An experimental study of obstacles and pedestrian classification by relative velocity distribution on urban-narrow bicycle-pedestrian road with 77 GHz FMCW radar

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Abstract: In recent years, the number of people using the bicycle as a means of transportation has increased due to heightened health awareness and environmental protection and COVID-19 pandemic, instead of public such as train and bus. Further, bicycle-related traffic accidents have rapidly increased due to the rapid growth of the food-delivery business with bicycle use, and thus countermeasures are urgently needed. In this paper, we propose a method for a bicycle to detect pedestrian separating from road obstacles such as guard poles and guardrails installed in an urban-narrow bicycle-pedestrian road with the use of frequency modulated continuous wave multi-input multi-output (FMCW-MIMO) radar. In the proposed method, from the distribution of the relative velocity of the detected objects, the objects gathering around the mode of the relative-velocity distribution are judged as the road obstacles, and the objects far from the mode are judged as pedestrian. In an experiment, a bicycle equipped with 77 GHz-band FMCW-MIMO radar, ran at a speed of 2 m/s and a pedestrian walked ahead at a speed of 1 m/s in a narrow bicycle-pedestrian road (school zone) in central Tokyo. Experimental result shows that the pedestrian was detected with about 1m/s-higher relative velocity than around 1.5 m/s of mode relative velocity, where road obstacles group distributed in the range of ± 0.5 m/s.

Keywords: bicycle, mm-wave, FMCW, MIMO, pedestrians, radar

Classification: Sensing

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1 Introduction

In recent years, the use of bicycles has been increasing worldwide from the viewpoints of heightened health awareness and environmental protection. More recently, people use bicycles instead of public transportation such as buses and trains to prevent infection due to the COVID-19 pandemic [1]. In addition, share cycling and food delivery services are expanding as businesses. There are many bicycle users in the city, and the ratio of bicycles to all means of transportation is increasing [2]. Safe riding support for senior cyclists had been investigated with radar technology [3]. With the increase of bicycle-to-pedestrian accidents, 24 GHz-band frequency modulated continuous wave multi-input multi-output (FMCW-MIMO) radar has been tested to prevent forward collisions of the bicycle and support visibility [4, 5], where objects (e.g., road obstacles, building, and cars) were detected in large space, not

in relatively narrow bicycle road. On the other, millimeter-wave (mm) radar has recently been put to practical use as a support for the safe driving of automobiles which has the advantage of being compact, inexpensive to design, and higher distance resolution compared with those features of the 24 GHz-band. Furthermore, mm-radar effectively detects many road obstacles (e.g., guardrail, guard pole, barricade, road sign, street light) on the bicycle path. The FMCW radar can detect distance and speed simultaneously and has a simpler circuit configuration, compact and inexpensive features compared with pulse and Doppler radars.

From this perspective, to prevent bicycle-to-pedestrian accidents, 77 GHz-band FMCW-MIMO radar was used to detect pedestrian and road obstacles in narrow urban bicycle-pedestrian-road [6, 7]. However, it was pointed out that moving objects such as pedestrians could not be detected stably due to the influence of many road obstacles when radar (bicycle) was moving, where a coherent integration was performed as a method of separating moving objects from stationary objects, but the radar was stationary [6]. In the other previous research, the moving pedestrian was detected, tracked, and its shape was measured by using four-dimensional radar processing and particle filter applying to detected point cloud [8]. Furthermore, machine learning was used for pedestrian classification in 79 GHz automotive radar systems [9]. However, the amount of calculation in these methods increases according to the number of point clouds and not suitable for real-time and cost performance required to personal mm-wave radar device. Therefore, in this paper, we propose an extremely simple algorithm for real-time and cost performance to detect pedestrian separating from road obstacles with FMCW-MIMO radar attached in running bicycle, in which the objects gathering around the mode of the relative-velocity distribution are judged as the road obstacles, and the objects far from the mode are judged as pedestrian [7].

2 FMCW MIMO radar signal processing

The ramp generator of the FMCW radar system periodically outputs a chirp signal. The frequency of each chirp signal is swept from f_{min} to f_{max} within t_c and it is swept linearly with a slope of S . The number of chirps one frame is K chirps, and the frame time is t_f . And the received signal is correlated with the transmitted signal by the mixer to produce an IF signal. The distance R can be expressed as:

$$R = \frac{cf_b}{2S} \quad (1)$$

where f_b is the frequency difference between the transmitted signal and the received signal, c is the speed of light, and S is the slope of the chirp, respectively. The velocity V is:

$$V = \frac{\lambda f_d}{2} \quad (2)$$

where f_d is the Doppler frequency extracted from the phase difference $\Delta\varphi$ obtained after Doppler-FFT, and λ is the wavelength. The angle θ is given as below:

$$\theta = \sin^{-1} \left(\frac{\lambda \Delta\omega}{2\pi d} \right) \quad (3)$$

Fig. 1. Algorithm to detect and divide pedestrian and road obstacle

where $\Delta\omega$ is the phase difference obtained after angle-FFT processing in the antenna direction with respect to the data obtained by Range/Doppler-FFT processing, and d is the distance between the receiver antennas.

3 Algorithm to detect and divide pedestrian and road obstacle

This section compares the relative velocities of each object and proposes an algorithm for pedestrian detection when the radar is moved. Figure 1 (a) shows a flowchart of the warning generation algorithm. First, the mode relative velocity V_m is calculated from the detected object data. Then compare the relative velocity v of each object with the mode relative velocity V_m . If there is an object whose relative velocity in the negative direction is greater than the mode relative velocity V_m , it is considered a moving object P_p $\{P_p = P(v < V_m - V_a)\}$, such as a pedestrian moving towards the radar., Where V_a is the value set to consider an object close to the mode relative velocity as an obstacle. Figure 1 (b) also shows a dangerous area when riding a bicycle. The half-value angle of the radar antenna used in this experiment in the horizontal direction is $\pm 35^\circ$, and unnecessary objects are detected when the bicycle is running. Therefore, $\pm X_a$ m in the horizontal direction of the bicycle and Y_a m in the traveling direction of the bicycle. We defined a dangerous area which was determined with the values X_a and Y_a after taking into account the conditions of the bicycle path due to the weather. If moving object P_a is in the danger zone (width $\pm X_a$ m, distance Y_a m), it will be judged as dangerous goods to ride a bicycle, and a warning will be issued. The relative velocities of detected objects (points cloud), which are just output of Doppler-FFT, are only saved and sorted in memory, and then the objects with values far from the mod value of the relative velocities (most frequent value in frequency distribution) are judged as a pedestrian in each frame. Thus, the amount of signal processing in the algorithm is extremely small and effective to real-time and cost performances.

4 Experimental results and discussion

We used a 77 GHz-band FMCW radar module with three transmissions and 4 receptions. Half of the antennas in the horizontal and vertical directions are $\pm 35^\circ$ and $\pm 4^\circ$ for both transmission and reception. The experiment was performed with the bandwidth of 1.014 GHz, the chirp slope of 40 MHz/ μ s, the frame time of 100 ms, and the chirp time of 48.98 μ s.

The experiment was conducted on a narrow bicycle-pedestrian road in Chiyoda ward, Tokyo. The pedestrian walked toward the radar. Radar-equipped bicycle velocity was about 2 m/s, and the pedestrian was about 1 m/s.

The environment of the bicycle-pedestrian road is shown in Fig. 2 (a). The detection results of pedestrians and obstacles are shown in Fig. 2 (b). In Fig. 2 (a) to Fig. 2 (d), numbers are assigned from #1 to #7 in descending order of signal

(a) Experimental environment

(b) A pedestrian and obstacles

(c) Relative velocity vs. Range vs. Relative signal amplitude

(d) Relative velocity histogram

(e) With width and range limit

Fig. 2. Detection results.

strength. Figure 2 (c) shows the signal strength at each point. As a result, a guardrail was detected at about 4 m from the left side of the radar. A building was detected at about 5 m to 9 m from the radar, and the pedestrian and guardrail were detected at about 6 m on the radar axis. Figure 2 (d) shows relative velocities histogram in the direction perpendicular to the radar. The relative velocities of the road obstacles were detected at about -1.1 m/s to -2.1 m/s. Since the road obstacles are immobile, the relative velocities are considered to be a group in the negative direction. The relative velocity decreases as the angle from the radar increases. A pedestrian was detected at a relative velocity of about -3.0 m/s and had a more negative relative velocity than the road obstacles group. Based on the above, it was possible to separate a pedestrian from road obstacles by the relative velocity distribution. Figure 2 (e) shows the detection result after limiting in the dangerous area (safety width $\pm X_a$, distance within Y_a). At this time, by applying the conditions of $X_a = 1.5$ m and $Y_a = 10$ m, only pedestrians are detected at about 7 m, and a warning is issued.

5 Conclusion

In this study, we detected objects on the narrow bicycle-pedestrian road with the 77 GHz-band FMCW radar. In the experiment, the pedestrian was detected with about 1 m/s of higher velocity (walking velocity) than that of the road obstacles group, from relative velocities histogram of the obstacles. In the future, in order to study a system that notifies the driver of danger, we plan to study improving the detection accuracy of a pedestrian when riding a bicycle. The extremely small amount of signal processing in the proposed algorithm is effective to real-time performance and enables further miniaturization and lower cost.