Millimeter-Wave Obstacle detection Radar

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Abstract

The road traffic in the 20th century has evolved into a megasystem. With the progress of increased automotive mobility, this road traffic has brought about both prosperity as well as negative conditions such as traffic accidents, congestion, and worsening of the environment. Today, joint efforts by industry, academic circles and the government are being promoted under the project name of ITS (Intelligent Transport Systems). The goal of this project is to correct such negative aspects and optimize the course of the megasystem as a high efficiency transport system.

This paper discusses the world of Smartway and some of the services being aimed by AHS (Advanced Cruise-Assist Highway System), with a major emphasis on the support for frontal collision prevention.

It also outlines the millimeter-wave obstacle detection radar developed by Fujitsu Ten and Fujitsu, and discusses its obstacle detection performance.

1. Introduction

As a form of technology supporting safe driving, an information collection infrastructure for sensing road conditions and supplying key information on road conditions to vehicles comprises an important theme for consideration. Development efforts are currently underway to come up with a practical infrastructure of this type.

The information collection infrastructure is expected to detect instantaneously the positions and velocities of obstacles on roads, such as things that have been dropped, or that have fallen on the road, standing or running vehicles. This technology is essential for constructing Smartway.

2. Changing Roads

This chapter explains Smartway and safety-related sections under the theme of "A Society Realizing Roads of Superior Safety and Comfort for the 21st Century."

2.1 Toward the Liquidation of Negative Assets

In the 20th century, we enjoyed a very high degree of mobility and industrial and economic prosperity, thanks to the prevalence of vehicles and widespread road networks. Now, toward the end of the 20th century, however, traffic accidents do not appear to be showing any signs of decreasing, traffic congestion is becoming more chronic, and vehicle emissions and other environment-related problems have become very serious. Numerous measures and significant efforts have been taken to solve these problems. ITS ¹⁾ is one of these.

ITS, which uses leading-edge technologies to unify vehicles, people, and roads, is designed to improve safety by eliminating traffic accidents, to ensure smooth congestion-free traffic for more comfortable driving and efficient transportation, and to transform roads into a better driving environment.

As for safety, it is said that about 50% of rear-end collisions and accidents at intersections and 30% of headon collisions could be avoided if only drivers could sense the potential danger 0.5 seconds earlier. Even in cases of accidents at sharp curves or where visibility is limited, a significant percentage of chain-reaction collisions could be prevented if there were only a system in place that could use road-installed sensors to detect the accident's occurrence and warn vehicles approaching the vicinity in time.

How are we to realize this type of safe road traffic?

The answer is Smartway equipped with ITS as an integrated form of the relevant technologies and system components.²⁾

2.2 A World realized with Smartway

Smartway (intelligent road) is an infrastructure that realizes Smart Cruise (Fig.1)³⁾ with Smart Car (intelligent vehicle) and Smart Gateway (intelligent communications).

More specifically, this road is equipped with a variety of information facilities and an administration system to apply the facilities to ITS services.

These information facilities include:

• sensors for collecting information on the traffic status, road conditions, and other information related to roads and traffic,

• an information processing system for processing collected information appropriately, and,

• a road-vehicle communication system for supporting exchanges of information among vehicles, drivers and pedestrians.

Fig.2³⁾ shows the road services provided by Smartway.



Fig.1 Smart Cruise Systems



Now, what will driving be like in an environment where Smartway and Smart Car begin to exchange information? Let's try to imagine a drive someday when this system is in place.

"Having finished work for the day, you head for home in the suburbs. You get the latest road traffic information from the road beacon located immediately outside your office. In accordance with this information, you enter an expressway as scheduled. An Electronic Toll Collection System (ETC) is in place, so you will not need to stop at a tollgate. After a while, you come to a curve where visibility is limited. The buzzer sounds suddenly and a voice message lets you know that there is an obstacle ahead. Before you can step on the brake, the vehicle slows automatically. On the road 50 meters ahead, you can see some cargo that has fallen from a truck. You carefully go around the scattered cargo and head on home. When you are about to cross an intersection, the buzzer sounds another warning. As you are now in the vicinity of your neighborhood, you have become a bit too relaxed, and you have failed to notice another vehicle approaching the intersection you were about to cross. The vehicle slows automatically. The other vehicle crosses the intersection in front of you. The system kept you out of an accident." 2)

This is the image of a not-do-distant future that has already been partly implemented. The accidentprevention scenario described above is one of the benefits anticipated with the Advanced Cruise-Assist Highway System (AHS).

2.3 Smart Cruise Systems

This section introduces seven services to be implemented by the Smart Cruise Systems. (Fig.3) ¹⁾

(a) Support for prevention of collisions with forward obstacles

Notification to vehicle: detects vehicles, headway objects, etc. in poor visibility.

Vehicle gives driver information, warming and operational support.

 (b) Support for prevention of over shooting on curve Notification to vehicle: detects the distance and shape of curves ahead before approaching.
Vehicle gives driver information, warning and

operational support.

(c) Support for prevention of lane departure Supplementation to vehicle: lateral direction information from lane markets which were installed in the road.

Vehicle gives driver information, warning and operational support.

(d) Support for prevention of crossing collisions

Notification to vehicle: detects the approaching vehicle with a right of way at intersection. Vehicle gives driver information and warning.

 (e) Support for prevention of right turn collisions Notification to vehicle: informs vehicle of intersections where right turns are possible and detect oncoming vehicle.

Vehicle gives driver information.

 (f) Support for prevention of collisions with pedestriaus crossing streets
Notification to vehicle: detects pedestrian crossing. Information service from vehicle to driver.

Vehicle gives driver information.

(g) Support for road surface condition information for maintaining headway etc.

Notification to vehicle: follows up on information such as road surface conditions.

Vehicle utillzes this data on maintenance of headway and other services.³⁾

"Smart Cruise 21" will be tested at a public demonstration to be held in the fall of 2000.³⁾ This demonstration will be jointly held by the Ministry of Construction and the Ministry of Transport, as a part of efforts to significantly improve road traffic safety by supporting safe driving. This demonstration will be held at the test course of the Public Works Research Institute of the Ministry of Construction in Tsukuba City, Ibaraki.

This experiment is expected to verify the usefulness of the Advanced Cruise-Assist Highway System (AHS) being promoted by the Ministry of Construction and the Advanced Safety Vehicle (ASV) being promoted by the Ministry of Transport to implement the Smart Cruise Systems.

As the AHSRA Fujitsu Laboratory of the Advanced Cruise-Assist Highway System Research Association (AHSRA), Fujitsu Limited will perform a variety of experiments using the millimeter-wave obstacle detection radar developed by the Fujitsu Group.

2.4 AHS

The objective of AHS is to provide drivers with information on obstacles and vehicles that remain out of sight, for significant improvements in driving safety and comfort, using information and communications technologies.

Fig.4³⁾ shows an outline of AHS. This system provides information on the position and behavior of the vehicle one is driving and surrounding vehicles. This



Fig.3 The Seven Services of Smart Cruise Systems

information is provided on a real-time basis to support safe driving with:

• information supplied from the information collection infrastructure and route guidance infrastructure using roadside cameras

• information collected using on-vehicle cameras and sensors, and

• information exchanged via roadway-vehicle and vehicle-vehicle communications.

This system also enables automated driving with information processing equipment for velocity and steering controls.



Fig.4 Assistance for safe driving

Fig.5 shows the service flow for forward obstacle collision prevention support, which is one of the seven services provided by the Smart Cruise Systems. This service is provided to cope with the causes of accidents.

If an accident occurs just beyond a curve where



Fig.5 Support Steps and Timing(Example of Forward Obstacle Collision Accident)

visibility is low, the information gathering infrastructure (millimeter-wave and image sensors) detects the obstacle and sends the information to the information processing equipment. The equipment judges the danger to other vehicles entering the vicinity afterwards and, if necessary, provides these vehicles with the information via road-vehicle communication.

To solve the causes of accidents, the system provides the following services:

- Advance supply of information to eliminate late detection
- (2) Subdued alarm to deal with errors in judgment
- (3) Emergency driving support to counter errors in driving³⁾

With its driving support functions, AHS can be classified into three subsystems:

- AHS-i (Information) to support part of information collection
- AHS-c (Control) to support some aspects of driving

as well as information collection

• AHS-a (Automated cruise) to support all information collection and driving and handle all aspects of safe driving

Fig.6 shows the concept of AHS evolution. The functions do not follow the evolution pattern of (i c a) simultaneously for all roads and vehicles. Functions requiring a high-grade infrastructure are first implemented on some roads and only vehicles equipped with the corresponding systems can receive their services. In other words, AHS evolves on a non-continuous basis in phases.²⁾

In fiscal 1996, the AHSRA Fujitsu Laboratory started developing millimeter-wave obstacle detection radar to realize AHS-i. By repeatedly conducting experiments, the detection distance was extended and the scanning and signal processing velocities were increased. Fujitsu system and elemental technologies and Fujitsu TEN's technological strength in developing millimeterwave radars, which complement one another, have promoted this development.



Fig.6 Evolving AHS

3. Millimeter-Wave Obstacle Detection Radar

The obstacle detection radar should be able to promptly detect the positions and velocities of things that were dropped, or that have fallen on roads, and vehicles either standing or running on roads, irrespective of the time zone or weather conditions.

3.1 Millimeter Wave

A millimeter wave is an electronic wave whose wavelength is 10 to 1 mm or whose frequency is 30 to 300 GHz.

This wave is not very affected by natural

environments (rain, fog, air turbulence, or sunlight) or the color of the targets detected. Compared to the microwave band or lower frequencies, this wave has a significant Doppler shift and makes possible the highprecision measurement of relative velocities. Because of these characteristics, the wave is very advantageous for the sensing function of obstacle detection equipment installed on roads.

A practical example of a millimeter-wave radar system for vehicle control is the Adaptive Cruise Control System (ACC), which has been partially implemented. This system is designed with emphasis on safety and convenience, and its millimeter-wave radar plays an important role as a key sensor.

3.2 FM-CW Radar System

Millimeter-wave radar systems are generally of the pulse, FM-CW, 2-frequency CW, or spread spectrum (SS) system.

Table 1 lists the system characteristics. For the current radar system, the Frequency-Modulated Continuous Waves (FM-CW) type was adopted because its high-frequency section can be created from a simple configuration and the distance to the target and the

Table 1	Millimeter-wave	radar	systems
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System	Features
Pulse	This system is not susceptible to the effects of multiple targets but requires high-speed broadband signal processing.
FM-CW	The structure of the high-frequency section is simple and the velocity characteristic can be identified.
2- frequency CW	The occupied bandwidth may be narrow but no measurement is possible when the relative velocity is 0.
SS	Developed as a means of information communication, this system is resists jamming or interference, and can send distance data immediately following measurement. However, a high-speed broadband correlator is required.

relative velocity can be measured simultaneously.

Fig.7 shows the principle of the FM-CW radar system. The frequency-modulated triangular wave is output from the antenna for transmission. To obtain the beat signal frequency, the transmitted wave is partially mixed with the wave received through the antenna after reflection on an obstacle or other object.

The beat frequency f_{B} is expressed as Formula (1). $f_{\mathsf{B}}=f_{\mathsf{R}} \pm f_{\mathsf{V}} \cdot \cdots \cdot (1)$

- $f_{\rm R}$: Distance frequency (Proportional to the distance to the target)
- $f_{\rm V}$: Velocity frequency (Proportional to the relative velocity with the target)



Fig.7 Principle of FM-CW radar

The positive sign in Formula (1) represents the frequency of the beat signal (downbeat f_{BD}) obtained where the transmitter frequency falls. The negative sign represents the frequency (upbeat f_{BU}) of the beat signal obtained where the transmitter frequency rises.

 f_{BD} and f_{BU} are expressed as follows:

 $f_{\mathsf{BD}}=f_{\mathsf{R}}+f_{\mathsf{V}}\cdots\cdots(2)$

 $f_{\text{BU}}=f_{\text{R}} - f_{\text{V}} \cdots \cdots (3)$

In addition, f_{R} and f_{V} are expressed as follows:

$$f_{R=} \frac{4 \quad f \in R f_{m}}{c} \cdots \cdots \cdots (4)$$
$$f_{V=} \frac{2 f_{o} V}{c} \cdots \cdots \cdots (5)$$

c : Radio propagation velocity (= Velocity of light) f_m : Triangular wave modulation frequency

 f_{\circ} : Central frequency

f: Triangular wave modulation width

From Formulas (1) to (5), distance R and velocity V are calculated as follows:

$$R = \frac{(f_{BD} + f_{BU}) c}{8 ff_{m}} \cdots (6)$$
$$V = \frac{(f_{BD} - f_{BU}) c}{4f_{o}} \cdots (7)$$

In other words, the beat signal frequencies f_{BU} and f_{BD} in the frequency increase and decrease sections are measured and their addition and substraction are calculated to determine the distance and relative velocity.

The receiving power of the reflected wave from the

target can be calculated as follows⁵:

$$Pr = \frac{{}^{2}P_{t}G_{r}G_{t}}{(4)}R^{4}LaLr \quad \cdots (8)$$

Where,

Pt,Pr : Transmitting and receiving power

- Gt,Gr : Transmitting and receiving antenna gains
- R : Distance to the target
- La : Atmospheric attenuation
- Lr : Rain attenuation
 - : Wavelength
 - : Reflecting cross-section

3.3 Requirements for Millimeter-Wave Obstacle Detection Radar

A millimeter-wave obstacle detection radar is installed on a gantry over a road or a similar high place (about 5 m) at a certain elevation angle.

The expected distance measuring range is from dozens of meters to over hundred meters, which is sufficient to detect an obstacle in a few lanes, irrespective of whether the object is dynamic or static. The expected measurement velocity is from 0 to about 200 km/h. The detection targets should include such low-reflection items as cartons, wood, people, and bicycles, and such highreflection items as cars and trucks.

In addition to the above requirements, rain attenuation, free-space propagation attenuation, and other factors should be considered when designing the necessary antenna gain and transmission power of the radar. Fine and quick object scanning and data processing technologies are also necessary for enhancing the precision with which object positions are detected and enhancing the performance with which objects moving at high speeds are acquired.

3.4 Configuration of Millimeter-Wave Obstacle Detection Radar

The developed millimeter-wave obstacle detection radar conforms to the contents given below that have been legislated as the technical requirements of lowpower millimeter-wave radars. This millimeter-wave radar has also received a certificate of conformance from Telecom Engineering Center.

Radio frequency band: 60 GHz Antenna power: 10 mW max Antenna gain: 40 dBi max Frequency bandwidth: 1 GHz max

Fig.8 shows a block diagram of the radar. A plane antenna is connected to the millimeter-wave circuit through a waveguide and driven with the transmitting and receiving circuits by an actuator for sideway scanning. The signal processor converts the beat signals from the radar, from analog into digital. The DSP circuit then analyzes frequencies and computes relative velocities, distances, and angle information. The computed values are sent through a bus to the detection circuit. The detection circuit ascertains the degree of danger and outputs the judgments thereon to the external display device through the communication control driver. Table 2 lists the main specifications. Table 2 Main specifications of millimeter-wave radar

Item	Specification	
Transmission frequency band	60 ~ 61GHz	
Transmission power	3 mW or less	
Modulation type	F3N	
Radar modulation type	FM-CW	
Maximum detection distance	100 m	
Antenna	Plane antenna	
Antenna gain	31 dBi min	
Angle coverage	± 14 ° max	

3.5 Millimeter-Wave Radar

The millimeter-wave circuit, which represents a significant breakthrough, is the most important part of the millimeter-wave radar. The transceiver unit is wade up of several modules of a monolithic microwave IC (MMIC) and combined with a bias circuit board for millimeter-wave transmission and reception.

Frequency modulating signals are input into the 30 GHz voltages controlled oscillator (VCO) is doubled and amplified, then 60 GHz wave signals are output from the antenna. Signals received at the antenna are amplified and mixed with transmission signals into IF signals. The MMIC is designed with a high electron mobility transistor (HEMT) by the InGaP/InGaAs compound semiconductor process whose gate length is 0.15 (μ m. This HEMT is a semiconductor device with superior high millimeter-wave characteristics⁶). The Fujitsu Group realized the millimeter-wave circuit by using semiconductor technologies that are the most advanced worldwide.



Fig.8 Block diagram

For the antenna section, a 512-element plane antenna of a triplet-line structure was adopted to reduce its thickness and size. The millimeter-wave obstacle detection radar is installed at heights of about 5 meters. To scan a certain range, the horizontal and vertical beam widths were took into consideration at the antenna design stage.

3.6 Signal Processing and Recognition Section

The signal processing and recognition section consists of a signal processing circuit and a detection processing circuit. The signal processing section converts beat signals obtained from the millimeter-wave radar from analog into digital and executes FFT processing and pairing with the DSP circuit to obtain distance, relative velocity, and angle information. From this information, the detection processing circuit detects the position of an object. This obstacle detection algorithm has an obstacle presence detection function and an obstacle position detection function. Fig.9 shows the processing flow for these functions.

In the above flow, data collected with no obstacles is stored first as background data. The measured data is then compared with the background data and the differences are grouped. The new group extracted in this manner is tracked at each scan. If it is not moving, this group is detected as an obstacle and its position is also detected for locating. Background data is obtained from input data by eliminating moving groups with a kind of low-pass filter.



4. Obstacle Detection Performance

The obstacle detection performance was verified with a variety of tests that took into consideration onroad obstacles and meteorological and other environmental conditions. These tests were carried out at the test course and rain and fog facility of the Public Works Research Institute of the Ministry of Construction and at the Ishikari Blowing Snow Test Field of the Civil Engineering Research Institute of the Hokkaido Development Bureau. The results of the experiments are explained next.



Fig.10 Millimeter-wave radar installation

4.1 Obstacle Detection Test during Fine Weather⁷

An obstacle detection test was carried out during fine weather, to collect basic data about detection performance. The millimeter-wave radar was installed on a roadside telephone pole, at a point about 4.5 m above the road surface.

4.1.1 Detection distance

Various obstacles were placed on the test course, at every 10 or 15 meters, for the detection test. The millimeter-wave radar was installed at the center of the rightmost of the three road lanes (lane width: 3.8m wide). The following obstacles were selected to make drivers feel a sense of danger:

- metal obstacles (10-cm, 30-cm, and 50-cm cubes)
- cartons (10-cm, 30-cm, and 50-cm cubes)
- wooden obstacles (10-cm, 30-cm, and 50-cm cubes)
- tires (for large and small vehicles)
- a bicycle.

Fig.11 shows the detectable range of each object. The experiment proved that the radar could detect even comparatively small objects at long distances. No obstacles were detected at a short distance (within 25 meters) because the half-power width of the antenna did not cover the range, owing to the radar installation conditions.

4.1.2 Distance error

As a representative sample, the 30-cm metal cube was analyzed in terms of distance error.

For this analysis, polar coordinates based on the millimeter-wave radar were converted into linear ones based on the road lanes and the relative errors were evaluated.

The distance error at each point was within one meter and the distance measuring precision was comparatively high. (See Table 3.)

Point	Center lane (m)		Left lane (m)		
	Actual distance	Measurement error	Actual distance	Measurement error	
25m	25.74	0.46	25.75	0.48	
40m	40.28	0.17	40.26	0.89	
55m	55.45	0.53	54.38	1.39	
70m	70.98	0.00	70.77	0.09	
85m	85.98	0.01	85.86	0.05	
100m	100.99	0.25	100.90	0.09	

Table 3 Distance errors

4.1.3 Position detection⁸⁾

A position detection test was carried out with a carton dropped from a running vehicle. In the experiment, a carton was dropped 40 meters ahead of the millimeter-wave radar from a running vehicle that did not stop. Fig.12 shows how this test was carried out.

Fig.13 shows the results of this experiment. The



Fig.11 Obstacle detection result



Fig.12 Photograph of position detection test

graph of (a) shows the data the moment the vehicle reached a point about 50 meters ahead of the millimeterwave radar, after dropping the carton. According to this data, the millimeter-wave radar detected the carton, vehicle, and roadside. The obstacle detection algorithm processes this data to display only the obstacle, as the data of (b) shows. The display of several points indicates that the millimeter-wave radar detected the obstacle with several beams during scanning. The position detection algorithm processes this data to locate the obstacle.



This experiment was repeated dozens of times and proved that obstacle positions can be detected securely with no detection failures or errors.

4.2 Obstacle Detection Experiment during Rain or Fog⁹

For comparison with the test carried out during fine weather, an obstacle detection experiment was performed

at a facility where the rain and fog conditions can be artificially controlled.

The millimeter-wave radar was suspended from a beam in the tunnel, at a point 5.4 meters from the ground, as shown in Fig.14.



Fig.14 Millimeter-wave radar installation



Fig.15 Photograph of conducting experiments in the facility for rain and fog test

Fig.15 shows the fog status generated for the experiment.

In the experiment, obstacles placed at every 10 to 15 meters were detected under varying rain-fog conditions. The following rain-fog conditions were generated:

- Rain: 20, 55, and 100 mm/h in rainfall
- Fog: 20, 50, and 100 m in visibility

Figure 16 summarizes the detectable range of each obstacle.

Compared with the results of the test carried out

during fine weather explained in 4.1.1, almost the same results were obtained with this test. The reason for no detection at short distances of 25 meters or less is as explained in 4.1.1.

4.3 Obstacle Detection Experiment in Cold Region¹⁰⁾

The millimeter-wave radar was installed on a gantry at a point 4.5 meters above the ground level, to detect an approaching vehicle as a target. The weather status was the equivalent of a snowstorm, and the visibility was 70 to 90 meters. Fig.17 and 18 show the millimeter-wave radar installation status and the test site.

According to the detection results in Figure 19, the detection performance was hardly affected by the snowstorm and the accompanying visibility range. In fact, the performance was almost equal to what one would expect during fine weather.

4.4 Summary of Experimental Results

Only some of the experiments and tests are mentioned here. The AHSRA Fujitsu Laboratory has been repeating obstacle detection tests and experiments under various conditions. (These tests and experiments have been conducted at the test course of the Public Works Research Institute of the Ministry of Construction.) Through these tests and experiments, the detectable range, position precision, velocity precision, and other basic data have been obtained in great quantities. Experiments and tests carried out under varying environmental conditions have also been performed, and have proved that the obstacle detection performance is stable irrespective of the weather conditions or time of day (fine weather, rain, fog, snow, nighttime).

If the millimeter-wave radar is installed on a road as an obstacle detection sensor, the basic performance of this device will be sufficient enough to realize obstacle detection.

5. Conclusion

As we approach the closing months of the 20th century, throughout the world, people are having to deal increasingly with traffic accidents, road congestion, and the adverse effects on the environment that have all been brought about by road traffic. The ITS has appeared to help free us of this burden which is our legacy from the 20th century, and help us to realize an efficient transportation system. To help realize our common aspirations for the 21st century, we will continue to work to promote further advances in this field.



Fig.16 Obstacle detection results under rain and fog conditions



Fig.17 Millimeter-wave radar installed on the gantry



Fig.19 Detection results in snowstorm for running vehicle

This study was conducted at the AHSRA Fujitsu Laboratory as a research done on behalf of the Public Works Research Institute of the Ministry of Construction. We would like express our gratitude to the Intelligent Transport Systems Division at the Public Works Research Institute for their guidance.

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Fig.18 View from the gantry of detection test

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