Error Correction Technique of Distance Measurement for ToF LIDAR Sensor

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Abstract

This paper presents design for error correcting algorithm of the time of flight (ToF) detection value in the light detection and ranging (LIDAR) system sensor. The walk error of ToF value is generated by change of the received signal power depending on distance between the LIDAR sensor and object. The proposed method efficiently compensates the ToF value error by the independent ToF value calculation from the received signal using both rising point and falling point. A constant error of ~0.05 m is obtained after the walk error correction while an increasing error up to ~1 m is obtained with conventional method..

Keywords: LIDAR, Time-of-flight, LRF, Walk error, Time-to-digital converter

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1. Introduction

A light detection and ranging (LIDAR) technology acquires information of surrounding environment by using the laser. It is applied to various fields such as space, earth environment, aircraft, architecture, traffic. In particular, it is important to obtain 3D image of surrounding environment in autonomous vehicle industry.

Interferometry, triangulation, and time of flight (ToF) are typical technologies for acquiring 3D object images and each method has trade-off relationship betweewn range and resolution [1]. ToF has advantages in an aspect of range. Therefore, ToF is the appropriate method for autonomous vehicle LIDAR sensors due to the fact that sensors require a wide range for recognition of the surrounding environment.

ToF technology is divided into pulsed ToF and continuous wave (CW) measurement [2, 3]. The pulsed ToF method is more advantageous for object recognition of long-distance than CW measurement [3]. However, the LIDAR sensor based on pulsed ToF has pulse delay time caused by the bandwidth limitation of the sensor and measurement result is distorted.

In this paper, the error correction technique for pulsed ToF LIDAR sensor is proposed. It corrects the error for the pulse delay time without additional bandwidth of the LIDAR sensor.

2. Walk Error of Conventional Pulsed ToF LIDAR System

This section explains conventional pulsed ToF LIDAR and walk error. The basic principle of pulsed ToF LIDAR is the arrival time measurement of the reflected signal.

2.1 Pulsed ToF Based LIDAR Sensor

The laser emitter emits a pulsed light source and the ToF sensor detects the reflected light by the object. The distance to object is calculated as follows:

$$D = \frac{c \cdot (t_a - t_e)}{2} = \frac{c \cdot \Delta T}{2} \tag{1}$$

where D means distance to object, c means speed of light, and ΔT means the ToF. t_a and t_e are the arrival time and the emission time of the pulse signal, respectively. It means the difference in delay time between the emitted pulse and the reflected pulse [4].

The pulsed light source is shaped on the laser emitter. The infinite bandwidth is required to generate accurate pulse signals. But pulse shape is distorted due to fact that LIDAR sensor has bandwidth limitation. A distorted signals are mathematically represented by Gaussian pulses, sech pulses, and Lorentzian pulses. In this paper, a Gaussian pulse model is used as mathematical model for signal analysis.

2.2 Walk Error of Pulsed ToF

The conventional ToF LIDAR sensor detects the intersection point of a received signal and a reference voltage. The measured point is regarded as arrival time of the reflected pulse signal and the distance of object is calculated by Eq. (1). However, the accuracy of conventional method is degraded by walk error [4].

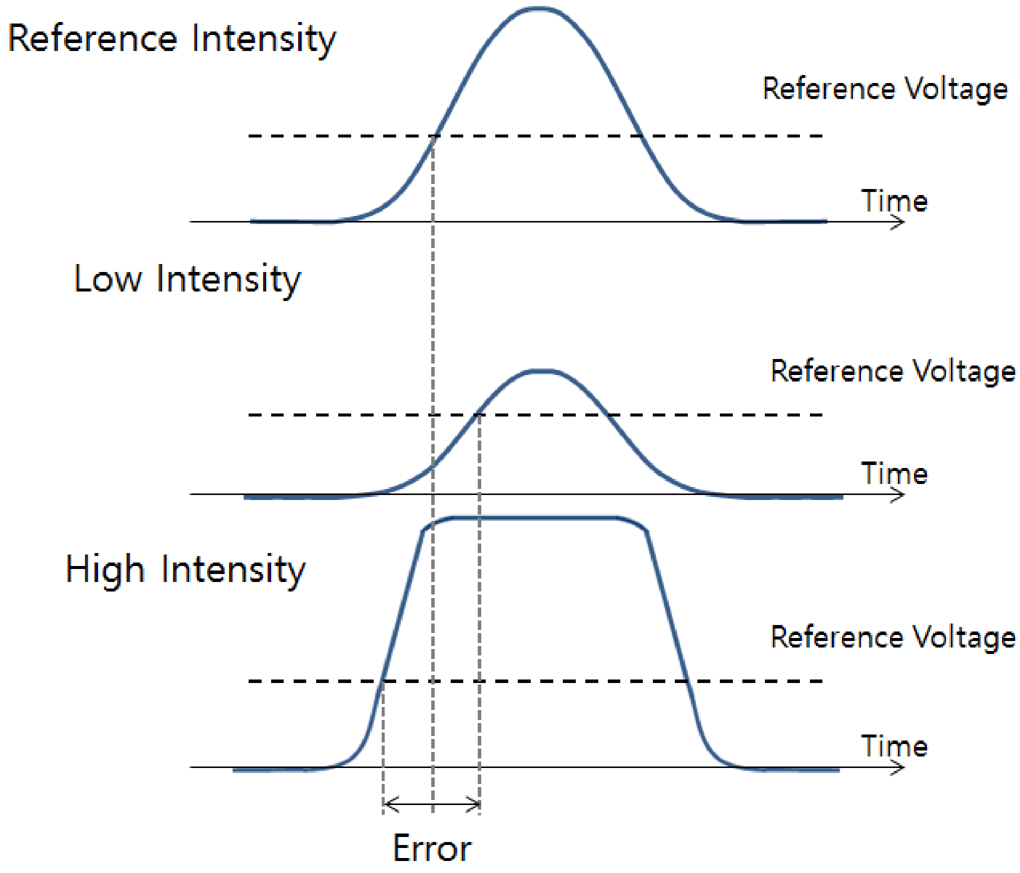

Fig. 1. An example of walk error due to signal intensity

Fig. 1 shows the signal intensity of the reflected signal and the example of walk error. When the distance between ToF LIDAR sensor and object is increased, the reflected signal power is decreased. Therefore, different time points are selected in comparison with the reference intensity case. If the signal intensity is low due to long distance, the detection time is delayed. On the other hand, the reflected signal by near object or high reflectance object is detected earlier than the reference intensity.

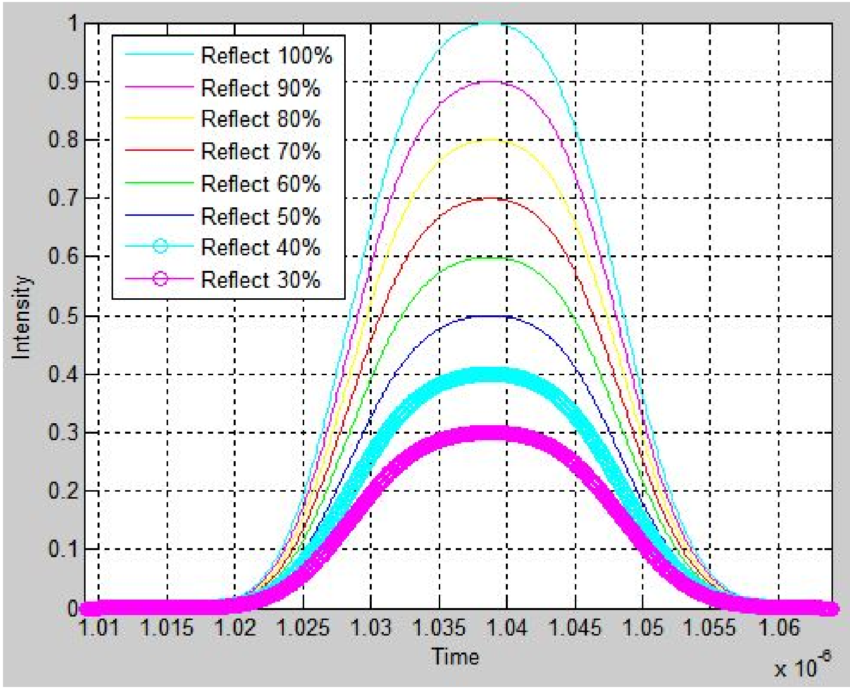

Fig. 2. The Gaussian pulse shape by reflectance

Fig. 2 shows the relationship between the reflectance and the Gaussian pulse shape of the reflected signal. The walk error of the conventional ToF sensor is proved by the intensity difference of the reflected signals.

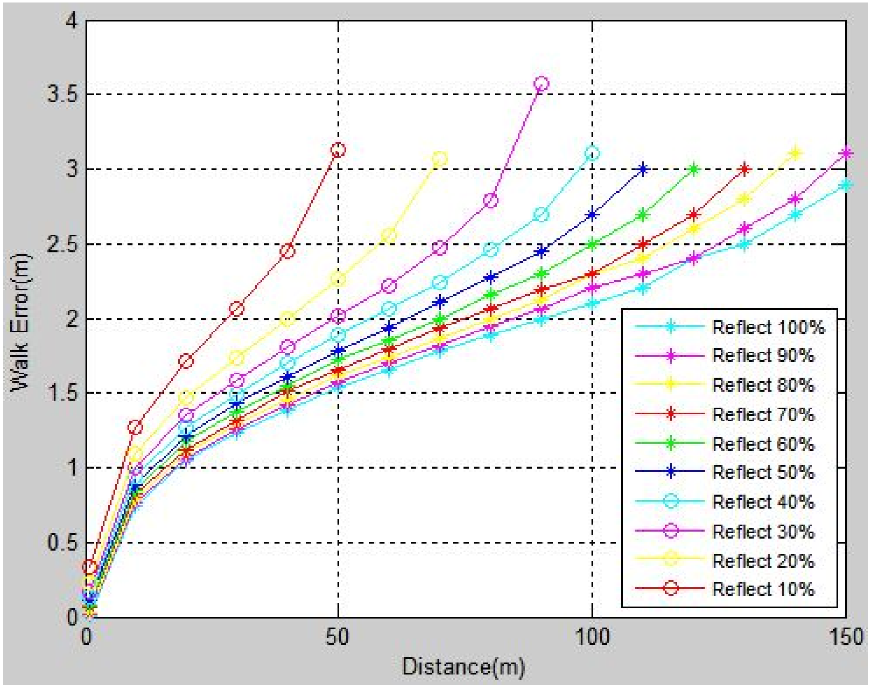

Fig. 3. The walk error performance of reflected signals

Fig. 3 shows the walk error performance of signals with different reflectance. The walk error increases when the distance from the object increases. In particular, a low reflectance signal has large walk error in spite of short distance.

The walk error correction technique had been proposed using the measured peak amplitude information by a peak detector and a Gilbert cell [5]. Another walk error correction technique compensates for walk errors by measuring the slope of the pulse waveform using two comparators with different reference voltages [6, 7]. However, conventional waveform measurement techniques have limitations such as complex signal processing, additional error when the signal peak exceeds the saturation power of the detector, measurement failure of low pulse signal. Techniques for measuring the pulse width of the returned signal had been developed to solve the conventional problems but these techniques require a multi-channel time-to-digital converter (TDC) [8-10].

3. The Proposed Error Correction Technique

The algorithm of the proposed technique compensates for the walk error by using the multi stop of the single channel TDC. Therefore, the complexity of the error correction scheme is low and the burden of signal processing is low.

3.1 The Proposed Error Correction Structure

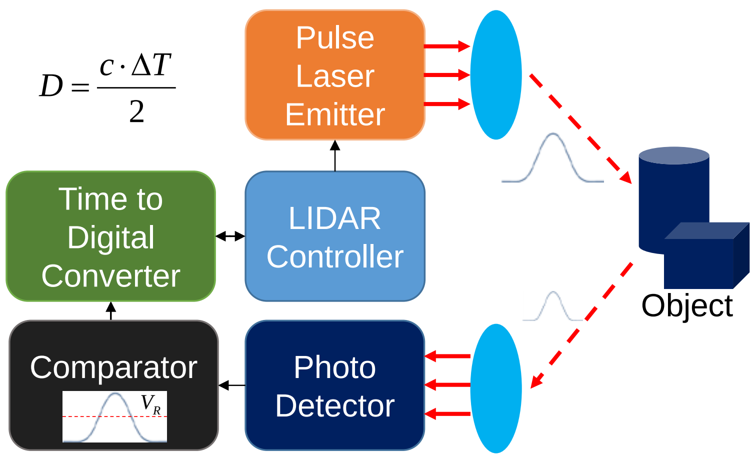

Fig. 4. The architecture of proposed ToF LIDAR sensor

Fig. 4 illustrates the structure of pulsed ToF based LIDAR sensor and basic principle of distance measurement. The pulsed ToF-based LIDAR sensor consists of LIDAR controller, pulse laser emitter, photo detector, comparator, and TDC. The operation principle of the LIDAR sensor is that the laser emitter emits a Gaussian pulsed light source when tirgger signal from controller is arrived, and the photo detector detects the reflected light from object. The detected signal is converted to transistor-transistor logic (TTL) level compared with the reference voltage set in the comparator and input to TDC. The time value measured in the TDC is input to the LIDAR controller. The distance to the object is obtained by calculating the difference between the pulse emission time in the laser emitter and the TDC time.

3.2 The Proposed Error Correction Algorithm

This section describes the proposed ToF error correction technique. In the proposed technique, the ToF sensor detects two time points.

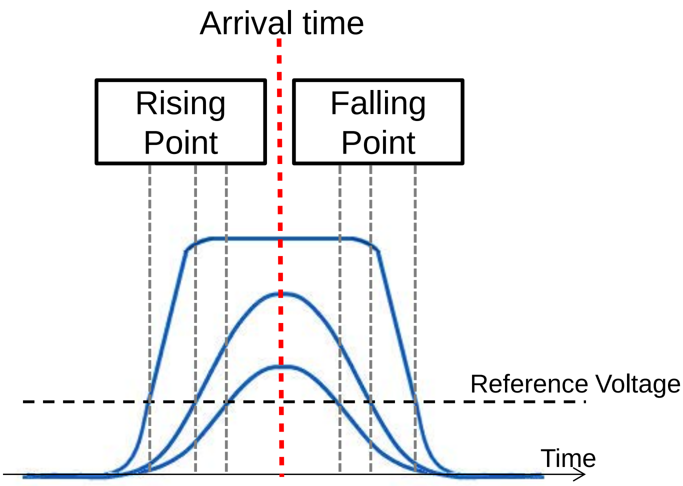

Fig. 5. The proposed error correction technique

The proposed technique is shown in **Fig. 5**. The rising point is the same as the detection point of the conventional ToF sensor. The falling point means that a voltage of a received signal falls below a reference voltage. The arrival time is the center point between the rising point and falling point. And it is used as a value for distance measurement. Since the arrival time is independent to a power of returned signal, precise ToF value can be obtained. The Gaussian pulse can be expressed by the following equation

$$h(t) = \frac{\exp(\frac{-t^2}{2\delta^2})}{\sqrt{2\pi} \cdot \delta} \tag{2}$$

where t means time, δ is a constant that determines the width of the signal waveform.

The time t_r of the rising point and the time t_f of the falling point are expressed as follows:

$$t_r = t_a - \delta\sqrt{2\ln(\frac{1}{\sqrt{2\pi}\delta V_R})} \tag{3}$$

$$t_f = t_a + \delta \sqrt{2\ln(\frac{1}{\sqrt{2\pi}\delta V_R})} \tag{4}$$

where V_R is a reference voltage for detecting Gaussian pulse light. The calculation formula of the arrival time is simply expressed as follows:

$$t_a = \frac{t_r + t_f}{2} \tag{5}$$

Therefore, the accuracy of distance measurement is improved by correcting the walk error by substituting the arrival time into Eq. (1).

4. Simulation and Measurement Results

4.1 Simulation Results

The simulation of the proposed ToF LIDAR sensor is modeled by the Matlab Simulink. The distance error difference between the proposed error correction technique and the conventional sensor structure using only the rising point is compared.

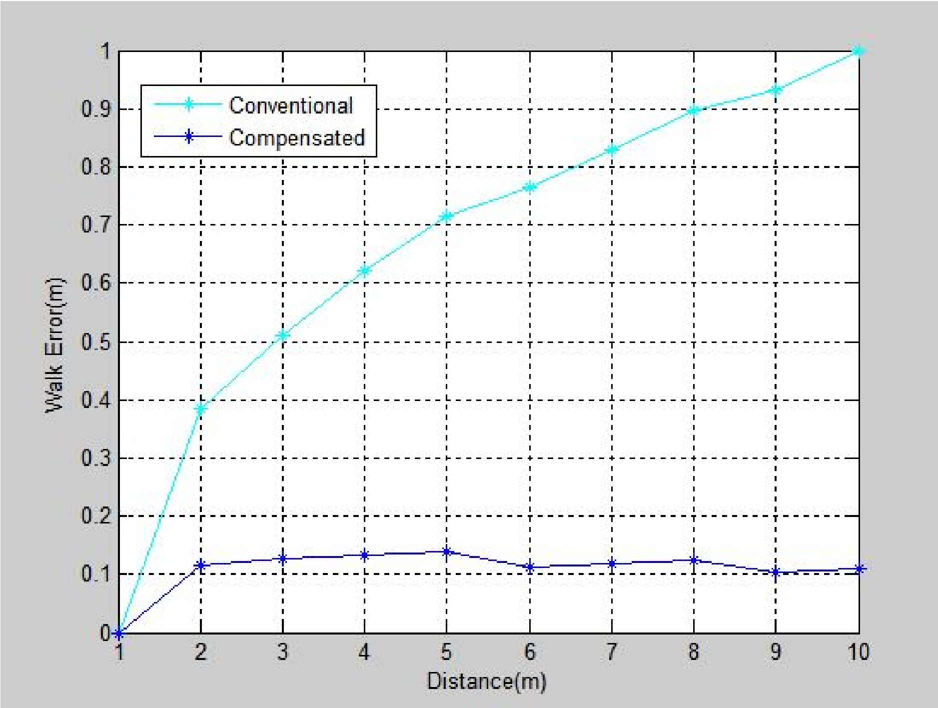

Fig. 6. The simulation results of proposed error correction technique

The simulation results of proposed and conventional error correction technique are represented in **Fig. 6**. In the graph, the conventional method has a walk error proportional to the distance to the object. In the graph, the conventional method has a walk error proportional to the distance to the object. On the other hand, the walk error performance compensated by the proposed error correction technique is constant regardless of the distance.

4.2 Experimental Results

The optical system of biaxial LIDAR is applied for the experiment of the proposed error correction technique. A measurement test board with FPGA and LIDAR control board is produced for pulse laser emitters, avalanche photo detectors (APDs), TDC control and received optical signal error correction signal processing.

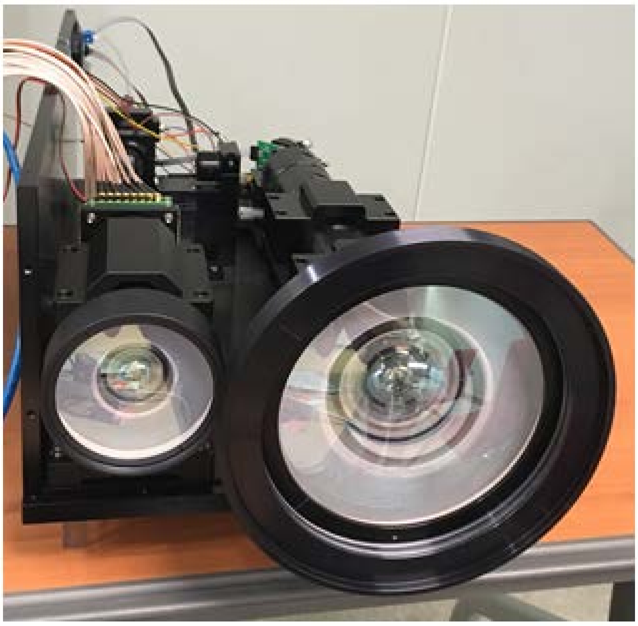

Fig. 7. The biaxial LIDAR optical system

Fig. 7 shows the biaxial LIDAR used in the experiment. Pulsed laser with 75W peak power is used and scattered light is received by APD. The optical signal received by the APD is output as an analog signal and is processed through the error correction technique in the manufactured measurement test board.

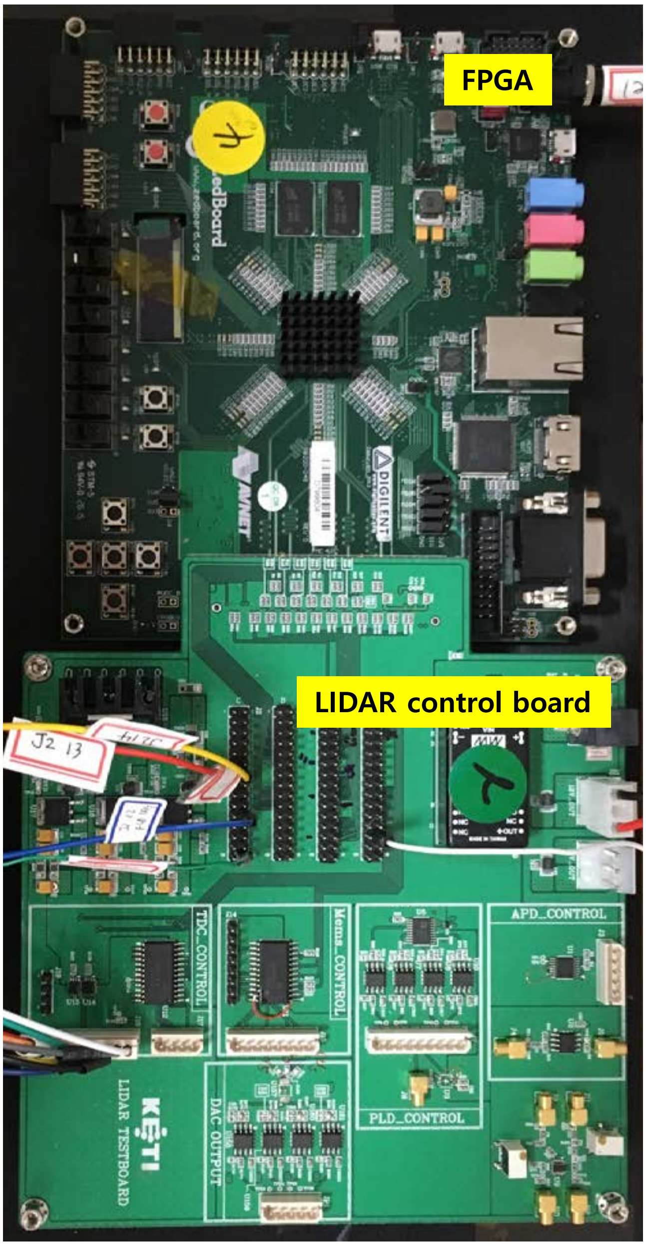

Fig. 8. Photograph of measurement test board

Fig. 8 shows a photograph of measurement test board of the proposed error correction technique. The single channel TDC is combined with a control board. The distance to a target object is measured by using the single channel TDC and the distance error result is compared with the results of the conventional technique.

The analog signal input to the measurement test board is converted to a digital signal by the comparator and input to the TDC.

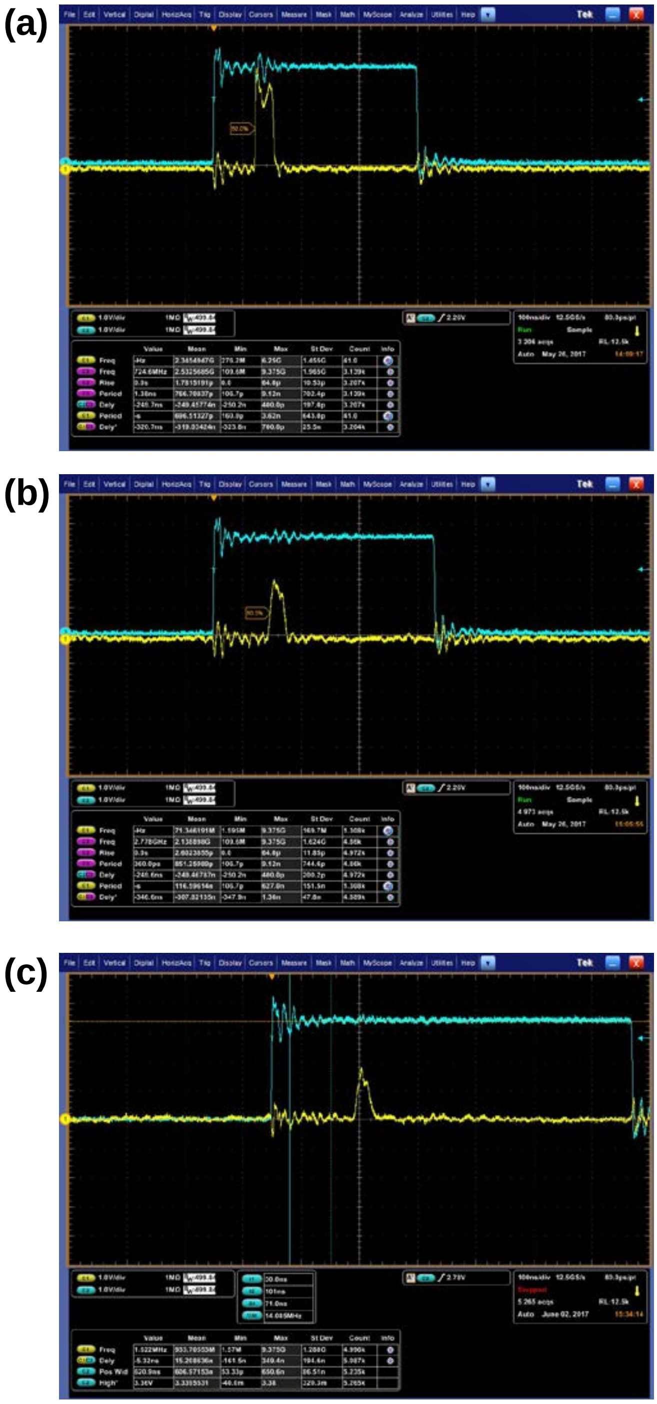

Fig. 9. Measured analog signal at (a) 3 m, (b) 6 m, and (c) 10 m

Fig. 9 represents the analog signal output from the LIDAR APD. In the **Fig. 9**, the signal of (a) scattered at the object at a distance of 3 m is distorted beyond the maximum output voltage of the APD, whereas the signal of (c) shows a edge of slow slope due to small intensity, and a walk error occurs.

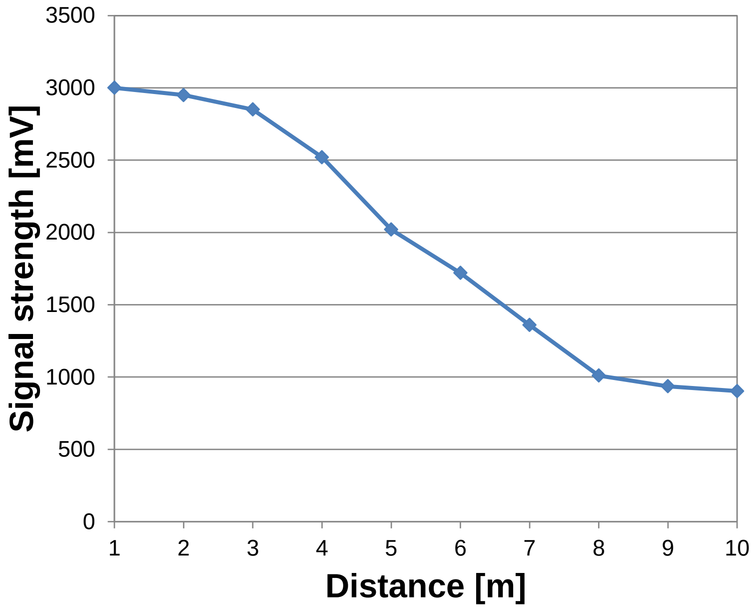

Fig. 10. Measured signal strength vs. distance

The intensity of the measured signal along the distance is shown in **Fig. 10**. In case of measuring only the rising edge of the received signal as the conventional method, a walk error occurs because the received signal strength becomes smaller as the distance increases.

On the other hand, the proposed method determines the arrival time by measuring TOF of the input signal for the rising edge and the falling edge.

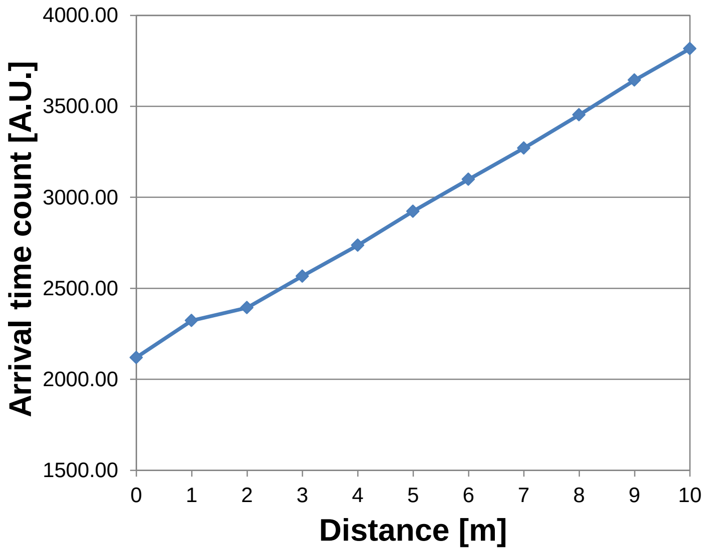

Fig. 11. Measured arrival time count vs. distance of TDC based on the proposed error correction technique

Fig. 11 shows the TOF value according to the distance measured by applying the proposed error correction method. The compensated measurements are linear and independent regardless of distance.

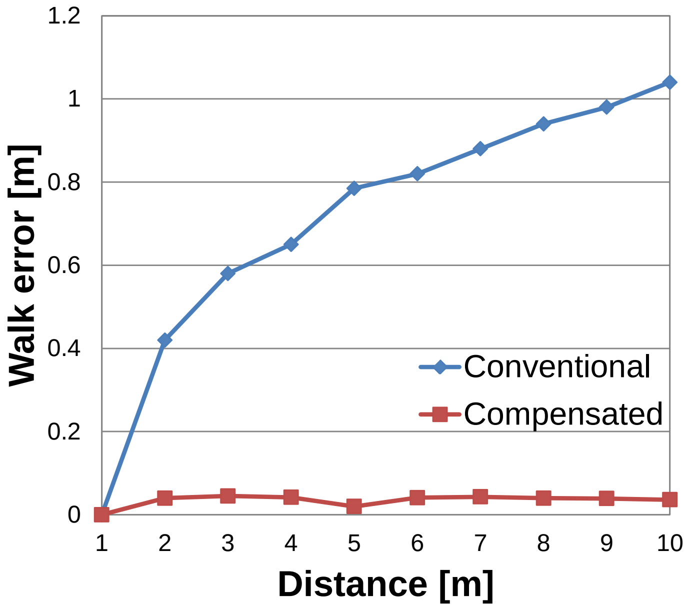

Fig. 12. The experimental results of proposed error correction technique

Fig. 12 shows the experimental results of the proposed and conventional error correction technique. Experimental results of the ToF LIDAR were measured from 1 m to 10 m with 1 m increments. The measurement distance was normalized to the 1 m point as reference.

Experimental results with the proposed signal processing technique show that the walk error is well corrected, while the experimental results with the conventional technique show an increasing walk error depending on the distance. The experimental results are also consistent with the simulation results. In the experiment, a constant error of about 0.05 m is generated after the walk error correction, but this can be solved by a simple offset compensation processing.

5. Conclusions and Further Works

In this paper, error correction technique of distance measurement for ToF LIDAR sensor is proposed. As the distance to the object increases, the conventional ToF sensor has a walk error due to change of the signal intensity. The proposed technique reduces the walk error by detecting the center point between the rising point and falling point of the received signal. In particular, the proposed technique is efficient due to the fact that it does not require additional bandwidth or hardware.

Future work may include multi-channel sensing technique and 3-dimensional point cloud reconstruction. The proposed error correction technique should provide an effective correction method in the field of LIDAR technique.

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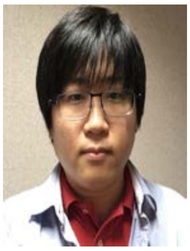

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