A Wide-Field Adaptive Spectral-Scanning LiDAR

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***Abstract*—We develop a 360º spectral-scanning frequency-modulated continuous-wave (FMCW) LiDAR system employing a grating and a rotator. A large FoV of 8º×9.5º and an angular resolution of 0.5º×0.19º are achieved. By controlling the scanning rate of the grating and rotator, adaptive imaging resolution can be obtained.**

Keywords—FMCW LiDAR, spectral scanning, wide-field, adaptive imaging

I. Introduction

Three-dimensional (3D) imaging technology is getting increasingly important and has been applied in numerous areas, including self-driving vehicles, drones, robots, medical and consumer electronic applications [1]. Light detection and ranging (LiDAR), as a practical approach in ranging and imaging, is drawing great attention in industry and academia. The working principle of LiDAR is straightforward, determined by the round-trip time delay of the light travelled to the target and reflected back [2]. As the number of LiDAR application scenarios proliferates, more and more requirements have been proposed, such as large-scale detection, high-speed imaging, and a simple but stable system architecture.

Various LiDAR approaches have been developed and commercialized to detect the surrounding environment. Under this circumstance, single-point detection can no longer address the needs. Thus, tremendous requirements for beam-steering mechanisms are emerging. Mechanical beam-steering methods can obtain a large scanning range with up to 360º field of view (FoV) [3]. Rotating scanning is one of the most popular 360º mechanical scanning mechanisms. It is because the rotating scanning mechanism can repeat the integrated orthogonal scanning pattern independently across the 360º horizontal FoV at a steady interval. Two-dimensional (2D) LiDAR has been proposed in combination with a flat mirror [4], achieving range detection in a single plane. To demonstrate a 3D LiDAR, microelectromechanical systems (MEMS) technology has been introduced [5], while the scanning FoV is limited by the vibration angle of the MEMS mirror. Besides, there are still other shortages of mechanical beam-steering methods, such as limited beam-steering speed and mechanical instability. By contrast, spectral scanning is an inertia-free solid-state beam-steering approach with an ultrafast scanning rate. A system with a maximum scanning rate at GHz has been demonstrated [6]. In the spectral-scanning scheme, by introducing a diffractive element, the output direction of the light beam is wavelength-depended. In other words, a laser source can be regarded as a spectral-temporal modulator that can realize one-to-one mapping between spectral and spatial positions based on diffractive optics. In addition, the spectral-scanning LiDAR system is interference-resistant. For the given direction, only light at the same frequency can be received [7]. Despite this, spectral scanning is inherently a one-dimensional beam-steering mechanism with limited FoV [8]. Two-dimensional beam-steering is usually realized by combining it with other scanners, such as optical phased array (OPA) [9] and crystal slow-light waveguide [10], which present higher complexity and lower scanning rate. In this case, combining the 360º mechanical scanning mechanism with spectral steering is an ideal option to achieve stable and high-speed omnidirectional scanning.

Here we propose and demonstrate a wide-field, resolution adaptive spectral-scanning FMCW LiDAR system with the combination of a 360º rotator and a grating. Compared with conventional MEMS mirrors, the grating can realize stable vertical scanning with higher angular resolution and larger scanning range. Furthermore, with a high-speed frequency-swept laser, the grating is able to achieve ultrafast one-dimensional large-range scanning. The adjustable speed rotator, together with the frequency-swept laser, enables adaptive sampling of the 3D point cloud and 360º panoramic scanning. By only placing the grating on the rotator, system stability can be significantly improved with relatively lower control difficulty. Based on this compact and stable architecture, we have demonstrated panoramic 3D imaging with the spectral-scanning FMCW method.

II. Experimental Setup and Principle

Fig. 1 illustrates the experimental setup of our proposed spectral-scanning FMCW LiDAR system. A frequency-swept laser with sweep range from 1490 nm to 1610 nm and sweep rate of 100 nm/s is employed. The light emitted from the frequency-swept laser is separated into two arms by a 1×2 optical coupler. 99% of the power feeds into the measuring arm for distance detection, while 1% goes into the auxiliary arm to suppress the frequency sweep nonlinearity [11]. An optical circulator is applied to realize the common axis of the transmitting optical path and the receiving optical path in the measuring arm. A delay fiber is then introduced to compensate for the additional optical path difference caused by the optical circulator. After passing through a collimator, the light transmits through the grating-based 360º scanner and is deflected in the vertical direction, while the horizontal scanning is achieved by the rotator. The collimator is placed 3

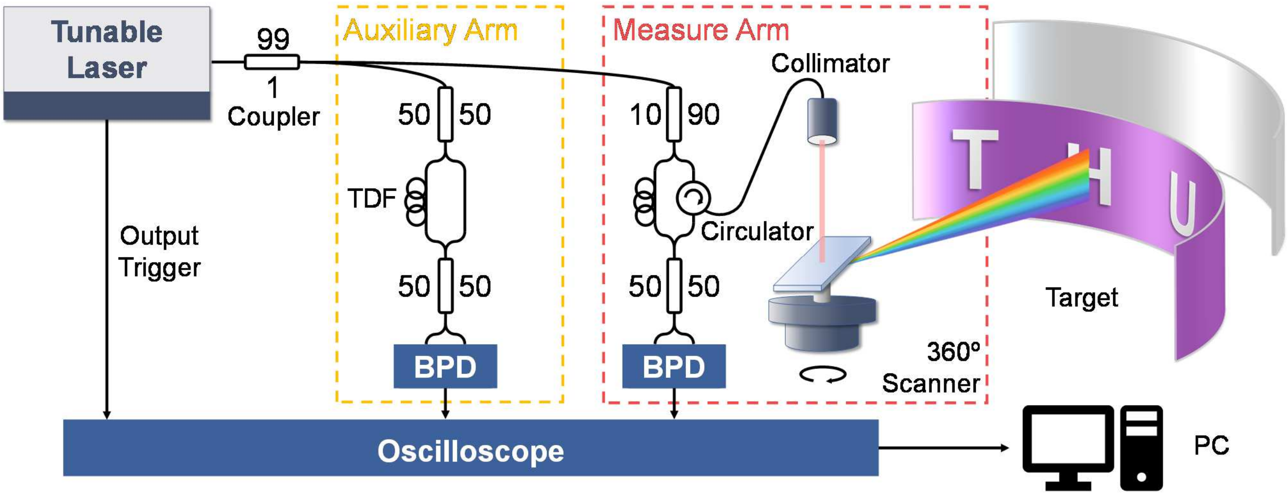

Fig. 1. The schematic diagram of the proposed 360º scanner-based FMCW LiDAR. TDF: time-delayed fiber. BPD: balanced photodetector.

cm above the grating at its focal length. And the incident angle of the laser is set at 46.8º to ensure the best diffraction efficiency under grating conditions. After being reflected from the surface of the target, the scanning light is collected by the collimator. Then the returned signal and the local signal are combined in a 2×2 coupler to generate a beat signal at the balanced photodetector (BPD). As illustrated in Fig. 2(a), the beat signal (green line) is generated by the reference signal (purple line) and the measuring signal (orange line). The frequency of the beat signal is proportional to the time of flight between the collimator and the target, which corresponds to the distance detected. Assuming the bandwidth allocated to a single FMCW measurement is Δf and the total scanning bandwidth is ΔF. Thus, the number of ranging points within a specific scanning line is $\Delta F/\Delta f$. Also, we can consequently use it to calculate the depth resolution of the proposed LiDAR system, which is given by $c/2\Delta f$. As a result, there is a trade-off between the depth resolution and the number of points.

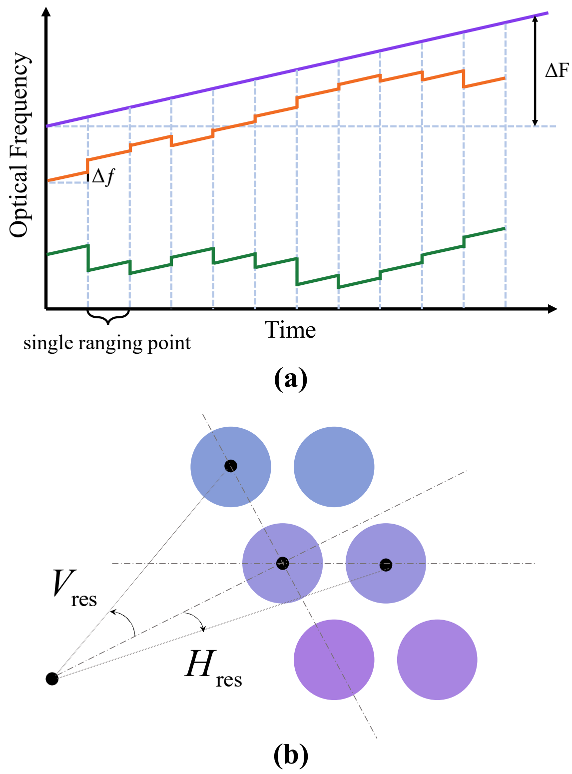

Fig. 2. (a) Ranging principle of the proposed FMCW LiDAR. (b) Diagram of the angular resolution in the proposed LiDAR system.

The 360º scanner consists of a transmission grating and an adjustable speed rotator. The grating presents vertical dispersion of light while the rotator realizes 360º horizontal scanning. Angular resolution is an essential metric of this panoramic imaging LiDAR system, defined by the smallest angular separation between two points that the system can distinguish, as shown in Fig. 2(b). The horizontal resolution of the proposed LiDAR system can be expressed as

$$H_{\text{res}} = \frac{f_{\text{rotator}} \times 360°}{f_{\text{spectrum}}}, \tag{1}$$

where f_{rotator} denotes the rotating rate of the rotator and f_{spectrum} represents the frequency sweep rate of the laser source. In this case, a higher ratio between the frequency sweep rate and the rotating rate can implement a better horizontal angular resolution. Since the point cloud density is proportional to the angular resolution, adaptive sampling can be obtained by controlling the scanning rate of the laser or the rotator. The vertical angular resolution is

$$V_{\text{res}} = \frac{FoV_{\text{y}}}{N}, \tag{2}$$

where FoV_{y} denotes the vertical FoV of the system and N represents the number of ranging points within a single spectral-scanning line. Considering the trade-off between the ranging resolution and the limited frequency sweep range of the light source, the number of ranging points should be calculated. The number of ranging points is not an arbitrary value while ranging resolution should be taken into account.

III. Experimental Results and Discussions

To investigate the performance of our proposed LiDAR system, a 3D target with several letters was designed. Two sheets of pasteboards were set 0.3 m apart. The front one was 0.74 m away from the 360º scanner. Characters of “THU”

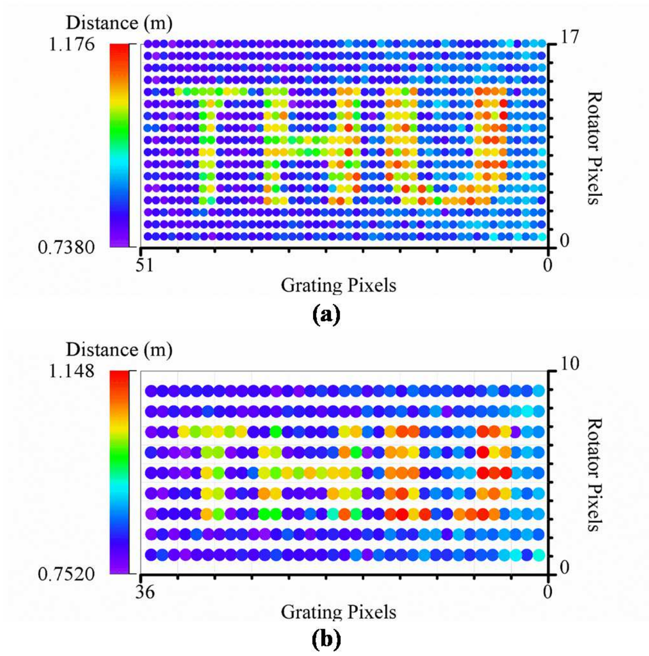

Fig. 3. 3D images of characters "THU". (a) The number of ranging points along vertical axis is set as 50 and rotating rate at 0.02 Hz. (b) The number of ranging points is set as 35 and rotating rate at 0.01 Hz.

were hollowed out from the front sheet. Within the set frequency sweep range, the transmission grating can realize a 9.5º beam-steering angle along the vertical direction. And a horizontal beam-steering angle of 8º was enough to cover the whole scene. Thus, an 8º×9.5º FoV with corresponding angular resolution at 0.5º×0.19º were performed for this target. According to (1), if the frequency sweep rate of the laser was set at 40 kHz, the horizontal resolution could reach 0.09º with a commercial-grade rotator at 10 Hz. Therefore, higher horizontal resolution and framerate can be achieved simultaneously by utilizing a VCSEL light source with faster frequency sweep rate [12]. For a single spectral-scanning line, 50 effective ranging points were obtained, considering both depth resolution and point density. Correspondingly, with 15 THz bandwidth allocated, 0.3 THz bandwidth was set for a single ranging point, indicating the theoretical depth resolution of 0.5 mm based on the definition of distance resolution on FMCW LiDAR.

As discussed, the density of the point cloud is proportional to the horizontal and vertical angular resolution. By changing the scanning rate and the number of ranging points, imaging results with different point cloud densities of the selected characters in both horizontal and vertical directions are shown in Fig. 3.

Here, as illustrated in Fig. 1, by fixing the laser beam at the same position of the grating during the 360º rotation, a complete and accurate image could be obtained without a complex calibration process. Since the beam size is small, requiring little space of the grating, the LiDAR system scale could be significantly reduced. Thus, it is theoretically promising to demonstrate a compact LiDAR system. For the imaging results, however, the distance to the target plane varies across the spectral-scanning direction. It is because the diffracted ray is at an angle to the target plane. This effect can be reduced by introducing the cosine of the azimuth angle together with optimized target placement [13].

IV. Conclusion

We have proposed a 360º wide-field and resolution adaptive spectral-scanning FMCW LiDAR with the combination of a transmission grating and a rotator. The horizontal scanning with 360º FoV is achieved by a rotator, while the vertical scanning is realized by a transmission grating. Large FoV at 8º×9.5º and stable architecture are demonstrated experimentally at the same time with promising framerate when incorporating a high-speed frequency-swept laser. By modulating the ratio between the scanning rate of the rotator and the laser, different resolutions for various applications can be achieved, referring to sparse and dense 3D point cloud sampling. Further, a stable and compact LiDAR system can be obtained by manufacturing a smaller grating.

Acknowledgment

The authors would like to express sincere thanks to the Shenzhen Technology and Innovation Council (WDZC20200820160650001).

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