Laser time-of-flight measurement based on time-delay estimation and fitting correction

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Abstract. We describe a method based on multichannel time-delay estimation with linear fitting correction for laser time-of-flight (TOF) measurement. The laser TOF measurement system is constructed with a laser source, a stop receiver channel, a reference receiver multichannel, an analog to digital converter (ADC) sampling unit, and a digital signal processing unit. Limited by the sampling rate, the precision of laser TOF measurement is restricted no more than the ADC sampling period in conventional methods. As this problem is considered, multichannel correlation time-delay estimation with linear fitting correction is devised. It is shown that the measuring precision is better than 2 ns with multichannel time-delay estimation and not influenced by signal-to-noise ratio. The experimental results demonstrate that the proposed method is effective and stable. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.7.076105]

Subject terms: time-of-flight; laser measurement; multichannel time-delay estimation; cross-correlation; linear fitting correction.

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1 Introduction

Laser time-of-flight (TOF) measurement is an active sensing technique widely used in laser ranging, laser imaging radar, and other laser direct detection applications. The time resolution of TOF measurement determines the precision of laser ranging and the definition of laser imaging radar, so it is of importance to measure the laser flight time accurately.[1–3] Laser TOF measurement system measures the time interval between the transmitted (start) and the received laser pulse signals (stop).

The basic problem of laser TOF measurement employing time-delay estimation is the determination of the time delay between the transmitted and the received signals. Restricted by the conversion rate of the ADC device, the precision of laser TOF measurement is restricted no more than the ADC sampling period.[4] In order to solve this problem, a novel method based on cross-correlation analysis multichannel time-delay estimation with linear fitting correction is proposed.

The paper is organized as follows: Sec. 2 discusses the principle of the method based on cross-correlation analysis multichannel time-delay estimation with linear fitting correction. Section 3 discusses the laser TOF measurement system design and performance results of the experiment. Section 4 discusses conclusions and future work.

2 Principle of the Proposed Method

Time-delay estimation is an important signal processing problem arising in various applications, such as radar, sonar, direction finding, source location, wireless communications, and so on. The basic problem of time-delay estimation is to determine the time delay between two receivers.[5,6] In most of the laser TOF measurement systems, there is only one receiver to receive the stop echo signal which cannot meet the requirement of two receivers. So, we built not only a stop receiver channel, but also a reference receiver channel first.

Assuming the time delay between the reference and the transmitted signals is so short that it could be negligible, we considered it as a known constant included in the system time delay. Then, the purpose to determine the time delay between the stop echo pulse and the transmitted laser pulse could be realized by estimating the time delay between the stop echo signal and the reference signal.

Due to the differences of propagating distances at the reference receiver channel and the stop receiver channel, the time delay is determined. The stop echo signal received from the stop receiver channel could be considered as the delayed and attenuated replicas of the reference signal received from the reference receiver channel. The reference signal $x_1(n)$ and the stop echo signal $x_2(n)$ may be modeled as

$$\begin{cases} x_1(n) = s(n - \tau_1) + n_1(n) \\ x_2(n) = \alpha \cdot s(n - \tau_2) + n_2(n) \end{cases}, \qquad (1)$$

where n is the digital signal form of the time (if the sampling interval is 10 ns, $n = 2$ represents 20 ns); $s(n)$ is the laser source signal, which is Gaussian-like; $n_1(n)$ and $n_2(n)$ are white Gaussian noises; α is the attenuation coefficient of the stop echo signal; τ_1 and τ_2 are the time delays for the reference signal $x_1(n)$ and the stop echo signal $x_2(n)$, respectively.

Many methods have been proposed for time-delay estimation in the past 20 years, and the cross-correlation technique is the most common and significant method for time-delay estimation.[7,8] In the mathematical model, $s(n)$, $n_1(n)$, and $n_2(n)$ are not correlative with each other, and the cross-correlation method is valid for the propagating environment.

Time-delay estimation between the stop echo signal and the reference signal based on cross-correlation may be expressed as

$$\hat{\tau} = \arg\{\max[R_{rr}(t - \tau_2 + \tau_1)]\} \quad = \tau_2 - \tau_1. \quad (2)$$

In this equation, $\arg(\cdot)$ is the function to get the independent variable and $\max(\cdot)$ is the function to get the maximum value.

Figure 1 shows the principle of the cross-correlation method for time-delay estimation. Time-delay estimation is used to identify the maximum value of the cross-correlation between the stop echo signal and the reference signal.

As shown in Fig. 2, the waveform above is the reference signal, the middle waveform is the stop echo signal, and the waveform on the bottom is the cross-correlation curve. The position of the peak in the cross-correlation curve is interpreted as time-delay estimation.

The time delay between the stop echo signal and the reference signal also could be described as the following:

$$\hat{\tau} = m \cdot T + \tau_s, \quad (3)$$

where T is the sampling interval, τ_s is the system time delay, and m is the number of sampling intervals.

By the Eqs. (2) and (3), we can make a summary that the precision of time-delay estimation is dependent on the ADC sampling interval and the cross-correlation coefficient between the stop echo signal and the reference signal. In order to improve the precision of the time-delay estimation,
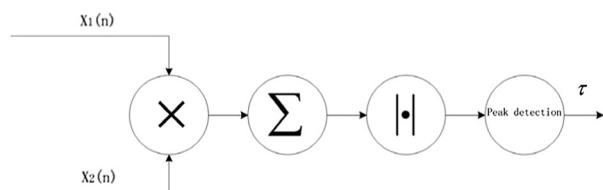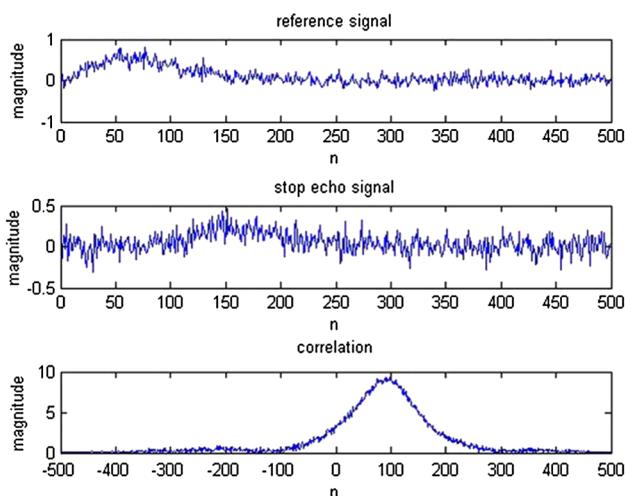
the most straightforward way is to increase the conversion rate of the ADC device. In this paper, the highest precision of the time-delay estimation is 5 ns with an ADC of 500 switch mode power supply (SMPS) conversion rate. If the conversion rate could reach up to 2 GS/s, the precision would rise to 0.5 ns correspondingly. However, the conversion rate of the ADC complementary metal-oxide-semiconductor transistor chip is restricted. It is difficult to raise the conversion rate of ADC, since its rise requires more complex and stricter circuit design, which is complicated for common researchers.

To ease the trade-off between the precision and the conversion rates on the basis of cross-correlation, we Transform the original reference signal into four reference signals including the original reference signal by the reference receiver multichannel, which has an analog time-delay circuit that could perform 0.5 to 1.5 ns time-delay functions with a 0.5 ns time interval. The analog time-delay circuit consists of three 0.5 ns time-delay subcircuits, which is accomplished by an inductance & capacity (LC) low-pass filter. As shown in Fig. 3, the analog time-delay circuit consists of four 1-ns time-delay subcircuits, which is accomplished by an LC low-pass filter.

The k'th reference signal x_{1k} could be evaluated as

$$x_{1k} = s\left(n - \tau_1 - \frac{k-1}{N}T\right) + n_{1k}(n), \qquad k = 1, 2 \ldots N. \quad (4)$$

T is sampling interval and N is the number of reference multichannel.

Then, the time-delay estimation between the stop echo signal and the k'th reference signal based on direct cross-correlation may be expressed as

$$\hat{\tau}_k = \arg\left\{\max\left[R_{rr}\left(t - \tau_2 + \tau_1 + \frac{k-1}{N}T\right)\right]\right\}$$
$$= \tau_2 - \tau_1 - \frac{k-1}{N}T. \quad (5)$$

Also, the time delay between the stop echo signal and the k'th reference signal could be described as the following:

$$\hat{\tau}_k = \left(m - \frac{k-1}{N}\right)T + \tau_s. \quad (6)$$
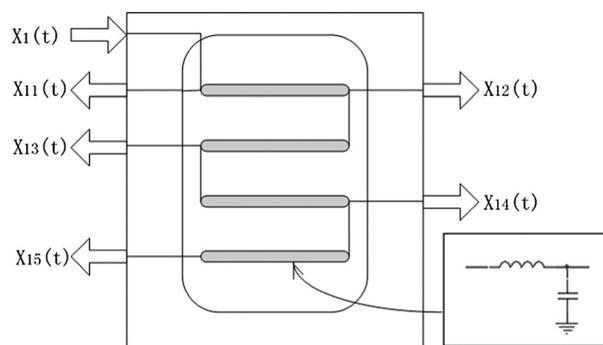

Fig. 1 Principle of cross-correlation time-delay estimation.

Fig. 2 The analog time-delay circuit.

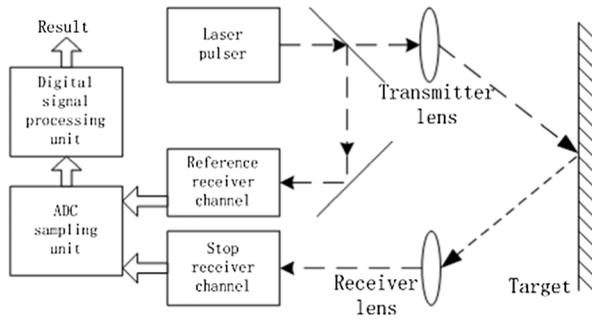**Fig. 3** Waveform of cross-correlation curve.

Fig. 4 Schematic diagram of laser time-of-flight (TOF) measurement system.

The resolution of the time-delay estimation could be improved from T to T/N by estimating the time delay between the N reference signals and the stop echo signal one by one. Ideally, the difference in time-delay value between the contiguous reference signals estimated with the stop echo signal is T/N. However, in the practical case, the measured results are in error because the sampling interval is wider than T/N. In order to correct the error, the linear fitting correction is considered. According to the concept of linear fitting correction, the correction factor for correcting the error is obtained by drawing a comparison between the measured data and their corresponding least squares.

A set of measured data is listed as $(k, \hat{\tau}_k)$ $(k = 1, 2, \ldots, N)$. The problem of linear least square fitting is to look for a function $\tau = f(k)$ to minimize the sum of squared residuals. The linear least square fitting could be expressed as

$$\|\delta\|_2^2 = \sum_{k=1}^{N} \delta_k^2 = \min \sum_{k=1}^{N} [f(k) - \hat{\tau}_k]^2, \quad (7)$$

where δ^2 is the minimum value of the sum of the variance between N-measured value and N-fitting value; $f(k)$ is linear fitting equation; k is the reference channel and there are a total of N reference channels; $\hat{\tau}_k$ is the average delay time of reference channel k; and $\min(\cdot)$ is the function to get the minimum value.

3 System Design and Experiment

According to the theoretical analysis in the preceding section, the laser TOF measurement system is designed as shown in Fig. 4. The laser TOF measurement system consists of a laser transmitter, a stop receiver channel, a reference receiver multichannel, an ADC sampling unit, and a digital signal processing unit. The laser transmitter consists of a semiconductor laser and a pulsing electronics. Both the stop receiver channel and the reference receiver multichannel consist of a photodetector, a transimpedance-type preamplifier, and a voltage-type postamplifier. One of the differences between them is that the stop receiver channel uses an avalanche photodiode as a photodetector, while the reference receiver multichannel uses a PIN diode. Another is that the reference receiver multichannel has an analog time-delay circuit which could perform 0.5 to 1.5 ns time-delay functions with a 0.5 ns time interval.

The ADC sampling unit changes analog pulse signal to a binary digital, which is fed to the digital signal processing unit. It contains five 10-bit, 500 SMPS conversion rate, monolithic ADC converters optimized for high speed and low power consumption, one for sampling the stop echo signal and the others for sampling the reference signals. The digital signal processing unit is the core of the laser ranging system. The most important property of the digital signal processing unit is to implement TOF measurement, determining the time delay between the stop echo pulse signal and the reference pulse signals. Methods to improve the precision of TOF measurement depend on the algorithms based on time-delay estimation.

An experiment was carried out to test the performance of the laser TOF measurement system based on multichannel time-delay estimation with linear fitting correction. As the speed of laser is known, measuring the laser flight time
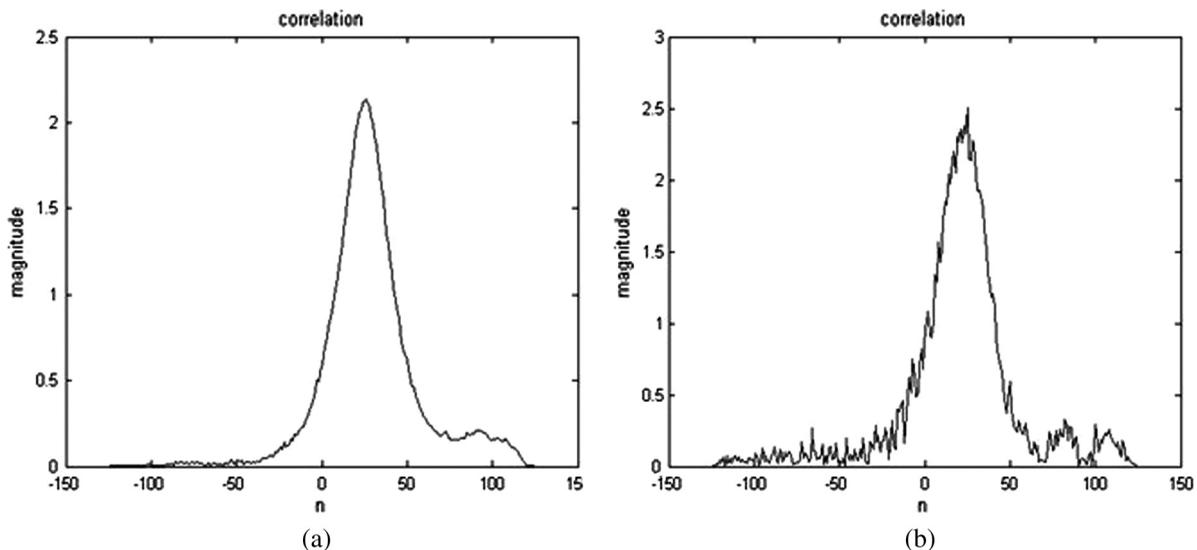

| (a) | (b) |

Fig. 5 Cross-correlation curve: (a) with high signal-to-noise ratio (SNR) and (b) with low SNR.
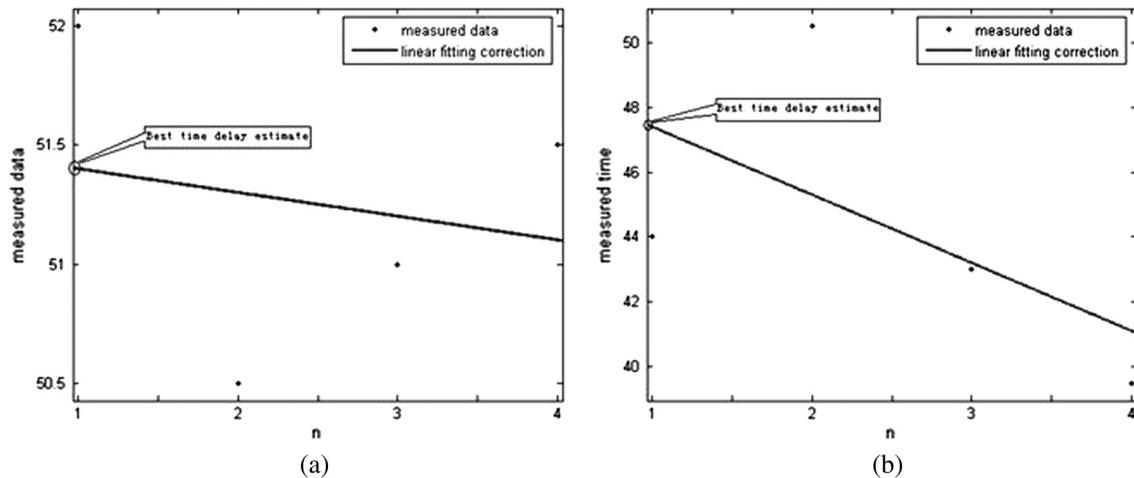
Fig. 6 Linear fitting correction for measured data: (a) with high SNR and (b) with low SNR.

actually involves measuring the distance. The distance of a target as far as 7.425 m was measured. In other words, the TOF of laser would be 49.5 ns.

Figure 5(a) and 5(b) shows the results of cross-correlation time-delay estimation between the stop echo signal and one of the multichannel reference signals with different signal-to-noise ratio (SNR). As shown in Fig. 5(a), the waveform is a cross-correlation curve with high SNR, and the position of the peak which is interpreted as time-delay estimation is 26. As shown in Fig. 5(b), the waveform is a cross-correlation curve with low SNR, and the position of the peak which is interpreted as time-delay estimation is 22. Since the sampling interval is 2 ns, the measured data is 52 and 44 ns, correspondingly. Drawing a comparison between the two curves, we can dig out that the waveform of cross-correlation curve with high SNR is smoother, the correlation intensity is similar, and the time-delay estimation result of cross-correlation curve with high SNR is more precise.

Measured data estimated between the multichannel reference signals and the stop echo signal with high SNR are 26, 25, 25, and 25 points, and converted into time are 52, 50, 50, and 50 ns. Added to 0, 0.5, 1, and 1.5 ns which are the time delay in the reference multichannel are 52, 50.5, 51, and 51.5 ns. As shown in Fig. 6(a), the experimental data are fitted with a linear relation using least squares, and the best time-delay estimation which is at the position corresponding to the first measured data is 51.4 ns. The absolute error of TOF measurement is not more than 2 ns.

In a similar way, the measured data estimated between the stop echo signal and the multichannel reference signals with low SNR are obtained. They are 22, 25, 21, and 19 points, and converted into time are 44, 50, 42, and 38 ns. Added to 0, 0.5, 1, and 1.5 ns they are 44, 50.5, 43, and 39.5 ns. As shown in Fig. 6(b), the experimental data are fitted with a linear relation using least squares, and the best time-delay estimation is 47.6 ns. The absolute error of TOF measurement is not more than 2 ns.

The results presented in Fig. 6 show that the precision of laser TOF measurement based on once cross-correlation time-delay estimation is easily influenced by SNR. As SNR

is high, the absolute error is small. However, the absolute error increases as SNR decreases. Based on multichannel time-delay estimation with linear fitting correction, the precision of laser TOF measurement is better than 2 ns. What is more, it is not influenced by SNR.

4 Conclusion

We presented a novel method based on multichannel cross-correlation time-delay estimation and linear fitting correction to ease the trade-off between the sampling rate of ADC and the precision of laser TOF measurement system. The experimental results presented in this paper showed that the laser TOF measurement system, which uses multichannel cross-correlation time-delay estimation and linear fitting correction, is more precise and stable than the conventional methods, with the precision better than 2 ns. Higher ranging precision could be achieved by increasing the number of multichannel reference signals, while the complexity of the analog time-delay circuit and the ADC sampling unit would be increased correspondingly.

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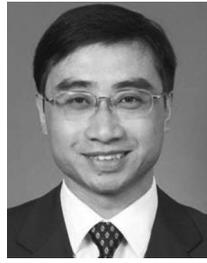
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Biographies and photographs of the other authors are not available.