Development and analysis of a photon-counting three-dimensional imaging laser detection and ranging (LADAR) system

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In this paper, a photon-counting three-dimensional imaging laser detection and ranging (LADAR) system that uses a Geiger-mode avalanche photodiode (GAPD) of relatively short dead time (45 ns) is described. A passively Q-switched microchip laser is used as a laser source and a compact peripheral component interconnect system, which includes a time-to-digital converter (TDC), is set up for fast signal processing. The combination of a GAPD with short dead time and a TDC with a multistop function enables the system to operate in a single-hit or a multihit mode during the acquisition of time-of-flight data. The software for the three-dimensional visualization and an algorithm for the removal of noise are developed. For the photon-counting LADAR system, we establish a theoretical model of target-detection and false-alarm probabilities in both the single-hit and multihit modes with a Poisson statistic; this model provides the prediction of the performance of the system and a technique for the acquisition of a noise image with a GAPD. Both the noise image and the three-dimensional image of a scene acquired by the photon-counting LADAR system during the day are presented. © 2011 Optical Society of America

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1. INTRODUCTION

Laser detection and ranging (LADAR) has recently become an important method for both distance measurements and acquisition of three-dimensional images. There are methods that can be used to measure distances with lasers [interferometry, time-of-flight (TOF), and triangulation methods] [1]. To acquire a higher-ranging capability, the direct-detection laser radar system that uses the TOFs of laser pulses with an avalanche photodiode (APD) as a detector has not only been investigated, but also commercialized [2]. A few research groups have employed a Geiger-mode APD (GAPD) or a GAPD focal plane array as the detector of their LADAR system because of its extremely high sensitivity [3–11]. The APD, which is reverse-biased above the breakdown voltage, operates in a Geiger mode, in which the primary electron generated by the absorption of a single photon initiates a self-sustaining avalanche process. The avalanche process constitutes an electrical current surge with a sharp leading edge, which allows high-resolution timing [4].

However, there are some negative aspects of GAPD as a detector of laser radar. First, the dark counts generated by thermal noise in the depletion region can cause false alarms during the ranging process. Second, a GAPD experiences a dead time in which the GAPD does not work after a photon is detected. In other words, a GAPD needs some time to reset after it detects a signal and creates the current surge, which is the signal that announces the arrival of photons. The dead time typically varies from 10 ns to 1 μs, depending on which material is used and how the quenching circuit is designed. Assuming a laser pulse repetition rate of tens of kilohertz, multiple stop signals for every laser pulse emitted, apart from the stop signal generated within the dead time after a stop signal is generated, can be generated by either the photons scattered from targets, solar noise, or by the dark counts during the gate time. In the case of a short dead time (multihit mode), most of the stop signals are measured during the gate time, whereas only the first stop signal can be generated in the case of a relatively long dead time (single-hit mode). In other words the systems operate in a single-hit mode, which means that only the first laser-return signal is detected, and the signals after that are discarded when a laser pulse is emitted, whereas in multihit mode, multiple laser-return signals are detected, except for the signal within a dead time of the GAPD. The combination of a GAPD that has a short dead time and a time-to-digital converter (TDC) functioning multistop acquisition enables the system to operate in a multihit mode [12].

In Section 2, both the hardware and the software of the photon-counting LADAR system are described in detail. A theoretical model of both the target-detection and the false-alarm probabilities of a photon-counting LADAR system that can operate in single-hit or multihit modes is established in Section 3. Noise image and three-dimensional images of a scene, acquired by the photon-counting LADAR system in the middle of the day, are shown in Section 4. Section 5 provides some summary remarks.
2. PHOTON-COUNTING LADAR SYSTEM

The laser radar system is divided into two parts: hardware and software. Figure 1 shows the schematic diagram of the system. A laser pulse is emitted by a light source and passes through the optical system, generating an optical start signal, which is then converted into an electrical start signal at the signal detection. The emitted laser pulse is scattered by the target. A part of the scattered laser pulse and background light in the field of view (FOV) are collected and routed into the signal detection stage by an optical system in which the background light can cause false alarms during the ranging process. An electrical stop signal is then generated, and the TOF data, the time interval between the electrical start and stop signals, are generated in the signal processing stage of the TDC. The TOF data are then transferred to the image processing stage in order to visualize the TOF data with the point cloud or the voxel method.

The performance of the system was specified by experimental results [10]. It was shown that the single-shot precision of the system was \(\sim 10 \text{ cm}(\sigma)\), and the precision was improved by increasing the number of laser pulses to be averaged so that the precision of \(\sim 1 \text{ cm}(\sigma)\) was acquired with more than 150 laser pulses scattered from the target. That means that there is a trade-off between the precision and the effective number of laser pulses where the effective number of laser pulses is given by multiplying the target-detection probability and the total number of laser pulses used together. In other words, either increasing the acquisition time or the repetition rate of laser pulses is needed in order to increase the precision in a given situation, e.g., energy of a laser pulse, range, and reflectance of target. The accuracy of the system was measured to be 12 cm when the energy of the emitted laser pulse varied with a factor of 7, and it improved by applying a technique that reduces the range walk error [13].

A. Hardware

The optical system including the light source is represented in Fig. 2. A diode-pumped passively Q-switched microchip laser with second harmonic generation (Alphalas PULSELAS-P-1064-300-FC/SHG) is used as a light source. The laser is constructed by using a short piece of Nd:YAG (gain medium) diffusion bonded to a similar piece of Cr\(^{4+}:\text{YAG}\) (saturable absorber). The pump-side face is coated to transmit 808 nm of pump light and reflect the laser light at 1064 nm. The high intensity of the output beam allows its frequency to be doubled when a small piece of potassium titanyl phosphate is placed near its output face. 532 nm wavelength laser pulses with a full width at half-maximum (FWHM) of 900 ps, a beam divergence of 6 mrad, and an energy of 9 \(\mu\text{J}\) are emitted at a repetition rate that varies between 2 and 20 kHz depending on the optical power of the pump light, because the laser is passively Q switched.

Because of the single polarization characteristic of the laser, half-wave plates (HWPs) are located before the polarization beam splitters (PBSs) in order to control both the transmission and reflection of the laser pulse at the PBSs. The start signals cannot be generated by the laser itself, because the laser is passively Q switched. Therefore, the \(S\) polarization

![Fig. 1. Schematic diagram of the LADAR system.](image1)

![Fig. 2. (Color online) Optical system. L, lens; HWP, half-wave plate; PBS, polarization beam splitter; QWP, quarter-wave plate; M, mirror; OBF, optical bandpass filter; PD, photodiode.](image2)
of the laser pulse is reflected to the fast photodiode (PD) at the PBS1 in order to generate the electrical start signal, and the start signal initiates the TDC. The fast PD used for the start signal is a Thorlab high-speed Si detector with a the rise/fall time of 14 ns and a dark current of 0.35 nA, which is specified in the data sheets. After PBS1, the energy of the laser pulse is controlled by HP2. The transmitted laser pulse is guided to the aiming point on the target by a two-axis galvano scanner and is then scattered. The two-axis galvano scanner used for controlling the beam pointing is from Cambridge Technology 6230H with a 10 mm aperture mirror, while its servo driver is a MicroMax 671 series. The two mirrors are controlled to rotate ±1° so that the field of regard (FOR) of the laser radar system is 4° × 4°. The scattered laser pulse and the continuous background light in the FOV of the system are collected into the GAPD (Id Quantique id100-20 ULN) through the two-axis galvano scanner, the quarter-wave plate (QWP), PBS2, the optical bandpass filter (OBF), and the focusing lens that has a 5 cm focal length in turn. Since the light source of the system, a diode-pumped passively Q-switched microchip laser, has a narrow spectral linewidth and temperature stability, an OBF that is centered at a 532 nm wavelength and has a bandwidth (FWHM) of 10 nm with a maximum transmission of 65.91% is used for spectral filtering.

The GAPD has a timing resolution (FWHM) of 40 ps, an after-pulsing probability of 3%, an output pulse width of 10 ns, a dead time of 45 ns, a photon detection probability of 35% at 500 nm wavelength, and a dark count rate that is lower than 1 Hz as specified in the data sheets [14]. Considering that the active area of the GAPD is 20 µm × 20 µm and the focal length of the focusing lens is used, the OBF of the laser radar system is 0.023°. The relatively short dead time of 45 ns is one of the factors that enables the laser radar system to operate in a multihit mode. The low dark count rate improves the target-detection probability of the laser radar system. The continuous background light is made up of scattered sunlight from the target and the atmosphere in the FOV of the optical system. This background light and the dark counts of the GAPD disturb the detection of the laser pulse and cause false alarms. For a high signal-to-noise ratio, the case covers the GAPD in order to block background photons, and all the mirrors are dielectric coated to reduce the background photons that pass through the OBF. The GAPD receives both the laser pulse scattered from the target and the noise and generates an electrical stop signal.

A charge-coupled device (CCD) camera (Pixelink PL-B953U) with a compact fixed focal length lens, of which the focal length is 75 mm, is used as a boresight camera mounted in the optical axis of the laser radar system in order to photograph targets. The FOV of the CCD camera is 5° × 3.5°, so that the FOR of the laser radar system comparatively accords with the FOV of the CCD camera.

The TDC (Agilent U1051A), which has a timing resolution of 50 ps and a range gate of 10 ns, receives both the electrical start and stop signal and measures the time interval between them [15]. The TDC, which is a compact peripheral component interconnect (cPCI) module, can measure the TOF values in either single-hit or multihit modes. A cPCI system, which includes the TDC, a CPU board equipped with a dual core processor at 2.2 GHz clock (EKF system CCG-RUMBA), and an arbitrary waveform generator (United Electronic Industries PDXI-AO-8/16) for controlling a two-axis galvano scanner, is built up for data acquisition and signal processing [16, 17].

B. Software

In order to convert the TOF data acquired by the system into noiseless three-dimensional output, the algorithm executes a series of functional steps. After receiving laser pulses, the system provides a two-dimensional depth image that contains angle–angle–range data for software processing and three-dimensional image visualization data. First, the TOF data are converted into Cartesian locations. Here it is possible to obtain the XYZ point in the Cartesian coordinate by using the scanning angle and distance information of each pixel. Using the XYZ points, image visualization can be carried out in two ways, namely, the point cloud scheme and the voxel scheme. In the point cloud scheme, each of the XYZ points in the received data is simply plotted in a three-dimensional Cartesian coordinate. Since we deal with a large amount of TOF data, including the information of the objects and noise, it is often difficult to distinguish the objects from the scene of point clusters. On the other hand, in the voxel scheme, the XYZ points are allocated into volumetric pixels, i.e., voxels, inside the specific volume of interest. By drawing the cubes for every XYZ point, the scene in the three-dimensional space becomes more geometric and provides a better three-dimensional image view than the image with point clusters. However, the voxel scheme, which draws the cubes’ surfaces with a certain volume of interest, in the three-dimensional coordinate causes time delay compared to simple point plotting. For further image processing to obtain a noiseless scene, our software converts the coordinates from continuous to discrete and it enables the three-dimensional information to be stored in tables with the distance information, which provides a direct connection with an integer index that represents the position of the element in the tables. After a certain number of laser pulses are transmitted and received, a single three-dimensional image is formed by showing all nonempty voxels in the three-dimensional space. In order to present the distance information with ease, we consider a color coating method that uses the hue, saturation, and value color coordinate, which presents color changes that depend on the distance of the scene. A color range from red to violet is used to show the three-dimensional image scene that ranges from the minimum range to the maximum range. Finally, in the thresholding stage, the three-dimensional image is cleaned by pruning voxels that contain a low number of counts, which most likely correspond to noise. By setting a certain threshold value (counts/volume), we can obtain a noiseless three-dimensional laser radar image that provides information on the distinguishable objects.

3. THEORETICAL MODEL

The mean number of photons that impinge on the detector is the sum of the laser signal photons and the background photons, the latter being composed of sunlight reflected from the target and scattered by the atmosphere in the FOV of the LADAR system.

As shown in Fig. 3, when emitting the laser pulse of which the instantaneous power is $P_{\text{emit}}(t)$, the instantaneous optical power of the laser-return pulse at the detector, which is
scattered from a flat, diffusely reflecting extended target (Lambertian target) at distance \( R \) with reflectivity \( \rho \), is

\[
P_{\text{RETURN}}(t) = P_{\text{EMIT}}(t - \tau_{\text{target}}) \times \frac{\text{FOV}^2 \rho}{\pi} \cos \theta_{\text{target}} \frac{A_R}{R^2} \frac{\eta_P}{\pi} \eta_{\rho \text{PE}} t^2.
\]

where

\[
\tau_{\text{target}} = 2R/c.
\]

\( c \) is the speed of light, \( \tau_{\text{target}} \) is the round-trip time of the laser pulse, \( \text{FOV} \) is the FOV of the receiver, \( \theta_P \) is the divergence angle of the laser beam, \( \theta_{\text{target}} \) is the angle of incidence of the laser beam relative to the surface normal, \( A_R \) is the area of the aperture of the receiver, \( \eta_P \) is the transmission of the transmitter, \( \eta_{\rho \text{PE}} \) is the transmission of the receiver optics, and \( \eta_{\rho \text{a}} \) is the one-way transmission of the atmosphere between the target and the receiver [18]. The rate function of the laser-return pulse for the mean number of firings is then expressed as

\[
S_{\text{PE}}(t) = \frac{\eta_0}{h} \int_{\tau_{\text{target}} + T_{\text{delay}}}^{\infty} P_{\text{RETURN}}(t - \tau_{\text{delay}}) \times \text{Jitter}(t - \tau) \, d\tau.
\]

where \( h \) is the Planck constant, \( \nu \) is the optical frequency, \( \eta_0 \) is the quantum efficiency, \( T_{\text{delay}} \) is the constant time delay due to the electronics and the optical path difference in the system, and Jitter\((t)\) is the overall timing jitter of the LADAR system [13]. This rate function represents the distribution of the firings in the time domain after the primary electrons are generated in the GAPD by the laser-return pulse. In this paper, the rate function of the laser-return pulse, \( S_{\text{PE}}(t) \), is assumed to be distributed uniformly within the \( j \)th time bin. Additionally, the rate function of the noise,

\[
N_{\text{PE}} = \eta_0 N_{\text{BG}} + f_{\text{dark}}.
\]

is assumed to be constant, where \( N_{\text{BG}} \) is the rate of solar background photons impinging on the detector, and \( f_{\text{dark}} \) is the dark count rate of GAPD. Thus, \( R_{\text{PE}}(t) \), the rate function for the mean number of firings attributed to various time bins, is the sum of \( S_{\text{PE}}(t) \) and \( N_{\text{PE}} \) as shown in Fig. 4.

In the case of a fully developed speckle, the number of primary electrons integrated by the receiver from a diffuse target

follows a negative-binomial distribution. When the number of photons received is much less than the speckle diversity, the Poisson distribution is a good approximation to the negative-binomial distribution [19]. For a Poisson process in the case of a GAPD, the probability that \( m \) primary electrons are created during times \( t_1 \) and \( t_2 \) is

\[
P(m; t_1, t_2) = \frac{1}{m!} \left[ M(t_1, t_2) \right]^m \exp[-M(t_1, t_2)],
\]

where

\[
M(t_1, t_2) = \int_{t_1}^{t_2} R_{\text{PE}}(t) \, dt.
\]

From Eq. (5), the probability that no primary electrons are created between times \( t_1 \) and \( t_2 \) is \( \exp[-M(t_1, t_2)] \). The probability that one or more primary electrons are created between times \( t_1 \) and \( t_2 \) is 1 - \( \exp[-M(t_1, t_2)] \) [20]. Hence, the detection probability on the \( i \)th time bin, which can be regarded as a TOF histogram of multiple laser pulses, is

\[
P_{\text{single}}(i) = \exp\left[ -\int_0^{(i-1)T_{\text{bin}}} R_{\text{PE}}(t) \, dt \right]
\times \left\{ 1 - \exp\left[ -\int_{(i-1)T_{\text{bin}}}^{iT_{\text{bin}}} R_{\text{PE}}(t) \, dt \right] \right\},
\]

\[
P_{\text{multi}}(i) = \exp\left[ -\int_{(i-1)T_{\text{bin}}}^{iT_{\text{bin}}} R_{\text{PE}}(t) \, dt \right]
\times \left\{ 1 - \exp\left[ -\int_{(i-1)T_{\text{bin}}}^{iT_{\text{bin}}} R_{\text{PE}}(t) \, dt \right] \right\},
\]

where \( T_{\text{bin}} \) is the time duration of a time bin and \( d \) is the number of time bins corresponding to dead time [11]. Hence, the target-detection probabilities in single-hit and multihit modes are respectively given as

\[
P_{\text{single}}(j) = \exp[-N_{\text{PE}}T_{\text{bin}}(j-1)] \times \{ 1 - \exp[-(N_{\text{PE}}T_{\text{bin}} + S_{\text{PE})})] \}.
\]

\[
P_{\text{multi}}(j) = \exp[-N_{\text{PE}}T_{\text{bin}}(j-1)] \times \{ 1 - \exp[-(N_{\text{PE}}T_{\text{bin}} + S_{\text{PE})})] \} \quad (j \leq d)
\times \{ 1 - \exp[-(N_{\text{PE}}T_{\text{bin}} + S_{\text{PE})})] \} \quad (j > d).
\]
respectively. Figure 5 shows the calculated target-detection and false-alarm probabilities in Eqs. (9)–(12) varying the $S_{PE,i}$ and $N_{PE}$, where $\tau_{\text{gate}} = N \times \tau_{\text{bin}} = 1 \mu$s. It is shown that the target-detection and false-alarm probabilities in a single-hit mode depend on a range, $N_{PE}$, and $S_{PE,i}$; they are already described in detail in [20]. On the other hand, it is shown that the target-detection and false-alarm probabilities in a multihit mode do not depend on a range but on $N_{PE}$ and $S_{PE,i}$; it can be additionally inferred from Eq. (10) that they also depend on a dead time of a GAPD even though the fact cannot be shown in Fig. 5. False-alarm probabilities of a multihit mode higher than those of a single-hit mode do not make the situation worse, because the false alarms are distributed randomly on the time.

![Fig. 5. (Color online) Target-detection (solid line) and the false-alarm (dashed line) probabilities versus $S_{PE,i}$ curves corresponding to the distance (a) 10 m, (b) 75 m, and (c) 140 m for single-hit mode (left) and multihit mode (right). The color of the line represents different noise conditions (red, top, $N_{PE} = 100$ kHz; blue, middle, $N_{PE} = 1$ MHz; black bottom, $N_{PE} = 10$ MHz), where $\tau_{\text{gate}} = 1 \mu$s).]
domain, while the target detections occur on the same time bin. That means that, with a given energy of a laser pulse, the multihit mode enables the photon-counting LADAR system to detect an object at a long distance. Besides, it was already shown that the multihit mode is more efficient in detecting the objects behind a sparse obstacle than the single-hit mode \[12\].

4. NOISE AND THREE-DIMENSIONAL IMAGES

Figure 6 shows the two-dimensional intensity image of the scene and its noise image acquired by the photon-counting three-dimensional imaging LADAR system in the middle of the day. As shown in Fig. 6(a), the scene is made up of the
roof of the building (135 m distance) and the antenna receiver (375 m distance). The noise measurement was carried by raster scanning the scene by 32 pixels × 32 pixels with blocking emitted laser pulses after the PBS1 in Fig. 2 and measuring 40,000 TOFs in single-hit mode on each pixel. This means the implementation of the Eq. (9) with setting the \( N_{PS} = 0 \). Every 40,000 TOFs on each pixel generates a TOF histogram of 20 ns time bin, and the curve fittings of negative exponential function are applied to the histograms. Then the values of \( N_{PS} \) are derived [18]. It is shown that the measured \( N_{PS} \) of the scene are between 80 kHz and 1 MHz; the sky generates more noise photons than the roof of the buildings.

The three-dimensional image is acquired in a multi-hit mode with 512 pixels × 512 pixels scanning by collecting 20 TOFs on each line of sight with a FOR of 4” × 4”. Figure 7 shows the three-dimensional images of the objects in the scene. Figures 7(a) and 7(b) show the three-dimensional images of the front and the top view of the roof of the building at 130 m distance, respectively; they are represented in the voxel method, where voxel size is 18 cm × 18 cm × 18 cm after thresholding with the value of 2 counts/(18 cm)³. It is shown that the inclined angle of the roof can be measured in Fig. 7(b), whereas it is hard to measure in a two-dimensional intensity image, Fig. 6(a). Figures 7(c) and 7(d) show the three-dimensional images of the front and the top view of the receiver antenna at 375 m distance, respectively; they are represented in the voxel method, where voxel size is 30 cm × 30 cm × 30 cm after thresholding with the value of 2 counts/(30 cm)³ found by trial and error. Because of the high \( N_{PS} \) values in the sky, it is hard to remove the noise by thresholding the remaining three-dimensional image of the receiver antenna.

5. SUMMARY

This paper describes a photon-counting three-dimensional imaging LADAR system that uses a GAPD with a relatively short dead time (45 ns). A passively Q-switched microchip laser is used as a laser source and a cPCI system, which includes a TDC, and is set up for fast signal processing. The combination of the GAPD with a short dead time and a TDC having a multistop function enables the system to operate in a single-hit or a multi-hit mode during the acquisition of TOF data. The software for the three-dimensional visualization and an algorithm for the removal of noise are developed. For the photon-counting LADAR system, a theoretical model of target-detection and false-alarm probabilities in both the single-hit and the multi-hit modes is established with a Poisson statistic; this model provides the prediction of the performance of the system and a technique for the acquisition of a noise image with a GAPD. Both the noise image and three-dimensional image of the scene acquired by the photon-counting LADAR system during the day are presented. The result shows that it is possible to take a three-dimensional image of a noncooperative target at a 375 m distance with laser pulses less than 9 μJ with an appropriate threshold value. Future work will investigate the implementation of a GAPD array having a short dead time and increase laser repetition rate in order to increase the speed of TOF data acquisition.

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