Modeling of detection techniques for FMCW lidar using OptiSystem

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Abstract. In this paper, we investigated the frequency modulation continuous wave (FMCW) lidar rang measurement principle, then designed a simulated distance measurement scheme and building the model. Using the OptiSystem system modeling simulation, the relationship between frequency modulation (FM) bandwidth, FM time and rang measurement accuracy is investigated, and the effect of different sweep parameters on the accuracy of the final rang measurement results is discussed in the time and frequency domains. The simulation tests the delay of the target at 30, 60 and 90 meters respectively, and the distance is derived by beating the frequency of the optical echo signal with the local oscillation optical signal and calculating the beat frequency.

1. Introduction

Lidar is developed on the basis of photoelectric radiation technology and microwave radar technology. The development of photoelectric radiation technology has enabled the improvement of the sensitivity and speed of laser detection technology. The mature technology system of continuous development of microwave radar makes the whole system of lidar develop continuously for commercial use[1,2].

According to the difference of laser carrier signal, lidar at present can be divided into pulse radar and continuous wave radar. Pulse radar means that the carrier signal of the radar is a pulse signal, and the distance of the target can be determined by measuring the time difference between the transmitted pulse and the received pulse. The working principle of pulse radar system is simple, but less accurate. The echo signal is received by incoherent detection, and the sensitivity is poor. According to the form of continuous wave, continuous wave lidar can be divided into single-frequency continuous wave, multi-frequency continuous wave and frequency modulation continuous wave (FMCW) lidar. Among them, there are a variety of frequency modulation (FM) modes of FMCW lidar, which is widely used in high precision lidar. It makes use of the characteristics of linear frequency modulation signal, and the transmitted signal has a very high time bandwidth product. It can meet the dual requirements of high power and large bandwidth. The linear frequency modulation laser uses coherent receiving system to obtain frequency and phase information. The detection accuracy is high, and the range and speed measurement accuracy can be very high.

2. The Measurement Principle of FMCW lidar

The technology of frequency modulated continuous wave laser rang measurement is to modulate the frequency of the laser emission signal. By measuring the frequency of the beat signal produced by the reflected signal and the local vibration signal, the beat frequency is calculated to determine the distance of the target[3]. As shown in Figure1, the specific principle of this rang measurement technology is as
follows: the FMCW signal generator generates a carrier signal with a certain FM slope and FM period, and the laser modulates the laser and the carrier signal into an FM optical signal. The optical transmitting system contains a deflection-preserving beam splitter, after the FM light signal passes through the deflection-preserving beam splitter, the FM light signal of one way acts as the local oscillation light signal, and the FM light signal of the other way acts as the detection signal to irradiate to the target to be measured, and the reflected light signal of the target to be measured is combined with the local oscillation light signal through the optical receiving system, and then enters the photodetector to subtract the echo electrical signal. The echo signal is multiplied by the local oscillation signal to obtain the beat frequency signal. The low pass filter further filters the beat frequency signal to eliminate other signal noise.

![Fig 1. optical laser rang measurement system](image1)

The time-frequency curves of transmitted signal, received signal and beat signal of FMCW are shown in Figure 2. The solid line is the laser transmitting signal frequency $f_r(t)$, and the dotted line is the laser receiving signal $f_o(t)$. Set the starting frequency of FMCW as $f_0$, the frequency modulation bandwidth as $B$, and $\tau$ is the time in which the laser is emitted from the transmitting system to the target and then returned to the laser receiving system. The beat frequency of the laser is $f_b(t)$.

![Fig 2. Time-frequency curve of FMCW](image2)
The curve shapes of the echo signal and the transmitted signal are both in the form of a triangular wave, but the echo signal has a certain delay in time due to the transmission delay[4], then the relationship between the delay time $\tau$ and the target distance $R$ is

$$\tau = \frac{2R}{c} \quad (1)$$

Where, $c$ is the light propagation velocity $3 \times 10^8 (m/s)$.

According to Fig.2, set the laser emission signal

$$f_r(t) = f_0 + \alpha t, \quad (0 \leq t \leq T) \quad (2)$$

Where $\alpha$ is the modulation slope: $\alpha = \frac{R}{T} \quad (3)$

Similarly, it can be concluded that the received echo signal $f_r$ is

$$f_r(t) = f_0 + \alpha(t - \tau), \quad (\tau \leq t \leq \tau + T) \quad (4)$$

The beat signal $f_b(t)$ is obtained by subtracting the laser transmitting signal $f_t(t)$ and the received echo signal $f_r(t)$

$$f_b(t) = f_t(t) - f_r(t) = \alpha \tau = \frac{2RB}{ct}, \quad (\tau \leq t \leq \tau + T) \quad (5)$$

By sorting out formula (2-5), we can get the formula of target distance $R$ to be measured as follows

$$R = \frac{cT}{2B} f_b(t) \quad (6)$$

3. Modeling and simulation of FMCW lidar system

In order to verify the correctness of the theoretical results, a FMCW radar system based on OptiSystem15.0 platform is built to provide a reference for the theory. OptiSystem is an innovative optical communication system simulation software[5], which can help designers complete optical system design, testing and simulation. The simulation model is shown in Figure 3.

![LIDAR simulation system](image)

Set the fiber-optic laser wavelength to 1550nm, power to 40mW, linewidth to 0.05MHz. Set FMCW signal bandwidth B 300 MHz (that is, Modulation constant =300MHz) and frequency modulated time $T$ to $10\times10^3s$ (That is, Time window =10), R and ‘Delay’ are target distance and fiber delay time respectively. The parameter settings are shown in Figure 4.
The rising sawtooth generator generates 0 to 10us rising sawtooth. After the sawtooth is input to the frequency modulator, it generates an FM continuous wave with a starting frequency of 100MHz and a termination frequency of 400MHz, that is, the frequency modulation period $T$ is $10 \times 10^{-6}$s, and the frequency modulation bandwidth $B$ is 300MHz.

The frequency-modulated continuous wave passes through the separator to divide the continuous wave into two paths, one is the electric signal local oscillator wave, and the other is the carrier signal. At the same time, the laser generates laser light with a wavelength of 1550nm, which is divided into two paths of light by an optical splitter, one is local oscillator light, and the other is signal light.

The signal wave loads the 300MHz bandwidth frequency modulated continuous wave onto the signal light through the Mach-Zehnder modulator, and then the optical signal is amplified and emitted by a 40dB optical gain amplifier.

The optical delay is used to simulate the time used in the process of reflection in space after light emission hits the target object. In this simulation, set different optical fiber delay parameters, simulate different target distances, and observe the beat frequency under different delay parameters.

The laser receiving module enters the delayed optical signal and the reference light into the subtractor for subtraction, and obtains the delayed FM continuous wave signal. After photoelectric conversion, a frequency-modulated continuous wave electric signal is obtained. The continuous wave signal and the electric signal local oscillation wave enter the multiplier for mixing, and finally a beat frequency signal is obtained. After passing through the low-pass filter, observe the signal frequency domain and time domain of the output point respectively.

The parameter settings in the lidar system simulation process are shown in Table 1, where $R$ is the distance of the target, $t$ is the time delay of the echo signal relative to the transmitted signal, and $f_b$ is the frequency of the beat signal.

| R/m | t/s          | $f_b$/Hz  |
|-----|--------------|-----------|
| 30  | $0.2 \times 10^{-6}$ | $6.0 \times 10^6$ |
| 60  | $0.4 \times 10^{-6}$ | $12.0 \times 10^6$ |
| 90  | $0.6 \times 10^{-6}$ | $18.0 \times 10^6$ |

After setting each parameter, the simulation experiment of the lidar system was conducted. Figure 5, Figure 6, and Figure 7 show the beat frequency signal spectrum waveforms for the measured distances of 30m, 60m, and 90m from the target respectively.
Fig 5. The beat frequency spectrum at a distance of 30 meters

A: (6E+006, 52.1049)

Fig 6. The beat frequency spectrum at a distance of 60 meters

A: (1.2E+007, 51.9956)

Fig 7. The beat frequency spectrum at a distance of 90 meters

A: (1.8E+007, 51.308)

The above three spectrum waveforms all contain only one peak. The peak is a beat signal produced by mixing the reference and received FM waveforms. The frequencies at this point are 6.0×10⁶ Hz, 1.2×10⁷ Hz, and 1.8×10⁷ Hz, respectively. The simulation results are consistent with the theoretical
values. However, it should be noted that the simulation process is carried out under ideal conditions. In the actual Lidar experiment process, due to the influence of various factors such as noise, interference from other targets, and different powers of the receiver, the experimental results may have a certain deviation with the theoretical value.

4. Conclusions
This article describes the basic principles of FMCW lidar distance measurement, and uses OptiSystem optical software to simulate the system. From the comparison of the theoretical value and the simulation result, it can be seen that the values of the two at 30, 60, and 90 m are basically the same, which confirms the theoretical feasibility of the FMCW lidar distance measurement. However, since no actual program measurement has been performed, there may be other interference factors. In the actual experiment process, due to various environmental factors and instrument errors in the actual scheme, the influence of factors such as noise, background light, and measurement deviation of the instrument itself has not been fully considered. The simulation experiment results may be some deviation between the simulation results and the theoretical value.

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