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RESEARCH ARTICLE

A Delay Modulation Method to Improve the Time Resolution for a 32×32 Array of MPPC Image Sensor

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ABSTRACT The array laser detector can achieve three-dimensional (3D) flash imaging via multi-channel parallel ranging, which significantly improves the imaging speed. However, the large number of the array makes it difficult to improve the ranging resolution through circuit evolution and data processing, even the imaging speed will be sacrificed. To overcome the problem, a delay modulation method on the transmitter of the laser is proposed in this study. The method is realized by using a 32×32 Multi-Pixel Photon Counter (MPPC) array and an improved phase-shifted clocks method. We eventually achieve 1024-channel 3D imaging that exceeds the depth resolution of the system. Experimental results show that, the Root Mean Square Error (RMSE) of plane fitting with delay modulation is 2.39-5.03 cm, which has come down to 48.6% than those without delay modulation. Using the delay modulation method, a target with a depth difference of about 4 cm can be clearly distinguished by 3D imaging at a distance of 5 m, even if the minimum resolution of the system is 5 cm. Results also demonstrate that the proposed method can easily and effectively enhance the measurement accuracy of 3D flash imaging.

INDEX TERMS Imaging, laser applications, added delay, MPPC, signal resolution.

I. INTRODUCTION

Light Detection and Ranging (LiDAR) is a well-known implementation of three-dimensional (3D) imaging, incorporating optical-electro-mechanical technology [1], [2], and its essence is the parallel laser ranging technology. The Time-of-Flight (TOF) method [3] obtains the distance by measuring the duration traveled of an excitation light through a medium, reaching the target object and returning to the detector, which is widely exploited in LiDAR [4]. Further requirements of array detection, such as long-distance, high-accuracy, high-sensitivity, and fast imaging, have led to the Multi-Pixel Photon Counter (MPPC) become a research hotspot [5], [6], [7]. The technology of the MPPC sensor is based on multiple Single-Photon Avalanche Diodes (SPAD) functioning as sub-pixels within one pixel [8]. Each SPAD is connected with a quenching resistor. The MPPC has both the characters of

linearity of linear mode and the sensitivity of Geiger mode. The single photon counting method integrates with the technique of Time to Digital Convert (TDC) to measure the pulse TOF, have become one of the recent developing directions of 3D imaging systems.

The measurement accuracy of TOF is one of the main factors limiting the range accuracy of 3D imaging systems [9]. TOF measurements are usually performed using the pulse counting method, and the timing error is the primary source of the system error. Tao et al. [10] proposed a pulsed laser ranging method based on a multi-echo delay trigger, which transmit the echo signal of the pulsed laser into a delay unit and generate an electric pulse with a fixed delay to trigger the laser transmitter to generate the pulsed laser. Multiple delayed echo signals are triggered within a fixed time window to transmit pulses in turn, then the distance can be calculated according to the several echo pulses received and recorded by a counter. The method has an accuracy of up to 2 mm, but the corresponding measurement times are several seconds long.

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Chen et al. [11] achieved high-precision time measurement via a TDC with Dual Delay Lines (DDL). The proposed DDL-TDC implemented a measurement accuracy of 32 ps (corresponding to 4.8 mm) by inputting a constant delay source. However, this method only achieves a measurement range of 0.9 m, being limited by the length of the delay line. Bin et al. [9] came up with a mathematical model and system design for serial counting measurement of phase-shifted clocks. The clock pulse is phase-shifted N times in one cycle, and the TOF corresponding to each phase shift is counted at the receiver. In the article [12], it was verified that the measurement accuracy could be improved by a factor of N . Still, the performance is limited by the waveform distortion caused by the nonlinear elements of the erbium-doped fiber amplifier. The classical analog interpolation method proposed by Nutt [13] completes time interval stretching by the capacitor charging and discharging, and the stretching multiplier N is the improved accuracy multiplier. However, due to the time stretching and nonlinear errors, the measurement duration and system complexity are substantially increased.

Current approaches to improve timing accuracy are mainly utilized for laser ranging with a single receiver channel, which usually requires additional circuit design or signal processing at the laser transmitter or receiver. However, the larger array of MPPC, the more channels of parallel laser ranging, which complicates the modulation method at the receiver. This article focuses on providing a novel and simple approach that is highly effective for improving the timing accuracy of the array imaging detector. Each pixel of the array MPPC studied in this paper has a TDC module [8]. The large number of arrays makes the above approaches difficult to realize. For example, the architecture of the phase-shifted clock requires an active fiber loop and a dual counter for each signal channel. The multi-echo delay trigger method delays the echo signal which makes it too slow for flash imaging. The analog interpolation method requires time stretching at both the transmitter and receiver sides.

This paper achieves the accuracy improvement of the array detector by simply performing N -delay on the clock signal at the laser transmitter. We build a 3D flash imaging system with an MPPC image sensor as the detector. Employing the phase-shifted clocks method, we modulate the clock pulse with N equally spaced delays within the minimum time resolution. Then, we improve the ranging accuracy of the array laser detector by N times by simply adding a time-delay module at the light source, and our approach is not limited to the size of the receiving array. In the imaging experiment at a distance of 5 meters, the depth resolution without delay modulation is 5 cm, and the Root Mean Square Error (RMSE) with delay modulation is decreased by about two times. The experimental results confirm that the proposed method can effectively resolve the problem of improving the accuracy of the flash imaging system.

The paper is organized as follows. The mathematical model of the phase-shifted clocks method is explained in Section II, and the design of the 3D flash imaging system is explained in

Section III. Section IV presents the system performance analysis. Section V presents the experimental process, results, and discussion. The concluding remarks are drawn in Section VI.

II. MATHEMATICAL MODEL

The pulse counting method measures the time interval by counting the clock pulses between the start and end timing signals [7]. The primary source of measurement error is the time difference between the rising edge of the start or end signals and the rising edge of the effective counting pulse. As shown in Figure 1, t is the time interval, t_m is the measured value, ε is the difference between the start signal and the first valid timing pulse, σ is the difference between the end signal and the last valid timing pulse, n is the count value, and the random jitter error (e) of the signal is introduced to the model of the phase-shifted clocks method.

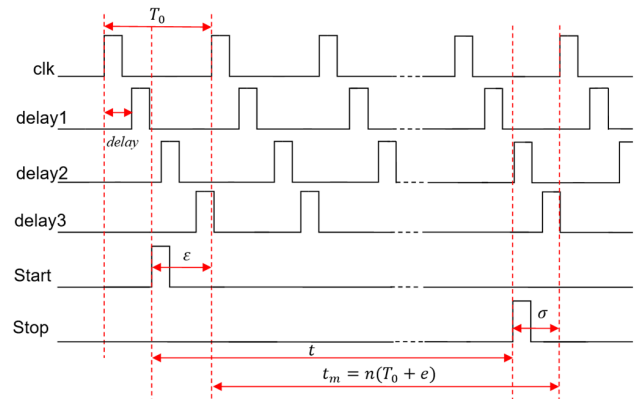


FIGURE 1. Diagram of phase-shifted clocks method and pulse counting error.

The truth value t can be obtained as:

$$t = t_m + \varepsilon - \sigma = n(T_0 + e) + \varepsilon - \sigma \quad (1)$$

where $\varepsilon - \sigma$ is the timing error and the maximum timing error is $\pm T_0$. An appropriate N is selected according to the performance of TDC's jitter and the time-delay module's jitter. Dividing T_0 into N parts, each delay for a measurement is $[T_0/N]$. The results of the clock signal after N delays can be summed as follows:

$$Nt = \sum_{i=1}^N n_i(T_0 + \sum_{i=1}^N e_i) + \sum_{i=1}^N \varepsilon_i - \sum_{i=1}^N \sigma_i \quad (2)$$

Among them, n can be obtained from a counter. We note that the ε and σ in (2) cannot be measured directly by counting, because only the integer portion of the pulse period can be measured by the counter. Both ε and σ are much smaller than the period, and suppose we discretize them with a counting period of $delay = [T_0/N]$, then, we round the ε and σ to $delay$.

$$Nt_m = \sum_{i=1}^N n_i(T_0 + \sum_{i=1}^N e_i) + \sum_{i=1}^N [\varepsilon_i] - \sum_{i=1}^N [\sigma_i] \quad (3)$$

We get the sum after each delay:

$$\sum_{i=1}^N [\varepsilon_i] = \sum_{i=1}^N [\sigma_i] = \frac{T_0}{N} [1 + 2 + \dots + (N - 1)] \quad (4)$$

From (4), we know that the summation results for ε and σ are equal and are independent of their initial positions. Organizing (3) yields:

$$t_m = \frac{\sum_{i=1}^N n_i (T_0 + \sum_{i=1}^N e_i)}{N} = \frac{\sum_{i=1}^N t_{mi}}{N} \quad (5)$$

From (5), the time interval is the average of the measurement results after N delay modulations, and the timing error is $\pm (T_0 + \sum_{i=1}^N e_i)/N$. In the absence of noise, the timing error is reduced to $\pm T_0/N$, and the timing accuracy can be improved by N . However, the improvement factor cannot reach the theoretical value due to noise and the device jitter.

During the operation, the system noise level is reduced and the signal is enhanced using averaging method. The phase-shifted clocks method increases the number of measurements by a factor of N , which is different from the arithmetic mean of N directly repeated measurements independently. The former introduces delay modulation information, and through N measurements, the timing error can be reduced by $1/N$, which can cut down the system errors. Whereas the latter is a way to reduce the random errors based on the principle of arithmetic mean, which can enhance the accuracy to $1/\sqrt{N}$ in mathematical statistics. In the meantime, random errors are also reduced in our approach. The accuracy increase for the phase-shifted clocks method is proportional to the measurement repetitions. We believe that the measurement accuracy can be significantly improved given the delay interval and system jitter are infinitely small.

III. DESIGN OF 3D IMAGING SYSTEM

To evaluate the accuracy improvement capability of the phase-shifted clocks method for the MPPC array detector, a 3D flash imaging system has been designed in this paper. The main device MPPC (*S15013-0125NP-01*, *Hamamatsu japan*) is a 32×32 -channel array image sensor, of which has 12 SPADs as sub-pixels within one pixel. The MC10EP195 programmable delay chip is serving as the time-delay module. The comparator is used to shape the signal and solve the voltage level matching between the delay chip and the laser. The system schematic and physical diagram are shown in Figure 2. The STM32 microcontroller controls the time-delay module which delays the pulse output from the MPPC. Then after level matching, the fiber laser outputs a pulse signal with a pulse width of 5ns and a pulse power of 0.36uJ. The main parameters of the system are shown in Table 1.

IV. SYSTEM PERFORMANCE ANALYSIS

Out of many parameters in table 1, the system jitter requires the most attention. The dominant noise in a pulsed TOF laser radar is typically from the receiver electronics [14]. We consider that the influence of the receiver electronics noise in the output waveform is mainly presented as time jitter, and we can reduce the random jitter error by repeating the measurement several times [15]. The statistical plot obtained by 9000 repetitions at a distance of about 5 m is shown in Figure 3. It can be seen that for a pixel in the MPPC array, the

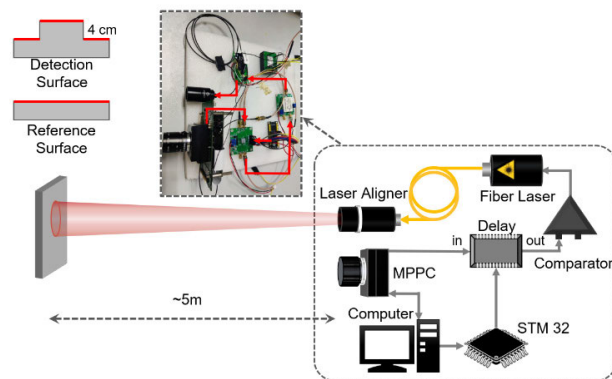


FIGURE 2. System diagram.

TABLE 1. System parameters table.

System parameter	Value
laser wavelength	905 nm
laser peak power	72.46 W
laser pulse width	5 ns
MPPC array size	32×32 ($100 \mu\text{m} \times 100 \mu\text{m}$)
MPPC photo detection efficiency	7% @ 900 nm
frame rate	≤ 10 kfps
TDC time resolution	~ 312.5 ps
TDC jitter	~ 135 ps
collimating spot divergence angle	0.2 mrad
objective lens aperture	2.9 mm-21.875 mm
delay interval setting value	100 ps
delay increments	10 ps
delay jitter	3 ps

statistical distribution of the measurements approximates a Gaussian distribution [16], [17], so the value with the highest number of repetitions will be used as the measured value in the subsequent experiments.

To evaluate the system performance, the depth resolution is first been verified. The timing error of the TDC in this paper is ± 312.5 ps, signifying the highest depth resolution of the imaging system is 4.6875 cm. As shown in Figure 4, we implement the equal interval ranging in the distance of about 3 to 4 meters, and each measurement is repeated 200 times. Adjusted R-Square [18] is used to reflect the fitting results. The value of Adjusted R-Squared decreases as degree of freedom increases also while considering R-Squared acting a penalization factor for a bad variable and rewarding factor for a good or significant variable. Adjusted R-Squared is thus a better model evaluator and can correlate the variables more efficiently. The value for Adjusted R-Square can range from 0 to 1, and the higher Adjusted R-Square points out the higher accuracy of the fit. We can see that the two lines almost overlap, and the larger ranging interval will be more accurate. When the ranging interval is 5 cm, the Adjusted R-Square reaches 0.95, from which we confirm that the system's depth resolution is 5 cm.

The timing-jitter of the imaging system also affects the random error of range, which largely influences the selection of delay interval. From table 1, we know that the TDC jitter is 135 ps. Although we can set the delay interval as low as

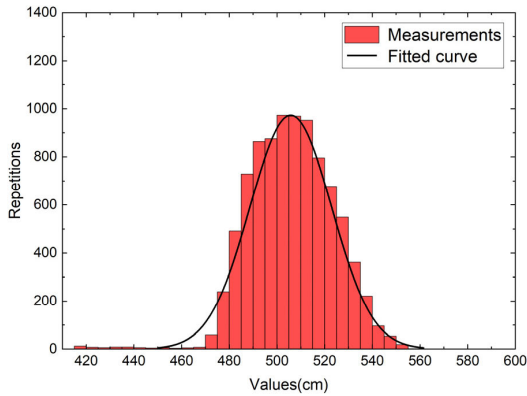


FIGURE 3. Distribution of 9000 measurements.

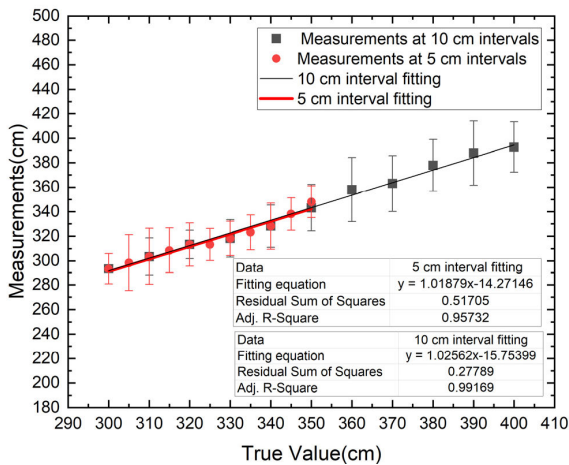


FIGURE 4. Linear fitting of ranging values at 5 and 10 cm intervals.

10 ps, small delay intervals will cause the amount of variation in measurement results to be directly drowned in the error of random system jitter. Therefore, we simulate the selection of different delay intervals. The simulation process is the model building process in Section II. In the case of $T_0 = 312.5$ ps, $T_{TDC_jitter} = 135$ ps, we select delay intervals such as $delay=20/30/50/60/75/100/150$ ps which corresponds to the multiplier $N = 15/10/6/5/4/3/2$. As shown in Figure 5, the red dots indicate the theoretical improvement of the range accuracy without any noise. The black square dots represent N of the corresponding delay interval after adding the random jitter error, and the simulation is repeated 200 times for each data set. It can be seen that even if the delay interval is as small as 20 ps, the improvement is far from than the theoretical result. In the experiment, the time resolution is tried to be exactly divisible by the delay interval. We also need to ensure the frame rate, so N should be small. Considering the above factors, we set the delay interval to 100 ps, and the number of delays to $N = 3$, which can theoretically improve the depth resolution of the system by 3-fold.

V. THE EXPERIMENT

The experimental results are quantitatively analyzed by calculating the RMSE. The average of numerous measurements is used as a benchmark to evaluate the effect of a small amount

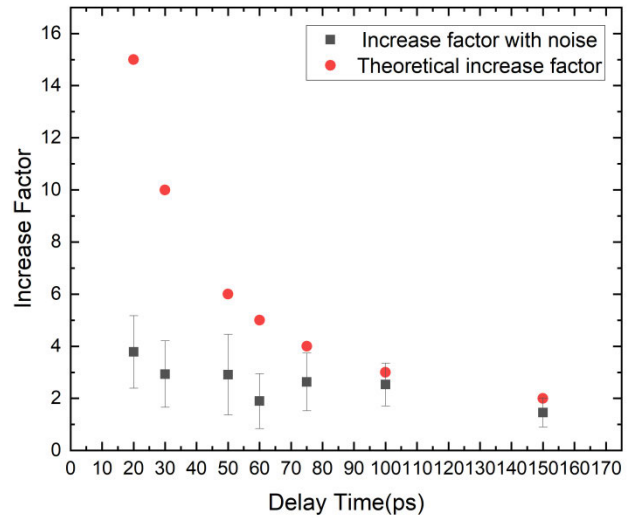


FIGURE 5. Simulation results of delay with/without noise.

TABLE 2. The RMSE before and after the delay modulation with different frame number.

Frame number	RMSE without delay/cm	RMSE with delay/cm
5	8.47	5.03
10	6.77	3.29
30	5.50	2.77
50	5.06	2.48
100	4.78	2.39

of data. The RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{ab} \sum_{i=1}^{ab} (y_i - y_{mi})^2} \quad (6)$$

The reference y is generated from 5000 frames of data without delay. y_m is the average of the imaging maps after three delays, and each measurement is repeated 5-100 times. Among them, a and b are the number of pixels of the detection array. In this paper, $a = b = 32$, and i is the i -th pixel.

A rectangular carton is used as the target with a size of 120 cm \times 40 cm. The measurement of distance is about 5 m when the spot is just filled with the target surface. The target and the reference map are shown in Figure 6.

The circle in the figure 6 shows the area covered by the spot, and the pixel value represents the depth information of the corresponding point in cm. The time-delay module generates 100 ps, 200 ps, and 300 ps delays in turn to obtain three measurement results, and the average of the three results is taken as the final measurement result of the pixel. We compare the RMSE without and with the delay modulation, and the results are shown in Table 2. It can be seen that the RMSE with delay is 1.68-2.06 times less than that without delay, and the RMSE using 10 frames delay is even smaller than the RMSE of 100 frames without the delay. As the number of frames increases, the RMSE of the results decreases no matter with delay or without delay. However, due to the TDC's jitter and the system's noise, the experimental results

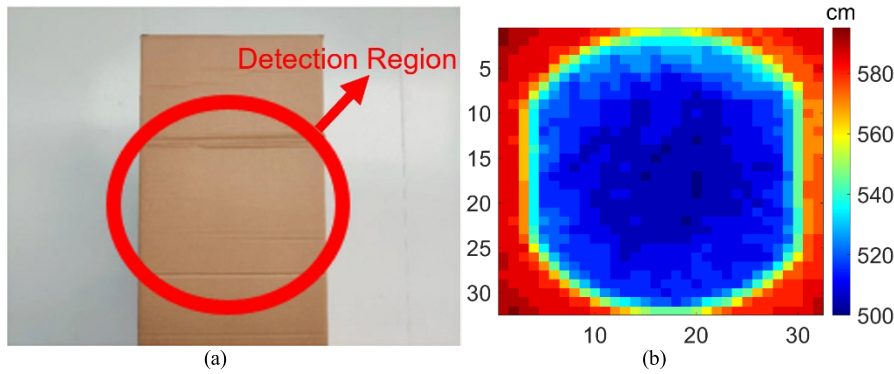


FIGURE 6. Planner target (a) Target image; (b) Reference imaging of planner target.

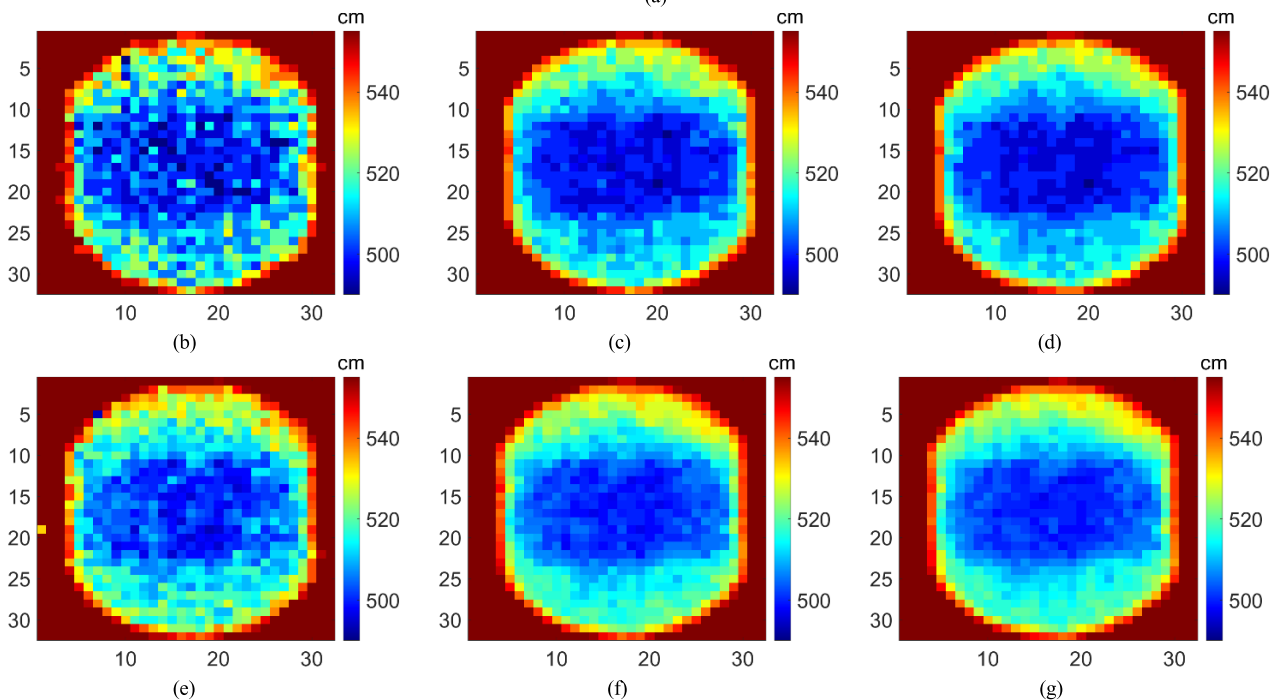
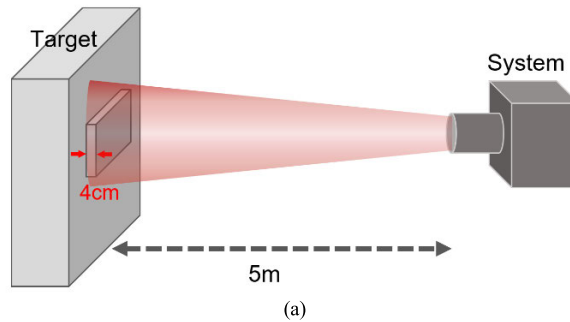


FIGURE 7. Imaging results. (a) Target image with depth difference of 4 cm. (b)-(d) without delay modulation: (b) 5 frames, (c) 50 frames, and (d) 100 frames; (e)-(g) with delay modulation: (e) 5 frames, (f) 50 frames, and (g) 100 frames.

do not achieve a 3-fold accuracy improvement, which is in accordance with the theoretical analysis and simulation.

The effect of the proposed method are intuitively shown in Figure 7. We image two targets at a depth interval of 4 cm, which is smaller than the system resolution. As can be seen from Figure 7(b)-(d), it is almost impossible to clearly distinguish the outline of the paper block in front. But after delay modulation, the square paper block in front

can be distinguished even in the case of less than five frames. In Figure 7(e)-(g), with the increase of repetitions, the square contour is clearer, together with a more uniform interior. When 100 frames are taken to reconstruct the image, the RMSE is reduced to 2.39 cm. The quantitative and qualitative analysis results show that the phase-shifted clocks method can improve the measurement accuracy of the array MPPC.

VI. CONCLUSION

In this paper, we proposed a novel delay modulation method to address the accuracy enhancement problem of MPPC image sensors with a 32×32 array. This approach expands the application field of the phase-shifted clocks method from laser range finder to 3D flash imaging. By analyzing the mathematical model of the phase-shifted clocks method, we simulated the effect of different delay intervals. This delay modulation is simply added to the laser transmitter. The RMSE of 10 frames of plane fitting with a distance of 5 meters is reduced from 6.77 cm to 3.29 cm, and the depth difference of 4 cm is distinguished by imaging visualization. The experimental results verify the effectiveness of the proposed method and provide a solution to improve the measurement accuracy of the MPPC image sensor.

Another issue that will be explored in future research is to achieve 3D imaging at hundreds of meters and even kilometers. In addition, the technology of data multiplexing is also of particular interest, and due to that, we hope to further reduce the number of frames used for 3D reconstruction. The related results are to be reported later.

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