

LOW POWER MILLIMETER WAVE RADAR SYSTEM FOR THE VISUALLY IMPAIRED

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Abstract

In order to help visually impaired people to avoid obstacles, a K-band millimetre wave (MMW) radar system based on the principle of frequency-modulated continuous wave (FMCW) is proposed in this paper. The FMCW basic principle and the signal processing algorithm are elaborated in detail. The prototype of the radar system has been designed and manufactured. The experiment results show the qualified detection accuracy in view of low deviation. The maximum deviations from the range measurement experiments for a person and a car are 0.14m and 0.47m, respectively. As a wearable system, the radar system has the characteristics of low power and small size, which is very suitable for blind navigation application. In addition, the MMW radar has broad application prospects in the field of automotive blind spot detection and small robots.

1. Introduction

According to the data from the World Health Organization (WHO), 285 million people were estimated to be visually impaired worldwide, and 39 million were blind [1]. It is very difficult for visually impaired people (VIP) to perceive and avoid obstacles at a distance.

RGB-Depth (RGB-D) sensors, LiDAR, Ultrasonic sensors, and millimeter wave (MMW) radar sensors are commonly used to help VIP to perceive obstacles and avoid them. Among these sensors, the MMW radar is the best candidate to measure the range and velocity with high accuracy and stability.

Auxiliary approaches based on RGB-D sensors have been investigated to help them to avoid obstacles [2]. However, the RGB-D sensors, including light-coding sensors, time-of-flight sensors (TOF camera), and stereo cameras, could not solve the problems of remote obstacle detection and velocity detection perfectly. The detection range of low power light-coding sensors is too small in outdoor environment, especially in sunny environment [2-5]. The measurement results of TOF camera are sensitive to ambient light and show poor performance in outdoor environments [6-8]. Remote measurement results derived from stereo cameras are not accurate and highly-textured scenes are preferred [9, 10]. Furthermore, it is difficult to measure the velocity of object using RGB-D sensors.

LiDAR measures the distance of a target by illuminating it with a pulsed laser light and receiving the reflected pulses with a sensor. It can be used to achieve high-resolution maps and acquire the accurate distance and velocity [11]. However, the high cost and power as well as its volume limit the application in the assistive wearable device for VIP.

Ultrasonic sensors are able to provide the presence and distance of a target in the field of view in low speed scenarios [11], with a relatively low cost and small package. But it is easily affected by air temperature, pressure and wind, so the detection range is limited to 5 meters approximately. Thereby, it is not suitable to integrate this type of sensor in assisting systems for VIP.

Thanks to the technological development, the MMW radar sensors have become small, low-cost and accurate, which makes them suitable especially for portable low-power applications. Moreover, radar's performance is not influenced by illuminance and outdoor environment [12, 13]. Radars have lower computational complexity and use less power. The range and velocity of the obstacle are calculated at the same time, and the accuracy of the range is very high, e.g., several centimetres. The radar signal can also penetrate opaque materials such as plastic.

The 24GHz band is mature in commercial implementation and is permitted to use in industrial, scientific and medical (ISM) application globally. Within this framework, a 24GHz MMW FMCW radar system is built to detect stationary and fast-moving object. The FMCW radar basic principle, the signal processing algorithm and the radar hardware system are introduced in detail. As a system consuming power of about 500mW, the detection range is 10m and 30m for a person and a car, respectively. This radar system is suitable for obstacle avoidance in portable applications for VIP.

The paper is organized as follows. In the next section, the MMW radar system is presented, including FMCW basic principle and the signal processing algorithm. In section 3, the radar hardware system is presented in detail. The experiments are described in detail in section 4. Finally, conclusions are presented in section 5.

2. Millimetre wave radar system

The FMCW basic principle, and the signal processing algorithm based on fast Fourier transformation (FFT) and constant false alarm rate (CFAR) are described in this section.

2.1 Frequency modulated continuous wave

FMCW radar is a technique that obtaining range and velocity information from a radar by the way of frequency modulating a continuous signal [14]. The method of frequency modulation takes many forms, and the sawtooth and triangular modulation are always used. Herein we apply the triangle modulation. Its basic principle is shown in Fig. 1.

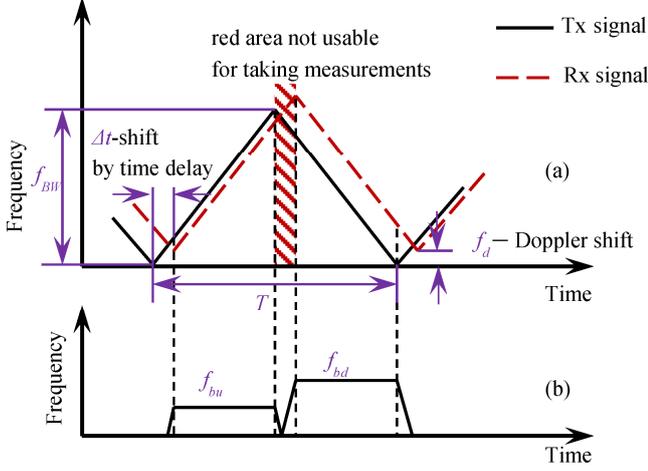


Fig. 1 FMCW radar waveform with a triangle shape in the frequency-time domain. (a) The transmitted and received signal, where the beat frequency in red area is not constant. (b) The corresponding beat frequency.

This frequency difference between the transmitter (TX) signal and the receiver (RX) is called ‘‘beat frequency’’, which carries the range information. Here, f_{BW} is the modulation bandwidth, T is the modulation period or sweep time, Δt is the delay time, f_d is the Doppler frequency, and the f_c is the radar carrier frequency. The beat frequencies for the up-chirp and down-chirp are named as f_{bu} and f_{bd} , respectively, as the Fig. 1(b) shown.

Velocity and range should be determined for a moving target based on the Doppler effect and the delay effect. The Doppler effect, which leads to a shift of the receiving frequency. Its calculation formula can be expressed as:

$$f_d = 2f_c \cdot \frac{v}{c_0} \cdot \cos \alpha \quad (1)$$

Here, v is the velocity of the moving object, c_0 is the Speed of light and α is angle of the direction of the object motion with the direct connecting straight line between sensor and object. To simplify the equation, we set the angle α to zero which means object moving straight towards or away from the sensor. Then the equation becomes:

$$f_d = 2f_c \cdot \frac{v}{c_0} \quad (2)$$

The delay effect leads to a time delay of the receive signal because of the range. Its calculation formulation is given as follows:

$$f_R = \frac{2R \cdot f_{BW}}{c_0 \cdot T} \quad (3)$$

Here, f_R is the range beat frequency, R is the range to the target. Combining both effects by a simple additional mathematical operation to calculate the range and velocity at the same time.

$$f_{bu} = |f_d - f_R| \quad (4)$$

$$f_{bd} = f_d + f_R \quad (5)$$

By combining the equation (2)(3)(4)(5), the range and velocity result can be calculated as:

$$R = \frac{|f_{bu} - f_{bd}| \cdot c_0 \cdot T}{4 \cdot f_{BW}} \quad (6)$$

$$v = \frac{c_0 \cdot (f_{bu} + f_{bd})}{4 \cdot f_c} \quad (7)$$

All parameters in (6) and (7) are either known values like f_c , c_0 , f_{BW} and T or they are determined by frequency measurement (f_{bu} , f_{bd}).

2.2 Signal processing algorithm

The special digital signal processing (DSP) algorithm, which is applied on the digital data coming from the ADC, is required to obtain the range and velocity information of the target. The basic block diagram of this module is presented in Fig. 2. The data producing directly by ADC contains the invalid signals. The beat frequency at the peak and valley of the triangle is not constant and not used for signal processing, which is called the invalid signal, such as the red shadow area shown in Fig. 1(a). Therefore, the data should be classified firstly to remove the invalid ones. Furthermore, the digital filtering, e.g., Finite Impulse Response (FIR) filter, Infinite Impulse Response (IIR) filter or wavelet filter, is adopted to improve the signal to noise ratio (SNR).

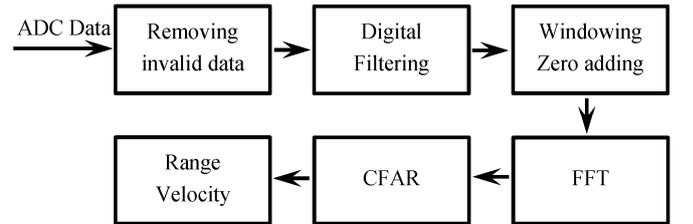


Fig. 2 The block diagram of the DSP module

If the sampling frequency is not a perfect multiple of the frequency of input waveform, there will be a break point between the last data point and the first data point of two successive input data periods. The break point causes energy leakage in FFT [15]. To solve this problem, a window that makes the input data into a particular shape is used. Several commonly used windows are Hamming, Hanning, Blackman and Triangle. Here we apply the Hanning window. After the data being windowed, the zero padding should be applied to get a better frequency resolution.

The targets are detected by an amplitude threshold using CFAR algorithm. In order to achieve the CFAR, an adaptive threshold is applied for reflecting the local clutter situation [16]. The cell averaging (CA) and ordered statistic (OS) CFAR are most commonly used. The CA-CFAR that we used

means all signal amplitudes inside the reference window contribute to the detection threshold, unlike the OS-CFAR that only selects a single amplitude [17].

The target is found after the threshold detection. And the range and velocity of the object will be calculated.

3. The hardware configuration

This wearable system is composed of a low power MMW radar, a pair of smart glasses [18] and a portable computer, and the block diagram of this system is shown in Fig. 3(a). The weight of the smart glasses and radar system is about 117g and 58g respectively, which is suitable for carrying. And the weight of the portable computer is about 277g, which always is put into the packet. The MMW radar includes a radar transceiver and a signal processing circuitry. The radar transceiver transmits and receives the millimetre wave to detect the object. The signal exported by the radar transceiver is processed by the signal processing circuitry. The radar transceiver and the signal processing circuitry are elaborated in subsection 3.1 and 3.2, respectively. The prototype of this MMW radar is shown in Fig. 3(b). It has a power consumption of about 500 mW and is simply powered by the USB port of the portable computer.

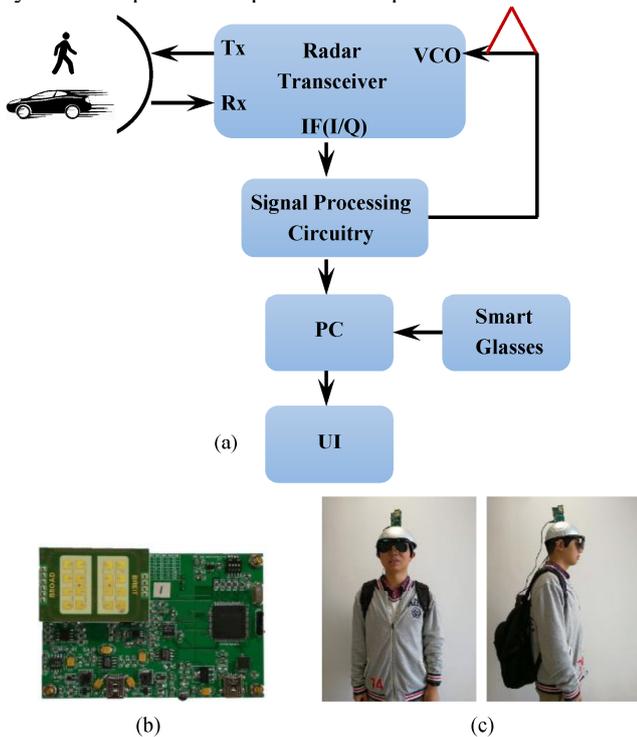


Fig. 3 Hardware configuration. (a) Wearable system block diagram; (b) MMW radar prototype; (c) Wearable system with MMW radar and smart glasses.

The smart glasses are composed of an RGB-D sensor and a bone-conducting headphone. The RGB-D sensor is used to detect the scenes nearby, such as the crosswalk and traffic lights. The bone-conducting headphone, which does not block the hearing completely, is used to convey effective interactive information in the wearable system. The whole wearable system with MMW radar and smart glasses is shown in Fig. 3(c). A portable computer in the backpack is used to achieve the DSP algorithm. The VIP could get the

message through the user interface (UI) based on the non-semantic sonification interface.

3.1 The radar transceiver

In this paper, the IVS-163 [19] planar monostatic radar transceiver with the radiating centre frequency of 24GHz is used, as shown in Fig. 4. Due to low power and compact outline dimension, it is convenient to integrate the radar transceiver in a wearable system. Its basic electrical characteristics [19] are presented in Table 1.

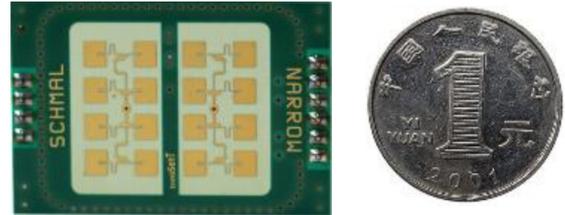


Fig. 4 IVS-163 radar transceiver and a coin.

Table 1 Electrical characteristics

Parameter	Value	Unit
Supply voltage	5	V
Supply current	35	mA
Transmit frequency	24.000-24.250	GHz
VCO tuning voltage	0.5-10	V
Output power	15	dBm
Full beam width @-3dB	Horizontal-70 Vertical-36	Degree

The radar transceiver employs the super-heterodyne architecture [12] which uses frequency mixing to convert a high radio frequency (RF) echo signal to a fixed intermediate frequency (IF) that can be more conveniently processed than the original RF frequency.

The linearity of the VCO needs to be considered when the FMCW is used in this monostatic radar, in that FMCW requires good linearity in the frequency ramp. The response of the radiate frequency to the VCO voltage of the transceiver is not a strict linear relationship, as the practically measured curve shown in Fig. 5. We select the linear segment of the curve (i.e. 3V to 7V). The corresponding frequency bandwidth (250MHz) conform to ITU Radio Regulations.

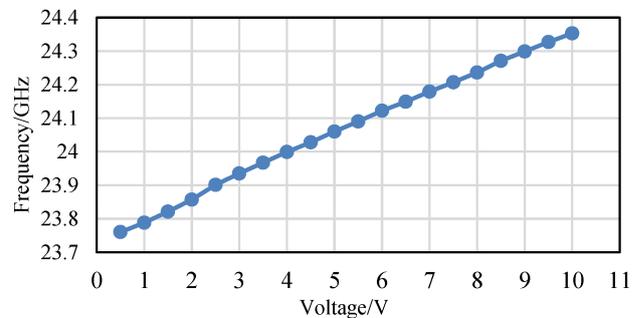


Fig. 5 Voltage-frequency response of the IVS-163 radar transceiver.

The other issue is the isolation. The IF signal generates an output even without an object in range because of the finite

isolation between the transmitter and receiver path. This effect is called self-mixing or “crosstalk”. The crosstalk signals may overdrive external IF amps under certain circumstances. To minimize this effect, filtering process should be taken as early as possible in the signal processing circuitry.

3.2 Signal processing circuitry

The IF signal coming from the radar transceiver needs further processes, including filtering, amplifying, sampling, removing the invalid data, packaging and transmitting. Therefore, the signal processing circuitry is designed and manufactured, its basic block diagram is shown in Fig. 6.

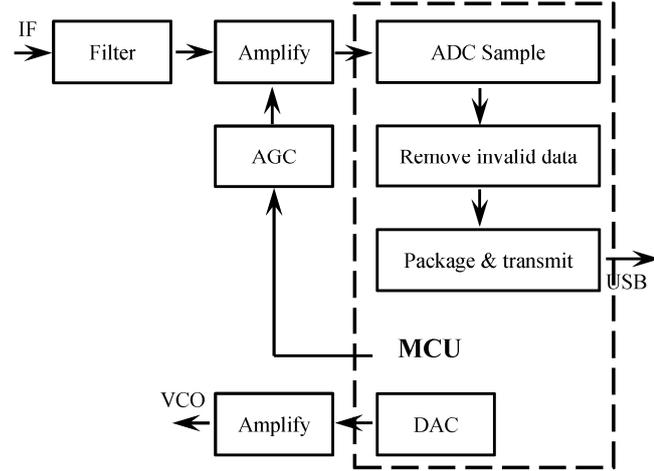


Fig. 6 Signal processing circuitry basic block diagram.

The IF signal generates non-zero outputs even without an object in the detection range, because of the finite isolation between the path of transmitter and receiver. The crosstalk signals may overdrive external IF amps under certain circumstances. To minimize this effect, the filtering processing should be the first step of the signal processing circuitry.

The amplitude of the IF signal, which goes through the filter, becomes very small. Then the IF signal needs to be amplified. The automatic gain control (AGC) circuit, which is managed by a ST Cortex M4 micro-controller (MCU), provides with a suitable magnification based on the data coming from the ADC of the MCU.

The IF signal is filtered and amplified via a custom analog circuit. Then it is sampled by the 12bit ADC of the MCU. The sampling frequency of ADC should meet the Nyquist criterion. As a short-range radar, it aims to detect the fast-moving car in 30m and walking pedestrian in 10m. The maximum frequency of the signal is the sum of f_d and f_R assuming a car with a range of 30m and a speed of 80km/h is detected. The maximum frequency is 13.5kHz based on the Eq. (2) and (3). Moreover, oversampling has the advantages of improving resolution, reducing noise, as well as avoiding aliasing and phase distortion. Therefore, the ADC sampling rate in this system is used as 100kHz.

The analog IF signal becomes the digital data after the ADC sampling. Then, the invalid data is removed by the MCU. The rest data is packaged and transmitted to the host machine by a UART-to-USB chip. The digital filtering, windowing,

zero padding, FFT, CFAR, as well as the calculation of the range and velocity is achieved by the MATLAB installed on the portable computer.

The triangular wave, which is produced by DAC of the MCU and amplified, is fed into the VCO. And the frequency of this triangle wave is 100Hz according to the practical experience.

4. Experiment

This low power MMW radar system is designed and manufactured to help VIP detect the stationary and moving object at a certain distance. The accuracy of the range detection is verified at the range measurement experiment. A person stands in front of the radar, as shown in Fig. 7. The radar system gives the distance between the radar sensor and the person. The radar signal processing results are shown in Fig. 8.



Fig. 7 A person stands in front of the radar

The raw data coming from the MCU are shown in Fig. 8(a), where the invalid data have been removed. The up and down sweep of the triangular modulation generate two IF signals. Then the IF signal of the up sweep is taken out and removed the DC component, as shown in Fig. 8(b). The results of going through the digital filter, windowing and the FFT after zero padding are shown in Fig. 8(c)(d)(e) respectively. The object is discovered in the frequency domain by the way of CA-CFAR, as shown in Fig. 8(f). The red dot dash line is threshold, and the amplitude of the effective object IF signal is higher than it. Then the frequency of IF signal of the effective object is calculated, the same processing on the IF signal of the down sweep. The range is calculated using the Eq. (6).

The field tests are also designed and carried out. We measure the range, which is between the radar sensor and the person, using the laser range finder at the same time. And the result of the laser ranger is regarded as the real value. The measurement results of different ranges are shown in Table 2. From Table 2, it can be seen that the maximum deviation is less than 0.35m, and the relative error is less than 8%. The measurement data for a person indicate our MMW radar system is able to detect a person within 10m, even though the radar cross section (RCS) of human being is very small.

The same tests were done for a car. Relative to the human being, the surface area of cars is much larger and not a plane. The laser range finder only measures a single point distance, but the MMW radar’s measuring result is the average of the whole car surface. However, the maximum deviation is only

about 0.5m, and the relative error is less than 6%, basing the data from Table 3. These experiments indicate the MMW radar system provides high-accuracy ranging results.

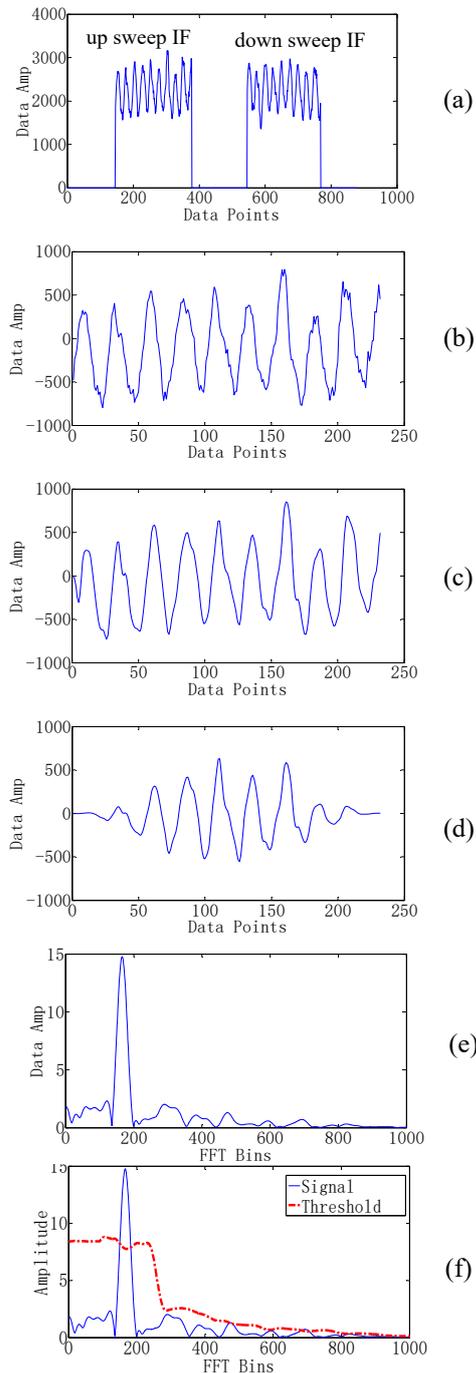


Fig. 8 The signal processing results. (a) The raw data coming from the MCU. (b) The IF signal of the up sweep. (c) The digital filtering. (d) Windowing. (e) The FFT after zero padding. (f) The result of CA-CFAR.

We also detect the velocity of the pedestrians and cars with the MMW radar system. The velocity of the normal walking pedestrians and moving car is about 5km/h and 20km/h respectively in our campus. Error analysis of the measurement system is not given because we don't know the real speed value at that moment.

In the experiments, we find the experiment results are influenced by the ground clutter sometimes. The vertical direction of radar transceiver is perpendicular to the ground, which is used to reduce influence of the ground. We also set the suitable parameters of the CA-CFAR, which further reduces the influence of the ground.

5. Conclusion

In this paper, a short range and low power MMW radar system based on the principle of FMCW is built to help VIP to avoid obstacles. The FMCW radar basic principles, signal processing algorithm and the whole hardware system are described in detail. Experiments show that the radar system is able to detect a person with range up to 10m and a car up to 30m. When measuring a person, the maximum deviation is less than 0.35m, and relative error is less than 8%. When measuring a car, the maximum deviation is only about 0.5m, and the relative error is less than 6%. The range accuracy is very high. The proposed MMW radar system has characteristic of small size, low power, which is very suitable for blind navigation application. In addition, in the field of automotive blind spot detection and small robot, the MMW radar has broad application prospects.

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Table 2 Range measurement data for a person

Times	1	2	3	4	5	6	7	8	9	10
Radar Range (m)	0.99	2.37	3.34	3.86	4.57	4.92	6.33	7.56	8.26	9.66
Real Value (m)	0.92	2.30	3.30	4.00	4.70	5.00	6.35	7.50	8.60	9.56
Deviation (m)	+0.07	+0.07	+0.04	-0.14	-0.13	-0.08	-0.02	+0.06	-0.34	+0.10
Relative Error (%)	7.61	3.04	1.21	3.50	2.77	1.6	0.31	0.8	3.95	1.05

Table 3 Range measurement data for a car

Times	1	2	3	4	5	6	7	8	9	10
Radar Range (m)	3.04	5.86	7.39	8.97	11.86	14.03	17.58	21.75	24.35	28.60
Real Value (m)	2.89	5.57	7.00	8.77	11.45	14.30	17.41	21.28	24.30	28.50
Deviation (m)	+0.15	+0.29	+0.39	+0.20	+0.41	-0.27	+0.17	+0.47	+0.05	+0.10
Relative Error (%)	5.19	5.21	5.57	2.28	3.58	1.89	0.98	2.21	0.21	0.35

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