# Ground Vehicle Control at NIST: from Teleoperation to Autonomy

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## ABSTRACT

NIST is applying their Real-time Control System (RCS) methodology for control of ground vehicles for both the U.S. Army Research Lab, as part of the DOD's Unmanned Ground Vehicles program, and for the Department of Transportation's Intelligent Vehicle / Highway Systems (IVHS) program. The actuated vehicle, a military HMMWV, has motors for steering, brake, throttle, etc. and sensors for the dashboard gauges. For military operations, the vehicle has two modes of operation: a teleoperation mode - where an operator remotely controls the vehicle over an RF communications network; and a semi-autonomous mode called retro-traverse - where the control system uses an inertial navigation system to steer the vehicle along a prerecorded path. For the IVHS work, intelligent vision processing elements replace the human teleoperator to achieve autonomous, visually guided road following.

## 1. INTRODUCTION

NIST's involvement in unmanned ground vehicles started in 1986 with the U.S. Army Research Lab's (ARL, formerly LABCOM) techbase program. This program became part of the Defense Department's Robotics Testbed program resulting in Demo I. NIST's responsibility included implementing a mobility controller and developing an architecture for unmanned ground vehicles (UGV) which would support integration and evaluation of various component technologies. [1,2,3]

In a typical scenario, military personnel remotely operate several Robotic Combat Vehicles (RCVs) from an Operator Control Unit (OCU). Each vehicle contains: actuators on the steering, brake, throttle, transmission, transfer case, and parking brake; an inertial navigation system; a mission package which performs target detection, tracking, and laser designation; and data and video communication links. The OCU contains controls and displays for route planning, driving, operation of the mission package, and control of the communication links.

A typical mission includes a planning phase where the operator plans a route using a digital terrain data base. The operator then remotely drives the vehicle to a desired location as the vehicle records the route using navigation data. The operator activates the mission package for automatic target detection, and when targets are detected, the mission package designates them with a laser. The vehicle then automatically retraces the recorded route, a process termed *retro–traverse*.

In 1992 NIST demonstrated vision based autonomous driving, expanding its vehicle control applications into the civilian area as part of the Department of Transportation's Intelligent Vehicle/ Highway Systems (IVHS) program [4–9]. IVHS is a major initiative of government, industry, and academia to improve the Nation's surface transportation systems [10]. One IVHS component, the Advanced Vehicle Control System (AVCS), employs advanced sensor and control technologies to

assist the driver. In the long term, AVCS will provide fully automated vehicle/highway systems replacing the human driver altogether.

The use of vision-based perception techniques for autonomous driving is being investigated in many programs in the United States as well as in other countries [11]. Use of machine vision as a primary sensor has promise in that the infrastructure impact is minimized relative to other approaches.

This paper describes the testbed vehicle and support van. It presents the RCS reference model architecture for an autonomous vehicle and its implementation on the NIST vehicle. The paperthen briefly describes the applications of teleoperation, retro-traverse, and autonomous driving.

## 2. TESTBED AND SUPPORT VEHICLES

The unmanned vehicle, a HMMWV, was actuated by NIST, ARL and the Tooele Army Depot as part of the DOD's Unmanned Ground Vehicles program [1,2]. Figure 1 is a photograph of the testbed vehicle. The vehicle contains electric motors for steering, brake, throttle, transmission, transfer case, and park brake and sensors to monitor the dashboard gauges indicating speed, RPM, and temperature.

**Figure 1.** Testbed vehicle followed by support van

A mobile computing and communications van was prepared to support NIST's development work [6,7]. This van houses development and support hardware, provides communication for operatc control units during teleoperation, and contains the required computing systems to support lane following on public roadways. During lane following, video imagery is gathered by a camera on the HMMWV and is sent by a microwave link to the chase van. The image information is processed in the van. Vehicle control commands are computed and then sent back to the HMMWV control computer via an RF data link. Although the ultimate goal is to mount all vision processing and vehicle mobility controller real-time computational resources on the test vehicle, a portable development and performance evaluation facility will still be necessary.

## 3. RCS CONTROL ARCHITECTURE

One of the first steps performed by NIST to support its evaluation of autonomous vehicle component technology was to develop a reference model. The reference model describes what functions are to be performed and attempts to organize them based on a consistent set of guidelines [1,2].

Figure 2 shows a portion of the reference model architecture for an autonomous land vehicle. Modules in the hierarchy are shown with Sensor Processing (SP), World Modeling (WM) and Task Decomposition (TD). The sensory processing modules detect, filter, and correlate sensory

information. The world modeling modules estimate the state of the external world and make predictions and evaluations based on these estimates. The task decomposition modules implement real-time planning, control, and monitoring functions. The roles of these submodules are further described in [8]. This reference model has not been fully implemented but has served as a guide throughout the years as various control nodes were completed and as the vehicle's capability increased from teleoperation to autonomous driving.

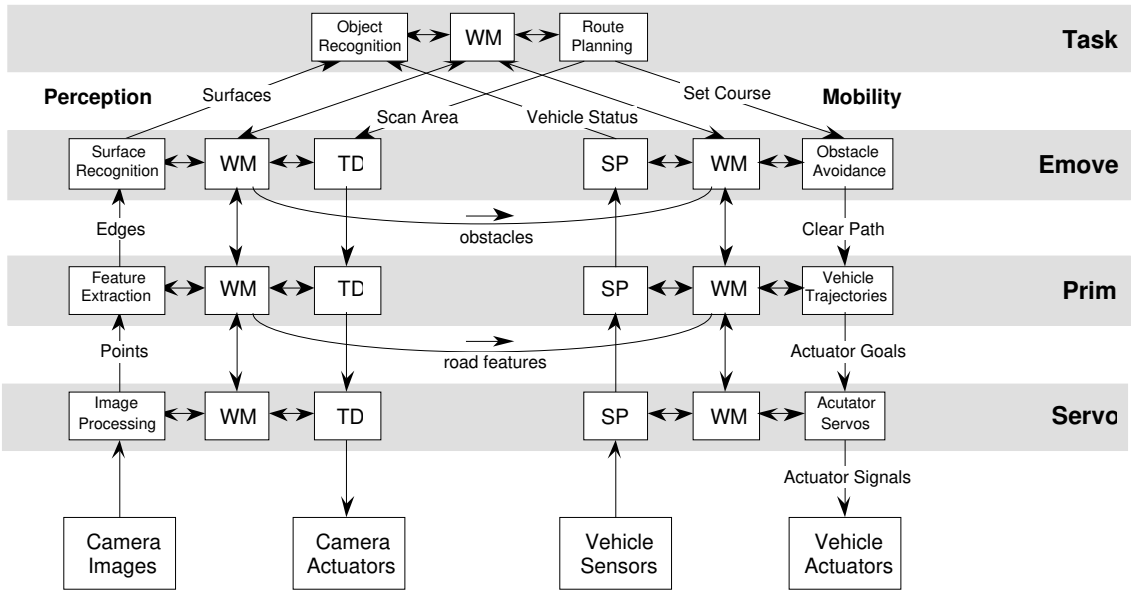


**Figure 2.** Reference model control architecture for an autonomous land vehicle.

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

The implementation for the U.S. Army Research Lab at Demo I used the lower two levels, Prim and Servo, of the mobility part of the reference model architecture to perform the mission elements. The servo level mobility controller drives motors for steering, brake, throttle, transmission, etc. and monitors the dashboard gauges. Vehicle navigation sensor data (position, velocity and acceleration) is processed and used to update the WM in the lowest level of the navigation subsystem. This data is used for steering and speed control of the vehicle during retro-traverse.

Extensions to the control system were necessary for implementing the IVHS autonomous road following [4, 5]. The lower two levels, Prim and Servo, on the perception side of the generic vehicle control system were developed. See Figure 2. The vision perception system uses a model of the lane edges to assist in the prediction and tracking of the lane markers on the road. The computed coordinates of the center of the lane are then used to steer the vehicle, in a similar fashion to retro-traverse.

Additional work on car following and collision avoidance requires the implementation of the next higher level of the control system, Emove. In this case the control system uses the visual surface features of the rear of the lead vehicle for lateral/longitudinal control in order to perform platooning [9]. Eventually, the performance of higher level tasks such as obstacle recognition/avoidance and route planning will require further extensions to the Emove and implementation of the Task levels of the architecture.

## 4. APPLICATIONS

### Teleoperation

Although the ultimate goal for robotic vehicles is a fully autonomous system, control technology has not advanced far enough to realize this goal. Some form of operator intervention is needed, at least part of the time. For IVHS needs, the driver resumes control when the automatic system can not function. In a military setting the vehicle is unmanned and operator control requires some form of teleoperation.

The ARL vehicles communicate to a variety of operator control units. One is a small suitcase controller developed by NIST for field testing and is called the Mobility Control Station (MCS). A second operator station is housed in a tracked vehicle and is capable of controlling four unmanned vehicles at one time. This is called the Unmanned Ground Vehicle Control Testbed (UGVCT) and was developed by FMC for the Tank Automotive Command. Each system allows the operator to control all mobility functions. High level commands are issued using a touch screen display. A graphic display presents vehicle status to the operator.

Teleoperation is surprisingly difficult, hampered mostly, perhaps, by the difficulty in perceiving motion from a video image. To aid the operator, several areas are being investigated: force feedback, graphic overlays, and delay compensation.

Force feedback of the steering wheel provides the operator a feel for road conditions as well as sense of turn rate and vehicle speed. Unfortunately, closing a high speed force reflection loop places increased demands on an already burdened communication link. A simulated force feedback is being investigated. Here, vehicle speed and the operator wheel position is used to emulate the straightening torque that would be felt on the vehicle. The operator cannot feel the bumps in the road, but can get a sense of wheel position and vehicle speed. In addition, safety limits can be imposed so the wheel is not allowed to turn past a limit which is a function of speed.

In many situations, the operator can locate a clear path in the video but has trouble determining how much to turn the steering wheel in order to steer the vehicle over the clear path. To facilitate this, we are using a graphic overlay to represent the position of where the vehicle will travel at the given steering position. The projected vehicle position represented in the video assumes a flat ground plane and moves further ahead of the vehicle as forward speed increases.

Finally, we are investigating controller delay compensation. During teleoperation, several steps occur sequentially. The video camera takes an image, it is transmitted to the control station, the operator moves the steering wheel, the commanded wheel position is transmitted to the vehicle, and the actuator responds. Each step takes a finite amount of time, adding to the control delay. This delay can be very large especially for some forms of video compression. During this delay, the vehicle moves and the location of the desired path as specified by the steering angle changes position relative to the vehicle. Using navigation sensors, the change in position during the delay can be measured and the location of the desired path relative to the current vehicle position can be determined.

### Retro-traverse

For retro-traverse, the vehicle's path is recorded during teleoperation allowing the vehicle to autonomously return along the path. During Demo I, this form of navigation allowed the vehicle to lay a smoke screen and travel through the smoke without the operator input. Driving through a smoke screen rules out the use of a vision system by a remote operator, but some form of obstacle detection is necessary in cases where vehicles or humans wander onto the path. A microwave sensor that would allow the vehicle to detect obstacles is being investigated.

The retro-traverse path is stored during the teach phase as a series of X-Y (or Northing-Easting) points. During the playback phase, a goal point is selected that is on the path and is a specified distance in front of the vehicle. The steering angle is computed using the "pure pursuit" method

[12]. The operator specifies the desired velocity and selects an automatic turnaround manuver. The Modular Azimuth Position System (MAPS), an inertial navigation unit, is used to sense vehicle position and orientation. MAPS uses ring-laser gyros and accelerometers to determine vehicle motion. An interface board (called the Navigation Interface Unit) and software to integrate vehicle odometry with MAPS data was developed by Alliant Tech and used during Demo I. Details of the navigation portion of the driving package are in [3].

**Autonomous Driving**

There are two low level functions required to drive a vehicle down the road, stay on the road and do not hit anything. NIST has been developing a vision based perception system to perform these functions.

The controller tracks the lane markers commonly painted on roadways and steers the vehicle along the center of the lane in the following steps. First, edges are extracted from the video image within a window of interest. Edges occur where the brightness of the image changes, such as where the image changes from a gray road to a white stripe. Then, quadratic curves that represent each of the two lane boundaries as they appears in the video image are updated. The system computes the coefficients of the curves using a recursive least square fit with exponential decay. The steering wheel angle that steers the vehicle along the center of the perceived lane is calculated using the pure pursuit method used for retro–traverse. Finally, navigation sensors compensate for the computation and transmission delay by adjusting the steering goal in accordance to the motion of the vehicle during the delay. More details of the vision processing and control algorithms can be found in [4,5].

Figure 3 shows the various scenes obtained when applying a window of interest to the road scene. The lateral position of the window of interest shifts in order to keep it centered on the road and its shape changes as a function of the predicted road curvature.

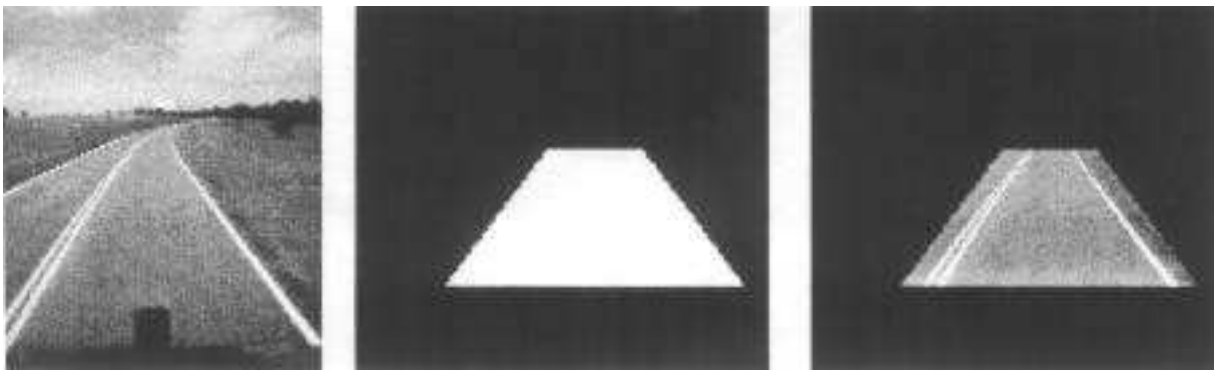

**Figure 3.** Road Scene, Window of Interest, Masked Road Scene.

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

Besides following the road, an autonomous vehicle must track and avoid obstacles and other vehicles. In addition, if the system can track another vehicle, it can follow that vehicle, forming a platoon. Platooning is envisioned by the military to reduce manpower requirements. In the IVHS version, vehicles would platoon at two meter spacings, in order to increase traffic throughput.

An approach to vision-based car following was developed that tracks the back of a lead vehicle or a target mounted on the back of the vehicle [9]. Since orientation is approximately constant during car following, the algorithm estimates only the relative translation of the lead vehicle. The system was tested using a video recording taken while the testbed vehicle was manually driven behind the lead vehicle. The system demonstrated tracking for vehicle separations of up to 15 meters.

## 5. SUMMARY

NIST's roles are to evaluate component technology for autonomous vehicles and to work with industry and academia to advance the state-of-the-art. To perform such a task, an architecture has been developed that will allow incremental development of autonomous capabilities in a modular fashion. The low levels of the control system have been implemented to support the DOD near term robotic tech base. That system was demonstrated at the 1992 Demo I. The control system was systematically extended to incorporate higher levels of autonomous capabilities to support further evaluations and developments in conjunction with the DOD tech base and DOT IVHS programs.

## 6. ACKNOWLEDGEMENTS

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