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Efficient model of photon-counting laser radar for distance error calibration

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ABSTRACT

An efficient model of a photon-counting laser radar for distance error calibration is proposed. Photon-counting laser radars have a distance error due to the dead time of their detectors and circuit elements. Although a method to correct the error by modeling the effect of dead time has been proposed, it suffers from a trade-off between the computational cost and precision because of a stochastic approximation by Monte Carlo simulation. Thus, it requires many simulations to precisely compute the distance error. The purpose of this paper is to present an error correction method with a small computational cost that maintains the model's precision. The proposed method applies a deterministic approximation that does not require iterative simulations. The evaluation results show that the proposed method can compute the distance error with a smaller computational cost and with the same precision as the conventional method using a Monte Carlo simulation. The proposed method takes 580–600 ms, while the conventional method takes 212–213 s; thus, computation is approximately 350 times faster.

1. Introduction

In recent years, photon-counting laser radars have attracted attention as tools for three-dimensional (3D) image acquisition. Several important applications of 3D images have been proposed in the fields of driver assistance systems [1] and robotics [2]. These applications have stimulated the study of various sensor technologies for obtaining 3D images (see chapter 1 in [3]). Among these technologies, time-of-flight (TOF) laser radars with photon-counting detectors are attractive for their long-range detection capability and high angular resolution [4]. The author is especially interested in driver assistance systems, and therefore, in addition to detection range and resolution, detecting obstacles (people, automobiles, buildings, etc.) with high distance accuracy is important.

Photon-counting laser radars exhibit a distance error that depends on the intensities of the received light. Detectors and some circuit elements in these laser radars show some dead time [5], i.e., they cannot respond for a certain time after detecting an event. Some events may not be detected, especially when the intensity is high. Therefore, the measured intensity waveforms are distorted due to the dead time effect, resulting in an error in the measured distance value. This phenomenon is called pile-up [5] or range walk error [6]. To correct the error, a correction table containing distance error values corresponding to the intensities of received light should be prepared in advance.

Making such a correction table is difficult because the error depends on the intensities of the background light and the laser-return pulses [7], and therefore, several studies of this problem have been performed. For accurate calibration, distance errors must be obtained under many intensity conditions. Tens of thousands of conditions may be needed to achieve a certain required accuracy. Manual measurements take time, and data acquisition itself may be difficult. Hence, several methods to compute these errors have been studied [6,7]. These methods formulate the effect of dead time, assuming that the responses of detectors follow a probabilistic model.

However, it is difficult to apply these approaches for the recently developed laser radars due to their complex signal processing circuit. For example, the laser radar proposed in [4] uses several detectors as a single pixel. The output signals of these detectors are summed up, followed by a thresholding process in a comparator. Each detector and comparator involve some dead time, and thus, the overall effect of dead time is complex.

While a method for modeling the effect of dead time in a complex signal processing circuit has been proposed [8], this method involves a trade-off between the computational cost and precision. This method simulates the behaviors of detectors and circuit elements using a Monte Carlo simulation. Monte Carlo simulation is a method for stochastic approximation using random numbers. In this method, to improve the precision of the approximation, it is important to increase the number of simulations (see chapter 11 of [9]). Therefore, precisely computing distance errors under various intensity conditions is quite time consuming.

This paper proposes an error correction method with a small computational cost while maintaining precision. The proposed method applies a deterministic approximation that does not require iterative

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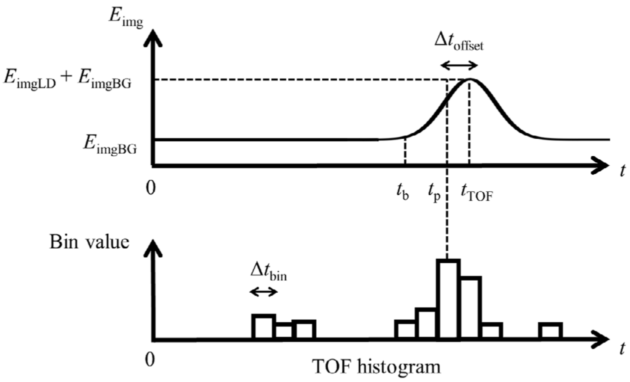

Fig. 1. Example waveform of the received light (upper graph) and time-of-flight (TOF) histogram (lower graph). The irradiance on the detectors' surface E_{img} is plotted against the elapsed time t since the laser-pulse emission in the upper graph. E_{imgBG} is the irradiance of the background light. E_{imgLD} is the peak value of the irradiance of a laser-return pulse. t_{b} is the time when the laser-return pulse reaches the detectors. t_{p} is the peak position of the TOF histogram. t_{TOF} is the time that corresponds to the TOF. $\Delta t_{\mathrm{offset}}$ is the peak position error due to the pile-up effect. Δt_{bin} is the time resolution of the TOF histogram.

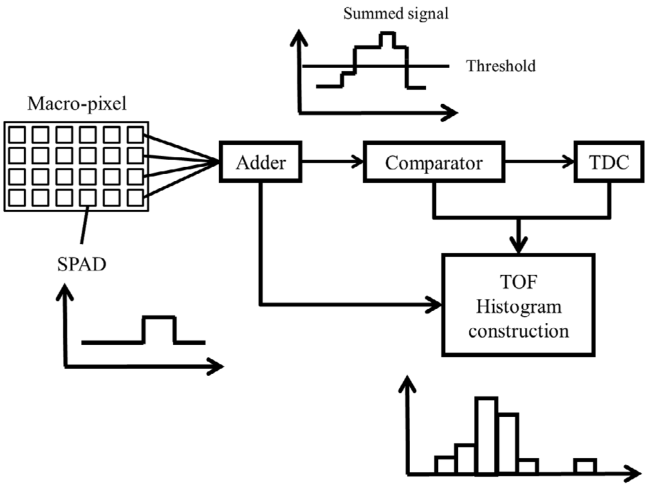

Fig. 2. Schematic block diagram of the signal processing circuit for TOF histogram construction as proposed in [4]. SPAD: single-photon avalanche diode, TDC: time-to-digital converter, TOF: time-of-flight.

simulations. The assumed laser radar is the instrument proposed in [4]. The evaluation results show that the proposed method can compute the distance error with a smaller computational cost than that of the conventional method using a Monte Carlo simulation but with the same precision. Moreover, the proposed method is more effective for smaller laser-return pulse intensities, especially under strong background light. For simplicity, the dead time model of each detector and circuit element is assumed to be the Saturable Model [10] (events in dead time are simply ignored, so they do not affect subsequent events or the length of dead time). The emitted light and surfaces of detected objects are assumed to be approximately orthogonal.

The rest of this paper has the following structure. Section 2 outlines the signal processing performed in the laser radar. Section 3 explains the proposed method. The proposed method is compared with the conventional method using a Monte Carlo simulation in Section 4, followed by conclusions in Section 5.

2. Signal processing in photon-counting laser radar

Photon-counting laser radars emit several laser pulses to an object and measure the intensity waveform of the reflected light. An example waveform is shown in the upper graph in Fig. 1. The irradiance on the detectors' surface E_{img} is plotted against the elapsed time t since the laser-pulse emission. Before receiving a laser-return pulse, E_{img} takes a constant value E_{imgBG}, which corresponds to the irradiance of the background light. E_{img} starts to increase at time t_{b} when the laser-return pulse reaches the detectors. E_{img} reaches its peak value at time t_{TOF}, which corresponds to the TOF. Let E_{imgLD} be the peak value of the irradiance of a laser-return pulse on the detectors' surfaces; then, E_{img} at t_{TOF} is calculated by adding E_{imgBG} and E_{imgLD}. E_{img} decreases to E_{imgBG} after t_{TOF}, which is detected by measuring the waveform and detecting its peak. Photon-counting laser radars measure waveforms by discretizing time at a certain interval Δt_{bin} and counting the received photons in each interval, as shown in the lower graph in Fig. 1. The measured waveforms are called TOF histograms [7].

Fig. 2 shows a schematic block diagram of the signal processing circuit for constructing the TOF histograms proposed in [4]. Single-photon avalanche diodes (SPADs) are used as detectors. Several SPADs operate as a single pixel (Macro-pixel). SPADs output a binary pulse signal with a certain probability when they receive a photon. The length of the pulse is set to the same value as the length of the emitted laser pulse. Pulse signals of SPADs in the Macro-pixel are summed up in an adder. The summed signal is thresholded in a comparator for noise reduction. Positive edges in the summed signal that cross a threshold value are detected in the comparator. A time-to-digital converter (TDC) is triggered by the comparator when a summed signal exceeds the threshold value. Then, the value of the summed signal is added to the corresponding bin. This process is repeated by emitting several laser pulses and a TOF histogram is constructed.

3. Proposed method

In this section, a method to calibrate the distance error caused by the pile-up effect is explained. The peak position t_{p} of a TOF histogram does not strictly coincide with the peak position of the intensity waveform of the received light due to the pile-up effect (Fig. 1). SPADs and some circuit elements cannot respond to any events at t_{TOF} if they respond to an event just before it. When the intensity of background light or of a laser-return pulse is high, the probability of these elements responding before t_{TOF} increases, and the probability of responding at t_{TOF} decreases. As a result, a peak position error $\Delta t_{\mathrm{offset}}$ occurs (Fig. 1). The distance error can be corrected by computing $\Delta t_{\mathrm{offset}}$ for each irradiance of the background light and the laser-return pulse. E_{imgBG} and E_{imgLD} must be estimated from a measured TOF histogram to correct for the distance error. These values can be obtained from the peak value of the TOF histogram if the relationship between the peak value of the TOF histogram and E_{imgBG} or E_{imgLD} is available. This relationship can be calculated using the model of the laser radar described below. E_{imgBG} can be independently obtained using a TOF histogram constructed without laser-pulse emission. E_{imgLD} is obtained by subtracting E_{imgBG} from the estimated total irradiance.

3.1. Model of the intensity waveform of laser-return pulses

If no background light is present, the intensity waveform of the received light is approximated by the shape obtained by multiplying the intensity waveform of emitted light by a constant. Laser radars emit a laser pulse in a certain waveform to an object (Fig. 3). When the emitted light is reflected from the object surface, the intensity waveform of the corresponding received light is deformed from the intensity waveform of the emitted light. The proposed method assumes that the intensity waveform of received light can be computed. Under the assumption described in Section 1, the waveform is computed as follows. Emitted light and object surfaces are assumed to be approximately orthogonal; thus, the deformation of the waveforms in the time direction

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