High-resolution three-dimensional laser radar with static unitary detector

Bongki Mheen, Jea-Sik Shim, Myoung Sook Oh, Jungho Song, Minhyup Song, Gyu Dong Choi, Hongsoek Seo and Yong-Hwan Kwon

A new simple method to obtain real-time high-resolution three-dimensional (3D) images based on a static unitary detector (STUD) is reported. The STUD consists of a common bias network, a partitioned photodetector, a preamplifier array and a combiner, which makes it possible to easily increase the effective photo-detection area for a wider 3D image acquisition without affecting the ability to detect short laser pulses for high-resolution 3D images. From an implemented experimental prototype based on a STUD, the intensity and 3D images with a very high resolution (320 pixels × 240 pixels) were obtained. The achieved range resolution and the spatial resolution of remote 3D objects at 50 m were measured to be <0.3 and 1.1 cm, respectively.

Introduction: Thanks to the shorter wavelength of light, compared with sonar or microwave, three-dimensional (3D) real-time time-of-flight (TOF) laser detection and ranging (LADAR) sensors have been deployed in various applications such as autonomous car navigation, remote sensing, robot vision, surface mapping for buildings and scenes where high 3D resolution is of prime importance [1]. However, the real-time acquisition of 3D images needs to process all reflected TOF laser signals from every direction for a region of interest (ROI) in real-time. One solution for this is a rotational motor-based method where each laser pulse from a vertical laser diode (LD) array is illuminated on the targets, and its reflection is detected independently in each channel of a detector array, and then the whole module of this vertical LD and detector array is mechanically rotated so that the next detection is conducted on the horizontally shifted position in a sequence [2]. This method provides a merit of 360° 3D image acquisitions, but the resolution in a vertical direction is restricted to the number of channels which cannot be increased significantly due to the size of the rotating sense head and the cost of the optical alignments of each channel.

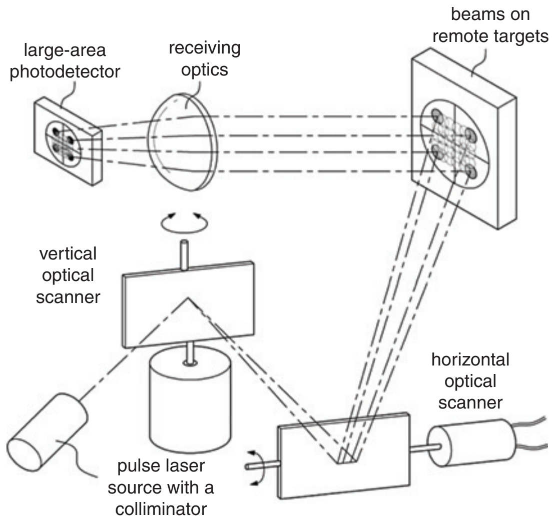

Fig. 1 *3D laser radar (LADAR) with large-area photodetector*

The other solution for real-time 3D images is to use a focal-plane-array (FPA) of the photodetectors and a readout IC (ROIC) [3]. A very high power (more than a peak power of 1 MW) laser pulse is illuminated over all the regions of a ROI at the same time and the reflected laser pulse signal at each target position is differently arrived at in each detector in a 2D format of an FPA. Hence, every detector and its corresponding circuits in an ROIC within a pixel need to be operated independently, whereas the size of one pixel should be strictly reduced around <100 μm for a higher 3D resolution. This method provides a unique merit of a flash image which means that it can detect the 3D image of a very fast object, since the used pulse width is normally <10 ns. However, the way to increase a resolution in this method is also restricted by the pixel number of the FPA and the ROIC, which makes this solution very expensive for a higher 3D resolution.

Proposed method: In this Letter, a new simple method to obtain real-time high-resolution 3D images is proposed. In this method, instead of using the rotational motion or the FPA array, a large-area photodetector is mainly utilised. All the required components for this configuration are shown in Fig. 1, consisting of a large-area photodetector to detect the returned pulse laser signals, receiving optics to collect returned optical signals to the detector, two high-speed optical scanners to spread laser pulses over a ROI and a master oscillator power amplifier (MOPA) laser module with a collimator to generate collimated laser pulses. Normally, since the increase of the photodetector area decreases its bandwidth, it needs to use a long laser pulse width in the TOF LADAR, resulting in a deteriorated range resolution in the final 3D images.

To make it possible to easily increase the effective photosensitive area of a large-area photodetector without any reduction in its bandwidth, a new technique, using a static unitary detector (STUD), is proposed. As shown in Fig. 2, the STUD consists of a bias network to provide a proper bias voltage to all the detectors, partitioned photosensitive cells to collect incident photons, preamplifiers to amplify the received signals of each cell independently and a signal combiner to sum all the outputs of each preamplifier. Since each cell has its own cascading preamplifier, each of the partitioned photodetectors can be independently operated, and does not affect each other, which makes its bandwidth unchanged. Therefore, it virtually has no limitation to increase the number of cells, and high-resolution 3D images acquisition on a large ROI is possible even with short laser pulses, which is inevitable for a higher 3D image quality.

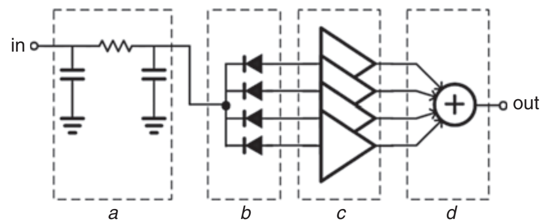

Fig. 2 *Constituent parts of STUD for large-area photodetector*
a Bias network which provides bias voltage to all photodiodes
b Multiple partitioned photosensitive cells in large-area photodiode
c Dedicated preamplifiers for each cell
d Summation network for all outputs of preamplifiers

This proposed method provides several merits. Among them, one is a cost-effective method to obtain 3D images, because there is no individual signal processing chain of each pixel or channel in aforementioned methods, but it has only one signal processing chain for a unitary signal port ('out' in Fig. 2) in a static sensor head. The other is the laser power efficiency. Since the proposed STUD-based method can illuminate one collimated pulse laser beam at a time in a specific direction, the required power level is not as high as the FPA-based method (normally the optical peak power of several MW). On the other hand, from the viewpoint of a photodetector, it does not need microlenses implementation over each partitioned photosensitive cell to have a higher signal-to-noise ratio (SNR) for each cell, because the detected intensity and the distance for each direction over a ROI are measured sequentially and, hence, it is not important to determine which partitioned photodetector detects the returned laser pulse signal. It is a quite competitive advantage over its counterpart of the FPA-based method where there is an effort to have a microlens over each small pixel for the higher fill-factor of pixels and a higher SNR.

Results: Even though the proposed STUD deals with multiple partitioned cells in a large-area photodetector, the operation scheme is exactly the same as the one single large-area detector, since each channel is isolated and independently operated by the following preamplifiers. In these experiments, we used a 2.2 ns laser pulse at a wavelength of 1550 nm from an MOPA laser module which provides a sufficiently high peak power up to 10 kW and a higher repetition rate over 200 kHz. For the partitioned photosensitive cells, a customised InGaAs avalanche photodiode (APD) was designed and fabricated to detect the returned laser at an eye-safe wavelength of 1550 nm. A required bias voltage (50.5 V) of the photosensitive APD cells was applied at the 'in' port of Fig. 2 through a proper power supply filter. According to the working principle of the STUD laser radar, the illuminated spot is changed in time by the controlled Galvanometer-based optical scanners, and the position of the photons arriving at the photodetector is also changed. Fig. 3 shows the accumulated 100-time measurements of the reflected laser signals on two positions in a STUD to understand the quality of the returned laser signals on each illumination position. At a given experimental setup, the root-mean-square noise voltages and the SNR of received laser signals were measured at the peak position of the averaged signal, and the jitter noise which determined the orange-feel effect (roughness of the obtained 3D image surface) were measured at a 50% threshold of the amplitude, all of which are summarised in Table 1. Even though the fluctuation noise was shown to be increased twice but detection will not be affected in the 3D images thanks to the sufficient SNR by the adopted high-power MOPA laser module, and the more important jitter is slightly changed, but sustained <0.12 ns in both the cases, which means the range resolution can be kept <1.8 mm over any illumined spot within a STUD, resulting in a high quality of the obtained 3D images.

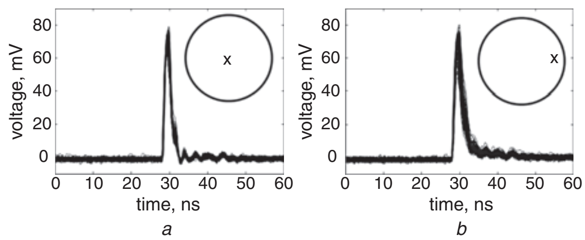

Fig. 3 *Measured received pulse laser signals with different illuminated positions in STUD*

a Centre
b Edge (100 μm right position from centre)

Table 1: Measured signal quality of returned laser pulses in STUD

Name	Signal SNR (dB)	Amplitude noise (mV)	Jitter noise (ns)
Centre	44.15	3.43	0.11
Edge	43.13	6.31	0.12

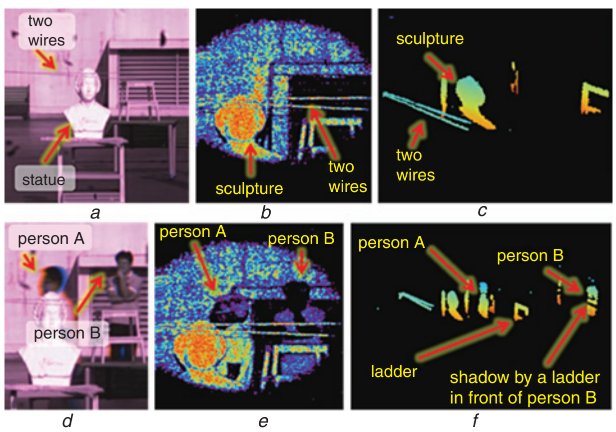

Fig. 4 *Obtained images from implemented prototype using STUD laser radar: CCD images; intensity images; 3D images*

a and *d* Obtained images from implemented prototype using STUD laser radar: CCD images
b and *e* Intensity images
c and *f* 3D images

From the implemented experimental prototype using the STUD method, the normal vision images from a commercial CCD camera, obtained intensity and 3D images from the implemented prototype for remote objects are shown in Fig. 4. Several objects between two narrow wires with a diameter of 3.8 mm and a wall were located between 20 and 50 m for a test. The intensity image (Figs. 4*b* and *e*) and the 3D images (Figs. 4*c* and *f*) have a spatial resolution of 320 pixels × 420 pixels and the two narrow wires in the scene are shown clearly in both intensity and 3D images, which proves that the proposed STUD method successfully provides high-resolution 3D images. The achieved range resolution and the partial resolution of remote 3D objects at 50 m were measured to be <0.3 and 1.1 cm, respectively.

Conclusion: Based on the proposed STUD-based method, a real-time 3D TOF LADAR system prototype was testified by using all the necessary components, including a STUD, a fibre-based MOPA laser module, two optical scanners with a collimator and receiving optics. It showed that the spatial resolution and the range resolution are <0.3 and 1.1 cm, respectively, at a very high resolution (320 × 240) of 3D images for given remote objects at 50 m, without any rotation or any FPA. Consequently, the proposed STUD-based method is proved to provide an efficient way to obtain high-resolution 3D images, which makes the solution suitable for applications which require high resolution such as in automobile and surveillance applications.

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One or more of the Figures in this Letter are available in colour online.

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