Study of High Precision Measurement System in Pulsed Laser Ranging

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Abstract. To improve the accuracy of time interval measurement in pulsed laser ranging system, a method which combines clock counting and differential delay line based on Field Programmable Gate Array (FPGA) is used in time interval measurement. FPGA sets up two delay lines in its internal, one of them consists of several buffers; another consists of several D flip-flops. The time delay between them serves as the smallest unit of time interval measurement, which is the step length of measuring time interval within half a clock cycle. Compared with clock counting method, this method put time interval measurement accuracy up to ten times. The experiment results show that time interval of system measurement reach at ±300 ps, and 3 cm measuring distance precision is achieved, which means that the method can satisfy the requirements of high precision ranging.

Introduction

The advantages of laser ranging cover simple construction, wide distance measuring range, high measurement precision and strong anti-interference ability, so it is widely used in military, aeronautics and astronautics, geographical mapping, etc. Laser ranging is divided into continuous laser phase measurement and pulsed laser time interval measurement[1], and the ranging precision of the former could reach several millimeters, but distance measuring range is limited since phase difference which is greater than 2π cannot be measured. The latter contains a lot of methods such as clock counting method, multiphase sampling method and analog interpolation method[2]. Pulse counting method could achieve wide distance measuring range, but its measurement precision is limited[3]. Multiphase sampling method further improve the precision based on the counting method, however phase shift of high frequency in FPGA will lead to a certain amount of phase difference[4]. Analog interpolation method easy to cause bad linearity and loud system noise because of the analog devices it used[5]. Generally speaking it is hard to balance wide distance measuring range and high range measurement precision. Aiming at problems above, this paper put forward differential delay line circuit structure. By using FPGA named EP2S130F780C4 belong to Stratix series of Altera building buffers and D flip-flops. The time delay between them is the smallest unit to measuring time interval, which ensure the measurement range and further improve the measurement precision, and strengthen the ability to resist noise at the same time.

1. The Principle of Pulsed Laser Ranging

Pulsed laser ranging system uses optical maser to emit light pulse whose width is very narrow. Light pulse will be partly reflected when it reach the surface of the object under test, and those which is reflected is converted to echo signals in APD photodiode. Meanwhile a few of the laser launched by optical maser is converted to main wave sampling signal by PIN photodiode. The two sampling signals are discriminated by CR-high pass time discrimination method, and then FPGA measures the time interval t between them. The distance between measurement system and the object under test can be calculated with the time interval t. Distance formula is as follows:
In the formula \( L \) is measured distance and \( c \) is light speed. According to the formula (1) pulsed laser ranging precision \( \Delta L \) is:

\[
\Delta L = c \cdot \Delta t / 2.
\]  

(2)

If we consider the light speed \( c \) is constant, pulsed laser ranging precision is depending on pulse flight time interval \( t \) measurement, and major factors of time interval measurement are pulsed laser time discrimination and time interval measurement precision. The former adopts CR-high pass time discrimination method that named zero point detection time discrimination also, and it would eliminate the pulsed laser drift error caused by amplitude fluctuations.

2. The Principle of Time Interval Measurement

The time interval measurement includes “rough time measurement” and “fine time measurement”. The former is clock counting, and time interval between start pulse and end pulse can be measured by calculating the cycle of counting clock, which is \( t_c \) in the figure(1) below. The latter is the measurement of time interval between start pulses rising edge and the first counting clock jumping edge after it, which is \( t_1 \) in the figure(1), and the measurement of time interval \( t_2 \) between end pulse and jumping edge. Naming counting clock cycle \( T \), and then the real time interval \( t \) of pulsed laser flight is:

\[
t = t_c + t_1 - t_2 - T/2 = t_c + t_1 - t_2.
\]  

(3)

Figure 1. the sequence diagram of time interval measurement.

The rising edge of start pulse and end pulse all correspond to the high level of counting clock in figure (1). The result fine time measured is the time interval between pulses rising edge and clock falling edge, and in the different case there are different measurement results of time interval. When the rising edge of start pulse corresponds to high level of the clock but the rising edge of end pulse corresponds to low level of the clock, \( t_1 \) is still time interval between the rising edge of start pulse and the falling edge of the clock, and \( t_2 \) is time interval between the rising edge of end pulse and the rising edge of the clock. The result of time interval is:

\[
t = t_c + t_1 + T/2 - t_2 = t_c + t_1 - t_2 + T/2.
\]  

(4)

When the rising edge of start pulse corresponds to low level of the clock and the rising edge of end pulse corresponds to high level of the clock, the result of time interval is:

\[
t = t_c + t_1 - t_2 - T/2.
\]  

(5)

When the rising edge of start pulse and end pulse all correspond to low level of the clock, the result of time interval is:
\[ t = t_c + t_1 - t_2. \]  

By the formula above we can see, time interval result depends on the measurement of \( t_c, t_1 \) and \( t_2 \). There is no error for \( t_c \) measuring as it is counted for clock cycle. The errors of time interval measurement mainly lie in measurement of \( t_1 \) and \( t_2 \).

3. The Presentation of Differential Delay Line Method

![Figure 2. The circuit structure of differential delay line.](image)

The delay time of the buffer names \( \tau_1 \) and the delay time of the D flip-flop names \( \tau_2 \). The transmission of end pulse faster than the transmission of start pulse because \( \tau_2 \) is greater than \( \tau_1 \). In the process of measurement, start pulses transmit on the delay line consisted of \( n \) D flip-flops and end pulses transmit on the delay line consisted of \( n \) buffers. With pulses through each level of delay line the time difference will reduce \( \tau_2 - \tau_1 \). If end pulse exceed start pulse after \( m \) class delay lines, the time interval between them is \( m \times (\tau_2 - \tau_1) \). In this circuit structure the amount of D flip-flops outputs which keep the high level are the amount of delay line transmit level. Because the fine time measurement is for measuring the time interval between pulse rising edge and the next clock jumping edge, the total amount \( n \) of delay line level have to satisfy the following conditions:

\[ m \times (\tau_2 - \tau_1) \geq T/2. \]  

FPGA will complete layout and wiring automatically by programming, and implement clock counting as well as set up differential delay line circuit. The highest PLL clock frequency of the FPGA reaches 400 MHz, but the counting clock which is more than 200MHz will lead to work unstably, so we chose 200 MHz frequency of counting clock. After the test, the delay time \( \tau_1 \) of buffer is 450 ps, and the delay time \( \tau_2 \) of D flip-flop is 700 ps, so the measurement precision is \( \tau_2 - \tau_1 = 700 - 450 = 250 \) ps. Through formula (7) we know that \( n \times 250 \times 10^{-12} \geq \frac{1}{2^{200+10^6}}, \) and it means \( n \geq 10 \). It would complicate the circuit if \( n \) is too large, so we consider that the delay line circuit consist of ten buffers and ten D flip-flops. FPGA outputs sixteen bits of time interval measurement result, and the front twelve bits of it is clock counting result, and the end of it is differential delay line measurement result. The twelve bits of counting clock can measure four thousand and ninety-six clock cycles, so the measurement system’s maximal measurement range reach three kilometers in theory with 200MHz clock frequency.

4. Experimental Verification

4.1 Time interval measurement

Because the precision of pulsed laser ranging depends on time interval measurement, we chose to complete time interval measurement experiment first. FPGA transmits sixteen bits measurement result to computer by development board CY7C68013A_CPLD. Computer displays the time interval measurement result and display distance result by calculating time interval according to formula (1). The pulse signal generator 81130A of Aligent Corporation exports two pulse signals whose time interval can be changed. The display resolution is 2 ps. The pulse signal generator
steady export two pulsed signals whose time interval is 100000 ps, and all of them are 3.3 v TTL signals. The two pulsed signals respectively connect to the main wave input port and the echo wave input port, and computer will display the time interval result. Repeating the experiment one thousand times, recording the time that computer displays every time, and we will get the frequency histogram after disposing data. As shown in figure 3, abscissa is measured error whose unit is ps, and ordinate is the occurrence number of each error. The curve in figure is fitting curve for frequency.

![Figure 3. Time interval measured error and fitting curve.](image)

The average value of time interval measured error is -2.284 ps, and the standard deviation is 154.8547 ps. As we can see in the figure3, the most of measured error is within ±300 ps, and the precision of clock counting method is 5 ns, so the differential delay line method helps a lot to improve time interval measured precision.

4.2 Pulsed laser ranging result

The experiment above involves time interval measurement only. The main wave signal and the echo wave signal are generated by pulse signal generator, so it have not referred to opticator. The procedure of pulsed laser ranging experiment is as following. Electrical signals FPGA exports according to a certain time interval drives laser device, and computer receives time interval information as well as displays measured distance. Placing target to be measured on the position ten meters from the measured system, and then moving the target while 0.5 meter is change unit. Repeating one hundred times experiments in every distance value and recording data. Distance measured results of 10 meter to 14.5 meter is shown in the table 1.

<table>
<thead>
<tr>
<th>Real value[m]</th>
<th>Average[m]</th>
<th>Maximum[m]</th>
<th>Minimum[m]</th>
<th>Standard errors[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.000</td>
<td>10.027</td>
<td>10.854</td>
<td>9.965</td>
<td>0.017</td>
</tr>
<tr>
<td>10.500</td>
<td>10.529</td>
<td>10.552</td>
<td>10.467</td>
<td>0.016</td>
</tr>
<tr>
<td>11.000</td>
<td>11.018</td>
<td>11.053</td>
<td>10.936</td>
<td>0.013</td>
</tr>
<tr>
<td>11.500</td>
<td>11.479</td>
<td>11.561</td>
<td>11.389</td>
<td>0.021</td>
</tr>
<tr>
<td>12.000</td>
<td>12.010</td>
<td>12.073</td>
<td>11.948</td>
<td>0.015</td>
</tr>
<tr>
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<td>12.513</td>
<td>12.547</td>
<td>12.432</td>
<td>0.014</td>
</tr>
<tr>
<td>13.000</td>
<td>13.021</td>
<td>13.066</td>
<td>12.962</td>
<td>0.017</td>
</tr>
<tr>
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<td>13.473</td>
<td>13.531</td>
<td>13.432</td>
<td>0.020</td>
</tr>
<tr>
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<td>14.017</td>
<td>14.072</td>
<td>13.965</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The range of distance measurement can reach three kilometers. In the experimental process view angle of laser have only 10 mrad. It is too hard to receive laser for laser detector if the ranging system is too far away from target being measured, so we chose to experiment in close range. From
table 1 we can see, the standard errors are within 2 cm stably, but the error of 11 cm could happen in single measurement. It is too difficult to appear for such a big error in the system. It means that the error appears in the aspect of non-time measurement.

5. Error Analyses

Considering the experimental indexes synthetically by analyzing testing data, and causes about measurement error of ranging system are as following.

(1) FPGA set up D flip-flops and buffers circuit inside it. The delay time 250 ps is minimal principle error of the ranging system, and it cannot be eliminated totally. Changing FPGA chip with higher frequency is the only way to reduce principle error.

(2) The sectional routing architecture of FPGA leads to a little unsteadiness and inscrutability in its internal delay circuit. Under the influence of environment temperature and working voltage fluctuation, the delay time of D flip-flops and buffers cannot always hold to measured values.

(3) The jitter of clock crystals will lead that the time interval of counting clock generates errors. Using more stable crystal will reduce this error.

(4) The impedance mismatching of the key transmission cables about main wave and echo wave will lead to reflection of signals. The judgments of signal trigger point are influenced for amplitude decreasing, so it is necessary to design impedance matching of each level circuit.

Summary

The advantages of pulsed laser ranging system based on FPGA include wide range of distance measurement and good linearity, and the precision of the ranging system can reach 3 cm. The key technology is differential delay line set up by FPGA, and the delay time between D flip-flop and buffer is regarded as the minimal measurement unit of the ranging system. It has been proved that the precision of time interval measurement is within 300 ps stably and it also avoids the error of clock jitter as increasing clock frequency. However, the delay time between them will get fluctuated because of the locating and wiring in FPGA, and there is error at nanosecond level in the time interval measurement. It has been proved for the precision and the range of this method to satisfy most of cases. Subsequent work has been lunching actively. Adopting more stable chip and clock crystal, optimizing locating and wiring of circuit to realize impedance matching, using time identification method under smaller influence of pulse amplitude fluctuations and all of them will help to increase the precision of pulsed laser ranging system.

References


