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# High resolution three-dimensional flash LIDAR system using a polarization modulating Pockels cell and a micro-polarizer CCD camera

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**Abstract**: An innovative flash LIDAR (light detection and ranging) system with high spatial resolution and high range precision is proposed in this paper. The proposed system consists of a polarization modulating Pockels cell (PMPC) and a micro-polarizer CCD camera (MCCD). The Pockels cell changes its polarization state with respect to time after a laser pulse is emitted from the system. The polarization state of the laser-return pulse depends on the arrival time. The MCCD measures the intensity of the returning laser pulse to calculate the polarization state, which gives the range. A spatial resolution and range precision of 0.12 mrad and 5.2 mm at 16 m were obtained, respectively, in this experiment.

**OCIS codes:** (280.0280) Remote sensing and sensors; (280.3640) Lidar.

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## 1. Introduction

Three-dimensional imaging LIDAR systems obtain range information of an interesting target, and use that data to generate 3D images. Today, they are employed in a variety of applications. Using the data collected by LIDAR systems, it’s possible to perform terrestrial landscape mapping, automatic target recognition and identification, autonomous planetary landings, and so on [1–3]. To successfully perform various missions, both high spatial resolution and range precision are needed, and the system also often needs to obtain high resolution 3D images in a relatively short period of time.

There are two methods that LIDAR systems typically employ to obtain 3D images, a scanning type and a flash type [4]. The scanning LIDAR system uses one or a few detector pixels and a scanner to acquire 3D images. Laser pulses are sent out from a laser system, and each laser pulse is directed to a different point on the target by a scanner; then its time-of-flight (TOF) is obtained for each target point, using a single detector pixel. The scanning LIDAR system requires a significant time overhead to acquire a high resolution 3D image, because the system needs to scan each point. This means the system requires increasingly more time to take measurements, to obtain ever higher resolution 3D images.

On the other hand, a flash LIDAR system utilizes a 2D array detector and a single laser pulse, illuminating the entire interesting scene to acquire 3D images. To acquire real-time images of moving targets, it is necessary to obtain the 3D image with a single laser pulse. Flash LIDAR systems can obtain images with just a single laser pulse, which makes it possible for them to obtain 3D images of moving targets. Moreover, 3D images can be acquired even when the LIDAR system or the target are in motion. Only the flash LIDAR system can meet this requirement [5].

Generally, two representative types of avalanche photodiode (APD) detectors are used in flash LIDAR systems. One detector is a linear mode APD focal plane array (FPA) with 128 x 128 pixel arrays [6]. The other detector is a Geiger mode APD FPA with 256 x 256 pixel arrays [7]. Due to the array size, when using these commercial sensors the spatial resolution or field of view (FOV) is limited. To acquire large scenes or high spatial resolution 3D images, commercial systems may need an additional scanner. In addition, each pixel requires its own high bandwidth timing circuit to measure the TOF.

The range precision of the flash LIDAR system is limited by several factors, including the pulse width of the laser, the bandwidth of the detector, the temporal resolution of the timing circuit, shot noise, the timing jitters generated by electronics, and so on [8]. These factors also limit the ability to improve range precision. Typically, the range precision of a commercial flash LIDAR system is several centimeters [9–11]. Increasing the number of pixels in the APD array with a higher performance detector and timing circuit is technically challenging.

In the early 90’s the Air Force had a project called LIMARS, Laser Imaging and Ranging System [12]. Two cameras and a polarization discriminator were used to detect the polarization state and obtain range information. Two companies, TetraVue and General Atomics, have researched and developed flash LIDAR systems based on this polarization method [13]. TetraVue provides a high frame rate for 3D images as well as a high range precision of several millimeters. CMOS is used for detecting the polarization state, so that high spatial resolution 3D images can be acquired. However, this system requires two cameras and a polarization discriminator to detect the polarization state, and it is difficult to align them so that the pixels of both cameras are looking at the same point. Furthermore, a system that uses two cameras and a polarization discriminator is complicated and bulky.

A high range precision 3D imaging LIDAR system using a Pockels cell and a quadrant photodiode (QPD) was also previously developed and demonstrated [14]. The Pockels cell changes the polarization state as a function of time and the QPD, which is aligned with micro-polarizers, measures the polarization state to acquire range information. The QPD is only capable of measuring the range of one point at a time, so that a scanner is necessary to acquire 3D images in this system.

As noted, some applications require 3D images which have both high spatial resolution and range precision, and to address these requirements, we propose an innovative flash LIDAR system which can produce high spatial resolution 3D images with high range precision. The proposed flash LIDAR system uses a PMPC and a MCCD which has 1024 x 1024 pixels. The large number of pixels in the MCCD can provide high resolution 3D images, and in this study it was shown that the PMPC technique can achieve a high range precision of 5.2 mm.

## 2. Principle of the technique

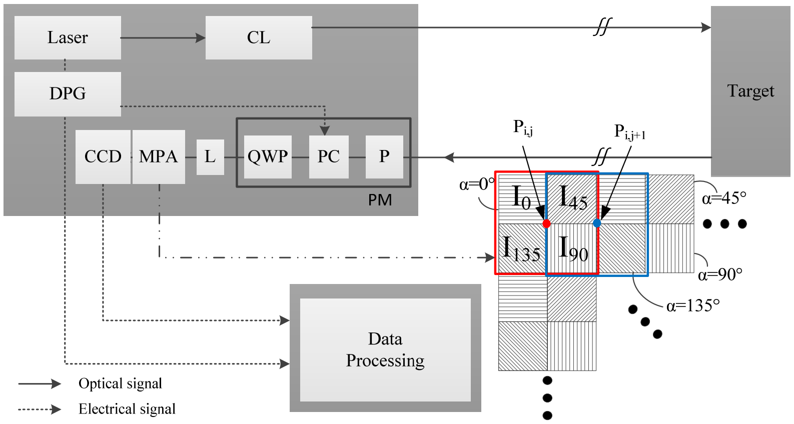
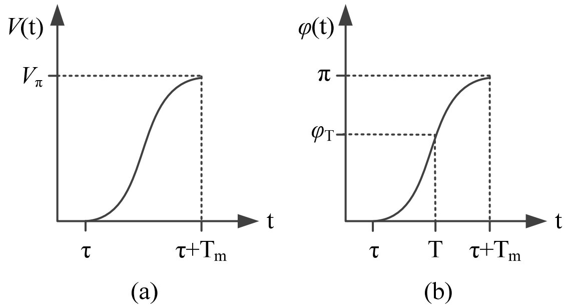


Fig. 1. A schematic diagram of the flash LIDAR system (CL: collimation lenses, DPG: delay pulse generator, P: linear polarizer, PC: Pockels cell, QWP: quarter-wave plate, L: lens, PM: polarization modulator, MPA: micro-polarizer array, α: angle of micro-polarizer, $P_{i,j}$: point i,j).



(a) (b)

Fig. 2. Voltage applied to a Pockels cell, $V(t)$, and measured phase retardation, $\varphi(t)$ (τ: delay time, $T_m$: modulation time, $V_\pi$: half-wave voltage of the Pockels cell, $\varphi_T$: measured polarization state, T: calculated TOF, t: time).

A schematic diagram of the proposed flash LIDAR system is shown in Fig. 1. A laser pulse from the laser passes through the collimation lenses, triggering the delay pulse generator (DPG). Then, DPG triggers the Pockels cell (PC) at a certain delay time (τ), and a time varying voltage, $V(t)$, starts to be applied to the PC during the modulation time, $T_m$. Since the applied voltage changes in time, as shown in Fig. 2(a), the phase retardation of the PC is also a function of time, as shown in Fig. 2(b), because the phase retardation is proportional to the applied voltage. The phase retardation can be expressed as

$$\varphi(t) = \frac{2\pi n_0^{\,3} r_{63} V(t)}{\lambda} = \frac{2V(t)}{V_\pi}, \tag{1}$$

where $\varphi(t)$ is the phase retardation, $n_0$ is the ordinary refractive index, $r_{63}$ is the electro-optic coefficient of the PC medium, $V(t)$ is the applied voltage to the PC, $\lambda$ is the wavelength of the laser, and $V_\pi$ is the half-wave voltage of the PC. The backscattered pulse from the target is detected by the MCCD through the polarization modulator (PM), consisting of a linear polarizer, a PC, and a quarter-wave plate. When the laser-return pulse travels along the PM, it experiences phase retardation $\varphi(t)$ and its polarization state is rotated by $\varphi_T$, which corresponds to its TOF, T, as shown in Fig. 2(b). Because the relationship between the phase retardation and time is definitely determined, TOF can be obtained from the polarization rotation angle of the laser-return pulse, $\varphi(t)$.

A MCCD (Polarcam, 4D technology) with a 1024 x 1024 CCD array was used in this work. The micro-polarizer array is composed of sets of four linear polarizers whose polarization axes are 0°, 45°, 90° and 135°, as shown in Fig. 1. The MCCD measures the intensity of the laser pulse through the micro-polarizer array. Using the values of the four intensities, the phase retardation can be calculated as

$$\varphi(t) = \tan^{-1}\left(\frac{I_{45} - I_{135}}{I_{90} - I_0}\right), \tag{2}$$

where $I_0$, $I_{45}$, $I_{90}$, and $I_{135}$ are the intensities after the micro-polarizers whose axes are 0°, 45°, 90° and 135°, respectively.

The four intensities in the red square shown in Fig. 1 can be used to calculate the phase retardation of $P_{i,j}$ (point i,j), and the corresponding range can be obtained from this value. The range of the $P_{i,j+1}$ (point i,j + 1) is calculated with the four intensities in the blue square in Fig. 1. Since the pixel pitch of the MCCD is smaller than that of commercial APD arrays, and the number of pixels of the MCCD is much greater than those of commercial APD arrays, higher resolution 3D images can be obtained with the MCCD.

When the DPG triggers the PC, the voltage applied to the PC begins to increase from zero voltage to the half-wave voltage. Typically, attaining the half-wave voltage takes a few nanoseconds. During this modulation time, $T_m$, the PM changes the phase retardation value in time. Thus, the $T_m$ decides the length of the range gate which represents the measurable section in one measurement. The length of the measurable section can be adjusted by changing the value of a resistor or a capacitor in the electric circuit of the PC. In the proposed system the length of the range gate is about 1.5 m, and the LIDAR system begins to obtain measurements at a certain delay time (τ) after the laser pulse is emitted. That is, objects in the range of 1.5 m can be detected in one measurement and the starting point of the range gate is controlled depending on the location of the interesting target.

## 3. Experimental setup and results

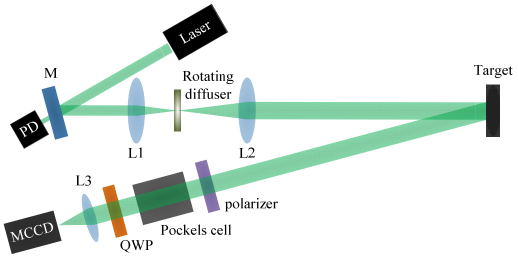
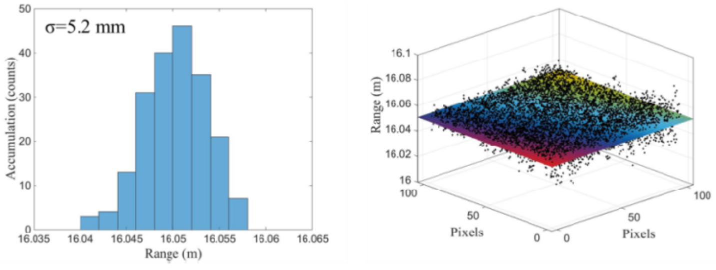


Fig. 3. Optical layout (M: mirror, L: lens, PD: photodiode, QWP: quarter-wave plate, MCCD: micro-polarizer CCD camera).

Figure 3 shows a schematic diagram of the flash LIDAR system. The laser is based on a diode side-pumped Nd:YAG regenerative amplifier which is seeded by a sub nanosecond output pulse from a hybrid seeding laser at 1064 nm. The fundamental wavelength at 1064 nm is converted to the second harmonic wavelength at 532 nm through the BBO crystal. Laser pulses with a width of 900 ps are transmitted, and the energy per pulse is 3.5 μJ at 1 kHz. The leak beam through the mirror is collected by the photodiode (PD) to generate the electrical start signal. The start signal from the PD is employed as the external trigger source of the DPG. Then, the DPG activates the PC after a certain delay time, τ. The laser pulse is collimated by lenses L1 and L2. The rotating diffuser at the focal point of the collimating lens system is used for laser speckle reduction. The laser beam is directed to the target and reflected. The backscattered light from the target is detected by the MCCD through the PM (linear polarizer, PC, and QWP). For this study, a FastPulse Technology, Inc. Q1059PSG-532 PC was used. The number of pixels in the MCCD array (Polarcam, 4D technology) is 1024 x 1024.



(a) (b)

Fig. 4. The histogram of range precision and 3D image of the flat target with plane fitting.

To check the range precision, a flat object was located at 16 m. Range measurement using the proposed system was performed 200 times. The range of each frame was obtained over 100 x 100 pixels. The statistical range distribution of one pixel was analyzed in the histogram in Fig. 4(a). An averaged standard deviation is

$$\sigma_{avg} = \frac{1}{p}\left( \sum_{j=1}^{p} \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i^j - \overline{x}_j)^2} \right), \tag{3}$$

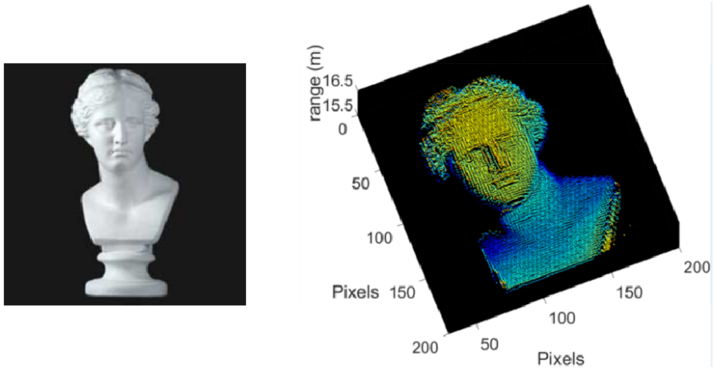
where $\sigma_{avg}$ is the averaged standard deviation, $p$ is the number of pixels (100 x 100 pixels), $n$ is the number of frames (200 shots), $\overline{x}_j$ is the averaged range of the j$^{th}$ pixel, $x_i^j$ is the measured range of the j$^{th}$ pixel of the i$^{th}$ frame. The averaged standard deviation of range of 100 x 100 pixels is 5.2 mm (approximately 35 ps in the time domain). This standard deviation in range is caused by jitters in timing. One major jittering source is the timing jitter of the output signal of the DPG used to trigger the PC (< 100 ps in a datasheet of the DPG) Compared to a commercial flash LIDAR system, the effect of the timing jitters caused by electronics and shot noise is small, since the MCCD only measures the intensity of the laser pulse, rather than TOF. In addition, if the $T_m$ of the PM is reduced while the amount of voltage change is maintained to be the half wave voltage of the PC, the slope of the function between the polarization state and time is increased. The steeper the slope becomes, the higher the range precision that is acquired. Figure 4(b) shows a 3D image of the flat target with plane fitting. The RMS error is calculated as

$$RMS = \sqrt{\frac{1}{p}\sum_{i=1}^{p}(x_i - m_i)^2}, \tag{4}$$

where $x_i$ is the measured range of the i$^{th}$ pixel, $m_i$ is calculated range of the i$^{th}$ pixel using the fitting plane. The RMS error of 100 x 100 pixels within a single shot is 4.8 mm.

Using the proposed flash LIDAR system, a 3D image of 200 x 200 pixels was acquired. The spatial resolution of the proposed system is 0.12 mrad. The target was a Venus plaster figure, as shown is Fig. 5(a). The size of the target was approximately 60 cm x 30 cm. Figure 5(b) shows the 3D image obtained using the proposed flash LIDAR system. The colors of the pixels are different depending on the range.

Calculating the distance using the intensities of 4 adjacent pixels results in one representative value for those 4 individual pixels. When an edge in the image is detected within the 4 adjacent pixels, the distance can be distorted owing to angular distribution. Consequently, even though most of the smooth parts in Fig. 5 are clearly shown, a few edges are distorted.



(a) (b)

Fig. 5. 2D image of the target and 3D image of the target.

## 4. Summary

Spatial resolution and range precision are important parameters for the flash LIDAR system. In this paper, we proposed and successfully demonstrated an innovative flash LIDAR system composed of a PMPC and a MCCD. As the polarization state of the PM changes in time, the range can be obtained from the phase retardation of the laser-return pulse, as calculated from the measured intensities.

To obtain higher spatial resolution 3D images, an MCCD typically has millions of pixels, as compared with APD arrays. Increasing the number of pixels of an APD array is technically challenging. Moreover, in a commercial flash LIDAR system, a high bandwidth detector and timing circuit are vital for high range precision. However, these components are unnecessary in the proposed flash LIDAR system since the proposed system only measures the intensity of the laser instead of TOF. This means that any sensor which is capable of measuring intensity, such as a CCD array or CMOS array, can acquire 3D images without timing circuits. Furthermore, the range precision can be further enhanced by controlling the rise time of the PC.

The averaged standard deviation and RMS error of the proposed system were found to be 5.2 mm and 4.8 mm, respectively, and its spatial resolution was 0.12 mrad. It is expected that the proposed flash LIDAR system will be an alternative method for various applications which need high spatial resolution and high range precision.

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