Design of Indirect Time-of-Flight Based Lidar for Precise Three-Dimensional Measurement Under Various Reflection Conditions

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***Abstract*—In the indirect TOF method, the distance traveled by light can be obtained on the basis of the phase difference between the reference signal and the measured signal. To utilize the lidar as a distance measurement sensor, measuring distance, resolution, and accuracy of the lidar should be considered most importantly. Optical system of the lidar should be optimally designed since a high intensity of measured signal increases the measuring distance and accuracy. Furthermore, electronic circuit design is also considered importantly in addition to the optical system design because the varying signal of the photoelectric current for the measuring distance can cause an inaccurate result of distance measurement. Different amplitudes of the signals due to different distance and object reflectivity cause additional electronic phase delays in the demodulation circuit in addition to the phase delay corresponding to the distance to be measured because of a constant gain bandwidth product limitation. In this study, optical system design, signal processing, and intensity control method are proposed, which can be applied to the lidar to achieve high resolution and linearity performance.**

Keywords- Time-of-flight; Lidar; Intensity control;

I. INTRODUCTION

Time-of-flight(TOF) based lidars are widely used in engineering fields such as robot navigation, automatic guided vehicle, and three-dimensional measurement applications in several industries because they have the advantages of non-contact, wide range, and high precision measurement [1].

Time-of-flight(TOF) methods are classified into direct and indirect TOF methods. For the distance measurement, the direct TOF method directly measures time interval between the emitted and detected signals, which are very short pulsed lights [2][3]. Thus, it requires techniques for generating the short pulsed light and time resolution of picoseconds for obtaining a millimeter resolution, which is hard to be implemented at a low cost. In the indirect TOF method, the distance can be determined by using a phase shift of a modulated light with either a sinusoidal signal or a pulsed signal [4][5]. Since the time interval can be obtained by the phase difference, it does not need techniques that the direct TOF method requires. Therefore, indirect TOF based sensors recently receive attention as 3D imaging systems due to its advantages of compactness and low cost with reasonable accuracy [1].

In the indirect TOF method, the distance traveled by light can be obtained on the basis of the phase difference between the reference signal and the measured signal. The modulation frequency of the signal is inversely proportional to the distance. Therefore, maximum measurable distance and distance resolution are determined by the modulation frequency. In other words, when a higher modulation frequency is used, a shorter measurable distance and a higher distance resolution can be obtained [6].

To utilize the lidar as a distance measurement sensor, measuring distance, resolution, and accuracy of the lidar should be considered most importantly. Optical system of the lidar should be optimally designed since a high intensity of measured signal increases the measuring distance and accuracy. Therefore, it is important to understand how the optical component layout affects the system performances. Optical component design for co-axial and bi-axial mechanisms are considered in this work. Furthermore, electronic circuit design is also considered importantly in addition to the optical system design because the varying signal of the photoelectric current for the measuring distance can cause an inaccurate result of distance measurement. When different colored object are measured, the intensities of the measured signals vary greatly even at the same distance. The different amplitudes of the signals due to different distance and object reflectivity cause additional electronic phase delays in the phase demodulation circuit in addition to the phase delay corresponding to the distance to be measured because of a constant gain bandwidth product limitation. Therefore, it is important to maintain the signal amplitude to be constant. In this paper, optical system design, electronic signal processing, and intensity control method are proposed, which can be applied to the lidar to achieve high resolution and linearity performance.

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II. OPERATING PRINCIPLE

In the indirect TOF method, the distance that light travels can be determined using the phase difference between the reference and measured signals, as shown in Fig. 1.

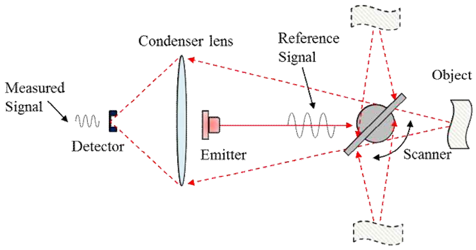


Figure 1. System configuration of the indirect TOF based lidar

When light travels a distance d, light reflected from an object is delayed by the phase, φ. The phase difference between the reference and measured signals is proportional to the distance traveled. When the modulated frequency of the reference signal is f, the distance d is obtained in terms of phase φ and f as

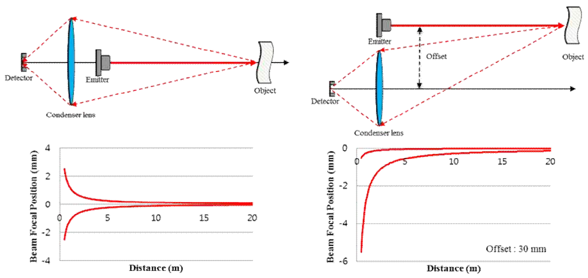
$$d = \frac{c}{2f} \bullet \frac{\varphi}{2\pi} \quad (1)$$

where c (=3 x 10^8 m/s) is the speed of light. According to Eq. (1), the distance resolution is related to the modulated frequency. Hence, the higher the modulated frequency used, the better the distance resolution that can be obtained.

III. THE INDIRECT TOF BASED LIDAR DEVELOPED

A. *Optical system*

To have a high accuracy of distance using the lidar, a high intensity measured signal should be received because the intensity determines the signal to noise ratio. Hence, optical design is one of the most important issues to be considered for design of the lidar for a given mechanical and electronic specifications. However, expanding the size of optical components to obtain high intensity is a limited way due to compact system configuration and various applications. In this section, optical system designs are presented according to detection range and application area.



(a) (b)

Figure 2. Optical system layouts of (a) the co-axial and (b) bi-axial types

Typically, there are two types of optical systems, co-axial and bi-axial types. Figure 2 shows the configuration of the co-axial and bi-axial type optical systems. In case of the co-axial type, all optical components, the detector, the condenser lens and the emitter, are on the same optical axis. Figure 2 also shows the results of the ray tracing of a detected beam spot at the focal position [7]. A Ø 50 condenser lens with a focal length of 50 mm was used. As shown in Fig. 2 (a), from the short range to the long range, all reflected signals can be focused on the detector. Hence, the co-axial type optical system is usually utilized with a mirror scanner for 3D applications.

However, the emitter part can make a shade to the focal plane by blocking the center of the condenser lens. Thus, optical power loss is caused by the shadow effect, which decreases the signal to noise ratio and results in a low distance accuracy. In addition, the back beam from the scanning mirror causes an optical crosstalk problem. When there are crosstalk problems, the sensor performance is easily deteriorated. For example, when the reflected signal from the object is weaker than the optical crosstalk signal from the scanning mirror, the distance cannot be obtained. Therefore, it is important to design the emitter part as small as possible without the optical crosstalk problem.

In order to solve the shadow effect of the coaxial type, a bi-axial type optical system is considered. As shown in Fig. 2 (b), the emitter part is located next to the condenser lens. As a result, the problem of intensity loss due to the shadow effect is removed. However, the returning beams are focused not in the detector center in short ranges as shown in Fig. 2 (b) because the condenser lens is not aligned with the emitter. The deviation from the center is more severe when a shorter distance is measured. Therefore, a bigger detector area is required to use for a short distance measurement. This bi-axial type optical system is more suitable for long distance detection since it can receive sufficient reflected beam intensity compared to the coaxial type optical system. However, it has a disadvantage that its structure becomes large in size when a rotating scanner should be used for 2D and 3D applications because the mirror scanner should be at least twice larger than that used in the co-axial type due to the fact that the mirror scanner should cover a cross section areas of the emitted part and condenser lens as well. As an alternative, a gimbal type scanner should be used to move the entire optical system for scanning, which makes the system heavy and large. Figure 3 shows the distance accuracy, obtained from each configuration. The experiment was performed with 40MHz modulation frequency, Ø 50 condenser lens, and a white object. The bi-axial type optical system, which has no intensity loss, is advantageous for long range detection. However, when using the bi-axial type optical system, the short range detection is difficult, and the system becomes complicated. Hence, it is necessary to select an appropriate optical system according to detection range and application area.

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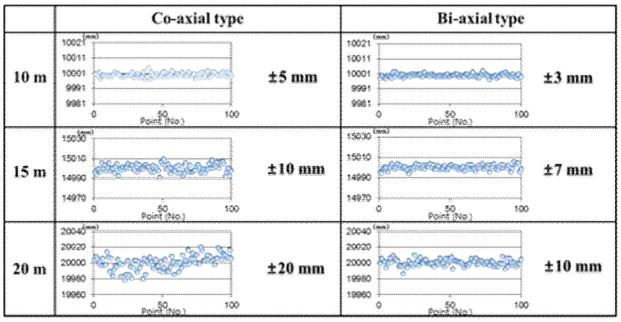

Figure 3. Distance accuracy according to optical system types

B. Demodulation processing

If assuming that a laser diode is modulated with a frequency of ω_{sig} and an amplitude of V_r. A signal emitted from the laser diode, V_{ref} can then be described as

$$V_{ref} = V_r \sin \omega_{sig} t. \quad (2)$$

A signal which is reflected from an arbitrary distance and measured by the photodetector, V_{mea} becomes

$$V_{mea} = \tilde{V}_m \sin (\omega_{sig} t + \varphi_d). \quad (3)$$

Here, φ_d represents the phase difference, which includes the distance information. In addition, $\tilde{V}_m$ is the amplitude of the measured signal, which varies due to the surface reflectivity and measured distance. Thus, using Eq. (1), measured distance can be determined by means of phase difference φ_d. Since high frequency signal gives better resolution according to Eq. (1), usually highly modulated frequency is used as ω_{sig} for high performance of the lidar.

Several demodulation methods have been proposed to obtain φ_d, such as a direct in-phase and quadrature demodulation [8], under-sampling [9], and multiple step phase demodulation methods [10]. In this study, a multiple-step phase demodulation method is used. In this method, another reference signal is needed to shift the frequency ω_{sig} to an intermediate frequency, ω_i. A demodulation reference signal has an amplitude of V_d and a slightly different modulation frequency, ω_d. Then, the demodulation reference signal is described as

$$V_{dem} = V_d \sin \omega_d t. \quad (4)$$

By mixing the measured signal and the demodulation reference signal, the frequency-shifted signal V_i is obtained as

$$V_i = \tilde{V}_m \sin (\omega_{sig} t + \varphi_d) \bullet V_d \sin \omega_d t$$

$$= \frac{1}{2} \tilde{V}_m V_d \cos(\omega_i t + \varphi_d) - \frac{1}{2} \tilde{V}_m V_d \cos(\omega_{sig} t + \omega_d t + \varphi_d). \quad (5)$$

Where $\omega_i = \omega_{sig} - \omega_d$. The second term of the second row in Eq. (5) can be removed by using a low pass filter. Consequently, the filtered output is represented as

$$(V_i)_F = \frac{1}{2} \tilde{V}_m V_d \cos (\omega_i t + \varphi_d) \quad (6)$$

In addition, a reference signal for obtaining φ_d can be defined as $(V_i)_R = \frac{1}{2} V_r V_d \cos (\omega_i t)$ by using the same processing. Then, the phase difference can be determined by means of comparison of $(V_i)_F$ with $(V_i)_R$.

C. Phase detection with the time counting method

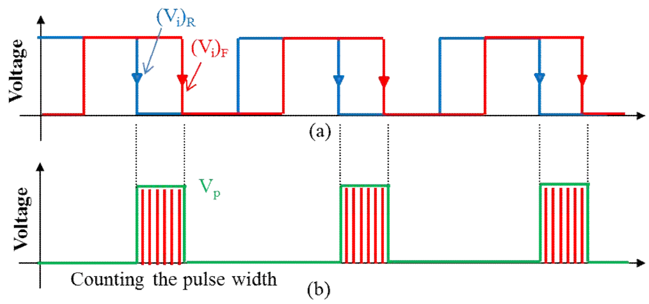

Figure 4. (a) $(Vi)_R$ and $(Vi)_F$ (b) Time counting processing of V_P

The obtained phase difference, φ_d should be changed to analog or digital signals to determine the measured distance via signal processing. The reference and measured signals are first converted to square waves as shown in Fig. 4 (a). Then, a new signal V_p, which is phase difference of two signals, can be obtained by commercial phase detectors. In this study, we used the time counting method[6] because the phase difference can be directly obtained as digital values without the noise effect. In the time counting method, converted square waves are considered as digital signals. In addition, pulse width of V_p is counted by a digital time counting circuit with a high frequency signal as shown Fig. 4 (b). Since the pulse width of V_p is directly measured by a digital processor, the phase difference can be converted to a digital signal without other processing. Moreover, it is not affected by pulse noises because it only measures time. Therefore, the time-counting method is capable of high-resolution and high-speed performance.

D. Intensity control

In the demodulation process for obtaining φ_d by using an analog circuit, many electronic components are implemented for mixing, filtering, amplification, and other types of

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processing. Since the amplitude of measured signal, $\tilde{V}_m$ has a wide dynamic range according to distance changes and varying object reflectivity, an additional electronic phase delay $\varphi'(\tilde{V}_m)$ is generated in the demodulation processing. In other words, distance errors are caused due to distance changes and varying object reflectivity.

There are primarily two reasons for the additional phase delay. The first reason is due to gain bandwidth product limitation of electronic components because $\tilde{V}_m$ has different voltage inputs according to different distances and object reflectivity. The second reason is a walk error. When measured signal is converted to a square wave digitally by comparing its amplitude with fixed positive and negative threshold values, additional phase delay, $\varphi'(\tilde{V}_m)$ is generated according to the varying amplitude in addition to the phase delay corresponding to the distance to be measured. Hence, the real demodulated signal, $(V_i)'_{\mathrm{F}}$ is

$$(V_i)'_{\mathrm{F}} = \frac{1}{2}\tilde{V}_m V_d \cos(\omega_i t + \varphi_d + \varphi'(\tilde{V}_m)) \qquad (7)$$

From the Eq. (7), we know that the phase delayof the measured distance becomes different at even the same distance when the reflectivity varies. It is a problem to be considered for the linearity performance of the lidar since a phase error of 1° signifies a 10 mm distance error when 40 MHz frequency is used for the modulation signal, as calculated from Eq. (1). Thus, the electronic phase delay, which causes distance errors must be reduced as much as possible.

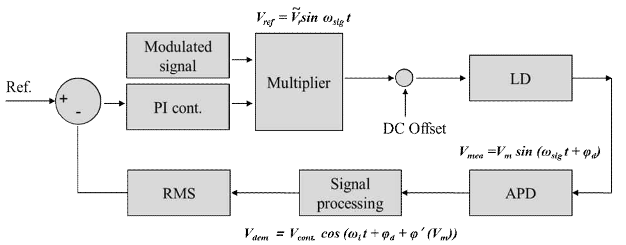


Figure 5. A block diagram of the intensity control method

To reduce the electronic phase delay, an intensity control method is proposed as shown in Fig. 5 [11]. Since the cause of distance errors is basically the varying amplitude of measured signal, in the proposed method, the amplitude of the modulated signal, V_r is controlled by means of a feedback signal to maintain the amplitude of measured signal to be constant. When the amplitude of measured signal reflected from an object becomes smaller than the reference signal of the controller, V_r is increased via the feedback control in order to keep the amplitude of the measured signal constant, and vice versa. Therefore, a constant amplitude, $V_{cont.}$ can be obtained at the detector regardless of the distance change and object reflectivity.

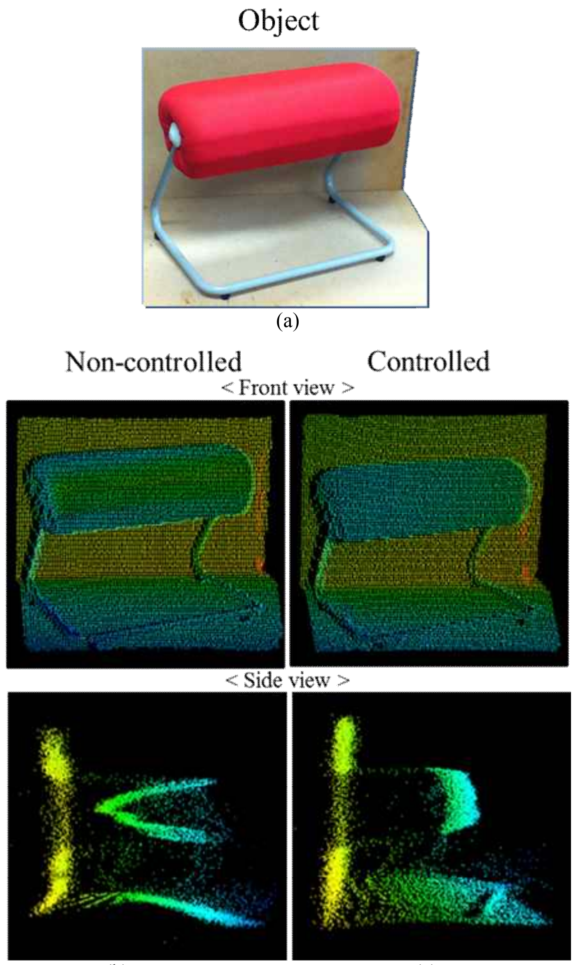
The demodulated signal in the proposed method is then represented as

$$\{(V_i)'_{\mathrm{F}}\}_{\mathrm{controlled}} = V_{cont.} \cos(\omega_i t + \varphi_d + \varphi'(V_m)) \qquad (8)$$

As indicated in Eq. (8), although a phase delay, $\varphi'(V_m)$ is still generated during the demodulation processing, it is constant. Thus, the phase delay does not affect the measured distance because it can be eliminated by shifting the phase of the reference signal, using a known distance.

IV. EXPERIMENTAL RESULTS

For the verification of the performance of the intensity control method, an object located at 3 m was measured with the modulation signal of 40 MHz as shown in Fig. 6.



(b) (c)

Figure 6. (a) A measured object (b) the non-contolled scanning result (c) the controlled scanning result

Clear difference between non-controlled and controlled results are appeared at short distance because deviation of measured intensity becomes larger when the measured distance get shorter based on the inverse square law of distance[1]. Since the measured intensity also changes according to the laser beam incident angle on the object, the non-controlled scanning result shows shape distortion due to distance errors, caused by the varying amplitude of measured signal, even though the object color is the same. On the other hand, the controlled scanning result shows that the object was scanned without the shape distortion.

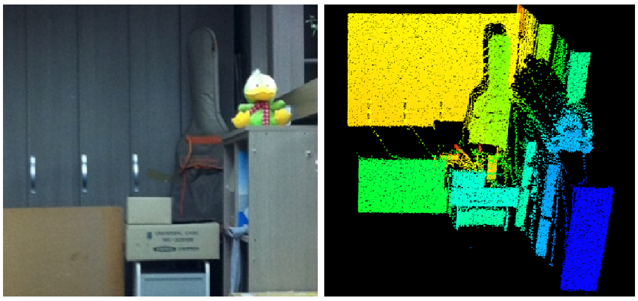


Figure 7. Scanning result for 3D measurement application

For the verification of 3D measurement application, various objects were scanned with the modulation frequency of 20 MHz and a condenser lens of Ø 50 as shown in Fig. 7 In addition, intensity control was applied for the precise measurement. As a result, the scanning results shows that objects were measured without shape distortions although scanned objects have different colors and diverse shapes.

V. CONCLUSION

For precise 3D measurement using the lidar, accuracy, resolution and linearity performances should be considered. In this study, optical system design, signal processing and intensity control method were proposed, which can be applied to the indirect TOF based lidar for high accuracy, resolution and linearity performance.

Optical system is one of the most important factors for the design of the lidar. In this study, appropriate optical systems were considered according to demanded detection range and distance resolution as shown in experimental results.

Demodulation processing and phase detection methods were presented for highly accurate distance measurement. Using the multiple step phase demodulation method, the high frequency modulation signal can be shifted to lower frequency bandwidth. It makes the signal processing easier, and noises are effectively removed during this processing. In the time counting method, analog signals, which have the phase information, can be directly inputted as digital signals. Besides, it is advantageous for noise effect because it only measures time interval corresponding to the phase difference. Therefore, these methods are reasonable for development of high performance lidars at a low price.

Intensity control method was proposed to resolve non-linearity problem caused by varying distance and object reflectivity. As a result, distance errors were significantly reduced, and we could obtain the exact 3D images without shape distortions. The proposed methods are expected to be utilized for other optical sensors as well as lidar sensors.

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