Delayed range-gating super-resolution imaging lidar with high accuracy

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We present a range-gating delayed detection super-resolution imaging lidar with high accuracy based on the signal intensities of three consecutive delay samples. The system combines the range and signal intensity information from multi-pulse detections to calculate the pulse peak position under the assumption of a Gaussian pulse shape. Experimental results indicate that the proposed algorithm effectively calculates pulse peak position and exhibits excellent accuracy with super-resolution. Accuracy analysis shows that accuracy is best improved by enhancing signal-to-noise ratio, strategically selecting samples, reducing pulse width, and appropriately choosing the delayed periods between samples.

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Range-gating imaging lidar constructs three-dimensional (3D) imaging information by detecting the pulses returned by targets at different distances and periods; detection is facilitated by range-gating techniques based on active illumination[1−4]. However, laser pulse width has become an obstacle in improving lidar resolution and accuracy because of laser performance limitations. To solve this problem, researchers have proposed many approaches. Busck *et al.*[2] established a laser radar system that applies a centroid method in processing echo signals to obtain range and intensity images of outdoor objects. Laurenzis *et al.*[5] reconstructed a 3D depth map with super-resolution from a sequence of gated viewing images with overlapping intensity profiles. To achieve the highest range accuracy, Zhang *et al.*[6] proposed an optimal bin number. Wu *et al.*[7] presented a multi-pulse gate-delayed method to improve the resolution of range-gating imaging lidar without changing the peak power and width of laser pulses.

A typical range-gating lidar system evenly divides the detection range into range bins, one detection is devoted to each bin. The range resolution of a range-gating imaging lidar system depends primarily on scanning step size $\Delta\tau_{\mathrm{stp}}$, as well as on the temporal variations of the sensor gate and laser pulse σ. Short pulse widths and scanning step sizes enable high resolution[4−6]. The achievable resolution for typical depth-scanning devices can be estimated from[5]

$$\Delta z_{\mathrm{scan}}=\left(\left\langle z\right\rangle^{2}-\left\langle z^{2}\right\rangle\right)^{1/2}\approx\frac{c}{2}\left(\sigma\Delta\tau_{\mathrm{stp}}\right)^{1/2}, \tag{1}$$

where z is the corresponding distance of the target and c is the speed of light.

Disregarding the temporal variations of the sensor gate and laser pulse σ, we can express resolution as

$$\Delta z_{\mathrm{scan}}\approx\frac{c\Delta\tau_{\mathrm{stp}}}{2}. \tag{2}$$

The measurement resolution and accuracy of a typical range-gating imaging lidar system heavily depend on the delayed period of the gate, which simplifies signal processing. The deficiency of the system is its use of only laser flight time without signal intensity information in range measurement. In this case, super-resolution is not achieved.

In this letter, an improved range-gating super-resolution imaging lidar system is proposed. The system calculates the peak position of laser pulses by determining the signal intensities of three consecutive detections with a delayed detection algorithm.

The range-gating delayed detection super-resolution imaging lidar system emits three laser pulses and records the detections in n bins within the scene for each pulse. Meanwhile, the sampling period is delayed for a small period $\delta\tau$ for each pulse according to the previous pulse. For each detection, the system records the opening position of the gates and the output signal intensities.

Generally, a laser pulse shape can be regarded as a Gaussian shape[2], which can be expressed at a certain moment as

$$P(t)=\frac{P_0}{\sqrt{2\pi}\sigma_{\mathrm{pulse}}}\exp\left(-t-\mu^2/2\sigma_{\mathrm{pulse}}^2\right), \tag{3}$$

where P_0 is the peak power of the laser pulse, μ denotes the peak time of the pulse, and σ_{pulse} is the width of the laser pulse.

To simplify the model, the output signal of the detector at different times can be regarded as the Gaussian shape samples of the laser pulse. The system takes three consecutive samples to calculate the peak time of the pulse as the target range, consequently improving resolution and accuracy.

Assume that there are three detections by consecutive pulses. We also assume that the output signal intensities are P_1, P_2, and P_3, and the periods are t_1, t_2, and t_3. The relationship of $t_2=t_1+\Delta\tau$ and $t_3=t_1+2\Delta\tau$ is shown in Fig. 1.

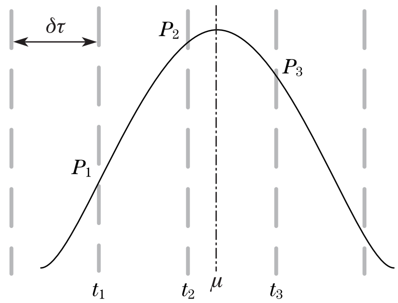

Fig. 1. Signal intensity increment of the Gaussian pulse.

The Gaussian laser signal echoes can be expressed as

$$P_i = \frac{P_0}{\sqrt{2\pi}\sigma_{\text{pulse}}} \exp\left[-(t_i-\mu)^2/2\sigma_{\text{pulse}}^2\right], \text{ where } i = 1, 2, 3. \tag{4}$$

For the three outputs,

$$A = \frac{\ln P_1 - \ln P_2}{\ln P_2 - \ln P_3} = \frac{2\,(t_1-\mu)+\Delta\tau}{2\,(t_1-\mu)+3\Delta\tau}. \tag{5}$$

Suppose $Q = \frac{t_1-\mu}{\Delta\tau}$. Then $A = \frac{2Q+1}{2Q+3}$ and $Q = \frac{1-3A}{2A-2}$.
Thus, the target range can be expressed as

$$\mu = t_1 - \Delta\tau Q, \tag{6}$$

where μ represents the peak time of the laser pulse or target range.

For experimental proof of this theory, a multi-pulse range-gating delayed detection super-resolution imaging lidar system is proposed, with the system structure shown in Fig. 2. The system includes a laser transmitter, transmitting antenna, control system, receiving array detector, and image coding system. The control system sends signals for the laser transmitter to control the emission of a laser pulse from the antenna to the targets. The echoes of the laser pulses are detected by the array detector and sent to the image coding system with the synchronous signals from the control system. The control system records the count k of the emitted pulse and controls delayed sampling period $k\delta\tau$. The image coding system calculates the target distance according to the time and intensities of the echoes, and then generates the depth map.

The central wavelength of the laser is 532 nm, and the pulse energy is 50 mJ. The repeated pulse frequency is 25 Hz, and the pulse width is 15 ns. An intensified charge-coupled device sensor records an 8-bit gray-level image with a resolution of 582×780 (pixel). The range bin is set to 25 m, and the width of the sampling period is 140 ns. The system works at a frame rate of 25 frames/s. The delay of the gate is 30 ns. The target of the experiment is a building about 500-m away (Fig. 3), and the experiment is performed during daytime.

Given that the depth of the target is only approximately 20 m, the 3D depth map of a typical range-gating imaging lidar system has no more than 2 depth values, preventing the system from providing building details. With the delayed gate, the system obtains 5 laser intensity images for the range bins of 475 to 500, 480 to 505, 485 to 510, 490 to 515, and 495 to 520. To acquire higher resolution, the system sets the delayed period of the gates as the length of the sub-range bin, thereby dividing the range bin into multiple sub-range bins of about 5 m. With the coded algorithm[7], the range-gating delayed lidar system constructs a depth map (Fig. 4). On the basis of Eqs. (5) and (6), the system reconstructs the depth maps (Fig. 5) with the five laser intensity images.

According to Eq. (2), the resolution of a typical range-gating imaging lidar system is 25 m, which results in the unsuccessful 3D imaging of a building with a depth of approximately 20 m. Figures 4 and 5 show the 3D image of the building. In Fig. 4, the right wall of the building shows four steps of building depth, demonstrating that the delayed period of the gates improves the system resolution to 5 m. Figure 5 shows the depth image that is calculated through a Gaussian pulse. Compared with Fig. 4, Fig. 5 shows more side wall steps; it also shows a clear image of the windows on the left side of the building, indicating that the resolution of the system further improves. Figures 4 and 5 demonstrate that the range-gating delayed detection imaging lidar system proposed in this letter achieves super-resolution.

According to Eq. (6), the error of the peak position becomes

$$\mathrm{d}\mu = -\Delta\tau\mathrm{d}Q = \frac{\mathrm{d}A}{(A-1)^2}. \tag{7}$$

From Eq. (5), we obtain

$$\mathrm{d}A = \mathrm{d}\left(\frac{\ln P_1 - \ln P_2}{\ln P_2 - \ln P_3}\right) = \frac{1}{(\ln P_2 - \ln P_3)^2} \cdot \left(\frac{\ln P_2 - \ln P_3}{P_1}\mathrm{d}P_1 + \frac{\ln P_3 - \ln P_1}{P_2}\mathrm{d}P_2 + \frac{\ln P_1 - \ln P_2}{P_3}\mathrm{d}P_3\right). \tag{8}$$

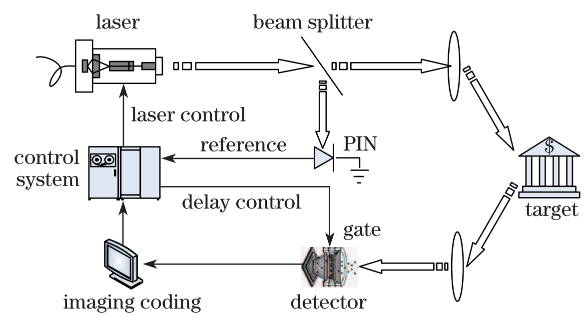

Fig. 2. Block diagram of the range-gating delayed detection super-resolution imaging lidar.

Fig. 3. (Color online) Image of the target.

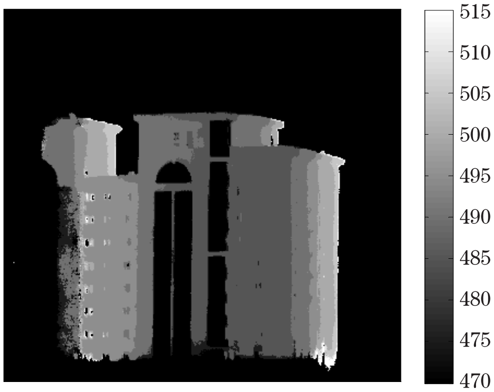

Fig. 4. Depth image without intensity calculation.

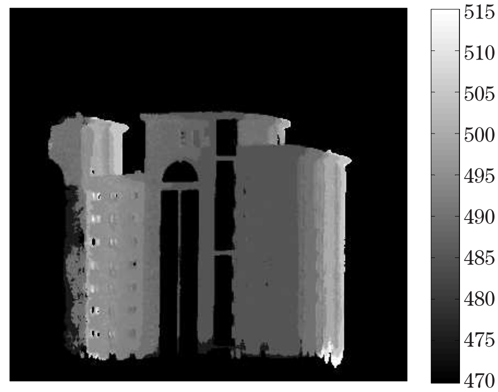

Fig. 5. Depth image with intensity calculation.

From Eqs. (4), (7), and (8), and $t_2 = t_1 + \Delta\tau$, $t_3 = t_1 + 2\Delta\tau$, Eq. (7) can be simplified to

$$\mathrm{d}\mu = -\frac{\sigma^2}{2\Delta\tau^2}\left\{\left[3\Delta\tau + 2\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_1}{P_1} + \left[-4\Delta\tau - 4\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_2}{P_2} + \left[\Delta\tau - 2\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_3}{P_3}\right\}. \quad (9)$$

Considering the signal-to-noise ratio (SNR), SNR= $\left|\frac{P}{dP}\right|$, with $\Delta\tau \geqslant 0$.
The error of the peak position can be determined by

$$\begin{aligned}\mathrm{d}\mu &\leqslant \frac{\sigma^2}{2\Delta\tau^2}\left\{\left|\left[3\Delta\tau + 2\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_1}{P_1}\right| + \left|\left[-4\Delta\tau - 4\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_2}{P_2}\right| + \left|\left[\Delta\tau - 2\left(t_1-\mu\right)\right]\frac{\mathrm{d}P_3}{P_3}\right|\right\} \\ &= \frac{\sigma^2}{2\Delta\tau^2}\left\{\left|\left[3\Delta\tau + 2\left(t_1-\mu\right)\right]\right|\frac{1}{\mathrm{SNR}} + \left|\left[-4\Delta\tau - 4\left(t_1-\mu\right)\right]\right|\frac{1}{\mathrm{SNR}} + \left|\left[\Delta\tau - 2\left(t_1-\mu\right)\right]\right|\frac{1}{\mathrm{SNR}}\right\} \\ &\leqslant \frac{\sigma^2}{2\Delta\tau^2}\cdot\frac{1}{\mathrm{SNR}}\left(3\Delta\tau + 2\left|t_1-\mu\right| + 4\Delta\tau + 4\left|t_1-\mu\right| + \Delta\tau + 2\left|t_1-\mu\right|\right) \\ &= 4\frac{\sigma^2}{\Delta\tau^2}\cdot\frac{1}{\mathrm{SNR}}\left(\Delta\tau + \left|t_1-\mu\right|\right). \end{aligned} \quad (10)$$

The results show that the accuracy of the algorithm is related to several factors: the delayed period of the gates, SNR, discrepancy between the first sample and the peak position of pulse $|t_1 - \mu|$, and pulse width σ. Measurement error is proportional to pulse width and inversely proportional to SNR. Measurement error increases with decreasing delayed period of the gates and increasing discrepancy between the first sample and the peak position of pulse $|t_1 - \mu|$.

Therefore, the methods that best improve the accuracy of the algorithm are enhancing SNR, selecting samples with the highest values as the first samples for the three consecutive detections, reducing pulse width, and appropriately choosing the delayed periods of the gates in accordance with the requirements for system resolution and measurement accuracy.

In conclusion, a range-gating delayed detection super-resolution imaging lidar system is proposed. Using three samples of laser Gaussian pulse echoes, the lidar system combines range information and signal intensity information to calculate the peak position of laser pulses. This peak position represents the range of a target under the assumption of a Gaussian pulse shape. The delayed detection algorithm effectively calculates pulse peak position and exhibits excellent accuracy with super-resolution. The accuracy analysis shows that measurement error is proportional to pulse width and inversely proportional to SNR. Measurement error increases with a decrease in the delayed period of the gates and an increase in the discrepancy between the first sample and the peak position of the pulse. Improving the accuracy of the algorithm necessitates enhancing SNR, choosing samples with the highest values as the first samples for the three consecutive detections, reducing pulse width, and appropriately selecting the delayed period of the gates in accordance with the requirements for system resolution and measurement accuracy.

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