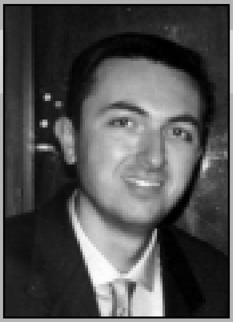

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Envisioning a Radar-Based Automatic Road Transportation System

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This installation of Intelligent Transportation Systems presents a detailed proposal of an ITS based mainly on active sensors (radars). It deals with such an automatic system's main requirements and specifies a possible architecture for both road users (vehicles) and infrastructures.

If you have any comment on this department, you are welcome to interact with me at broggi@ce.unipr.it (www.ce.unipr.it/broggi); I seek contributions on the current status of ITS projects worldwide as well as ideas about and trends in future transportation systems.

Please also visit the IEEE ITS Council's official Web page at www.ieee.org/its and the next IEEE Conference on ITS at www.ewh.ieee.org/tc/its/2001.

—Alberto Broggi

Current technology makes possible the design of a fully automatic road transportation system. Such a system can be affordable and can be implemented progressively in combination with present driver-controlled traffic. This article presents a proposal for such a system's architecture.

Requirements

Merely scheduling vehicles on designated tracks is insufficient; an automatic road transportation system must also consider noncooperative road users (drivers, bicyclists, and so on who are not part of the automatic system) and random obstacles. So, the system has these requirements:

- It must provide automatic guidance for cooperative vehicles—based on user commands for destination, preferred route, mode, priority, and so on—while considering the local and global traffic situation.
- It must detect and monitor noncooperative road users and random obstacles and consider them when generating guidance commands.
- It must register and consider road conditions and traction parameters for individual vehicles.
- It should guarantee optimum traffic flow with respect to road congestion, noise, fuel consumption, and so on.
- It should provide advantages obtainable only with full automation—for example, unmanned transportation of goods, and driverless vehicle movement to parking facilities.

The basic architecture

Figure 1 depicts a system that would fulfill these requirements. It has three major components:

- A network of short-range, high-resolution radar sensors that monitors traffic space. Such surveillance covers all fixed and moving objects in a relevant area by measuring their location, size, and velocity vector. Radar provides all-weather capability and allows 24-hour operation. Equipment inside the autonomous vehicles could supplement these sensors, as I describe later.
- A network of sensors, some in the vehicles, that registers road conditions and traction parameters.
- A computer network that performs central guidance. It receives information from the two sensor systems and the road users and generates guidance commands.

Different types of roads require different system architectures and operation modes:

- On rural high-speed roads, the system must consider obstacles intruding into areas adjacent to the roads—for example, animals approaching the lanes.
- Pedestrian sidewalks must be blocked off by a fence, if the speed allowed for vehicles is much faster than walking speed, because the automatic system cannot anticipate a sudden intrusion of a pedestrian into the lane.
- In living areas, parking lots, and so on, vehicles must operate at a very low speed. The local guidance system might communicate with road users by indicating its intentions through visible and audible signals. It also

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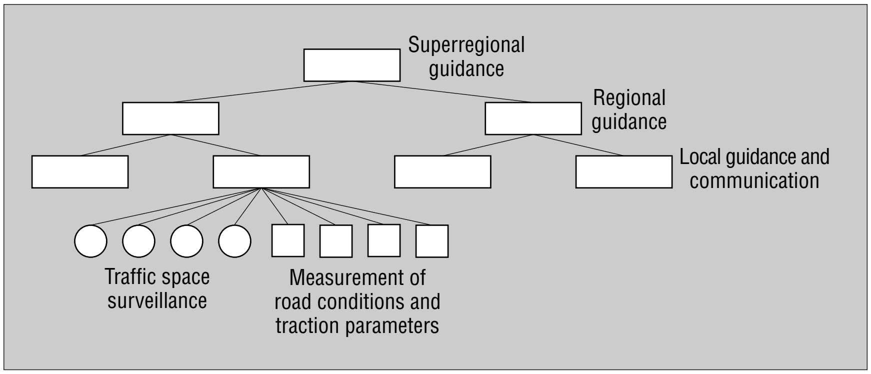

Figure 1. A proposed system architecture for an automatic road transportation system. The system has three main components: traffic surveillance sensors, sensors for measuring road conditions, and a computer network for central guidance.

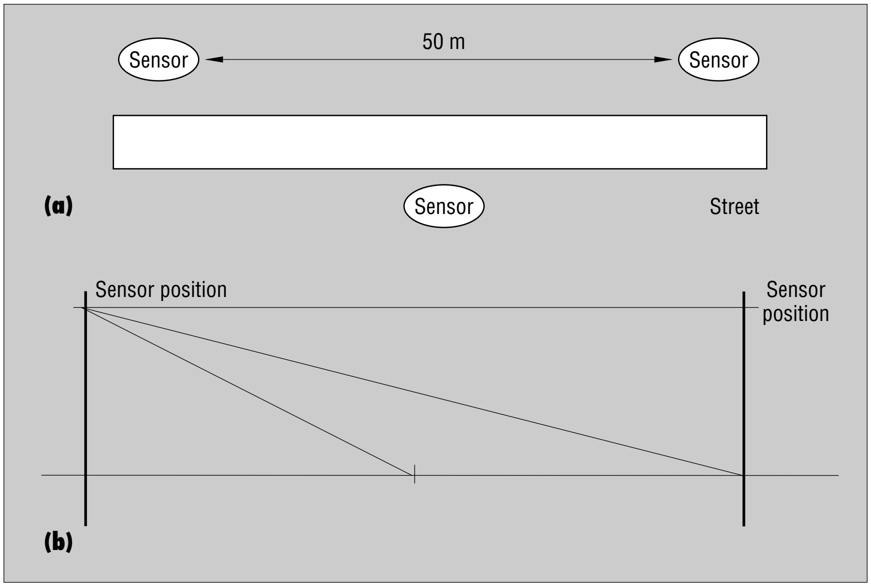

Figure 2. Sensor (a) arrangement and (b) surveillance range. Sensors are at elevated positions located alternately on both sides of the road. This minimizes shadow areas behind targets.

might communicate with pedestrians acoustically and accept requests from pedestrians—for example, from terminals provided at the roadside.

Traffic space surveillance

The network of radar sensors guarantees low-power operation and flexibility in case of road expansions. The sensors have these requirements:

- They must detect all targets on the roads and in neighboring safety zones.
- The radar spatial-resolution cell should be a cube approximately 20 centimeters wide. This will allow localization of detected obstacles with accuracies on the order of 20 cm, which seems adequate for road vehicle guidance.
- The sensors should unambiguously measure radial velocities between −150 and +150 meters per second. This velocity interval is larger than that of present road vehicles and includes the velocities of high-speed trains, so it seems adequate for a future system.
- To guarantee the detection of any relevant obstacle within 10 milliseconds, the sensors must detect a target with a radar cross-section of 1.96×10^{-3} square meter (−27 decibel-square-meter), corresponding to a metal sphere of 5 cm diameter in the optical region, after 10 ms of coherent processing time. Such sensors likely will detect objects with larger radar cross-sections in shorter times. Because a vehicle at maximum velocity moves only 1.5 m in 10 ms, this maximum processing time seems reasonable.
- The sensors should minimize shadow areas behind targets, to avoid obscuration of other important targets.
- Radar signals should also be able to serve for precision navigation.

To minimize shadow areas, the radar sensors should be at elevated positions—for instance, at the tops of poles located alternately on both sides of the road (see Figure 2).

A combination of different sensor networks is also conceivable. For example, a network of densely spaced sensors on poles of lower height, with detection times on the order of 100 ms, would monitor road surface obstacles. A network of more widely spaced sensors on higher poles, with lower spatial resolution but coherent integration times of 10 ms or less, would monitor vehicles.

Because a radar sensor's maximum observation range is only a few dekameters, even at very high radar frequencies atmospheric attenuation is small. The targets to be detected might be only a few centimeters in size, so I propose the use of millimeter-wave radar, which also means small antenna dimensions.

Kamal Sarabandy, Eric Li, and Adib Nashashibi have investigated the radar backscatter of road surfaces at millimeter-wave frequencies.[1] I have also considered high-resolution radar operating with Lüke-Schotten codes fulfilling the above requirements; the radar's frequency is 200 GHz, corresponding to a wavelength of 1.5 mm.[2,3] The necessary radar transmitter power is on the order of 2 milliwatts, far below any hazardous limits.

Precision navigation

The radar signals should be such that the cooperative vehicles could determine their own location and velocity vectors, with accuracies on the order of 20 cm or less for their locations and 0.5 meters per second or less for their velocities. These figures seem to be reasonable for vehicles with dimensions on the order of meters and velocities up to 150 meters per second. Using interferometric antenna arrangements, the vehicles might also determine their turn rates from the signals.

As an alternative to designing radar signals such that they also serve for vehicle navigation, the system could transmit special navigation signals in addition to the radar signals.

The processing of the signals is similar to that in a Global Positioning System; the only difference is that the required navigation accuracy for automatically guided road vehicles is much higher than that for aircraft.

Secondary radar concepts

The in-vehicle precision navigation system might also transmit the vehicle's position, velocities, turn rates, and so on to the central guidance system. This would substantially reduce the tasks for the fixed-installation radars, which would then only detect and observe noncooperative road users and random obstacles.

Also, noncooperative road users and pedestrians might carry responders that communicate with the central guidance system. Because of the low signal powers involved, the responders could even be integrated in wristwatches.

Progressive system implementation

During the conversion to an exclusively automatic road transportation system, vehicles with drivers might have transceivers that communicate with the central guidance system. The reception of guidance information would allow for participation in optimum traffic management.

The realization of the automatic transportation system should start with a small prototype to successively refine the definition of sensor requirements and the algorithms for the central guidance system. Simultaneously, there should be development of detailed computer simulation models for the system components and the complete system, to extensively study the system's behavior well before final implementation.

The proposed radar frequency is at the upper limit of available transistors, although researchers have worked on semiconductor amplifiers even in the 350-GHz region.[4] The necessity of large numbers of identical radar sensors in the proposed system, however, would justify the development of a sophisticated radar sensor with the required parameters.

Although today's technology enables the realization of the central guidance system as a network of computers, researchers have not yet developed any basic concepts or algorithms. This is also true for sensor systems for registering road conditions and traction parameters. However, the tremendous gain in efficiency and safety from an automatic road transportation system should provide stimulus for such research.

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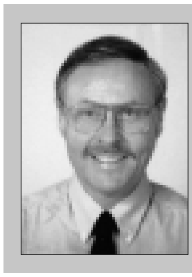

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