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Accuracy improvement of imaging lidar based on time-correlated single-photon counting using three laser beams

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ABSTRACT

Time-correlated single-photon counting (TCSPC) is one of the most active technologies for optical time-of-flight ranging and three-dimensional (3D) imaging. Ranging accuracy is one of the most critical issues of lidar system. We propose a three-laser-beam TCSPC lidar system. Besides the main measuring laser beam, the second beam is used to decrease the error caused by jitter of time synchronization. The third beam has n + 0.5 time bins' difference with the main measuring beam, and it is used to correct the error caused by the discrete sampling of time-to-digital converter (TDC). To validate the feasibility of the three-laser-beam TCSPC lidar system, a series of simulation experiments using the scheme is carried out. The results show that this method is effective to improve the ranging accuracy of TCSPC lidar system.

1. Introduction

Three-dimensional (3D) lidar technique has been widely used in a variety of fields such as city construction, topographic mapping, underwater detection and robotics, et al. [1–11]. Time-correlated single photon counting (TCSPC) lidar has attracted a great deal of attention in recent years because of its high sensitivity and high time precision [12–20].

Ranging accuracy is one of the most critical issues of lidar system, and there has been a lot of research done on this subject [21–27]. In practice, the time jitter of lidar system will degrade the accuracy of an absolute measurement of the distance. To overcome this, J. S. Massa et al. introduced a second laser beam to illuminate a reference surface and made relative measurements of the distance between this and the target [28], as shown in Fig. 1.

One of the most important factors influencing the accuracy of the TCSPC lidar system is time measurement unit. Usually, the time measurement unit is a time-to-digital converter (TDC). The time bin size influences the resolution of TDC. The time bin size of TDC commercially available is about 10–250 ps [29,30]. There exists discrete sampling error for narrow pulse signal, and this paper introduces the third laser beam to reduce the discrete sampling error and improve ranging accuracy, based on J. S. Massa's research. We then perform a series of simulations to validate the novel lidar system. The results of simulation with different time bin sizes and laser pulse widths are discussed, and it shows that the three-laser-beam TCSPC lidar system is effective to improve the ranging accuracy.

2. The three-laser-beam TCSPC lidar system

To analyze the error, the shape of the echo signal reconstructed in the memory of the TCSPC system after many signal periods is approximated using a Gaussian function [31].

$$I = I_0 e^{-\frac{(x-x_0)^2}{2\tau_0^2}}, \tag{1}$$

where I_0 is the number of counts at the peak of the reconstructed signal, τ_0 is the signal width, and x_0 is the center of the signal. The theoretical distance can be calculated by

$$R_0 = \frac{1}{2}ct_{TOF} = \frac{1}{2}cx_0 t_{bin}, \tag{2}$$

where R_0 is the theoretical distance, t_{TOF} is the time of flight (TOF) of the laser pulse, and c is light speed in the air.

For the ith time bin, the number of counts is the integral of $I(t)$ in the interval $[x_i-0.5,\ x_i+0.5]$ in essence,

$$I_i = I_0 \int_{x_i-0.5}^{x_i+0.5} e^{-\frac{(x-x_0)^2}{2\tau_0^2}}\,dx, \tag{3}$$

where I_i is the counts of the ith time bin.

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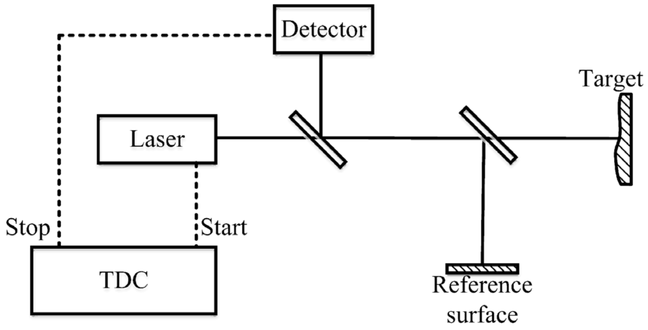

Fig. 1. TCSPC imaging lidar system using two laser beams.

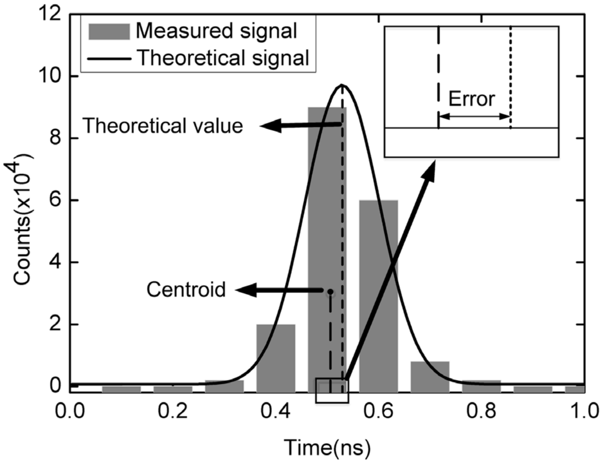

Fig. 2. The error between the calculated value and theoretical value.

The time bin at the peak of the target can be obtained by calculating the centroid on the time-resolved axis.

$$x_{cal} = \frac{\sum_{i=N_1}^{N_2} iI_i}{\sum_{i=\mathrm{N}_1}^{N_2} I_i} = \frac{\sum_{i=N_1}^{N_2} i \int_{i-0.5}^{i+0.5} e^{-\frac{(x-x_0)^2}{2\tau_0^2}} dx}{\sum_{i=N_1}^{N_2} \int_{i-0.5}^{i+0.5} e^{-\frac{(x-x_0)^2}{2\tau_0^2}} dx}, \tag{4}$$

where x_{cal} is the calculated coordinate value of the signal reconstructed in the memory on the time-resolved axis, and N_1, N_2 are the N_1th, N_2th time bin which are the boundary of the time gate. Similarly, the calculated distance can be obtained by

$$R_{cal} = \frac{\sum_{i=N_1}^{N_2} \frac{ict_{bin}}{2} \cdot \int_{i-0.5}^{i+0.5} e^{-\frac{(xct_{bin}-2R_0)^2}{2c^2\tau^2}} dx}{\sum_{i=N_1}^{N_2} \int_{i-0.5}^{i+0.5} e^{-\frac{(xct_{bin}-2R_0)^2}{2c^2\tau^2}} dx}, \tag{5}$$

where R_{cal} is the calculated distance of the target, and $\tau = \tau_0 t_{bin}$.

The echo signal has a size of several time bins in general. Because the time bin is the minimum measurement unit of TCSPC system, and it cannot be separated, the accuracy distance cannot be got by calculating the centroid with a limited number of discrete values. There is an error between the calculated value and theoretical value, as shown in Fig. 2.

The error, E between the calculated distance and the theoretical distance can be calculated by

$$E_A = R_{cal} - R_0 = \frac{\sum_{i=N_1}^{N_2} \frac{ict_{bin}}{2} \cdot \int_{i-0.5}^{i+0.5} e^{-\frac{(xct_{bin}-2R_0)^2}{2c^2\tau^2}} dx}{\sum_{i=N_1}^{N} \int_{i-0.5}^{i+0.5} e^{-\frac{(xct_{bin}-2R_0)^2}{2c^2\tau^2}} dx} - R_0. \tag{6}$$

To decrease the error caused by TDC discrete sampling, the third beam (Beam C) is utilized, as shown in Fig. 3. There is a preset optical path difference (OPD) between Beam C and Beam A, and the OPD leads to an $n + 0.5$ time bins difference between the two echo signals in TDC.

The three-laser-beam TCSPC lidar system not only overcomes the jitter of the system, but also decreases the discrete sampling error. Additionally, this method is easy to implement, because there is no need to adjust the most of the lidar system, such as detectors, receiving system, electric circuit structure and so on. Only splitters and reflectors should be added in the optical path.

$$L_{OPD} = (n + 0.5)\, ct_{bin}, \tag{7}$$

where L_{OPD} is the OPD between Beam A and Beam C, and n is a positive integer. The corrected distance is obtained by calculating the mean value of the distance measured by

$$L = \frac{1}{2}\left[L_A + (L_C - L_{OPD})\right], \tag{8}$$

and the error can be expressed as Eq. (9). The simulation results are shown in Fig. 4.

$$E_{A+C} = \frac{1}{2}(E_A + E_C). \tag{9}$$

In order to study the discrete sampling error clearly, some factors are ignored in the simulation, such as system time jitter, signal transit time spread (TTS) in the detector, and noise, et al. I_0 is equal to 10 000, because enough counts can decrease ranging error. In the simulation, $t_{bin} = 100$ ps, $\tau = 10$ ps, and the theoretical distance is 5.98–6.02 m. From Fig. 4, it can be seen that E_A, E_C and E_{A+C} vary with R_0 periodically, and the error of Beam A and the error of Beam C are almost opposite to each other, and therefore the error of the mean value of the two beams is much smaller. The root mean square error (RMSE) of E_A and E_C is 3 mm, and the RMSE of E_{A+C} is 0.8 mm. The results show that the error of measured distance can be decreased to ~26.7% of the initial value using this solution. This method can improve the depth accuracy of the TCSPC system significantly.

3. Simulation and results

In order to analyze the third beam more integrally, a series of simulation experiments are carried out. The target is set as an inclined plane with the farthest distance of 6.02 m and the nearest distance of 5.98 m. The situations of different sizes of time bin and pulse widths are studied.

Under the same pulse width conditions, the simulation results of three different time bin size are studied in Fig. 5. Fig. 5(a) shows that the 3D images obtained by Beam A are not as flat as the theoretical image The folds are caused by the discrete sampling. The folds become smaller gradually along with the decrease of the time bin. The RMSE decreases an order of magnitude from 7.8 mm for $t_{bin} = 200$ ps to 0.78 mm for $t_{bin} = 50$ mm, which can be seen in Fig. 5(c). A conclusion can be reached that the correction 3D images of the mean of Beam A and Beam C in Fig. 5(b) are much flatter than the initial 3D images of Beam A. After calculating the ratio of correction values and initial values in Fig. 5(c), it can be found that the ratio is decreased from 36% to 4.6%, which says that the smaller time bin we use, the more effective the method is.

Under the same time bin size conditions, the simulation results of three different pulse widths are studied in Fig. 6. It shows that the error gets smaller with the increase of the pulse width, and this conclusion seems to be not in accord with the common sense. People tend to assume that the narrower the pulse width is, the smaller the error is. However, TCSPC is a process of photon accumulation and statistical analysis, and wider pulse width does not increase the ranging error if enough signal periods are counted in the TCSPC experiment. Considering the influence of the TDC discrete sampling, conversely, wider pulse width decreases the ranging error as shown in Fig. 6(a). For $t_{bin} = 100$ps, while $\tau > 100$ps, the RMSE of Beam A is $<8.9\times10^{-9}$mm which can be ignored. In the