THE 1997 AUTOMATED HIGHWAY FREE AGENT DEMONSTRATION

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ABSTRACT

In August of 1997, The US National Automated Highway System Consortium (NAHSC) presented a proof of technical feasibility demonstration of automated driving. The 97 Demo took place on car-pool lanes on I-15, in San Diego, California. Members of the Consortium demonstrated many different functions:

- Vision-based road following
- Following magnetic nails
- Following a radar reflective strip
- Radar-based headway maintenance
- Ladar-based headway maintenance
- Evolutionary systems
- Close vehicle following (platooning)
- Cooperative maneuvering
- Obstacle detection and avoidance
- Mixed automated and manual driving
- Mixed automated cars and buses
- Semi-automated maintenance

CMU led the effort to build one of the seven demonstration scenarios, the Free Agent Demonstration (FAD). The FAD involved two fully automated cars, one partially automated car, and two fully automated city buses. The scenario demonstrates lane entry, speed and headway control, lane following, lane changing, obstacle detection, and cooperative maneuvers.

This paper describes the free agent demonstration itself, the technology that made the demonstration possible, and the future work to analyze the feasibility of turning the demonstration system into a practical prototype.

BACKGROUND AND MOTIVATION

The most important motivation for building automated vehicles and highways is improved safety. In the US alone, accidents cost 40,000 lives, and $150 billion dollars, every year. The number of fatalities has decreased since the mid 1960's, due to safer highways and vehicles. At this point, the dominant cause of accidents is human error: in 90% of all accidents, the driver is at least partly to blame. In order to really improve safety, we need to eliminate driver error, either by offering driver assistance or by automating the vehicles.

Congestion is also an increasing problem. Vehicle miles traveled have steadily increased in the US at 4% per year, much faster than the rate of growth of highway miles. The Interstate Highway System is now complete. Adding new lanes in congested urban areas can cost as much as $100 million per lane-mile. Automation is an attractive solution to many congestion problems. On today's roads, with manual driving, the maximum capacity is about 2000 vehicles per lane per hour. If traffic were evenly spaced, this would translate, at 100 kph, to an average spacing of 50 meters per vehicle. But traffic is not evenly spaced; there is bunching and gapping, and lane changing and weaving. Automated vehicles, communicating with each other and with the infrastructure, should be able to maintain much closer and more even spacing, and double or triple roadway capacity.

In order to address these problems, the US Congress passed legislation calling for the creation of an automated highway system, and asking for a "proof of technical feasibility demonstration" by 1997. While the legislation was passed in 1991, Congress didn't fund the program until 1995. The National Automated Highway Systems Consortium, which was formed to do the work, is in the third year of a seven-year program. Activities of the NAHSC include technology development, system design, simulation development, outreach, and societal and institutional studies, as well as development of the demonstration.

The 1997 AHS Demo had seven demonstration scenarios, designed to showcase different technologies and different functions:

- Platoons, with closely-spaced vehicles following buried magnets
- Free agents, with cars and busses using vision and radar
- Evolutionary, showing how this technology can be introduced incrementally for driver assistance
- Control transition, using both vision and buried magnets
- Alternative technology, using a radar-reflective strip for lateral control
- Infrastructure diagnostic, checking the accuracy of the magnets
- Heavy trucking, using radars for smart cruise control and driver warning

The CMU group led the team that built the Free Agent Scenario. Our partners were Houston Metro, which provided the transit busses and funding; K2T Inc, which did the mechanical work on the busses; Assistware, which built the vision systems; General Motors, which provided the cars and controllers; Delco, which provided radars and human interface displays; and Hughes, which provided digital radios.

FREE AGENTS

The philosophy behind the Free Agent scenario is to surround the vehicles with sensors, putting all the sensing and decision-making on board the vehicles. When the vehicles see other automated vehicles, they can communicate with them and drive close to each other. But they have enough perception and reasoning that they can drive, by themselves, mixed in with conventional manually driven vehicles. This ability to run by themselves is why they are called "free agents".

Building the Free Agent vehicles has several advantages over many of the other demo scenarios. First, since the vehicles are independent of any infrastructure and are surrounded by sensors, they can be used for driver assistance even when they are not driving autonomously. The vision system has been developed to warn drivers who are falling asleep and drifting off the road; the radar can warn drivers of stopped vehicles in front; and so forth.

Secondly, Free Agent vehicles create an opportunity for incremental deployment of automation. It probably makes sense in the long term, in crowded urban areas, to have special lanes dedicated to only automated vehicles. If all the vehicles are computer-controlled, they can run at very close spacings, and improve throughput on all lanes. But there is a chicken-and-egg problem: it is difficult to build the dedicated lanes until there are cars to run on them, and difficult to sell the cars if there are no special lanes. With free agent vehicles, we can let them run mixed in with the regular traffic flow. Since they still have to keep a safe space from other, manually driven cars, they don't provide as much of an improvement in throughput, but there is an increase in safety and in driver convenience for the very first automated vehicle sold.

Free agents running in mixed traffic may also be the only practical way to introduce automated driving in rural areas. If an interstate only has two lanes each direction, it would probably not be practical to take one of those lanes and dedicate it to only automated vehicles: that would leave the manual vehicles with no passing lanes, which would be pretty unpopular. So for applications such as long-haul trucking, free agents may be the best way to go.

FREE AGENT DEMONSTRATION SCENARIO

The Free Agent demo includes five vehicles: two fully-automated Pontiac Bonneville sedans, a partially automated Oldsmobile Silhouette minivan, and two fully automated New Flyer city busses. Each of the vehicles in the scenario shows slightly different functions. As an example, here is the trace of a run on one of the sedans. The vehicles are named Navlab 6 and 7 (the Bonnevilles), 8 (minivan), and 9 and 10 (busses). (Figure 1)

The Navlab 7 enters the AHS lane following a bus, a sedan, and another bus, and trailed by the minivan. All vehicles start under manual control. As the vehicles pick up speed to 50 mph, the lead vehicles drift off the road under manual control, to demonstrate the lane departure warning system. The warning system beeps, the drivers note they are drifting off the road, and they steer safely back onto the roadway. Once the vehicles are all safely back in their lanes, the Navlab 7 driver engages auto control by pressing the cruise control engage switch. A gentle voice says "automatic control on", a confirming display appears on the interface screen and on the HUD, and the driver takes his hands off the wheel and his feet off the pedals.

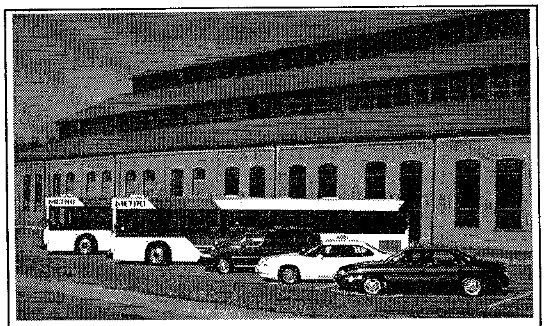
Figure 1: Navlabs 6 - 10, front to back

In a real AHS system in an urban environment, there could be a Traffic Management Center sending speed commands to the vehicles. For the demonstration, we don't have a TMC, but we simulate receiving a command to increase speed. The computer communicates with the cruise control, and we increase speed to 55 mph automatically, passing the lead busses and car.

The minivan, driving manually, approaches from the rear at 65 mph. The minivan driver receives a warning, triggered by his forward-looking radar. On Navlab 7, the rear looking ladar detects the approaching van. The human interface announces "high speed vehicle approaching". Navlab 7 checks its vision system to see if there is a lane to the right, checks its side looking sensors to confirm that the lane is clear, and checks its rear looking sensor for vehicles approaching in the right lane. If it is not clear of the busses, Navlab 7 holds its position. Once it is safe to change lanes, the voice and displays indicate "changing to right lane", and the vehicle smoothly changes lanes, allowing the minivan to pass.

Later, the second sedan pulls in behind the Navlab 7. The two vehicles communicate by digital radio to establish that they are both automated. The trailing sedan tracks Navlab 7 by radar, and keeps a comfortable 1.5 second gap. Navlab 7 detects an obstacle in its lane, in this case an orange plastic construction barrel. Inside the vehicle, the interface indicates "obstacle detected - swerving to left", and the Navlab moves to the side. Since the radar has high angular accuracy, the vehicle only moves over far enough to clear the obstacle. It also communicates the location of the obstacle to the trailing sedan and busses, which automatically and safely change lanes even before their own sensors have spotted the obstacle.

The trailing sedan passes Navlab 7, and pulls back into the right lane. The driver of Navlab 7 wishes to re-pass the other sedan, without disengaging automated control. He presses the "change lanes left" button, presses the "increase speed" cruise control button, and the Navlab 7 changes lanes, speeds up, and passes the other sedan. Similarly, he requests a slowdown and a return to the right lane, and, once the spacing is clear, the Navlab 7 changes back.

Eventually, the Navlab 7 detects obstacles completely blocking its lane. For this part of the scenario, a simulation is set up indicating that there is traffic in the left lane, so it is impossible to change lanes. Navlab 7 brakes to a safe halt, and through a combination of radio communication and radar sensing, the trailing sedan also comes to a halt, followed by the busses.

UNDERLYING TECHNOLOGY

Much of the underlying technology in the Free Agent Demo is new, built specifically for the Demo. Other components have been adapted from previous work. To as great an extent as possible, all systems on the three passenger cars and the two busses are identical. Components include the following:

RALPH: The vision system on all 5 vehicles is the RALPH system, built by Pomerleau[1]. This system uses a forward-looking video camera, mounted behind the rear view mirror of the cars and on the inside of the bus windshield, to image the road. The image is re-sampled to produce an overhead view of the road. The overhead view is processed to find the road curvature, by looking for the swept arc that maximizes the sharpness of edges along the swept line segment. This effectively finds the curve that most closely follows all visible road features. This is especially important for the 1997 Demo, since highways in California use raised dots instead of painted lines, so vision systems that rely on continuity of lines may have difficulty with this course. RALPH uses the raised dots, but also uses pavement joints and the edge of the shoulder and other parallel linear features, in order to find and track the road. This system is now commercially available through Assistware Inc.

Radar: Headway maintenance (keeping a consistent gap from the lead vehicle) relies on a radar. Our partner Delco electronics supplied a 77GHz mechanically scanned radar with software for detecting and tracking targets. It is important to measure both target range and bearing; commercially available automotive radars usually have no measurement of bearing, and therefore cannot properly track targets on curved roads. We have integrated the radar output with RALPH to register detected targets with detected road position. This lets our vehicles classify targets as to whether they are in the current lane, in an adjacent lane, or off the road. The sensors used on the busses are commercially available radars from Eaton Vorad that report range but not bearing.

Side-looking sensors: Each vehicle is equipped with four side-looking short-range radars from Eaton Vorad for detecting objects adjacent to the vehicles.

Rear-looking sensors: The rear-looking sensors are scanning ladars from Riegel. They have a field of view of approximately 30 degrees.

Lane changing: The logic requesting a lane change is based on desired speed, speed of preceding vehicles, and locations of vehicles in adjacent lanes. For the demonstration, the scenario is constructed so lane changes are easily executed when expected. In the more general case, deciding on a lane is an example of "tactical driving", the subject of a recent thesis in our group by Rahul Sukthankar.3 His SAPIENT simulated vehicles do careful analysis of upcoming exits, velocities as well as positions of surrounding vehicles, and other factors, all combined in a distributed behaviorist framework.

Actuators: The car brake and steering actuators are custom provided by our partners at General Motors. The bus air brake and steering actuators are custom built by K2T, Inc. For both vehicles, the throttle actuation is through the existing cruise control. The Free Agent philosophy is to have large enough separations between vehicles that high-bandwidth throttle and brake servos are not needed. Using the existing cruise controls shows that low-bandwidth speed control is sufficient. As an added benefit, it reduces cost, provides commonality of interface between buses and cars, and increases safety by using tested commercial components.

Safety circuit: There are several safety checks in the system, to go as far as possible in ensuring safety. First, at the lowest level, any actuator can be overridden by the human safety driver. The steering motors and amplifiers are deliberately torque-limited to be easily overpowered by a person. The driver can similarly drive the throttle or brakes, and the computer controls have no way to backdrive the pedals. As a last hardware check, an independent safety board can at any time cut power to all actuators. The safety board continually monitors computer heartbeat, steering wheel travel and speed, lateral acceleration, and state of emergency kill switches. In addition, the vehicle driving behaviors in the Free Agent philosophy are designed to keep safe space around vehicles, and to provide opportunity for defensive driving.

RESULTS

The 1997 Demonstration took place near the end of the third year of a planned seven-year research project. The Free Agent vehicles made 20 trips each during the actual demonstration, plus 12 to 16 trips on each of the three preceding weekend dress rehearsals, plus 32 early morning warm-up trips to ensure the system was running properly. Each of these trips was open to passengers, and many were full. This is in addition to the many test and development runs conducted during the course of five weeks at the San Diego test site.

All runs proceeded safely. During development, a few minor bugs were found and fixed. For example, radios that worked for our testing in Pittsburgh and Ohio did not work in San Diego; Hughes graciously supplied digital radios. For the actual runs, each vehicle followed a script, designed to showcase all the desired functions. The script was also used to turn on and off obstacle detection: early tests showed that our radars would pick up overpasses as obstacles, and incorrectly slow the vehicles until the roadway began to dip down and the radar pattern fell below the level of the bridge.

During the live runs, there were a few occasions when the system disengaged. For example, there were several small prestressed concrete bridges that caused the vehicle to bump, which occasionally set off the lateral accelerometer and caused the safety circuit to disengage. The drivers smoothly resumed manual control, re-engaged the automated driving, and continued the runs.

IMPLICATIONS AND PLAN BEYOND THE DEMO

While the Demo is an important part of our current effort, there are also several longer-term research themes that the Consortium is pursuing simultaneously, and that will build on the results of the Demo after its conclusion. The questions being pursued include:

- What is the best method of lateral position sensing? Our partners at Berkeley are using magnetic markers; we are using vision and integrated INS/GPS; others are using radar reflective tape and other methods.
- What is the best method for obstacle handling? Obstacles could be sensed with vision, or radar, or ladar, mounted on the vehicles. They could be sensed with the same sensors mounted along the roadside. They could be excluded from the roadway with fences. Or, some combination of the above might be needed to be both effective and inexpensive.[2]
- What is the right vehicle grouping strategy? One answer is to space vehicles far enough apart that even if one vehicle fails and locks its brakes, the following one can come to a safe stop. An alternative answer is to space vehicles so closely that if there is a collision, it will be at very low relative velocity, and will therefore still allow for safe control.
- Do we allow mixed human and automated traffic, or do we need dedicated lanes occupied only by robot cars? A dedicated lane system is easier to build technically, but may not be deployable: it may be difficult to build the lanes until enough cars are ready to use them, and difficult to persuade customers to buy cars until the lanes are ready. Mixed traffic is more difficult technically, but would immediately enable people who buy the cars to use their automated capabilities.[3] [4]

Our group at CMU is composed of technology optimists. For the last issue above, in particular, we want to pursue the question of technical feasibility of driving in mixed traffic. The Free Agent Demo systems will show many of the capabilities required for driving in mixed traffic, but certainly not all. The SAPIENT thesis work shows more of these capabilities, but only in simulation. We will pursue a program of progressive automation. First, we will continue to build and test vehicle-sensing systems, until we are confident that we can reliably detect all vehicles in our vicinity. Second, we will run our tactical driving system as a passive passenger. It will accept inputs from lane tracking, vehicle tracking, and map positioning systems, and will generate suggestions for the human driver. As we gain confidence in the outputs of the system, we will enable more and more automated control functions. At the same time, we will collect statistics on the driving behavior of vehicles around us, so we can model the worst aspects of human driving, and build systems smart enough to cope with that type of traffic.

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