SANDIA REPORT

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Smart Vehicular Transportation Systems

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Abstract

This work builds upon established Sandia intelligent systems technology to develop a unique approach for the integration of intelligent system control into the U. S. Highway and urban transportation systems. The Sandia developed concept of the COPILOT controller integrates a human driver with computer control to increase human performance while reducing reliance on detailed driver attention. This research extends Sandia expertise in sensor based, real-time control of robotics systems to high speed transportation systems. Knowledge in the form of maps and performance characteristics of vehicles provides the automatic decision making intelligence needed to plan optimum routes, maintain safe driving speeds and distances, avoid collisions, and conserve fuel.

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Introduction

The research presented addresses the integration of sensors and real-time computer control into driver operated vehicles. A major objective of the work is to provide automatic driver assistance to reduce accidents, improve fuel economy, and reduce the nation's need for new highways and urban roads. This research extends he Sandia developed COPILOT control concept in which a human operator and real-time intelligent control computer share overall system control to enhance performance. Key to the COPILOT control concept is the Sandia developed KRITIC (Knowledge based Review and Intervention To Impose Constraints) controller which employs a parallel computing control architecture to simplify software development and provide robustness. We have applied these concepts to a vehicle operated in highway environments.

This research was motivated by recently heightened awareness in the US that highways are overly congested with traffic not only at rush hours, but during many other times of the day. The conventional approach to relieving this overcrowding is the construction of more highway systems However, this is very expensive, and in may areas there is little room for additional highway construction. Thus, a concept termed Intelligent Vehicle-Highway Systems (IVHS) currently under aggressive development in Europe and Japan is receiving increased attention in the US Almost all work in IVHS worldwide is focused on developing technology to automatically provide information (e.g., road conditions, map locations, etc.) to the vehicle operator to allow informed decision making by the driver.

We have focused on the concept of an Intelligent Vehicle. Almost all other research in the IVHS area focuses on information systems for the driver. Sandia has an extensive technology base in Intelligent Machine Systems, which we have used to develop systems for an intelligent driver-operated highway vehicle. We have combined an intelligent on-board agent in the form of the COPILOT control concept to assist a human driver. The system is modular, and allows the evolution to more autonomy with less driver interaction as intelligent system technology evolves.

During this project, we modified a small commercial vehicle to allow shared driver/COPILOT control. A parallel computing environment, with the KRITIC controller was integrated into the vehicle as the on-board real-time computing environment. In addition, sensors to detect obstacles and automatically avoid collisions were integrated into the vehicle. The focus of the research was the development and testing of shared control algorithms.

Statement of the Problem

Most of the world's highway systems are outdated and extremely congested even during non-rush hour times. In many cases the construction of new additional highway systems is infeasible due to costs incurred or lack of space, especially in metropolitan environments. Development of technologies which better utilize existing highway systems and reduce the extent of new highway construction is needed. Such development programs are already underway in Europe and Japan and are now just receiving attention in the US The basic goals of all of these programs is to incorporate a range of technologies to improve mobility and transportation productivity, enhance safety, maximize the use of existing transportation facilities and energy resources, and to protect the environment.

The problem is reaching a critical stage. A 1986 study of 29 major cities estimated that $24 billion per year was lost in those cities alone due to congestion. In each of the 12 largest

metropolitan areas, losses exceed $1 billion per year in 1986 and have been increasing since. Europe and Japan are aggressively pursuing the development of IVHS technology with a principal focus on information systems. However, neither Europe nor Japan have significant efforts in the development of intelligent control systems for highway vehicles.

Literature Search and Interactions with Automotive Industry

A focused literature review of the Pilot-Assisted Vehicles on the Interstate Highways was completed to determine key needs areas. The literature review of highway driving lead to the realization that highway construction is guided by specific design principles which in a computer control sense adds structure to the highway driving environment. These characteristics of good highway construction provide key modeling information needed to construct computer models to provide the technology for Intelligent Highway Vehicle Systems. In addition, during the review of technology needs for advanced highway systems, automated collision prevention for operation on narrow lane highways (which can increase the capacity of existing highway systems 25% to 50%) and for prevention of hazardous materials spills were identified as key need areas. It was learned, for example, that regulations governing environmental damage in California preclude much needed shipments of hazardous waste to central processing sites due to fear of in-transit accident and spills. Intelligent, computer assisted driving employing technology under development in this project directly addresses this critical problem.

System Description

A small commercial vehicle was chosen as a development platform for this program. The vehicle was modified as described below to test and develop autonomous driving, which in turn allowed us to develop and test the shared driver/COPILOT control. Fully autonomous control was extended to remote control, including on-board computers, communication via radio frequency communications, and a base station with additional computing. This enabled the vehicle to be used for other projects as well, but was somewhat mandated by ES&H concerns of putting a driver in a prototype platform. The results were quite satisfactory for this research. We were able to test a full range of operator/COPILOT shared control. One noticeable side effect is the reduction of operator stress and fatigue, do to the error detection and correction capabilities.

Figure 1. Vehicle   Figure 2. Vehicle Control Center

- **The Vehicle**

The vehicle shown in Figure 1 consists of a Honda Pilot off-road vehicle modified for remote operations by installing actuators on the gear shift, throttle, brake, and steering mechanism. The on-board computing systems and communication modules were placed at the original location of the driver to provide a weight distribution similar to that of a standard unmodified Honda Pilot. The control computers use sensory information and models of the vehicle performance to map and modify the remote driver commands into control inputs for the vehicle control actuators. Other equipment includes cameras for live video, a global positioning system, and various sensors to monitor on-board system status and others that monitor external parameters, such as nearby obstacles. Electrical power for the added equipment is produced by a generator mounted on the vehicle.

- **Control Center**

The Mobile Control Center (MCC) is built into a 24 foot dual axle trailer. The operator control console and other hardware and controls are mounted in the front end of the trailer. The control center is built around an SGI (Silicon Graphics, Inc.) UNIX-based graphical workstation, with a large central monitor. Smaller video monitors are included for real-time visual feedback. Other equipment includes video and digital communication systems, a VME rack used for image processing, and a global positioning system. The vehicle robot is transported in the back of the trailer which is also equipped as a workshop for minor repairs and maintenance of the vehicle. The trailer is equipped with a generator, air conditioner, heaters, lights, and electrical power conditioners to enable self-contained operation.

- **Deploying The Vehicle**

The operator sits in front of a large computer console (shown in Figure 2). Primary interactions occur through a mouse, using a point & click interface for the majority of the commands. A second input device, a 6 degree of freedom space ball, is also used during shared control of the vehicle. Also, the keyboard is used to name objects within the graphic interface.

- **Communications**

Communications between the vehicle and MCC occur by means of two commercial Radio Frequency links. Digital and video feedback are transmitted on separate frequencies. The communications system allows operation of the vehicle as far as five miles away from the control center trailer.

Vehicle Sensors

The vehicle is equipped with additional sensors to enable the COPILOT functions. Sensors providing feedback for normal driving operations included actuator position sensors for throttle, brake, and steering; sensors for speed, fuel level, oil pressure; and a video camera to allow the operator to see were the vehicle was going. The COPILOT system required ultrasonic range sensors and a GPS system for navigation and obstacle avoidance. Figure 3 shows the location of the GPS antenna and the location and field of view for the ultrasonic sensors.

- **Global Positioning System**

A global positioning system (GPS) was purchased to support map following an automatic, driver assisted navigation. The GPS system was tested at the Sandia Robotic Vehicle Test

Range. The system was later deployed on the target vehicle. A second GPS system was installed in the MCC, and differential GPS operation was made available.

• Ultrasonic Sensors

Ultrasonic sensing was used to detect the location of unknown objects. The ultrasonic sensors are piezoelectric transducers using a chip based driver circuit to transmit a pulse and detect the return sound wave. The system uses two 26 KHz (long range) and two 40 KHz (shorter range) transmitters. The output was transmitted in an approximately 30 degree cone.

In the past the range has been a limiting feature (out to 10 feet). Thus, a project was initiated to increase the useful range of this sensing technology for use on the vehicle. A prototype ultrasonic sensor system was designed and tested with excellent results. The effective range of the ultrasonic sensing system has been increased to approximately 50 feet. A key feature in this new range sensing system has been the development of a dynamic sensitivity function which automatically varies the sensor sensitivity with range. Thus, objects at large distances are detected with increased sensitivity while close objects are detected with reduced sensitivity to reduce noise.

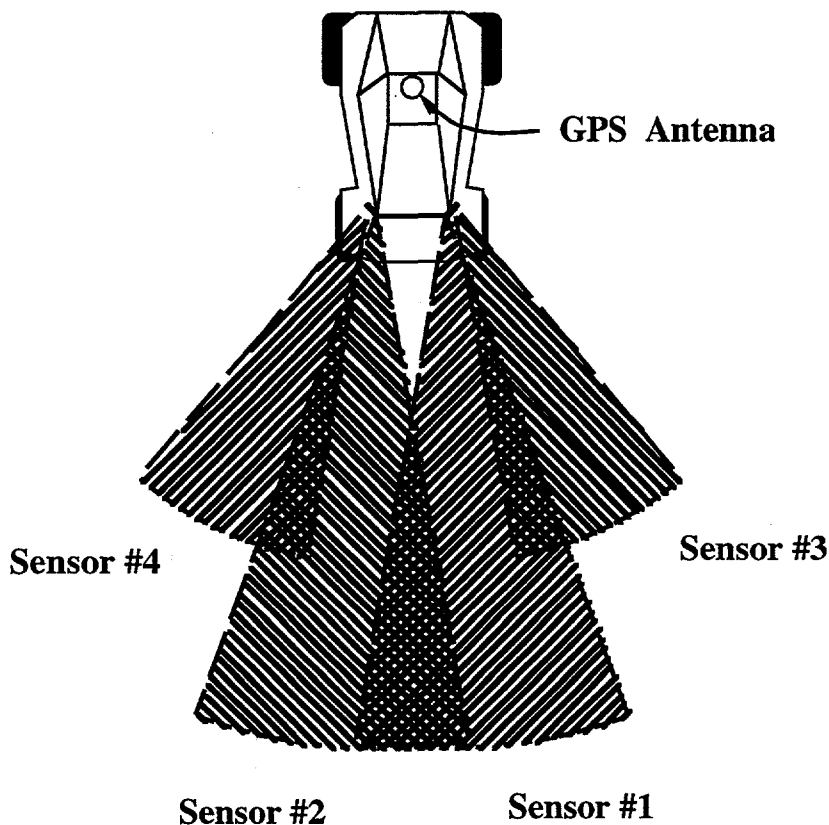Figure 3. COPILOT Sensor layout

Control Architecture

• Copilot Subsystem

Using the Sandia developed KRITIC supervisory control structure, the vehicle's on-board computers use sensory information and models of vehicle performance to map and modify

the remote driver commands into control inputs for the vehicle actuators. The KRITIC architecture consists of a modular parallel structure where each module is responsible for a different part of the overall system behavior. The basic function of the KRITIC controller is to monitor motion commands, evaluate the impact of those commands with respect to the robot's operating environment, and modify the commands if necessary to achieve the robot motion in a safe manner. The basic assumption is that the motion command comes from a supervisory level. However, the command generator—whether it is human or a computer path planner—may not know all the constraints that can prevent the completion of a commanded operation. Consequently, the motion commands are assumed to be valid, but they may require adjustments to account for environmental and robot constraints.

KRITIC Controller
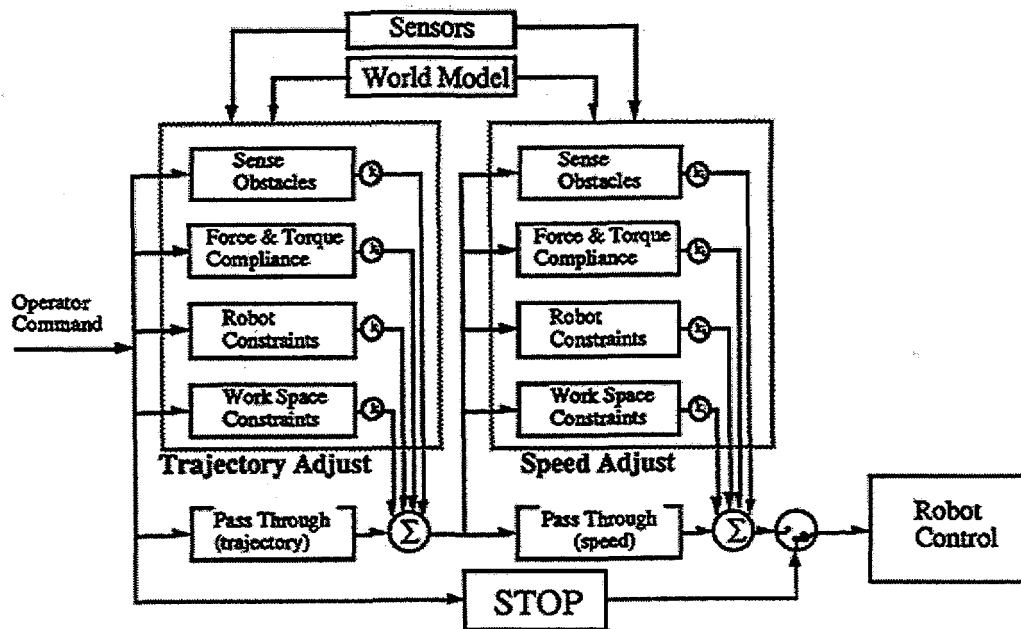
Figure 4. KRITIC Control Architecture

• Vehicle Computer Architecture

The computing structure of the vehicle system is shown in Figure 5. As indicated, a UNIX-based supervisory system communicates with a VME based on-board multiprocessor environment and a VME based real-time base station [5]. VxWorks™ provides the operating system needed for coordination of multiple CPUs, of which there are four on the vehicle. One CPU is responsible for the command and control of all functions relating to the vehicle. A second CPU is used to control a global positioning system and navigation system. A global memory management system allows all CPUs to share data.
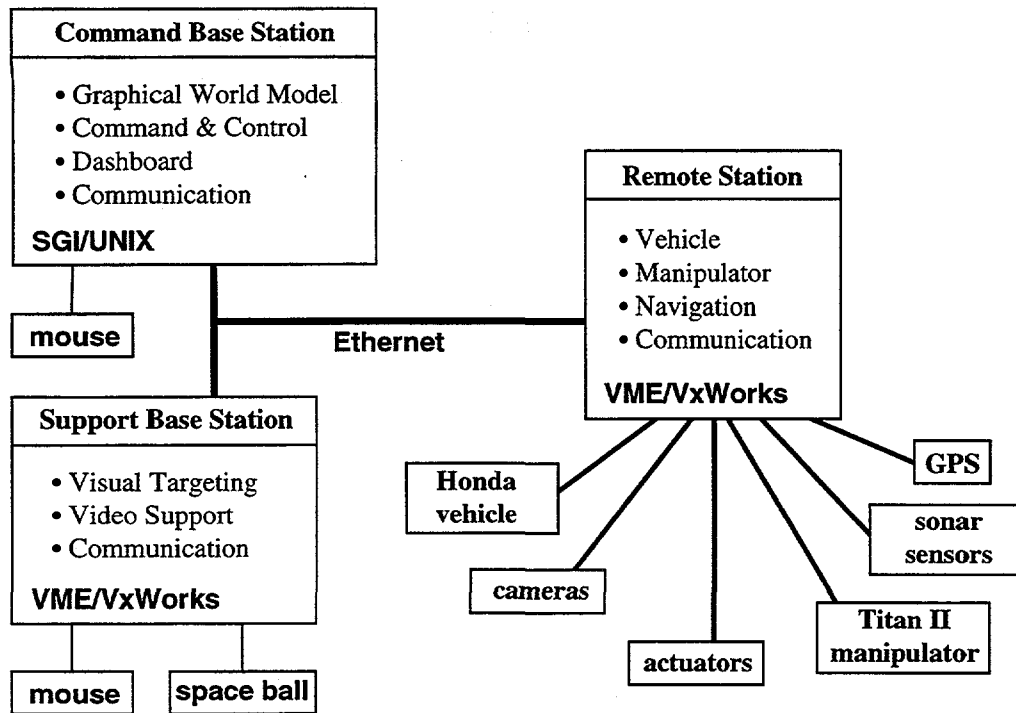
Figure 5. Vehicle Computer Architecture

Operator Interface

The principal goal in the design of the operator interface for the vehicle was to make programming and operation of the vehicle easier in unstructured environments. To accomplish this end, the operator needs to be able to act in a supervisory role: that is, to send task level commands instead of low level control commands whenever possible. However, when shared control is required, the operator can provide direct input into the on-board vehicle control systems. This input will be overridden if commands are sent that are hazardous to the system, such as running the manipulator into the vehicle, or driving the vehicle into a sensed obstacle.

In order for the robot to interact automatically with its environment, the environment must be known. The operation of a robot in an unstructured environment necessitates the need for knowledge about the environment, which, in turn, forms the philosophy [5] for the operator's interface to the system:

- If you have knowledge, use it

- If you don't have knowledge, obtain it

- If you use knowledge, assume it is incomplete.

Knowledge about the robot, such as its geometry, kinematics, etc., or, possibly, even the surface terrain of the work environment obtained from topological maps, becomes the basis of the world model used by the robot. Additional information is added to the world model through sensors, such as the Visual Targeting System (described later), which allows the robot to learn about its environment and further protect itself. However, the knowledge that is in use must be assumed to be incomplete, both because of the limitations of the sensors and because of the changes in the real world due to the vehicle's interactions. Real time sensors, such as the ultrasonic obstacle avoidance system as it is tied in with KRITIC, add safety where the model is incomplete.

Integration of sensors with model-based control concepts allows rapid programming of safe operations even for inexperienced personnel. Computer controlled autonomous operation greatly reduces the time for remote operations while improving safety.

As shown in Figure 6, the interface incorporates real-time computer models to view the entire operation of the vehicle, as well as graphical images that display status information and all available system commands. The graphical display console is divided into three sections: a world model, a graphical dashboard, and a command menu system.

• World Model

The world model is a more advance view of the environment, that comes in use for more automated control. For the world model to be effective, as much information as possible about the robot itself and the workspace surrounding it must be provided. This can occur if topology maps are available for a given area. Additional geometric information can be added using the visual targeting sensor. The model can then be used to detect imminent collisions and help insure safe operation for autonomous operations.

The world model is also important in assisting the operator in task planning. This information is presented to the operator in a 3-D graphics window. The world model allows the operator to see the position and orientation of the vehicle and other modeled parts of the environment at all times and from any point of view. This greatly enhances the operator's perspective of the system beyond the live video signal. The operator can also interact with the world model to preview all motions before execution to insure safe operation. The world model is also used to define other vehicle functions such as selecting a goal position for the vehicle in preparation for autonomous driving.

The world model is an application of the Graphical Programming paradigm [8] as it has been developed by Sandia for application to robot system control. This technology has integrated sophisticated 3-D graphical modeling into the real-time control of robot systems. Graphical Programming is distinguished from conventional off-line programming by real-time updating of the graphical model to allow continual validation of robot motions. The vehicle system uses a SGI (Silicon Graphics, Inc.) graphics engine to allow real-time update rates of the world model. IGRIP [7] is currently being used as the modeling software. This window appears in the center of the graphical display. See figure 6

• Graphical Dashboard

The graphical dashboard appears on the bottom of the operator's graphical display. This feature provides quick visual information for the majority of the system's operating parameters. The graphical indicators used to display the information are similar to those found in cars and aircraft. There are indicator and warning lights for:

- fuel level
- engine temperature
- transmission gear selected
- communication link health
- hydraulic pressure, etc.

The vehicle driving parameters including brake, throttle, gear, steering, speed, and engine rpm are also displayed on the graphical dashboard. Additional feedback to the operator beyond that normally found in a vehicle was implemented because the remote driving of a vehicle can present unique problems. For example, both the commanded throttle position and the actual throttle position are located adjacent to each other on the display. The operator can then determine quickly if the commanded responses are followed by the subsystems. The

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operator is also presented with position and direction information that is measured from both a differential global positioning system and dead reckoning.
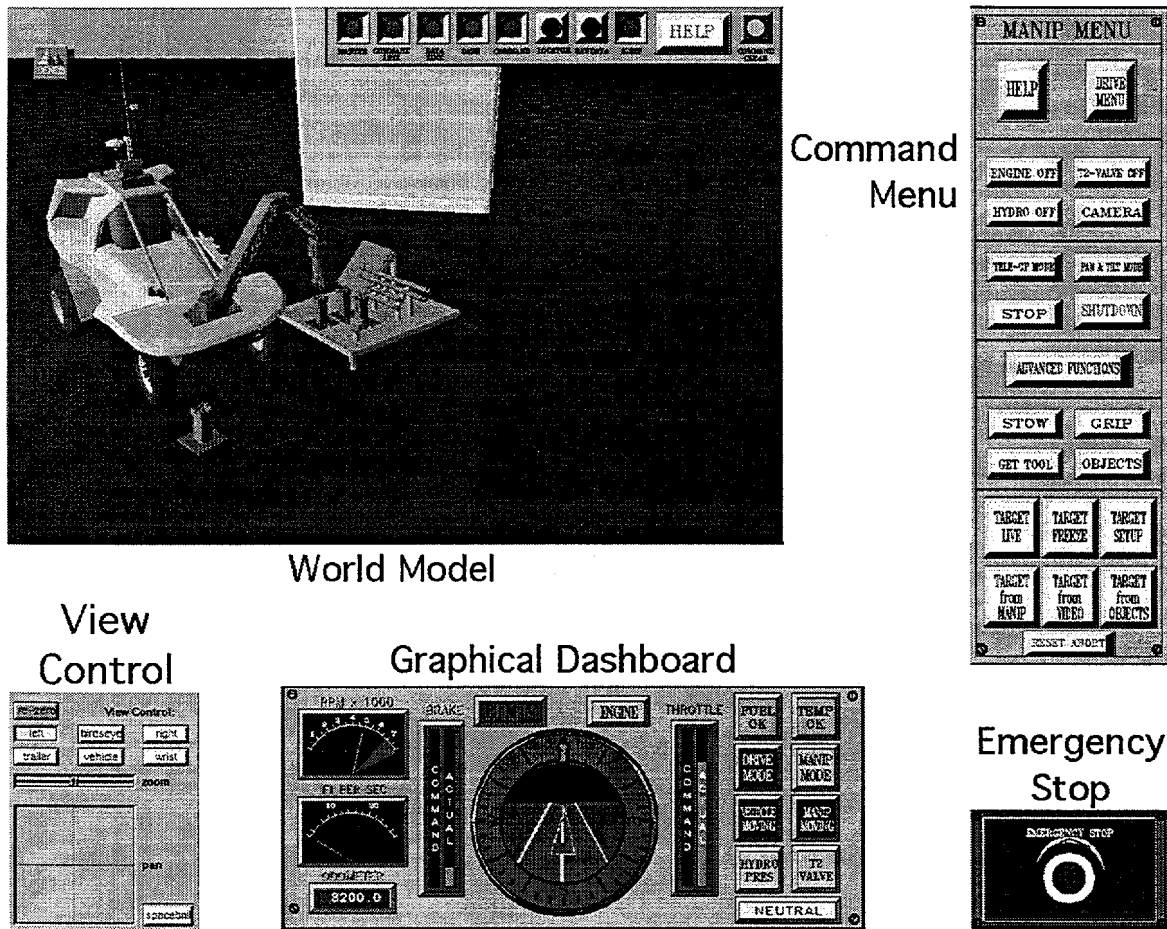

Figure 6. Graphical Operator Interface

- **Command Menus**

The command menu appears on the right side of the screen as shown in Figure 6. The menus are organized by functions, and the commands are generally task oriented, such as "start engine," or "switch camera." The command menus are also responsible for rejecting commands and displaying to the operator a list of all functions that must be executed before the selected command is allowed, thus "leading the operator by the hand" through the appropriate sequence of commands. The principal menu is the Driving Menu. Sub-menus and message prompts to the operator appear in pop-up windows.

- **Driving Menu**

The operator controls the major functions for vehicle control, such as engine-on or gear selection, from the driving menu. A switch for teleoperation of the vehicle allows the operator to drive the vehicle in a shared control mode. A space ball is used for teleoperation allowing simultaneous control for steering, throttle, and brake. KRITIC control parameters are selected from this menu. A camera select button controls a video switcher on the vehicle. There are six cameras mounted on the vehicle. A pan and tilt mounted camera on the top of the vehicle is well suited to the driving of the vehicle. Other cameras are used for precise vehicle and manipulator positioning and as part of the Visual Targeting System.

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- ## Visual Targeting

The Visual Targeting System [6] is a computer vision system used to locate objects, or targets, in space. It is based on stereo imaging. Any two cameras aboard the vehicle are used to present two video views of a scene to the operator. The location of corresponding features is identified in each image. The position and orientation of the cameras, the geometry of the calibrated camera models, and the corresponding image locations are all used to determine the 3-D location of the feature in space. Multiple target points can be combined to define the extent and orientation of an object, or the position and orientation of a grasp point.

Typically, the vehicle will be driven to a location and the video cameras will be used to survey the area visually. When an object of interest, such as a gas bottle or ordnance is identified, the Visual Targeting System is used to locate the object. The operator types a name for the object into an object list, and this information then becomes part of the system's world model. Six buttons on the interface control the acquisition and control of targets by using the Visual Targeting System. This system enables goal points to be determined for automated driving, without the need for a predetermined map.

- ## Driving

The automated driving function enables the operator to select a destination and a suggested path, and then take a supervisory role of monitoring while the vehicle drives autonomously. The world model is continuously updated using position and orientation data from the vehicle through the global positioning system and dead reckoning. Live video is also displayed at the control center. Additional help is provided through the ultrasonic obstacle avoidance system on the vehicle and the KRITIC control system.

Experimental Testing Results

Figure 7. Driving with automated obstacle avoidance

• COPILOT Driving Tests

As mentioned in the sensor section, ultrasonic sensing was used to detect the location of unknown objects. This new sensor system proved very effective in field tests. Figures 8 and 9 show the test layout and results for obstacle avoidance and lane following tests respectively. In the obstacle avoidance test the vehicle was aimed at a 2 ft. diameter obstacle, the operator applied full throttle and maintained a straight forward steering input. As Figure 8 shows, the COPILOT system avoided both the obstacle and the cones without operator input. The speed limiting module prevented the vehicle from over driving the sensors' range. As sensor 2 detected the obstacle, COPILOT applied a left steering correction. As the distance to the obstacle decreased the steering correction increased and a brake/throttle correction slowed the vehicle. After clearing the first obstacle, the steering returned to straight forward and the vehicle speed increased somewhat. As the row of traffic cones was detected the process was repeated with right steering corrections turning the vehicle away from the cones. Figure 7 shows the vehicle during an obstacle avoidance test. Note the large steering angle of the front tires and recall that the operator is providing only a straight ahead steering input. For the lane following test shown in Figure 9, The vehicle approached the row of cones at a shallow angle. As the COPILOT corrections pushed the vehicle away from the cones, the operator applied a left turn input which would have caused the vehicle to collide with the cones if COPILOT were not active. The COPILOT , detecting the cones in sensor s 1 and 3 produced a right steering correction that balanced the operators left turn input and the vehicle maintained a track parallel to the line of cones. Depending on the magnitude of the operators left turn input the track of the vehicle would be closer to (larger steering input) or farther from (smaller steering input) the cones. As the vehicle was forced closer to the cones the COPILOT would generate a larger brake/throttle correction slowing the vehicle. In the extreme, COPILOT would stop the vehicle before it could collide with the cones.

Initial Heading

Initial Heading

Operator
Steering Input

2 ft. Diameter Obstacle

2 ft. Diameter Obstacle

Traffic Cones
(3 ft. centers)

Traffic Cones
(3 ft. centers)

Final Heading

Final Heading
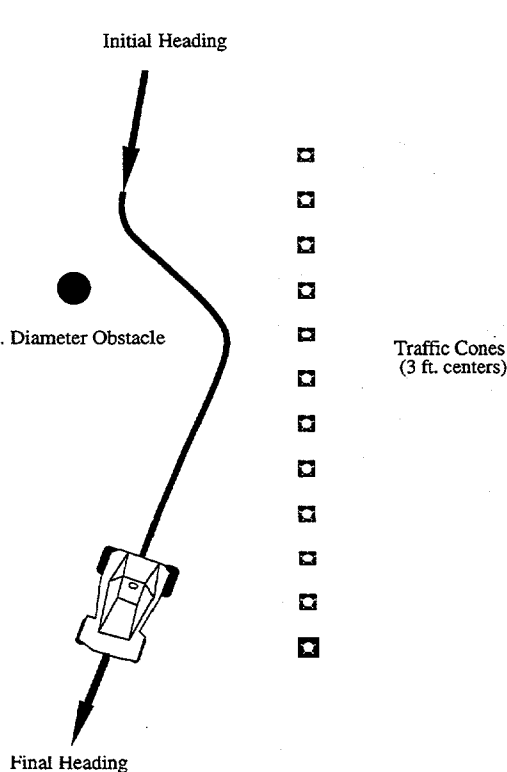
Final Heading

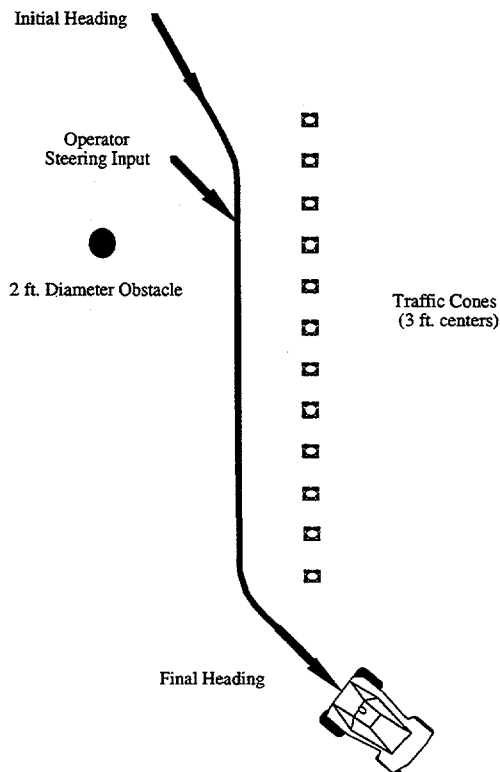Figure 8. Obstacle Avoidance Test   Figure 9. Lane Following Test

Conclusion

We have designed and developed technology that can be applied to make vehicles smarter. This includes a computer assisted COPILOT system to increase human performance by integrating on-board sensors. This includes ultrasonic sensors, compass, accelerometers, wheel encoders, GPS sensors, and other traditional sensors such as fuel level, temperature, oil pressure, etc.. These sensors have been used to alert the user, and in some cases take over, to drive the vehicle safely.

This work in this project has been extended to the create an telerobotic mobile platform for a robotic manipulator. The smart vehicle designs serve as the base for this next program, and serves well as a development platform to add new functionality, simply by adding on the COPILOT concept for user assisted operation.

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