Simultaneous measurement of target distance and azimuth in four quadrant detection

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Abstract. Realize the synchronous solution of target azimuth information and distance information in narrow pulse laser high-speed detection process to improve the time efficiency of detection system. A high-speed analog-to-digital (A/D) sampling chip, field-programmable gate array (FPGA) and related hardware circuit are used to establish a high-speed sampling and signal processing hardware system by performing related program configuration on each chip. Related algorithms such as pulse laser ranging method and azimuth resolution method based on four-quadrant detector are applied. At the same time, the denoising method based on Gauss white noise is adopted. Related simulation experiments and measured experiments are carried out. The simulation and experimental results show that the system realizes the synchronous solution of target azimuth information and distance information during the narrow pulse laser high-speed detection process, in which the distance error is not more than 1% and the azimuth error is not more than 5% and improve resource utilization rate.

1. Introduction

The laser detection technology utilizes a high-energy concentrated laser beam to non-contact detection of the target. Lidar detection is well used in 3D detection [1-4]. The laser signal is used to Since the laser pulse signal has the characteristics of large peak power, causing far detection distance [5] and the ability to resist electromagnetic interference is strong. The essence of laser detection is to project the laser pulse signal onto the target, and analyze the received echo signal to obtain the position information of the target. In a pulsed laser detection system, the positional information of a target can be decomposed into distance information and azimuth. In Literature [6], a system using a four-quadrant detector to measure the azimuth angle is designed. It does not show how to use the four-quadrant detector for laser ranging. The Literature [7] designed a pulsed laser ranging system that can be designed by hardware. Apply to the four-quadrant detection system. In this paper, a pulse laser detection system based on four-quadrant detector is designed. The correlation algorithm is used to measure the distance information and azimuth at the same time to improve the utilization efficiency of circuit resources.

2. Position measurement method and simulation result

2.1. Pulsed laser ranging

The pulsed laser can be applied to the laser ranging method [8]. The linear distance between the laser source and the target:
\[ s = \frac{1}{2} ct, \quad c = 3 \times 10^8 \text{ m/s} \]

Which \( t \) is the time required for the laser to transmit to receive the echo.

The key to laser ranging using the pulse method is the measured actual value \( t \), which can be measured using the time-to-digital conversion method. As the Figure 1 shows:

![Figure 1. Schematic diagram of time-t measurement.](image)

Can be drawn:

\[ T = \Delta T_1 + nT_p - \Delta T_2 \]  

The START signal is triggered by the rising edge of the clock, so \( \Delta T_1 = 0 \). \( nT_p \) is measured by a single clock sign. Then \( \Delta T_2 \) is measured by a time interpolation method. The measurement accuracy is increased by \( N \) times by a series of clock signals with a phase difference of full period (\( N \) is the number of clocks).

2.2. Azimuth measurement based on four-quadrant detector

The four-quadrant detector consists of four identical photodiodes located in four quadrants I, II, III, and IV. There is no photosensitive device in the intersection between the quadrants, which is called the dead zone [9]. It can be applied to the detection of azimuth. As the Figure 2 shows:

![Figure 2. Schematic diagram of four quadrant detector principle.](image)

Assume that the spot is an ideal circular spot, the light intensity is evenly distributed over the spot area, and the output current of the four-quadrant detector is proportional to the spot area:

\[ I_n \propto S_n, \quad n \in N^*, \quad n \in [1,4] \]
The weak current of the detector is amplified to $U_n$ by a two-stage amplification of the transimpedance amplifier and the back-end amplifier, and converted into a strong voltage signal. The amplification factor of the four-channel amplifier is $k$:

$$U_n = k I_n, n \in \mathbb{N}^* \& n \in [1,4]$$ (4)

According to geometric relationship, the solution value $(\sigma_x, \sigma_y)$ of the centroid coordinate $(x_0, y_0)$ and the relationship of the spot in each quadrant area $S_n$ can be expressed as:

$$
\begin{align*}
\sigma_x &= \frac{(S_1 + S_4) - (S_2 + S_3)}{S_1 + S_2 + S_3 + S_4} \\
\sigma_y &= \frac{(S_1 + S_2) - (S_3 + S_4)}{S_1 + S_2 + S_3 + S_4}
\end{align*}
$$ (5)

(4) (5) (6) is united:

$$
\begin{align*}
\sigma_x &= \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4} \\
\sigma_y &= \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}
\end{align*}
$$ (6)

The solution value $(\sigma_x, \sigma_y)$ can be obtained by measuring output voltage $U_n$ of amplifier. The relationship between solution value and actual value is simulated. As the Figure 3 shows:

![Figure 3](image)

**Figure 3.** Schematic diagram of relation between solution value and actual value.

When the spot is near the center of the detector, the solution value is almost linear with the actual value:

$$
\begin{align*}
x_0 &= k \sigma_x \\
y_0 &= k \sigma_y
\end{align*}
$$ (7)

Calculated result:

$$k \approx \frac{\pi}{4} r, \text{Spot is evenly distributed}$$ (8)

$$k \approx \frac{\sqrt{\pi}}{2\sqrt{2}} \omega, \text{Spot is Gaussian distribution}$$ (9)

Where $r$ is the uniform spot radius and $\omega$ is the Gaussian spot beam waist radius.
2.3. Echo waveform denoising method

Laser pulse echo waveform can be denoised by coherent averaging method. The pulsed laser echo waveform output by the detector can be approximately decomposed into its pulse echo and Gaussian white noise. Can be expressed as:

\[ s(t) = A_s(t) + s_n(t) \]  

(10)

Where \( s_0(t) \) is the pulse echo normalization result, \( s_n(t) \) is the zero mean white noise whose effective value is \( \sigma \), \( A \) is pulse echo amplitude. Peak signal-to-noise ratio \( SNR_1 \):

\[ SNR_1 = \frac{A^2}{\sigma^2} \]  

(11)

Perform \( L \) times echo stacking, the result of the superposition is:

\[ s'(t) = \sum_{i=0}^{L-1} [A_s'(t) + s'_n(t)] = \sum_{i=0}^{L-1} A_s'(t) + s'_n(t) \]  

(12)

Its signal-to-noise ratio \( SNR_2 \):

\[ SNR_2 = L \frac{A^2}{\sigma^2} \]  

(13)

The signal-to-noise ratio is increased by \( n \) times. However, if the value of \( L \) is too large, the amount of calculation will increase greatly. So, the value is normally less than 10, in the experiment, \( L = 8 \).

The simulation results are as the Figures 4-6 follows:

**Figure 4.** Noise-free pulse signal graph.  
**Figure 5.** Superimposition of Gauss White Noise and Pulse Signal.  
**Figure 6.** Denoising result diagram.

The denoising result shows that the SNR is obviously improved. The SNR is improved by \( 9.03 dB \).
3. Hardware circuit design

3.1. Overall design

The overall design of the hardware circuit is based on the FPGA to control the timing of each signal, including the control of the ADC, etc.; the use of FPGA for time identification, the calculation and acquisition of target distance information, and the use of FPGA FIFO to detect four quadrants. The echo information of the device is buffered in parallel and then serially read out to the host computer for subsequent signal processing to obtain the azimuth information of the target. The general block diagram of the hardware circuit is as follows:

![Functional block diagram of hard circuit.](image_url)

FPGA generates a laser emission pulse signal and drives the laser emitter to emit a narrow pulse laser after being level-converted by the laser emission driving circuit. After the laser is hit on the target, the echo is received by the four-quadrant detector, and the signal is amplified and then subjected to peak hold and A/D conversion. The digital signal is synchronously transmitted to the four FIFOs of the FPGA in parallel, and the serial output is transmitted to the host computer via the USB chip, and the subsequent signal processing work is performed to obtain the orientation information of the target. The amplified echo signal passes through the comparator to form a square wave signal, and the square wave signal is processed by the ranging module in the FPGA to obtain the distance information of the target.

3.2. Echo signal amplifying circuit and A/D sampling circuit

In order to obtain higher magnification, the amplifier circuit adopts a two-stage amplification mode, and its circuit diagram is as follows:

The first stage is a transimpedance amplifier that converts weak current signals into voltage signals. Connect the output of the detector to the inverting input of the op amp. The bidirectional diode acts as a limiting resistor to protect subsequent circuits from large signals. The resistor $R_1$ is the core component of the transimpedance amplifier and is the ratio of the output voltage to the input current, which is the transimpedance gain. The feedback capacitor $C_1$ acts to offset the effects of the parasitic capacitance of the op amp. The second stage is a voltage amplifier that controls the amplification factor by controlling $R_1/R_2$. As the Figure 8 shows:
3.3. FPGA timing control program

As the core device of the whole experimental system, FPGA plays the role of overall control. Generally, the operation of the corresponding circuit system is controlled by configuring the timing of the relevant signals. The module block diagram is as the Figure 9 follows:

![Control block diagram of FPGA](image-url)

**Figure 9.** Control block diagram of FPGA.
Complete timing control through the integrated wiring layout of the top-level module. Four echo signals sampled by A/D are synchronously transmitted to the FIFO of the FPGA through the I/O pins of the FPGA for data buffering. The laser emission driving signal generating module can generate a laser emission driving signal to drive the laser emitter; the use of FIFO needs to configure the read and write clock, read and write requests, and set the corresponding module for related timing configuration; the main frequency of the FPGA used is that the clock signal with high frequency multiplication frequency is needed for the ranging module, and the PLL is used for frequency multiplication, and a set of clock signals with equal phase difference are generated to perform rough measurement and fine measurement. Also passed out through FIFO; when the USB chip transmits data, it needs to configure the enable signal, which is generated by the USB chip control signal generation module.

3.4. Main module introduction

3.4.1. FIFO read and write request and laser emission signal generation module. The 4-channel 12-bit signals obtained by the A/D sampling chip are synchronously input into the FIFO of the FPGA in parallel. Then asynchronous serial output. Thus, the read/write request signal of the FIFO is configured in the module.

3.4.2. FIFO readout and USB chip control signal generation module. In order to complete the function of FIFO asynchronous serial output, this module is designed. According to the timing of FIFO read request, the 4-channel buffered echo data FIFO and 2 FIFO output signals with serial ranging information are serially output and output signals. It is unified to 16 bits, and less than 16 bits are used for zero padding.

3.4.3. PLL module. The phase-locked loop (PLL) module mainly performs clock multiplication and phase shift to generate each clock signal required for ranging.

3.4.4. Rough ranging module. The coarse ranging module uses the 200MHz clock generated by the phase-locked loop multiplier to collect the rising edge of the laser transmitting signal and the echo signal. The result of the ranging is the number of clocks \( n \), \( nT_p = n \times 5ns \).

3.4.5. Fine ranging module. The fine ranging module uses 16 200MHz clocks with a phase difference of 22.5° to measure. 16 clocks respectively perform the measurement method of the coarse ranging module, record 16 sets of ranging results, arrange according to the phase difference, and mark the clock labels when the ranging result changes separately, and record that the marking result is recorded by a 15-bit data. Then, \( \Delta T_2 = \frac{m}{16}T_p = \frac{m}{16} \times 5ns \) and the time measurement accuracy is 0.3125ns, the distance measurement accuracy is 0.0477m.

4. Experiments and results

Use the hardware device described above as a field experiment, the site map is as follows:

The specific process of the experiment is divided to ranging and angle measurement experiment.

Ranging experiment is as follows: Set the target to a white plate, placed at a distance of 7.1m from the laser source. The light source and detector are placed in the same plane that is parallel to the target plane. Use a high emission power collimated laser beam of wavelength 1550nm to achieve laser detection. The reflected echo is received by the four-quadrant detector and amplified by the back-end amplifier. After the peak is held and A/D is acquired, the data is controlled by the FPGA, transmitted to the host computer by the USB chip, and echoed by the coherent average denoising algorithm on the host computer. Denoising and algorithm implementation, the experimental results are displayed by the host computer program. As the Figure 10 shows:
Angle measurement experiment is as follows: In order to ensure the reliability and accuracy of the experiment, the optical path calibration of the system is required before the experiment to reduce the experimental error. A filter is attached to the front of the QD lens to reduce interference from external light other than the laser source. The laser beam is irradiated on the photosensitive surface of the four-quadrant detector. By adjusting the relative positions of the laser, the four-quadrant detector and the optical system, the output signals of the QD quadrants are the same, and the spot position is at the center of the photosensitive surface. The azimuth is set to 34° by controlling the displacement platform. The experiment results are processed and displayed by the host computer program.

The experimental results are as the Figure 11 follows:
As shown above, the data is displayed on the left side of the result graph. The ranging result is displayed as 7.03125m. The relative error of ranging is 0.97%. According to the echo data, the calculated solution values $\sigma_x$ and $\sigma_y$ are displayed in the middle of the result graph. According to the calculation, the azimuth is 35.564°, and the relative error is 4.6%. The result meets the needs of the experiment.

5. Conclusions

Based on the four-quadrant detector, a high-speed analog-to-digital conversion sampling chip, field-programmable logic gate array and related hardware circuit are used to establish a high-speed speed by performing related program configuration on each chip. Sampling and signal processing hardware systems. Based on the principle of uniformly distributed spot four-quadrant angle measurement and time-interpolation laser pulse ranging, the Verilog language is used to control the ranging angle measurement module through FPGA, and only a set of hardware devices is used to achieve the target position information in laser detection. Distance information is used for the purpose of simultaneous measurement. The simulation and experimental results show that the system realizes the simultaneous measurement of target azimuth information and distance information during high-speed detection of narrow pulse laser. The distance error is less than 1% and the azimuth error is less than 5%, which improves the resource utilization efficiency.

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