Real-time structured-light depth sensing based on ultra-compact, non-mechanical VCSEL beam scanner

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Abstract: We realized real-time scanning structured-light depth sensing with accuracy of less than 270μm for distance of 35cm using ultra-compact (<0.5mm^2) non-mechanical beam scanner. The peak output power can be as low as 1mW. © 2020 The Author(s)

1. Introduction

Structured-light depth sensing [1] has been attracting much attention since iPhoneX was firstly equipped with Face ID based on such sensing technology. With reduction of power consumption or improvement of sensing accuracy, structured light sensing also shows potential to be applied in other fields such as 3D printing, gesture capturing and 3D sensing in factory automation and robotics. Thanks to its extraordinary performances it could be preferable in short-range sensing among current depth sensing technologies like time of flight and passive stereo vision. A scanning sensing technology has been approved as an efficient method for designing a structured-light sensor with lower power consumption or higher accuracy because of its larger power density and signal to noise ratio than conventional flash sensing with the same average power. However, a small-size, low-cost, and high-resolution scanning projector has not been available. Though there are some solutions for scanning projector such as MEMS [2], many issues like stability, integrability, number of lateral resolution points are still critical to make them practically applied. Previously, we proposed a non-mechanical VCSEL beam scanner with external light [3] with large number of resolution points (>1000) and demonstrated scanning structured-light sensing based on it [4], but it was difficult to be integrated in mobile devices due to requirement of an external light source. Recently we successfully designed and fabricated beam scanner integrated to a tunable VCSEL [5], of which the chip size was only <0.5mm^2, and through which the beam scanning could be realized by electrical driving without any external light source. In this paper, we demonstrated a structured-light sensing to obtain real-time depth image of designed target using the beam scanner integrated to a tunable VCSEL.

2. Non-mechanical beam scanner integrated to a tunable VCSEL

A VCSEL amplifier scanner is laterally integrated with a tunable seed VCSEL as shown in Fig. 1. The chip size is smaller than 0.5 mm^2. The vertical structure is similar to conventional VCSELs with the quantum-well active region sandwiched by two DBRs but was fabricated based on a half VCSEL structure. A stable uni-directional coupling was realized thanks to wavelength detuning between a seed VCSEL and VCSEL scanner through wet etching in VCSEL side [5]. As reported before, the VCSEL scanner works as both amplifier and beam scanner by varying the wavelength of coupled light [3]. In this device, the operated wavelength of the seed VCSEL could be tuned due to self-heating with different injected current I_{VCSEL}, and the deflection angle of output beam emitting from the VCSEL scanner would also change correspondingly with a large angular dispersion of 1°/nm [3].

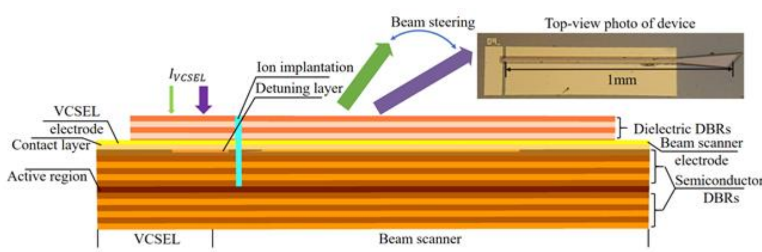

Fig. 1 The structure of beam scanner integrated to a tunable seed VCSEL.

A planar target was set 35cm away from the device and the reflected pattern was captured by a CMOS camera as shown in Fig. 2 (a). When the current injected to the VCSEL was varied from 1.5mA to 5.5 mA and current of 40mA was injected to beam scanner, the stripe pattern covering a field of view of $6° \times 12°$ could be clearly observed.

Furthermore, the dynamic scanning properties of our scanner were also measured as shown in Fig. 2 (b), which indicates that we could get maximum scan range of 6 degrees and the 3dB-down scanning speed can be over 100 kHz.

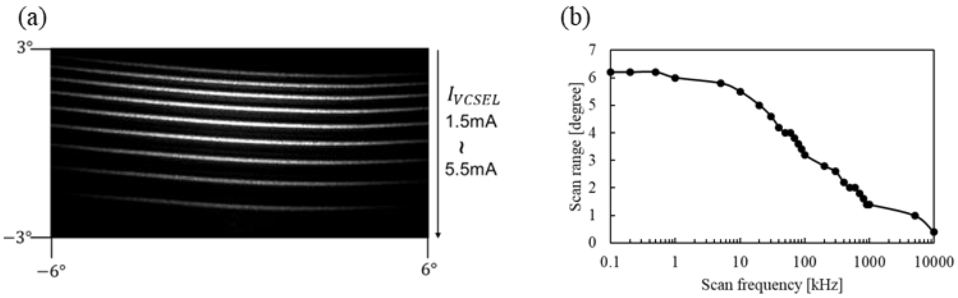

Fig. 2 (a) Reflected pattern (b) Scan frequency and range of the beam scanner.

3. Real-time scanning structured-light depth sensing

Structured-light sensing system is composed of a projector, a camera and a detected target as illustrated in the part surrounded by red frame in Fig. 3. For conventional flash sensing, the projector needs to cover the whole detected region at the same time while the projector of scanning sensing only needs to cover part of detected region and measures the whole region by beam scanning. In our system, the scanning projector was replaced by our beam scanner and the output beam was projected to the target after being reflected by a fixed mirror. The pattern reflected by the target would be captured by a camera and depth information of target could be obtained through the displacement between pattern reflected by the target and reference plane Δx_{λ_n} [4]. To realize real-time measurement, the synchronization of beam scanner and camera must be implanted through the system as shown in Fig. 3.

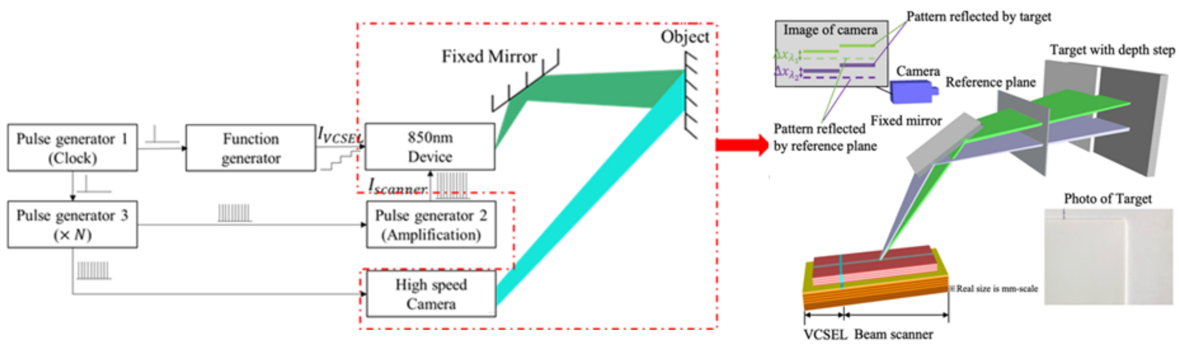

Fig. 3 Schematic of synchronization system and structured-light depth sensing system

4. Experiment results and discussion

The structured-light sensing system shown in Fig. 3 was established and real-time depth information of designed target was measured. In our experiment, the target to be measured was designed as a step object shown in Fig 3. (b) by bonding two white boards, the front of which has a thickness of 3mm. Considering the operation distance for face identification, the target was placed 35cm away from the camera. To obtain depth information of such target, we injected current of 40mA to the beam scanner to obtain output power of 1mW and variational currents from 1.5mA to 5.5 mA by 20 steps to the seed VCSEL. By setting the exposure time of camera to be 3.6ms, the pattern reflected by the target was captured by the camera as shown in Fig. 4 (a). A field of view of 6° × 12° was covered by 20 stripes radiated from the beam scanner. Because of the thickness of the front board, the step of stripe could be clearly observed at the boundary of the front board from Fig. 4 (a). It also shows enough resolution to distinguish targets with depth of 3 mm. Through the reflected pattern, depth image of designed target could be obtained as illustrated in Fig. 4 (b) where x axis and y axis represent the order of pixel in x direction and y direction of captured images respectively, and color accounts for the depth from detected point to the camera. For each stripe, depth data of more than 500 points could be obtained, so there are 10000 depth data points in a single depth image at least. Repeating the measurement 50 times with slight lateral movement, the depth standard deviation that is defined as accuracy here, is 266μm.

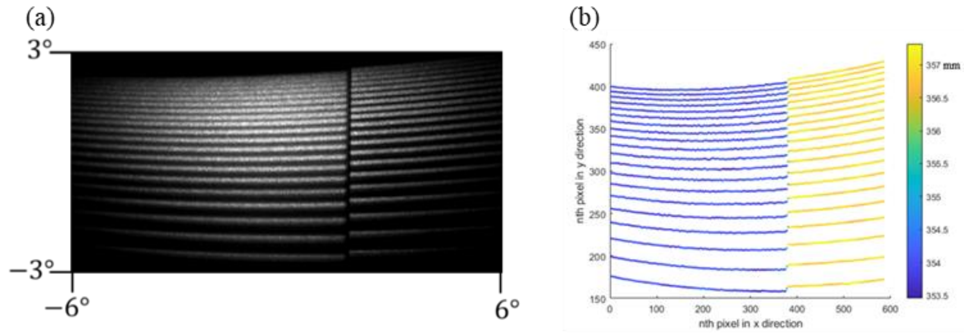

Fig. 4 (a) Pattern reflected by the target (b) single depth image of the target.

To realize real-time measurement, the beam scanner and camera were synchronized, and the frame rate of camera was set to be 200Hz, which brings depth data fresh rate of 10 Hz if 20 stripes were captured in single depth image. In our experiment, 10 continuous depth images were measured in 1 second as shown in Fig. 5 (a), which means 100,000 depth data points could be obtained per second. With same setting of the camera and beam scanner, the detected range was expanded from 35cm to 1m, the measured depth accuracy and relative accuracy were shown in Fig. 5, where relative accuracy was defined as the ratio of the depth accuracy and distance range. It shows the relative accuracy remains less than 0.16% even if the range was expanded to 1m with light power of only 1mW. The source of accuracy degradation with range expanding is mainly considered as speckle noise of radiated beam and magnification of the CMOS sensor.

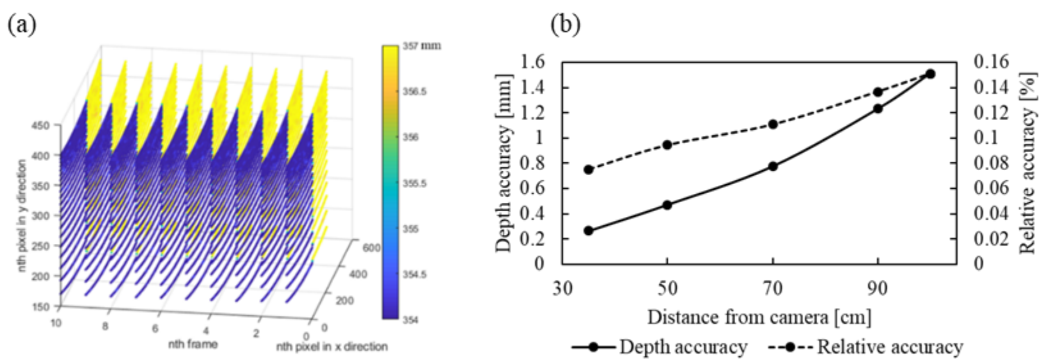

Fig. 5 (a) Continuous 10 depth images of designed target (b) The accuracy with detected ranging increasing.

5. Conclusions

We demonstrated a real-time structured-light depth sensing system based on an ultra-compact, non-mechanical beam scanner for the first time. The chip size of the beam scanner is as small as 0.5 mm^2. The real-time depth image was obtained with a field of view of 6° × 12° and data fresh rate of 10Hz. Thanks to the scanning technology, even if the output peak power was as low as 1mW and detected range was expanded to 1m, relative depth accuracy of less than 0.16% and depth data flood of 100,000/s were achieved at the same time. If a higher-speed camera is adopted, potential fresh rate of 50Hz and data flood of 500,000/s could be expected. By integrating a micro-heater to the seed VCSEL, the system could also enlarge the detected field to 30° × 12° and provide data flood of more than 2,500,000/s.

Acknowledgement

This work was supported by JST ACCEL program.

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