Vehicle Tracking with Multiple Millimeter-Wave Radar

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For reducing traffic accidents and congestion, the need for infrastructure sensors is increasing worldwide. In order to cover a large area, multiple infrared sensors are deployed and work together to detect and track vehicles. We have developed a system and detection algorithm to integrate multiple infrared millimeter-wave radars. In this paper, we present the features of the system and the results of field tests.

Keywords: safe-driving, traffic congestion mitigation, millimeter-wave radar

1. Introduction

As the age of self-driving cars approaches, demand is growing for sensors of detecting vehicles on expressways and at merging points as well as sensors of detecting vehicles and pedestrians on general roads, with the aim of ensuring safe-driving and traffic congestion mitigation. Some sensors are deployed on the roads, and such infrastructure sensors are expected to acquire information on the movement of vehicles and pedestrians in zones outside the driver’s field of view and on accidents and provide the driver with the acquired information as read-ahead information.

Millimeter-wave radar, camera-type sensors and lidar-type sensors are the typical sensors for these uses. Among these, millimeter-wave radar is superb in terms of immunity to weather and variations of light and shade, as shown in Table 1. It is relatively free of the need for regular cleaning, making it simple to maintain. Consequently, it is suitable as an infrastructure sensor.

In March 2018, Sumitomo Electric Industries, Ltd. began shipping infrastructure millimeter-wave radar products for pedestrian detection, using its advanced antenna designing technology and unique object detection algorithm to enable a wide detection range and high detection accuracy.

For the next step, in addition to downsizing and cost-cutting of infrastructure millimeter-wave radar, we have developed a new system integrating plural radars to cover larger range in expressways, as illustrated in Fig. 1. This coordination capability, with which multiple millimeter-wave radar units share detection information, enables detection over a wide area. Additionally, it also becomes possible to track vehicles traveling across the detection areas of individual millimeter-wave radar units. Following the development of this capability, Sumitomo Electric conducted an on-road experiment. This paper reports on the newly developed functions and its evaluation results.

Table 1. Comparison of Infrastructure Sensors

Property	Millimeter-wave radar	Camera	Lidar
Detection range	Good	Fair	Fair
Range accuracy	Good	Fair	Good
Speed accuracy	Good	Fair	Fair
Shape capturing	Poor	Good	Fair
Environmental Resistance	Good	Poor	Fair
Maintainability	Good	Fair	Fair
Cost	Good	Good	Fair

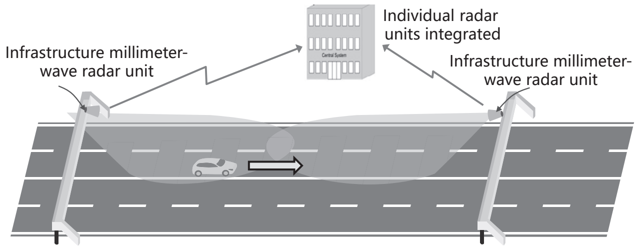

Fig. 1. Coordination of multiple infrastructure millimeter-wave radar units

2. Millimeter-Wave Radar Specifications

Figure 2, Table 2, and Photo 1 present the configuration, specifications, and appearance, respectively, of the newly developed millimeter-wave radar. This chapter describes the operating principle of millimeter-wave radar and the features of Sumitomo Electric’s millimeter-wave radar.

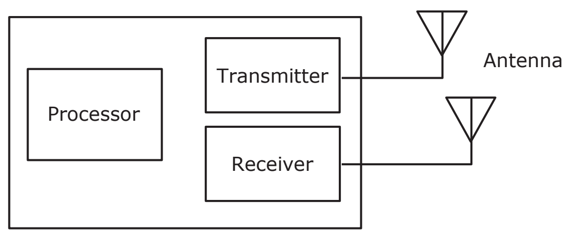

Fig. 2. Configuration of millimeter-wave radar

Table 2. Specifications for Infrastructure Millimeter-Wave Radar

Modulation	FMCW
Power supply voltage	90 to 220 V (AC)
Power consumption	Up to 25 W
Frequency band	76.0 to 77.0 GHz
Bandwidth	Up to 1 GHz
Transmitter power	10 mW
Temperature range	−25°C to 65°C
Dimensions	245 × 245 × 50 mm
Weight	Up to 3.5 kg (including brackets)

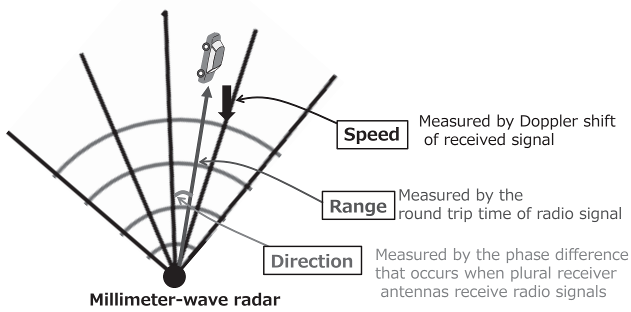

Fig. 4. Principles of object measurement with millimeter-wave radar

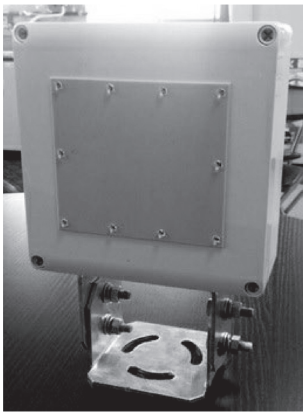

Photo 1. Appearance of millimeter-wave radar

2-1 Operating principles of millimeter-wave radar

Infrastructure millimeter-wave radar is designed to transmit radio waves from a radar unit installed on an on-road gantry or a pole and analyze the reflected radio waves from the target, as shown in Fig. 3. The frequency-modulated continuous wave (FMCW) method is employed for the radar system. This system measures the amount of time required between the transmission and the reception of the radio wave reflected from the target to compute the distance between the radar unit and the target, as illustrated in Fig. 4. It also measures the direction of the target based on the phase difference arising from the differential time occurring when plural receiver antennas placed within the millimeter-wave radar units receive the reflected radio wave. Furthermore, it measures the speed of the target based on the Doppler shift of the received radio wave. These acquired time-series data of the location (distance and direction) and speed of the target are used to determine the class (vehicle, pedestrian, or fixed object) of the target by our detection algorithm.

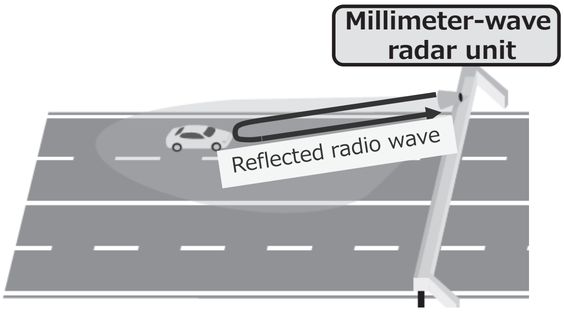

Fig. 3. Example of vehicle detection with millimeter-wave radar

2-2 Features

The general features of millimeter-wave radar are described in (1). The features of the millimeter-wave radar developed by Sumitomo Electric are described in (2) and (3).

(1) Superb environmental resistance and maintainability

Millimeter-wave radar is immune to variations in light and shade during the day and at night. Weather conditions have minimal impact on its wave transmission characteristics. Accordingly, it also resists bad weather conditions such as rain, snow, and fog. Camera-style sensors and other photo-detecting sensors are subject to declining performance due to soiling of their lens surfaces. They need cleaning on a regular basis. In contrast, millimeter-wave transmittance is minimally affected. Consequently, millimeter-wave radar requires no cleaning and is superb in terms of maintainability.

(2) High detection accuracy

The newly developed algorithm offers the capability of analyzing reflected signals to identify characteristic information of the targets and distinguish vehicles from pedestrians and track them to infer their movements. Thus, even if a large object temporarily blocks the radio signal, this estimation capability complements the lack of reflected radio waves and enables tracking to detect the target continuously with high accuracy.

(3) Wide detection area

Sumitomo Electric's antenna designing technology makes it possible to set up a detection area according to the geometry of the target road. Moreover, by suitably combining the placement of the receiver antennas and the detection algorithm to reduce noise on the received reflected signal, it is possible to perform detection even when the reflected signal is at a low reception level. This combination of the antenna designing technology and detection algorithm ensures a wide detection area.

3 Coordination of Multiple Radar Units

This chapter describes the vehicle detection algorithm developed by Sumitomo Electric. This algorithm has been extended into a coordinated detection algorithm, which coordinates multiple radar units to detect vehicles in a wide area and is capable of tracking vehicles in the detection areas of multiple millimeter-wave radar units. The coordinated detection algorithm and mechanics designed to implement it are also described in this chapter.

3-1 Vehicle detection algorithm

We devised a tracking logic incorporating a time-series filter*[1] as a target detection algorithm. The tracking logic first extracts, as observed values, the locations and speeds of objects with which the intensity of the reflected signal is higher than a threshold.[(1)] Next, the time-series filter operating from moment to moment is applied to these observed values used as input information. In this process, the time-series filter changes its state, as illustrated in the state transition diagram presented in Fig. 5. The vehicle candidate state is the first transition state taking place after the extraction of observed values. This state waits until the error distribution of the time-series filter converges. The vehicle detection state is a state whereby a tracked object has been recognized as a vehicle. Transition to this state occurs when after the error distribution converges, the conditions that express the likelihood of a vehicle are fulfilled. At this point, individual vehicle identifications (IDs) are assigned. Meanwhile, the algorithm was designed to cancel tracking by the time-series filter if in a vehicle candidate state or vehicle detection state, no observed value is acquired continuously for a predetermined amount of time.

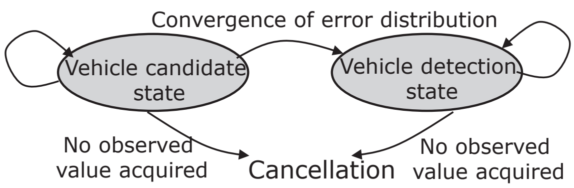

Fig. 5. Status transition diagram of a tracked target

In some instances, the intense signal reflected from a large vehicle can obscure the relatively weak signal reflected from a small vehicle. In other instances, a small vehicle goes behind a large vehicle and the radio signal from the small vehicle is temporarily blocked. Even in these instances, using the present logic, it becomes possible to continue vehicle detection. Moreover, if before the vehicle detection state expires, the signal reflected from the target vehicle is received again, the same vehicle ID will be retained, enabling the vehicle to be recognized (identified) as the same vehicle detected before it disappeared.

3-2 Coordination of multiple radar units

As a method of using multiple millimeter-wave radar units to cover a wide area as on an expressway, it may be viable to have individual radar units operate separately and in a post-process, to integrate vehicle data acquired with each radar unit. However, if different radar units acquire different detection results in the overlapping portion of their detection areas, this method cannot determine which radar detection results to adopt. Moreover, to track a vehicle that is traveling unlawfully, radar units operating individually would make it difficult to identify the detected vehicle.

As a solution to this challenge, we devised a system of plotting integrated information on a large virtual map, allowing multiple radar units to extract the locations and speeds of objects with a reflected signal intensity higher than a threshold, as described in the preceding chapter. We then unified the state transition flow illustrated in Fig. 5 for multiple radar units to ensure that they output unified detection results. These processes enabled the seamless linking of detection algorithms in overlapping detection areas of different radar units and the tracking of vehicles moving across the detection areas of different radar units.

To integrate data from multiple radar units into one vehicle detection algorithm, the multiple radar units must operate with the same timing. To synchronize the time, the multiple radar units were set up to obtain time information from a network timing protocol (NTP) server, as shown in Fig. 6. Incidentally, this sort of coordination capability can be realized by collecting information from each radar unit and sending it to a server or edge device, as illustrated in Fig. 1.

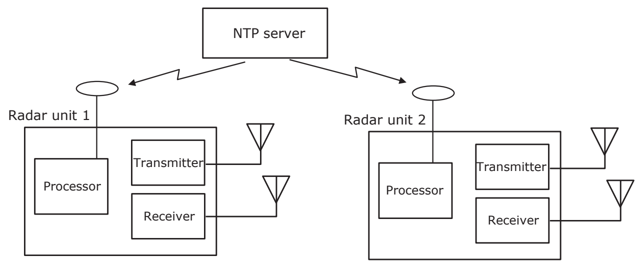

Fig. 6. Time synchronization between radar units

4. On-Road Performance Evaluation Experiment

Using the newly developed millimeter-wave radar and coordination capability, a performance evaluation experiment was conducted on an actual road in Hyogo, Japan.

4-1 Experimental environment

Figure 7 roughly depicts the placement of experimental devices. Millimeter-wave radar units were tentatively installed in opposing orientation on two pedestrian

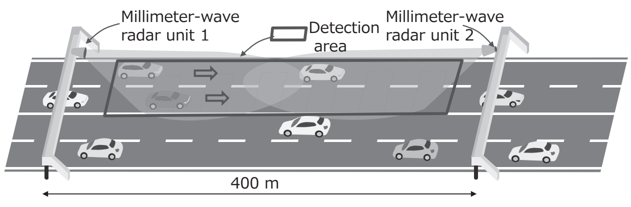

Fig. 7. Placement of experimental devices

bridges about 400 m away from each other. The two radar units detected vehicles between them in two lanes in one direction except for the areas immediately below them. They were installed at a height of about 7 m above the road surface.

Figure 8 presents an example of comparison between the vehicle detection results produced in the experiment using the millimeter-wave radar and images from the camera. The figure shows an approximately 50 m section in the upstream zone of the detection area (zone close to millimeter-wave radar unit 1 in Fig. 7). The millimeter-wave radar assigned IDs to vehicles in order of detection. Six moving vehicles were present in the section in Fig. 8. The millimeter-wave radar detected all of them and assigned vehicle IDs respectively to them.

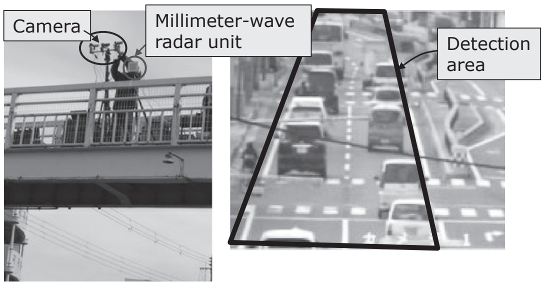

Photo 2. Installed devices and road used for detection

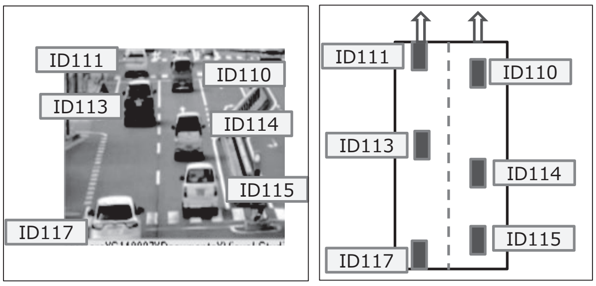

Fig. 8. Image from camera and millimeter-wave radar detection results

4-2 Tracking detected vehicles

Figure 8 presents an example of comparison between the vehicle detection results produced in the experiment using the millimeter-wave radar and images from the camera. The figure shows an approximately 50 m section in the upstream zone of the detection area (zone close to millimeter-wave radar unit 1 in Fig. 7). The millimeter-wave radar assigned IDs to vehicles in order of detection. Six moving vehicles were present in the section in Fig. 8. The millimeter-wave radar detected all of them and assigned vehicle IDs respectively to them.

These vehicles were to enter the detection area of millimeter-wave radar unit 2 several tens of seconds later. Although vehicle-to-vehicle distances changed during traveling, the millimeter-wave radar was able to track them with the same IDs, as shown in Fig. 9. (Figure 9 presents an approximately 50 m section close to millimeter-wave radar unit 2. Note that the image from the camera and millimeter-wave radar detection results are reversed in relation to those presented in Fig. 8.)

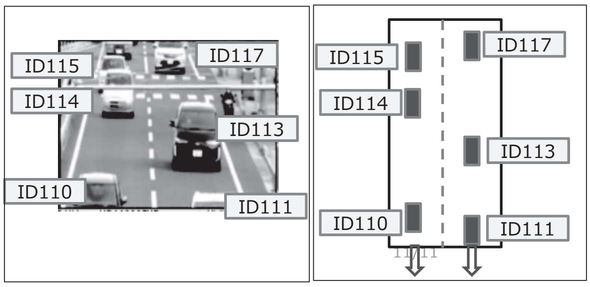

Fig. 9. Vehicle tracking with two millimeter-wave radar units

4-3 Detection accuracy evaluation results

The experiment used the following evaluation indicator for detection accuracy.

(a) Number of vehicles detected in a 60 seconds detection duration of the millimeter-wave radar

(b) Actual number of vehicles in the 60 seconds duration

Detection accuracy = (1 − |(b − a)/b|) × 100 [%]

In the equation above, the actual number of vehicles (b) was counted using the cameras installed next to the radar units.

Using this indicator, the detection accuracy was evaluated with 4,585 vehicles that passed through the detection areas within 9 min. Figure 10 presents the evaluation results.

Owing to the newly developed coordination capability of multiple radar units, high detection accuracy was achieved, averaging 95.9%. Moreover, the newly developed radar correctly identified all vehicles traveling across the detection areas of the two radar units, except for some vehicles that turned right or left and exited the detection areas. Consequently, the implemented tracking capability is exceptionally high.

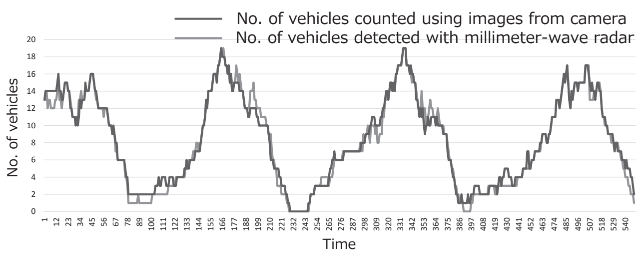

Fig. 10. Detection accuracy evaluation results

Meanwhile, the millimeter-wave radar at times failed to detect some vehicles (non-detection) and at other times determined the presence of non-existent vehicles (misdetection). Major causes of these errors are explained in (1) and (2) below. Future tasks include developing measures to counter these imperfections.

(1) Non-detection for vehicles crossing an intersection

Vehicles may enter from an intersecting road and cross the intersection, as pictured in Photo 3. The current detection algorithm of Sumitomo Electric is not optimized for such vehicles and, as such, often fails to detect them.

Photo 3. Vehicles crossing intersection

(2) Misdetection at the appearance of hidden vehicles

Sumitomo Electric's detection algorithm can track small vehicles even if they are temporarily behind a large vehicle, as described earlier. Moreover, when the receiver again picks up the signal reflected from a previously hidden vehicle, the algorithm can identify that the vehicle is the same vehicle the radar detected previously. However, when the traveling status (speed and lane) of the vehicle substantially changes within the duration it is hidden, the algorithm sometimes fails to identify it as the same vehicle and recognizes it as a new vehicle, resulting in counting it as two vehicles.

Photo 4. Appearance of a previously hidden vehicle

5. Conclusion

We have developed a coordination capability of multiple radar units with the aim of enabling vehicle detection in a wider area, using multiple infrastructure millimeter-wave radar units that offer superb environmental resistance and maintainability as well as excellent detection performance and a wide detection area. The experimental results produced on an actual road proved that the newly developed capability offers high vehicle-detection accuracy in a wider area and superb vehicle tracking performance. Planned future tasks include implementing measures to counter the problems identified in the experiment and applying the capability to various applications designed to help realize safe and smooth traffic environments.

Technical Term

∗1 Time-series filter: A technique designed to infer or control the state of a dynamic system, using observed values involving errors.

Reference

(1) A. Higashi, M. Kishi, R. Morinaka, N. Higashida, H. Shiranaga, S. Kido, "24-GHz Band Radar for Driving Safety Support Systems," SEI Technical Review No. 88 (2019)

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