Design and implementation of distance measurement system based on FMCW technology

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Abstract. In this paper, the distance information is obtained according to the relationship between distance and beat frequency in FMCW ranging principle, the ranging process of sawtooth wave as frequency modulation signal is described in detail, and the causes of ranging error are analyzed briefly. The distance measurement system of simulation uses Matlab software to write, and the hardware ranging platform is built by DB77M24A6426V2 millimeter wave radar module. It is verified that the distance measurement system design in this paper achieves more accurate ranging in the short distance measurement, and provides a relatively simple ranging waveform, which provides a relatively powerful reference basis for the subsequent ranging system design and hardware selection.

1. Introduction
Frequency Modulated Continuous Wave (FMCW) technology is a technology that uses to measured distance in recent years. Because it has advantages such as small size, low power consumption, low cost, high range resolution and relatively simple signal processing\cite{1-6}, it has been widely applied and studied in the field of ranging. At the same time, more and more attention has been paid to the advantages of high detection accuracy, lower environmental requirements and strong anti-interference ability of FMCW radar. FMCW radar ranging system, not only can process the transmitted signal, but also can process the reflected signal, to get a better SNR, so as to achieve more accurate ranging.

2. Principle
FMCW radar ranging technology is used to measure the distance from the transmitting point to the target. However, the accurate measurement of distance cannot be realized in one step, so this technique converts the measurement of distance to the measurement of beat frequency which has a direct proportional relation with the phase change as the connection point. If the measured beat frequency is accurate enough, the relatively accurate distance value can be guaranteed.

2.1. Principle of sawtooth modulation signal ranging
There are three kinds of modulation signals in common use, namely sawtooth wave, triangular wave and sine wave. The sawtooth modulation signal is used in this paper. Since the target is in static state, it is assumed that the modulated signal is an ideal sawtooth wave with the modulation bandwidth of B, the
period of the FMCW is $T$, $\Delta t = \frac{2R}{c}$, $c$ is the speed of light, and $\Delta t$ is the time that it takes for the millimeter wave to arrive at the target point and then reflect back to the launch point. The angular frequency of the local oscillator signal in a period can be expressed as the following formula:

$$\omega(t) = 2\pi \alpha t + \omega_0$$  \hspace{1cm} (1)

Where $\alpha = \frac{B}{T}$ is the slope of the swept-frequency signal, $B$ is the bandwidth of the swept-frequency signal, $T$ is the period of the swept-frequency signal, and $\omega_0$ is the central frequency of the modulated signal. The reflected signal is theoretically the delay of the local oscillator signal in $\Delta t$ time. Because the local oscillator signal and the reflection signal after mixing, the electric field intensity $I_{\text{BF}}(t, \Delta t)$ of the beat signal can be obtained. The corresponding simplification is carried out and the mathematical formula can be converted to obtain the following formula:

$$I_{\text{BF}}(t, \Delta t) = \left| E_1(t) + E_2(t, \Delta t) \right|^2 = I_0 \left[ 1 + V \cos \left( -\pi \alpha \Delta t^2 + 2\pi \alpha t \Delta t + \omega_0 \Delta t \right) \right]$$  \hspace{1cm} (2)

Where $E_1(t)$ is an expression for the local oscillator signal, $E_2(t, \Delta t)$ is an expression for the reflected signal, $I_0$ is the average electric field intensity of the beat frequency signal, and $V$ is the comparative intensity of the beat frequency signal. By taking the derivative of the phase of the electric field intensity $I_{\text{BF}}(t, \Delta t)$ of the beat frequency signal, the angular frequency of the beat signal can be obtained. Then, according to the relationship between frequency and angular frequency, the beat frequency $f_{\text{BF}}$ can be obtained as follows:

$$|f_{\text{BF}}| = \alpha \Delta t$$  \hspace{1cm} (3)

Then substitute $\alpha = \frac{B}{T}$ and $\Delta t = \frac{2R}{c}$ into beat frequency formula (3), and the formula of distance $R$ can be obtained as follows:

$$R = \frac{cT|f_{\text{BF}}|}{2B}$$  \hspace{1cm} (4)

So as long as we can get the beat frequency $f_{\text{BF}}$, the distance $R$ can figure out. According to the above formula, when the beat frequency reaches the maximum $f'_{\text{mBF}}$, that is, when the difference frequency value between the transmitted signal and the reflected signal reaches the maximum, the system can measure the maximum distance $R_m$:

$$R_m = \frac{cT{f'_{\text{mBF}}}}{2B}$$  \hspace{1cm} (5)

2.2. Principle of measurement error

It can be seen from formula (4) that the measurement error of distance $R$ is related to four factors, including $c$, $T$, $B$ and $f_{\text{BF}}$. Because the propagation rate of light in air differs very little from that in vacuum, the effect of the speed of light $c$ in ranging is negligible. The sweep frequency band $B$ and sweep frequency period $T$ mainly depend on the hardware design. In the simulation experiment, the values of $T$ and $B$ will not be affected by the hardware design, so the error caused by $T$ and $B$ can also be ignored. Therefore, the error of beat frequency signal is the main influencing factor of distance measurement error. According to formula (4), the impact of beat frequency $f_{\text{BF}}$ on distance measurement error can be expressed as follows:
The error of beat frequency signal mainly depends on the design of algorithm. In this paper, the rootmusic algorithm is used to estimate the beat frequency value and it can construct the function directly and write the vector of the noise subspace into the matrix form. Finally, the problem of signal frequency estimation is transformed into the root-finding problem of the unary higher order equation, so as to avoid searching peak of frequency spectrum and reduce the calculation amount to some extent. The distance between two adjacent sampling points is $\frac{1}{T}$. When the frequency of beat signal is exactly between the two sampling points, the frequency error estimation of beat frequency reaches its maximum value. In the effective time range $T_0 = T - \Delta t$ ($T \geq \Delta t$), the frequency error of beat frequency can be expressed as:

$$\Delta f_{\text{BF}} = \pm \frac{1}{2T}$$

By substituting equation (7) into equation (6), the ranging error of the distance measurement system can be obtained as follows:

$$\Delta \sigma = \pm \frac{c}{4B}$$  \hspace{1cm} (8)

It can be seen from the above formula that the ranging error of the FMCW ranging system is inversely proportional to the bandwidth of the sweep frequency signal. Therefore, the ranging accuracy can be improved by increasing the bandwidth of the sweep frequency signal appropriately.

3. **Simulation system and hardware implementation**

3.1. **Simulation system parameter setting**

Use code to simulate the system. The general flow of simulation is as follows: By sweep bandwidth, sweep period, and sweep time generates FMCW signal. Radar transmits signal to radiate electromagnetic wave into the air, the signal is transmitted to the target and reflected by the target, mixed with the transmitted optical signal, and then returns to the radar receiving end. The received signal is compressed and stored in a buffer. After a certain amount of sweep signal fills the buffer, it is processed to extract beat frequency, and these results can be used to estimate the distance of the target. The main parameter settings of simulation are shown in Table 1:

| Parameter name/unit | number |
|---------------------|--------|
| Operating frequency /GHz | 60     |
| Maximum measurement distance /m  | 10     |
| Range resolution /m           | 0.05   |
| Frequency sweep time/us       | 1      |
| Sweep bandwidth /GHz          | 3      |
| Maximum beat frequency /MHz   | 200    |
| Sampling frequency /GHz       | 6      |

3.2. **Generation of simulated FMCW waveform**

Whether the waveform of FMCW is correct affects the accuracy of ranging results. According to the sweep bandwidth, sweep time and sampling frequency in the simulation parameters, the waveform of FMCW signal can be established. The sweep signal can be obtained by using STFT (Short Time Fourier Transform). The spectrogram function in Matlab soft can realize STFT, set internal window and FFT parameters, and generate the swept-frequency waveform and spectrogram through simulation, as shown in Fig 1(a). The waveform sweep bandwidth obtained by simulation in this paper is set to 3GHz. In order
to observe the influence of parameters on the waveform signal, the frequency sweep time was reduced by 10 times by using the control variable method, and the waveform in Fig 1(b) was obtained.

As shown in Fig 1(a), the frequency of FMCW signal gradually increases with the increase of frequency sweep time, and the lines are getting denser. A complete sawtooth frequency modulation signal can be seen from the spectrogram. In Fig 1(b), the frequency sweep time is shortened, which is equivalent to only intercepting the front end in Fig 1(a). Clearer waveforms can be seen, but the spectral changes are small. When setting waveform parameters, only when the sampling frequency is no less than the sweep band width can avoid aliasing to ensure the authenticity of the signal.

3.3. Hardware test platform

In order to verify whether the simulation system designed in this paper matches the hardware requirements, DB77M24A6426V2 millimeter wave radar core plate produced by Dabao Technology Company is applied. The millimeter wave radar module composed of the core board and the debugging board is shown in Fig 2(a). Its function is consistent with TI's IWR1642BOOST development board. The core board adopts the industrial design standard and fully considers the requirements of the actual product application on heat dissipation and size, which can verify the rationality of the simulation system design in this paper. Using software CCS (Code Composer Studio), the Code file to burn wrote in millimeter wave radar module,and installing XDS110 simulator, open ppcount_gui host computer
software. In the pplcount_gui host computer software, click “Connect” and “Start” to run the simulation program successively, and then you can see the detected target points. The hardware test platform is shown in Fig 2(b). The millimeter wave radar module is driven by the PC side, and the location information of the target point can be displayed during the test. As the target point, the plank can receive a larger echo. The distance is measured manually and marked on the ground at a distance of 0.5 meters, so as to serve as the target reference distance. During measurement, the millimeter wave radar module is fixed firmly with a wooden stick and a tripod. Its plane is parallel to the target board and is located directly in front of the center of the board. The target board is vertically aligned with the marked scale on the ground, and the detected target distance information will be displayed on the PC.

4. Experimental results and error analysis

4.1. Experimental verification of simulation system

In order to obtain sufficient data information and ensure the accuracy of the experiment, the simulation process is cycled 64 times to simulate the radar transmitting, reflecting and receiving signals, and the dechirp function is used to mix the transmitted signals and reflected signals. The key point of the theory is to separate the phase information of the beat frequency signal and use the phase to get the beat frequency. The rootmusic function sets relevant parameters, and the beat frequency value can be obtained directly. The spectrum diagram of beat signal of sawtooth frequency modulation signal ranging is shown in Fig 3. The distance R measured here is set as 2m and 5m, and the spectrum diagram of beat signal corresponds to Fig 3(a) and Fig 3(b) respectively. The spectrum diagram shows that the beat signal of sawtooth frequency modulation signal ranging is unitary. This makes the processing of late signals much simpler. In order to verify whether the system results are correct, the beat frequency results in Fig 4 are calculated and estimated. As shown in Fig 3(a) below, when R=2m, $f_{BF} = 40$ MHz can be calculated by the sawtooth wave ranging principle. As shown in Fig 3(b), when R=5m, $f_{BF} = 100$ MHz can be obtained through calculation. The calculation result is basically consistent with the simulation result, which proves that the simulation system can achieve accurate ranging.

![Spectrum for received and dechirped signal](image.png)

(a) R=2m  
(b) R=5m

Figure 3. Spectrum of beat signal

4.2. Experiment verification of hardware

The target board should be aligned with the surface scale, and 0.5 meters will be added for each scale, record the experimental data at each scale. At this time, it should be noted that the board should be perpendicular to the ground as far as possible, and the object in front should be controlled to prevent interference from other non-target objects. When the PC side recognizes the target, it can be displayed as shown in Figure 4 below. The PC side target recognition diagram can not only clearly give the target distance, but also correct the target position. If the target is deviated, the position of the target point in
the diagram can be visually seen to be deviated from the measured direction. In Fig 4, the target plate with a distance of 2 meters can be recognized and the target position is in the vertical direction; In Fig 4, the figure on the right corresponds to relative power of all target points on the left figure.

Figure 4. Hardware platform ranging

4.3. Experimental data and error analysis

In order to compare the simulation value with the experimental value, the simulation system ranging results and hardware experimental results are shown in Table 2 below.

| Default value (m) | Simulation value (m) | Simulation error (%) | Hardware experiment (m) | Experiment error (%) |
|-------------------|----------------------|----------------------|-------------------------|----------------------|
| 0.5               | 0.5000               | 0                    | 0.5010                  | 0.2000               |
| 1.0               | 0.9999               | 0.0100               | 1.0190                  | 1.9000               |
| 1.5               | 1.4999               | 0.0067               | 1.5004                  | 0.0267               |
| 2.0               | 1.9997               | 0.0150               | 2.0059                  | 0.2590               |
| 2.5               | 2.4996               | 0.0160               | 2.5090                  | 0.3600               |
| 3.0               | 2.9994               | 0.0200               | 3.0390                  | 1.3000               |
| 3.5               | 3.4992               | 0.0230               | 3.5060                  | 0.1700               |
| 4.0               | 3.9989               | 0.0275               | 4.0490                  | 1.2250               |
| 4.5               | 4.4987               | 0.0289               | 4.5300                  | 0.6667               |
| 5.0               | 4.9981               | 0.0380               | 5.0480                  | 0.9600               |

As shown in Table 2, the maximum simulation error is 0.038%, while the maximum hardware experiment error is 1.9%. According to formula (8), the theoretical measurement error of the system is ±2.5cm, which is better than most ranging algorithms. In the simulation system, because FFT is used to calculate the data in the algorithm, there are inevitably errors in the calculation process, which will affect the final ranging result. In addition, the setting of the receiver noise factor is also one of the factors affecting the ranging result. In the hardware experiment, there are many factors that affect the ranging result, including outdoor environment, inaccurate scale of artificial measurement and internal factors of hardware, etc., which make the ranging error larger.

5. Conclusions

In this paper, a ranging system based on FMCW radar technology is designed according to the principle of sawtooth frequency modulation signal ranging. Matlab software was used as the system simulation platform, and DB77M24A6426V2 millimeter wave radar module was used to build the hardware
verification platform, which has a guiding significance for the subsequent system design and hardware selection. Based on the above results, it can be seen that the simulation ranging error of the FMCW radar ranging system designed in this paper is very small and completely meets the requirements of ranging. The maximum error of the hardware experiment is less than 2%, and the ranging accuracy is high, which proves that the system can achieve more accurate ranging. The experimental results show that the beat frequency of sawtooth frequency modulation signal is unitary, which obviously reduces the complexity of the system. However, because the simulation process of the system is realized in a relatively ideal situation, and in practical application, the hardware cannot meet the ideal requirements, some errors are bound to occur, so that the measurement results of the hardware deviate from the simulation results, resulting in greater errors.

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