Experimental study on a two-frequency secondary-radar system to detect pedestrians beyond blind corners using large anechoic chamber

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Abstract: We investigated a two-frequency secondary radar system to prevent traffic accidents between pedestrians and vehicles at intersections with poor visibility. We measured a ranging property between a vehicle and a pedestrian, and direction detecting property. This paper shows the results of these experiments measured in a large anechoic chamber with a wooden L-shaped wall to emulate an NLOS condition. A measurement error in NLOS was larger than that in LOS. However, it was able to detect a pedestrian in NLOS and the direction of the one.

Keywords: two-frequency secondary radar, frequency doubler, pedestrians detection, beyond blind corners, L-shaped corner, anechoic chamber

Classification: Navigation, Guidance and Control Systems

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1 Introduction

The number of traffic accidents in Japan has been decreasing over the past few decades [1]. One of the reasons would be the development of sensing technologies such as radars with millimeter-waves, lidars with visible, and infrared lights that can detect obstacles on roads to avoid the collision. They are designed for line-of-sight (LOS) operation. In order to achieve a further decrease in traffic accidents in the future, it is meaningful to develop the radar system that can detect pedestrians or other vehicles in blind intersections in dense urban areas or residential areas. As other methods to detect obstacles in non-line-of-sight (NLOS), some technologies such as vehicle-to-vehicle communication system, or communication between vehicles and radars installed in the blind street have been studied [2]. However, it would be challenging to install these systems on all the blind intersections because of the high-cost of introduction. We investigated a radar system, “two-frequency secondary radar,” which can be installed in low-cost [3]. A simple transponder carried by a pedestrian emits a radio-wave as a response to the radio-wave from an onboard transmitter. Detection of pedestrians behind blind corners will prevent collision accidents at the blind intersections, where the required ranging resolutions would be a few meters.

This letter reports a proof-of-concept experimental demonstration of our proposing radar system. We have measured basic characteristics such as radio propagation, range, and direction of arrival estimation in a large anechoic chamber. To simulate the NLOS operation, we set up a wooden L-shaped wall whose back is covered with wave absorbers in the chamber.

2 Radar system and principle of operation

It is necessary that transmitted waves from an onboard device can diffract at the corner and reach a blind area to detect obstacles. In addition, wave propagation loss in NLOS is larger than in LOS because of diffraction and reflection [4]. So, we utilized microwave signals whose frequency are much less than millimeter waves. We investigated this experiment using “two-frequency radar” because this radar has a high range resolution with a narrow frequency bandwidth. Furthermore, we introduced a secondary radar that a target transmits a dedicated response signal towards signal from an onboard system to distinguish between the signal from target and the other unnecessary signals caused by radio scattering at some corners. The target has to equip a dedicated device to respond the received signal. It is desirable for this device to be a simple structure, low cost, and quick response [5]. Based on these points, we used a frequency doubler as a transponder. The response signal can be generated by the transponder without using any complicated configurations consisting of oscillators or synchronizing circuits. As shown in Fig. 1 (a), we performed an experiment of detecting obstacles in NLOS using a two-frequency secondary radar.
Our proposing radar system is shown by Fig. 1 (b), where transmitted wave from the onboard transmitter consists of two frequencies $f_1$ and $f_2$ (frequency difference: $\Delta f$) that are transmitted per continuum alternately. This is two-frequency CW (continuous-wave) radar. When the signal is received by the transponder carried by the pedestrian, the transponder generates a frequency doubled signal ($2f$: $2f_1$, and $2f_2$). The phase of received $2f$ signal can be measured by using a frequency doubled reference signal generated in onboard transponder. When the initial phase is fixed, the distance between the onboard transmitter and the transponder can be calculated from the phase. However, it would be rather difficult to estimate the initial phase in actual radio systems. Two-frequency CW radar can provide distance measurement from the phase difference between two frequency components. The phases of $2f_1$ and $2f_2$ are denoted by $\varphi_1$ and $\varphi_2$. The distance $R$ can be calculated from the difference between the phases $D\varphi$ as follows Eq. (1),

$$R = \frac{c\Delta\varphi}{8\pi\Delta f}$$

where $c$ is the speed of light. The phase difference of this configuration is double the difference of the conventional CW radar system, because the transponder double the frequency. To avoid ambiguity in the ranging, the phase difference should be smaller than $2\pi$ so that the maximum length which the radar can measure can be expressed by Eq. (2).

$$R_{\text{max}} = \frac{c}{4\Delta f}$$

The range precision $\delta R$ is given by Eq. (3).

$$\delta R = \frac{c\varepsilon}{8\pi\Delta f}$$

where the phase measurement error is $\varepsilon$ [rad]. For example, the maximum length $R_{\text{max}}$ and $\delta R$ are, respectively, 25m and 14cm, where $\Delta f$ and $\varepsilon$ are 3MHz and 1 degree.
In this radar system, we measure the phase difference arisen among two receiving antennas of the onboard system, in order to specify the position of target. The phase difference causes by path difference of signal received by each antenna, to originate from the incoming direction from the transponder. Incoming agree from the transponder $\theta$ is given by Eq. (4).

$$\Delta \phi_r = \frac{2\pi d \sin \theta}{\lambda}$$  \hspace{1cm} (4)

$\Delta \phi_r$ is the phase difference between two receive antennas. $\lambda$ is the wavelength of the signal, and $d$ is space among two antennas. It is necessary that the measured phase difference is in the range from $-180$ [deg] to $180$ [deg] to avoid ambiguity in detecting. By measuring the phase difference, we can identify the direction of the target.

### 3 Experimental results

Figure 2 shows the experimental set up in the anechoic chamber and the block diagrams of our radio system. A wooden L-shaped wall was located to emulate a NLOS condition. In regard to the experiments of the ranging property, we measured two patterns that we move the transponder along the sight direction and crosswise direction. We also measured direction detecting property with moving the transponder along the crosswise direction. In each measurement, we performed the experiments automatically using LabVIEW, and obtained the standard deviation of $\phi_1$ and $\phi_2$ from 100 data samples. Figures 3 (a), (b) shows raging results, where the frequencies, where $f_1$ and $f_2$ are, respectively, 2.45GHz and 2.453GHz [6]. In Fig. 3 (b), the blue and red broken lines represent the gap of 50 cm from a theoretical value.

**Fig. 2.** Experimental set up and block diagrams of each property.
Figure 3 (c) expresses the result of the direction detecting property [6]. This experiment was performed using two types of configurations: with an L-shaped wall (w/ a wall), and without the one (w/o a wall). The space among two antennas \(d\) was 7 cm, then some of measured phase differences were out of the range to prevent ambiguity. As shown in Fig. 3 (d), we also calculated the expected the direction detection performance with \(d = 4\) cm, by using Eq. (4). Eq. (4) shows that the narrower \(d\) is, the smaller measurement phase difference becomes (If \(d\) becomes half of the original, phase difference will also become half of the original). We calculated the reduction ratio of the phase difference when we adjusted \(d\) to 4 cm, and revised the measured phase difference using this ratio. In this way, the phase differences are in the range to keep the measured range like. In each result, measurement error in NLOS was larger than that of LOS. However, it was able to detect the existence of objectives in NLOS, and distinguish which side of the road the pedestrian is in, by using the measured phase differences.

4 Conclusion

Measurement error in NLOS was larger than that in LOS. This error depends on radio scattering caused by L-shaped wall. However, the radio system for the vehicle (main system) could catch the response signal from the target (sub system), so it was be able to detect existence of target. Moreover, the target position could be identified to use phase difference.

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