The Embedded Implementation of Millimeter Wave Radar Signal Processing System

Xingbo Ren, Zhiyuan Liu and Tengfei Fu

1 Introduction

The high rate of traffic accidents seriously threats the safety of people's lives. So the intelligent automobile which can improve the traffic safety is more and more concerned by the automobile manufacturers and the public [1]. One of the biggest problems with intelligent automobile is how to accurately identify the environment around the automobile [2]. In the aspect of environmental perception, millimeter-wave radar has been widely used because of its wide range of measurement, less susceptible to environmental factors and moderate price.

In foreign countries, such as the United States, Japan and Germany, the major automobile manufacturers began the millimeter-wave radar technology research from the sixties of last century [3]. At present, some countries even have products that can be used in the car. However, in China, the research on millimeter-wave radar started lately. And most colleges that study millimeter-wave radar are still in the stage of theoretical research and experimental testing [4]. At present, there is no reliable product in China that can be used in the car [5, 6].

In this paper, We designed a hardware platform of radar signal processing and a algorithm of radar signal calculation using the K-MC3 millimeter-wave radar sensor from RFbeam company. The system can realize the recognition of the distance, velocity and direction of the objects in front of the radar.

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2 Measurement Principle of Radar

The K-MC3 radar used in this paper is a frequency modulated continuous wave radar. Its working principle is as follow: the modulation signal whose amplitude is in the form of triangular wave controls radar transmitting millimeter wave signal whose frequency is changed in the form of triangular wave. Then, if there is an obstacle, the millimeter wave signal will be reflected. Next, the millimeter wave signal is received by the receiver of the radar. Finally, the intermediate frequency signal is generated by subtracting the transmitted signal and the received signal [7]. The principle of the intermediate frequency signal generation is shown in Fig. 1.

In Fig. 1a, the vertical axis is the frequency, and the horizontal axis is the time. The solid line is the frequency with time curve of radar transmitting wave. And the dotted line is the frequency with time curve of radar receiving wave. The difference frequency signal in Fig. 1b can be got by subtracting the transmitted signal and the received signal. According to the principle of Doppler Effect and the principle of electromagnetic wave we can get the formulas for calculating the distance and velocity:

$$R = \frac{c_0}{2}\frac{f_{b+} + f_{b-}}{2f_M}\frac{T_M}{2} \tag{1}$$

$$v = \frac{c_0}{f_0}\frac{f_{b+} - f_{b-}}{4} \tag{2}$$

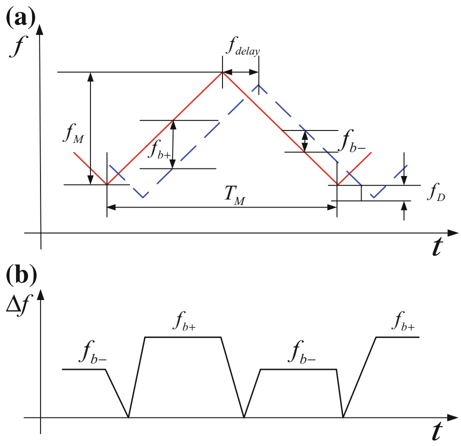


Fig. 1 The schematic diagram of IF signal generation

3 System Hardware Structure

The overall structure of the hardware circuit is shown in Fig. 2. The hardware circuit includes the main control unit, the communication module, the modulation signal generation module and the radar signal processing module.

The system chose TMS320F28335 from TI as the main control chip. TMS320F28335 is a 32 bit floating point DSP whose frequency can reach 150 MHz. And the DSP integrates a wealth of peripheral resources [8]. In the signal processing algorithm, a large amount of data needs to be stored. So the RAM space of F28335 was expanded using IS64LV12816 chip.

The CAN Communication Module is mainly used to send out the results of radar signal processing algorithm.

3.1 Modulation Signal Generation Module Design

In order to produce transmitting wave whose frequency changes like the shape in Fig. 1a, we must give the radar a input signal like shown in Fig. 3.

The modulation signal generation module is composed of DSP, DAC and amplifier. First of all, the modulation signal data is sent to the DAC chip through the DMA channel of DSP. Then, the DAC chip transforms the data into analog signal. Finally, we can get the modulation signal after a 2.5 fold amplifier.

3.2 Radar Signal Processing Module Design

When the radar works, the output signal of the sensor is like Fig. 4. It can be seen from the figure that there are two obvious problems in the original signal. One is that the output signal is mixed with the 100 Hz leaky wave signal. And the

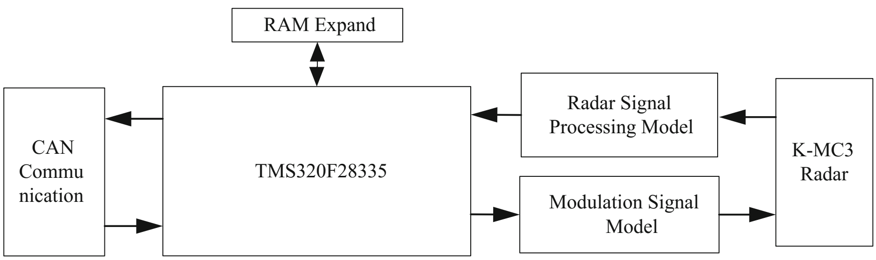


Fig. 2 The structure of hardware circuit

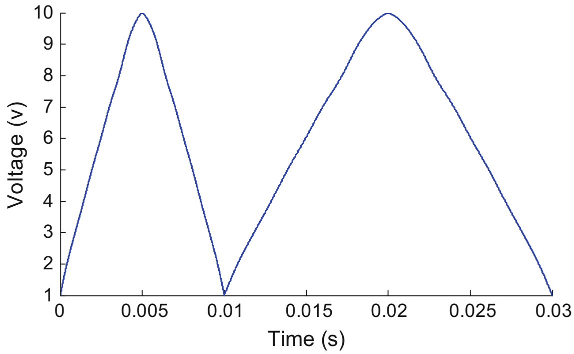


Fig. 3 Modulation signal

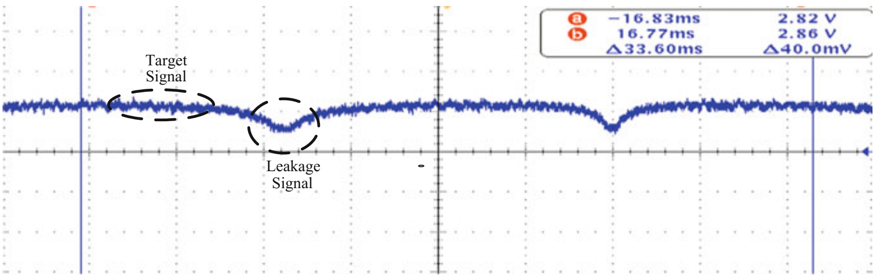


Fig. 4 The output signal of radar

amplitude of leaky signal is much larger than the amplitude of target signal. The other is that the amplitude of target signal is very small, which is not conducive to the ADC.

In order to solve the above two problems, it is necessary to design the radar signal processing circuit. The function includes two parts: filter and amplification.

The filter circuit is used to filter the low frequency leaky signal and the high frequency interference signal. So it is necessary to design a band-pass filter. The high cutoff frequency is determined by the frequency range of the target signal. According to formula (1) and (2), We can get the formula (3) to calculate the target signal frequency.

$$f_{b+} = \frac{4Rf_M}{c_0 T_M} + \frac{2vf_0}{c_0} \tag{3}$$

It can be seen from the formula (3) that the maximum frequency of the target signal can be obtained when the distance and velocity are taken to the maximum. The target measurement range of radar in this paper is as follows: the distance is less than 120 m, the speed is less than 110 km/h. Then we can get that the highest frequency of the target signal is about 40 kHz. So the high cutoff frequency was taken as 40 kHz. On the other hand, the low cutoff frequency is determined by the leaky wave signal and the target signal. The frequency of the leaky wave signal is about 100 Hz. And the target signal frequency is from 0 to 40 kHz. So when filtering out the leaky wave signal, we are filtering out some useful target signal. Then we can get the selection principle of low cutoff frequency. The principle is that the frequency should be as small as possible when it can filter out the leaky wave signal. After the simulation in Pspice, we chose the low frequency 400 Hz. Above all, the pass-band of the band-pass filter is 400 Hz–40 kHz. In this paper, we used LM2904 of TI to design the band-pass filter.

The purpose of the amplifier is to amplify the target signal to the range of ± 1 V. The function consists of two parts: a fixed gain amplifier circuit and an adjustable gain amplifier circuit. The fixed gain amplifier was designed 30 times enlarge the signal using LM2904 chip. The amplitude of the target signal is related to material, size and distance of the target. So it is necessary to design an adjustable gain amplifier circuit that can adjust the output signal automatically to the range of ± 1 V according to the amplitude of the input signal. In this paper, the AD603 chip was used as the amplifier chip, and the half wave detection circuit was used as the negative feedback circuit to design the adjustable gain amplifier circuit.

4 Radar Signal Processing Algorithm Design

The radar's output signal was processed by the hardware circuit and then sampled by the ADC module. After sampling the radar signal, DSP needs to deal with a series of data to get the information of the targets.

First of all, in order to further eliminate the interference caused by high frequency signal, a low-pass digital filter was designed. Then, we need to design algorithm to separate the signal corresponding to every target, and accurately identify the exact frequency of every target signal. Finally, it is easy to appear false alarm and missing alarm when recognize targets. So it is necessary to design algorithm to eliminate some of the interference, so as to avoid the phenomenon of false alarm and missing alarm.

A low-pass digital filter was designed using FIR. The maximum frequency of the pass-band was set to 40 kHz. And the minimum frequency of the stop-band was set to 60 kHz.

4.1 *Peak Frequency Determinate*

It can be seen from the formulas (1) and (2) that we need to identify the peaks' frequency of the targets in order to calculate the targets' information. In this paper, FFT and Chirp-z algorithm were used to determine the peaks' frequency.

The output signal of radar is the mixture of multiple targets' signal. So the output signal cannot be separated until we transform the data into frequency domain. For the purpose of improving the speed of calculation, this paper used the Fast Fourier Transform (FFT) algorithm to realize the Discrete Fourier Transform algorithm. Firstly, we must determine the sampling frequency. According to the sampling theorem, the sampling frequency should be at least two times as much as the highest target frequency 40 kHz. But when using, we always choose the sampling frequency at least four times as much as the highest target frequency. So the ADC sampling frequency was chose as 187,500 Hz. Then, we must determine the points' number of FFT transform. If the ADC work as 187,500 Hz, It can sample 937 points during the rising segment of the 100 Hz modulation signal. Removing about 200 points that at the beginning and at the end, we can only use about 700 points to calculate the FFT. On the other hand, there is fence effect error in FFT. The error is:

$$\Delta f = \frac{f_s}{n} \tag{4}$$

From the formula (4), we can see that we must increase the number of FFT in order to reduce the fence effect. Therefore, the sampling points n was finally taken as 512. The error brought by the fence effect was 366.21 Hz.

In order to further reduce the error caused by the fence effect, the Chirp-z transform was used in this system. In theory, the Chirp-z transform of m point can reduce the error of FFT by m times [9]. Therefore, from the point of view of error analysis, the 16 point Chirp-z transform can reduce the error of the fence effect to 22.89 Hz. At this time, the error of the fence effect on the measurement results can be small enough to meet the requirements. However, in practical application, it was found that the result of 16 point Chirp-z transform was always different from the result of FFT. That is because 16 point is only a small part of the sampling point. It is easy to be influence. so we must further increase the number of Chirp-z transform. It was found that when the number of points is 128, it can achieve a good amplification effect. Finally, the points of Chirp-z was taken as 128.

4.2 False Targets Exclude

False alarm is that the number of solved targets is more than that of actual targets. While the missing alarm is that the number of solved targets is less than that of actual targets. The false alarm phenomenon will cause the vehicle frequently braking. And the missing alarm will seriously affect the safety of the vehicle. So the elimination of false alarm and missing alarm is very important during recognizing targets that in front of radar. In this paper, we used CFAR algorithm to remove the interference of environmental factors firstly. Then, the peaks match algorithm and false targets exclude algorithm were used to avoid false alarm and missing alarm.

There is not only the targets' information, but also the interference of the surrounding environment information in the radar's output signal. And it is generally considered that the interference signal of the environment obeys Rayleigh. In order to eliminate the false targets caused by environmental disturbance, a SO-CFAR algorithm was designed based on arithmetic average value [10]. The algorithm used the average value of the signal intensity near the target signal to estimate the intensity of the environmental disturbance at the target signal.

From the formula (1) and (2), it can be seen that we need the frequency of peak in the ascending branch and the frequency of peak in the descending branch to calculate the information of the targets. When there are many targets, there will be multiple peaks in ascending branch and descending branch. So we need to design a peaks match algorithm to match different peaks. The principle that we can use is that the power of the corresponding peak in the ascending and descending branch should be the same. In order to avoid the missing targets, every peak in ascending branch is matched with two peaks in descending branch.

When we matched peaks, some false targets were introduced. In order to eliminate these false targets, this paper designed false targets exclude algorithm. It can be proved that when the frequency of the modulation signal changed, the results of real targets will not change, but the results of false targets will change. According to this principle, we inputted modulation signal like Fig. 3 to the radar. Then we compared the two groups of results. If the distance, velocity and direction were the same, the target was a real one. Then we outputted the information of the target.

5 Experiment

In order to verify the effect and accuracy of the designed system on the distance, velocity and direction information calculation of a single target,this paper built a test environment like Fig. 5. The target signal of the radar sensor was processed and calculated in the hardware circuit, and the result was sent to the PC through the CAN module.

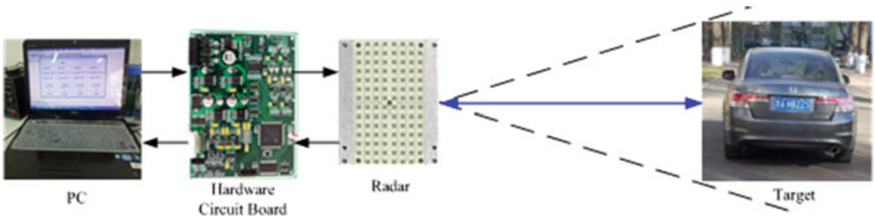


Fig. 5 The experimental environment

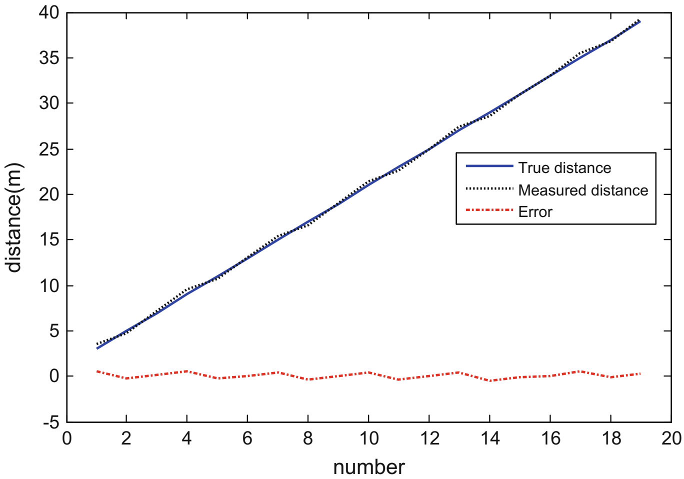


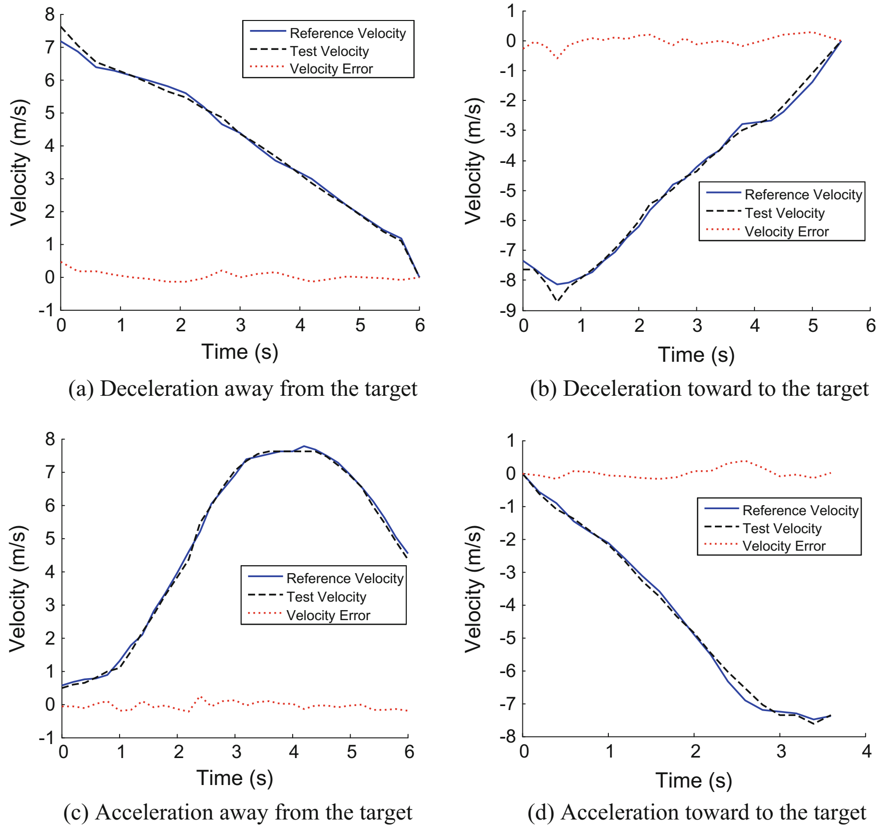
Fig. 6 The experimental results of single target's distance

First, let the car rest and measured its distance. A series of tests were carried out by changing the relative distance between the target vehicle and the radar. The measured distance, the true distance and the test error were represented in Fig. 6.

It can be seen from Fig. 6 that the measurement error is within ±0.6 m.

Then we tested the velocity of the moving car. The car moved deceleration away from the target, deceleration toward to the target, acceleration away from the target and acceleration toward to the target. In this paper, the test results of the Delphi product radar were taken as the reference value, and compared with the test results of the radar signal processing system designed by ourselves. The reference velocity, test velocity and velocity error were expressed in the same graph. The test results of four processes were shown in Fig. 7.

As can be seen from Fig. 7, the direction of the reference movement and the test movement are always consistent. And in speed value, the change rule of the test speed is consistent with the reference speed, and the error of the velocity is always in the range of ±1 m/s.



(a) Deceleration away from the target

(b) Deceleration toward to the target

(c) Acceleration away from the target

(d) Acceleration toward to the target

Fig. 7 The experimental results of single target's velocity

6 Conclusion

The paper designed a radar signal processing hardware circuit and radar signal calculation algorithm based on the K-MC3 mm wave radar. Then the algorithm was programmed in C language and downloaded to the hardware circuit to do some test. The test results show that the millimeter wave radar signal processing system designed in this paper successfully realizes the calculation of the distance, velocity and direction of the targets. What is more, the error of the distance identification is within ±0.6 m, the error of speed identification is within ±1 m/s.

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