span the spatial frequency range that defines the extent of the main peak in the transform, respectively. If Al is the first such area and A2 is the second, then according to the authors, the first index (11) is A1/A2, while the second index (I2) is simply A2.

Five different roadway surface types were measured by this optical system: dry asphalt, wet asphalt, fresh snow, trampled snow, and black ice. Plots of 11 versus I2 serve to distinguish these various road surface conditions and are illustrated in Fig. 10 from this reviewed paper. Figure 10 shows five distinct clusters of data points for dry asphalt, wet asphalt, trampled snow, black ice and fresh snow. The clustering is most compact for wet asphalt, black ice and dry asphalt and less so for trampled and fresh snow.

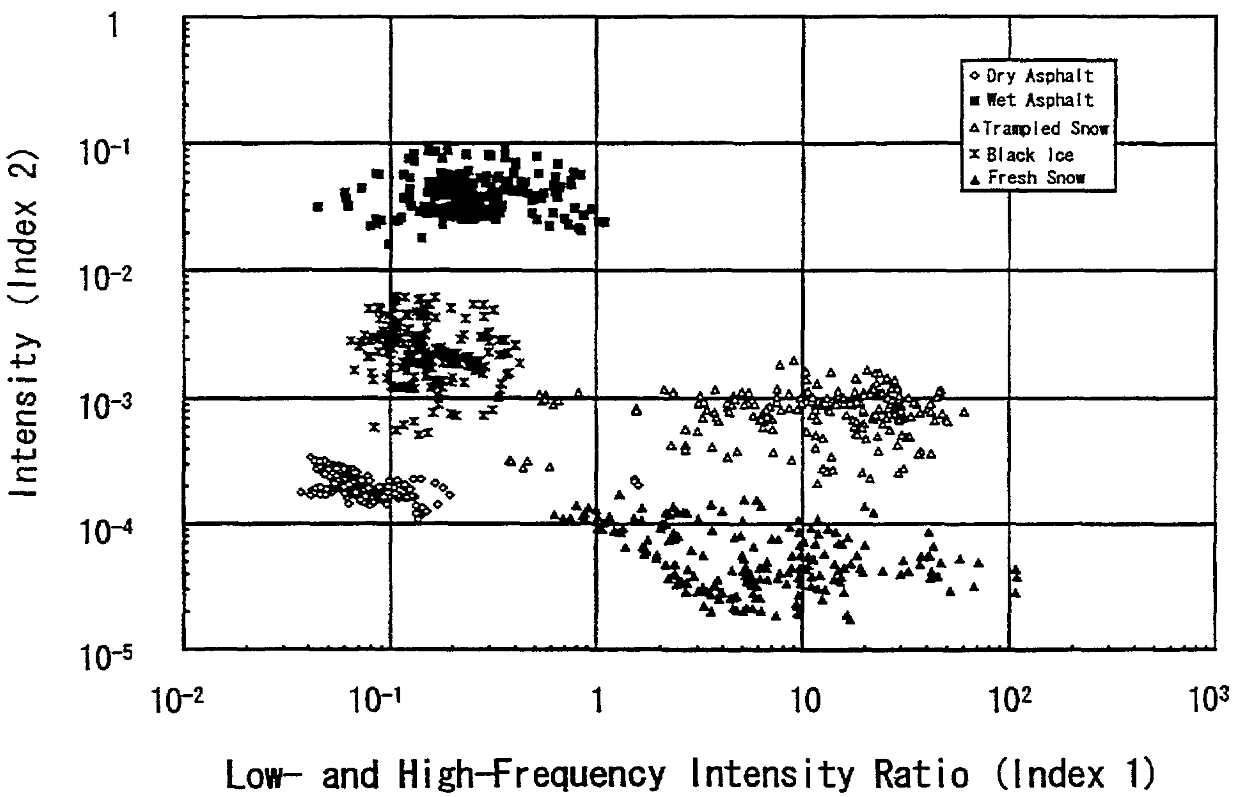


Figure 10 Road Surface Recognition by 2 indices

Key Findings

Applications: This optical technique provides the capability of determining the condition of road surfaces by equipping a vehicle with an instrumentation package having the above mentioned components. As the vehicle traverses the roadway, a real-time scan can be acquired to provide data needed for vehicle control. A highway service vehicle could be equipped with this laser scanner so that the results of scanning could be transmitted by an rf link to a central traffic control facility, which could broadcast roadway conditions to motorists. A laser scanning system could be outfitted on individual vehicles, but there would be no preview information, since laser scanning by this method is strictly in the direction perpendicular to the direction of motion.

mote: There is a company, Aerometrics, which has developed a laser scanner to determine the position of painted roadway markings by differentiating between the back scattered laser beam from the painted line (i.e., a spectral component) versus the diffuse reflection from the rest of the pavement (e.g., concrete, tar). This program has been supported by the National Highway Traffic Safety Administration (NHTSA). It is interesting to speculate if the power density spectrum of the laser (Aerometrics) return beam could be characterized according to the wetness of the roadway surface, assuming that the laser beam could be set to impinge on the roadway surface at a distance in front of the subject vehicle. If such a characterization were possible then the Aerometrics system could provide preview information in contrast to this reviewed system, which does not]

Specifications: As a velocimeter, this system will measure velocities from 2 to 220 km/hr with accuracies of +/- 1.5 km/hr (2-50 km/hr) and with +/- 3 9 km/hr (50-220 km/hr). The response time is 30 ms. Mounting on a vehicle can be at a height of 300 +/- 70 mm. The detecting diameter of the laser beam is 50 mm.

Cost: Although this factor was not directly addressed, the components are all off-the-shelf and could be assembled into a high volume commercially available unit, at least in principle. It is not clear at this writing whether drivers would want to buy such a system.

Maturity: N/A

Safety: Although this system has demonstrated some potential, it should be field tested under a greater variety of conditions.

Reliability: Consideration could be given to indices other than the ones plotted in Fig. 10 to achieve even more compact clustering and avoid possible ambiguity (i.e., not knowing whether a data point belongs to trampled or fresh snow).

Availability: N/A

Acceptance. N/A

Technical feasibility/deployability: The laser scanning system has potential as seen by preliminary data. However, further tests are required, either on individual vehicles or on a highway service vehicle so that advanced roadway conditions could be made available to a large number of drivers.

Hazard Detection and Warning (Infrastructure-Based)

Hazard Detection and Warning Svstems

There is a requirement for sensors to measure roadway surface conditions to broadcast that information to motorists in advance of the actual roadway area, which may be effected by water, snow and ice Such information could be used by an in-vehicle SVRD countermeasure system to determine braking distances for road surfaces with reduced coefficients of friction and to define safe entry speeds to roads with horizontal curvature. Given below are excerpts from vendor literature that have this capability This sampling is not meant to be necessarily representative but rather to provide an indication about the feasibility of in-pavement measuring systems.

Product Literature from Surface Systems, inc., 11612 Liburn Park Road, St. Louis, MO 63146

SCAN FP 2000 Roadway Sensor

This product is an in-pavement, cylindrically shaped sensor, which is designed to measure the freeze point, percent of ice in the measurement, percent of chemicals in the solution and the depth of the solution. According to the product literature, this sensor operates from -22 to 122 deg F, provides depth of solution readings from 0.01 to 0.50 inches, solution freeze points from -5 to 32 deg F, and percent of ice (slush) from 0 to 100%. The sensor is 5.25 inches in diameter, 1 75 inches in height, weighs 2.75 pounds (without a cable), and is outfitted with cables from 75 to 300 feet. The in-pavement sensor is connected to a remote processing unit (RPU), which can be located up to 2500 feet. After processing several in-pavement sensors, the RPU transfers the data to a central monitoring facility.

Product Literature from Vaisaia, Helsinki, Finland

Icecast, Ice Warning System

Real-time information about road surface conditions can be obtained with the Icecast system, which consists of several road sensors, as well as other sensors that measure atmospheric parameters, such as wind speed, precipitation, dew point, and air temperature. This system calculates freezing points, and differentiates between the following surface conditions: wet and salty, moist, dew, hoard frost, snow, wet, dry and black ice. According to the Vaisala product literature, features include:

- “Forecast graphs of road surface temperature and conditions for the next 24 hours”
- “Real-time data automatically plotted against the forecast graph”

- [] "Forecast temperature maps, which show the minimum road surface temperature across a network"

- [] "Forecast anti-icing route maps, which show the minimum road surface temperature across individual treatment routes"

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