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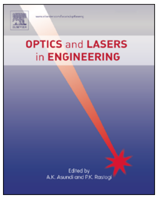

Correction of linear-array lidar intensity data using an optimal beam shaping approach

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ABSTRACT

The linear-array lidar has been recently developed and applied for its superiority of vertically non-scanning, large field of view, high sensitivity and high precision. The beam shaper is the key component for the linear-array detection. However, the traditional beam shaping approaches can hardly satisfy our requirement for obtaining unbiased and complete backscattered intensity data. The required beam distribution should roughly be oblate U-shaped rather than Gaussian or uniform. Thus, an optimal beam shaping approach is proposed in this paper. By employing a pair of conical lenses and a cylindrical lens behind the beam expander, the expanded Gaussian laser was shaped to a line-shaped beam whose intensity distribution is more consistent with the required distribution. To provide a better fit to the requirement, off-axis method is adopted. The design of the optimal beam shaping module is mathematically explained and the experimental verification of the module performance is also presented in this paper. The experimental results indicate that the optimal beam shaping approach can effectively correct the intensity image and provide ~30% gain of detection area over traditional approach, thus improving the imaging quality of linear-array lidar.

1. Introduction

Lidar, as an active remote sensing technique, has been continually developed in recent years. At present, lidar mechanisms mainly include: point scanning lidar, focal plane array lidar, and linear-array coding lidar. The point scanning lidar is the earliest lidar, which exhibits various deficiencies. As a scanning imaging lidar that operates by scanning an object point-by-point with a mechanical scanning device, it cannot achieve high frame rates or precision, especially in the case of a moving target. Moreover, it has a large size and high cost [1,2]. In contrast, the focal plane array lidar has recently been widely researched and applied [3,4]. The Lincoln Laboratory of the Massachusetts Institute of Technology (MIT) is the representative developer of the focal plane array lidar. From 2001 to 2011, the size of Geiger-mode avalanche photodiodes (GM-APDs) was constantly scaled up by MIT. Specifically, the GM-APD lidar was put into the Jigsaw programme to detect and identify a camouflaged and foliage-obscured target [5–9]. However, the technological development has been limited by the design of large scale detectors. Therefore, the linear-array coding lidar mechanism has been proposed to solve the problem. The laser source is expanded, shaped and demodulated before projecting onto the object. A combination of multiplexing and coding techniques enables the lidar system to achieve non-scanning, large field of view (FOV) and high lateral resolution using fewer detectors [10]. The work presented in this paper is based on this type of mechanism.

The principle of the linear-array coding lidar can be described as follows. The laser pulse is first expanded and shaped into a line-shaped beam. The line-shaped beam is then encoded by the optical encoder before being projected onto the object. The receiver employs a linear APD array to synchronously acquire the backscattered signals and a multi-channel data acquisition system to digitally record the waveforms from the pixels. The characteristic information involving the amplitude and time of flight is decomposed by denoising and demodulating methods. The intensity and range information are finally obtained and used to reconstruct a 3D image of the target. However, previous work did not focus on beam quality, which leads to inaccuracy and poor image quality. Our work aims to correct the intensity data by improving beam quality. In the traditional intensity correction approach which has been applied to laser scanning data, the errors result from objective factors such as spherical loss, as well as topographic and atmospheric effects [11]. On the contrary, the intensity deviations and errors introduced by our linear-array coding lidar result mainly from beam quality. Therefore, we redesign the beam shaping module to improve the laser beam quality, thus achieving the intensity correction.

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The remainder of this paper is structured as follows. Optimised structure and the principle of operation of the linear-array lidar are introduced. Then, the optimal beam shaping module is mathematically deduced to demonstrate its feasibility and availability. Finally, the performance of the optimised lidar system is experimentally tested and compared with that of the original lidar system. The results demonstrate that the optimal beam shaping approach can achieve image intensity correction and improvement of 3D image quality.

2. Structure and principle of optimised linear-array lidar system

The linear-array coding lidar is a recently developed lidar system, the measurement mechanism of which is based on a novel principle, which distinguishes it from the traditional point-scanning method. The laser source is first expanded and shaped to a line-shaped beam, which is then modulated by an optical encoder and vertically projected to the target and horizontally pushed scanning. Moreover, the multiplexing method employed on the receiver side allows each detector to obtain multiple-pixel information. Thus, the system is capable of achieving efficient surface detection. Fig. 1 shows the schematic structure of the linear-array lidar system, which consists of a transmitter and a receiver. The transmitter part includes a pulsed laser, beam expander, beam shaper, encoder and transmitter camera, while the receiver part includes a receiver camera, fibre bundles, APD array, data acquisition system and a PC. The working principle is described as follows. The solid-state laser produces a laser pulse with a certain frequency and pulse width. The laser source is then expanded to a large-diameter beam by the beam expander and shaped to a line-shaped beam by the beam shaper. The line-shaped beam is demodulated by the encoder and then projected to the target. A portion of the demodulated laser beam is diverted by a reflector and captured by a PIN detector, which triggers the data acquisition system. At the receiver side, the backscattered echo signals are collected by the receiving camera and transmitted to the APD array via the fibre bundles. The output is digitally recorded by a data acquisition system and transferred to a PC via the Ethernet port. Signal processing, including denoising, demodulation and decomposition is employed to obtain the intensity and range data for all target pixels.

The beam shaper shown in Fig. 1 is the optimal component proposed in this paper. It consists of a pair of conical lenses and a cylindrical lens. Contrarily, the traditional approach is to simply use a cylindrical lens to convert the large-diameter beam to a line-shaped beam. The main problem associated with the traditional approach is that the shaped linear beam has a Gaussian characteristic. In other words, most of the energy is concentrated in the central region, which leads to inhomogeneity of the intensity data and serious information loss at the edge region. The optimal approach we applied will effectively solve this problem. Detailed theory and analysis regarding the optimal approach will be presented in the next section.

3. Theory and analysis

3.1. Theory of laser beam shaping

According to laser beam propagation theory, the intensity distribution per unit time per unit area (i.e., irradiance) should be Gaussian, which means the most energy per unit area is in the centre of the beam [12]. Laser beam shaping is the process of redistributing the irradiance and phase of a beam of optical radiation using a specially designed optical system. At present, there are various laser beam shaping approaches and apparatus, such as interception, diffractive optical elements, holographic method, aspherical lens, etc. [13,14]. The interception method employs a diaphragm to intercept the Gaussian beam to reserve the relatively uniform part in the centre. Obviously, this method leads to huge loss of beam energy. In contrast, diffractive optical elements method is more widely used. This method is based on diffraction theory and the Huygens–Fresnel diffraction integral formula, and aims to convert a Gaussian elliptical beam to a uniform circular beam. However, the design of this device is still limited by machining technology. Currently the damage threshold of the optical element remains low and thus this method is infrequently applied to high power laser detection. Different from the traditional optical methods, holographic method provides a more advanced approach, which can achieve beam shaping by the holographic lens controlled by computer. However, the method is generally applied to laser materials processing like laser cutting, peeling and grooving of materials instead of lidar imaging. Two reasons are considered. First, the computer-controlled method is not convenient for airborne or vehicle-borne operation. The

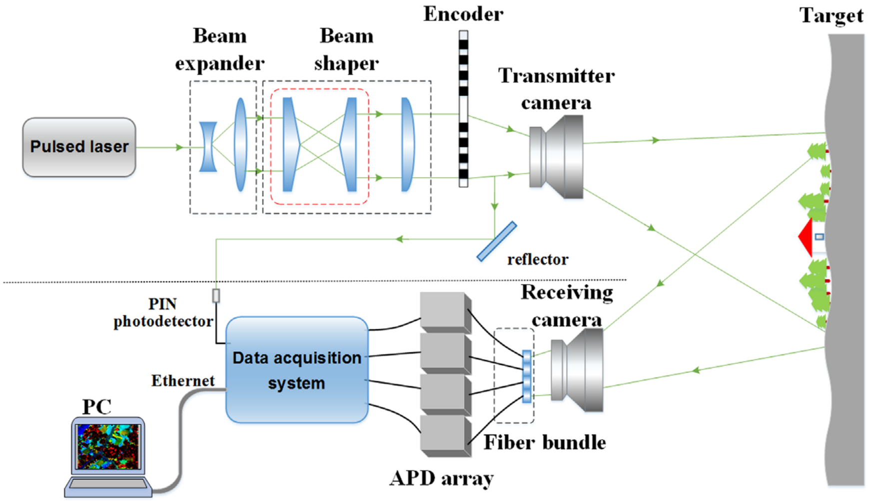

Fig. 1. Schematic of linear-array coding lidar system which consists of a transmitter and receiver. The beam shaper is our proposed optimal component made up of a pair of conical lenses and a cylindrical lens.