Research on Key Technologies of MEMS-based 3D Imaging LIDAR Vision System

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Abstract. In this paper, a new type of 3D imaging light detection and ranging (LIDAR) vision system based on Micro-Electro-Mechanical System (MEMS) mirror and novel optical system is proposed. The co-aperture transceiver optical system offers a compact architecture and wide Field-of-View (FOV), which also solves the problem of stray light affecting the system. Thanks to the MEMS and the optical system, the detecting FOV is greatly enlarged and the system volume is much smaller compared to the traditional system. The whole system is designed and verified by simulations and experiments.

1. Introduction
In recent years, due to the development of perceptual technologies such as three-dimensional reconstruction and object detection, the laser radar system for 3D imaging has been widely concerned by scholars all over the world. At the same time, because the laser itself has the advantages of strong anti-interference ability and good reliability, the 3D imaging LIDAR systems can obtain pictures with higher definition and resolution. LIDAR has many civilian and military applications, including indoor positioning, target identification, terrain mapping, autonomous driving[1], ground robots[2] and so on. The LIDAR of new generation is hoped to have a long detection distance, a large FOV, high precision, small volume and low cost. In order to achieve the goals above, there are many options for the vision system. Marius[3] and his co-workers developed a 4 × 4 Avalanche Photo Diode (APD) array to detect a laser pulse. Motaghian[4] chooses a nodding polygon mirror as a scanner. But the problems of size and power consumption exist. Considering power requirements, mirror sizes and scan frequency, MEMS (Micro-Electro-Mechanical System) is the best option for laser scanning. Besides, the mechanical tilt angle of a MEMS mirror is often less than 10 degrees and optical system extending the scan angle is needed. Xiaobao[5] uses a 2-axis tilt MEMS scanning mirror for laser scanning and theoretically proposes an optical system to expand the scan angles from 8° to 40°. On the other hand, most of the existing LIDARs use division systems for transmitting and receiving, that is, they do not share the same optical axis. In this way, there are problems that the detecting FOV is limited and system volume is increased accordingly. Siepmann[6] proposes the theoretically simplified structure of a co-aperture transceiver optical system consisting of a quarter-wave plate, a half-wave plate and a PBS (Polarizing Beam Splitter). They do not fabricate the system and conduct actual experiments.

In this paper, we propose a 3D imaging LIDAR vision system based on the co-aperture transceiver optical system and a two-axis MEMS mirror with an aperture of 4.3mm, where the transceiver optical
system composes of two PBSes, two focusing lenses and one beam expanding lens. The assembled system is compact and both scanning and detecting FOV of it reach up to $72^\circ \times 72^\circ$ through the experiment.

2. Theoretical Principle and Design Scheme

2.1. Design of the Optical Isolation System

Simplified diagram of our proposed 3D imaging LIDAR vision system is shown in figure 1. Optical isolation system which is used to isolate transmitted light and reflected light is the most important part of the whole system. Polarizing beam splitter which can split beams into reflected S-polarized and transmitted P-polarized beams is suitable to be used as an optical isolating switch in our system.

![Figure 1. Simplified diagram of 3D imaging LIDAR vision system.](image)

Different from the previous work[6], the quarter-wave plate and the half-wave plate are not used but one PBS is added, which is mainly based on the following aspects. First, we choose a pulsed fiber laser with a wavelength of 1064 nm and horizontal polarization, so half-wave plate which is used to adjust the polarization direction to match the PBS is not necessary in our design. Second, the PBS with high damage threshold has an extinction ratio of 3000:1 and is coated with an anti-reflection coating on all four sides. Even so, through experiments and theoretical calculations, it is found that less than 0.25% of the reflectivity of each surface will still affect the system. That is to say, there will be a very small amount of stray light entering the APD detector directly as indicated by the green arrow in figure 1. The direct detective LIDAR we designed obtains the distance information through the time delay between the system transmitting the laser and receiving the laser. Therefore, we take receiving the stray light and the reflected light as the starting signal $T_1$ and the end signal $T_2$, respectively. The distance $D$ is calculated by equation (1), where $c$ represents the speed of light.

$$D = \frac{c}{2}(T_2 - T_1)$$

On this basis, a second vertically placed PBS is added to completely transmit the S-polarized beams, thereby weakening the stray light so that the intensity of the reflected light is on the same order of magnitude with it, which facilitates subsequent time identification. Finally, in the previous theoretical block diagram[6], a quarter-wave plate is placed behind the PBS and its fast axis is at an angle of 45 degrees to the optical axis of the PBS. This can make the transmitted P-polarized beams to be reflected by the target and then pass through the quarter-wave plate twice to become S-polarized beams, which helps to achieve optical isolation. However, it has been found through experiments that the quarter-wave plate with a surface reflectance of less than 0.25% will additionally introduce S-polarized stray light and cannot be eliminated due to the same polarization direction as the reflected light. Therefore, we remove the quarter-wave plate and use the S-polarized component of the reflected light for reception. Although there is a loss of received energy, it has little effect on the detection.
2.2. Design of Co-aperture Transceiver System

In the 3D imaging LIDAR systems, the MEMS scanning mirror is considered as one of the most suitable devices because of its excellent performance, including small size, fast scanning speed, low operating voltage and flexibility[7]. In our study, the electromagnetically driven two-axis MEMS with the mirror diameter of 4.3 mm has a maximum optical scanning angle of ±3° at an operating voltage of ±3V, which is obviously not enough for 3D imaging LIDAR vision system. To extend the scan angle, we put two lenses, namely, a positive and a negative lens in front and back of the MEMS mirror to make FOV from 6° × 6° to 72° × 72° and enable linear scanning angle amplification.

Combining the above MEMS scanning system with the optical isolation system, we get our proposed co-aperture transceiver system. And it has many advantages over previous division transceiver systems where the receiving system and the transmitting system are separated from each other. The contrast between co-aperture transceiver system and division system is shown in figure 2. Because the photosensitive diameter of the APD is 800um, as shown by the green arrow in figure 2, the reflected light at a large angle will not be received. Compared with it, since the reflected light goes into the receiving system through the MEMS mirror along the original optical path, it is obvious that our proposed co-aperture system has a larger detecting field of view. For one thing, since the echo FOV and the receiving FOV are almost completely coincident, the staring field receiving is theoretically practicable. For another, the co-aperture transceiver system has lower requirements on the size of the photosensitive area compared with the division system, so we can select a faster photodetector and less background light will be introduced accordingly.

![Figure 2. Contrast between co-aperture transceiver system and division system.](image)

A converging lens with a focus on the APD is introduced to allow the reflected light to be completely received by the photodetector. Besides, a narrow-band filter of 1064nm wavelength is fixed on the APD surface to further remove background light and improve receiving efficiency. All of the above is the design scheme of our 3D imaging LIDAR vision system and the next chapter will introduce the implementation and experiments of the entire system.

3. Experiments

3.1. Evaluation of the optical isolation

PBS is the core component of the optical isolating switch and its transmittance and isolation determine our image quality. We placed the PBS horizontally and then allowed the P-polarized light to be incident perpendicularly, as shown in figure 3. We use a variety of different laser powers to measure the received light power of each surface to test the performance of PBS. Table 1 shows the laser power $P_a$ and the transmitted optical power $P_b$, $P_c$, $P_d$ of the other three surfaces, respectively. $\xi_1$ represents the transmittance of the PBS and is averaged by equation (2), where $n$ is the number of experiments.

$$\xi_1 = \frac{1}{n} \sum \frac{P_b}{P_a}$$

(2)
In addition, the stray light of the microwatt level is detected on the surface D, which may be caused by the reflection of the surface B in figure 3. We hope that the reflected light signal from the target is stronger than $P_d$, so our detection will be much easier. LIDAR distance equation [8] is shown in equation (3), where $P_r$ is the receiving optical power, $\xi_2$ is receiving efficiency, $\tau_0$ is atmospheric transmittance, $r$ is the reflectivity of the target surface and $S$ is receiving area. Through calculation and experiment, it is found that $P_r$ is much smaller than $P_d$. Considering that photodetector with an amplification gain of 100K is used, in order to facilitate the subsequent time identification of the circuit, we add another identical PBS to make $P_d$ and $P_r$ on the same order of magnitude.

$$P_r = \frac{\xi_1 \xi_2 \tau_0^2 r S}{\pi D^2} P_a$$  \hspace{1cm} (3)

Figure 4 shows the optical pulse obtained from the photodetector when we measure the target at 2m away in the experiment. The two pulses are clearly seen in the picture, the former represents the starting signal $T_1$, and the latter represents end signal $T_2$. This also verifies our system, and we can easily get the distance information.

### 3.2. Evaluation of LIDAR vision system

According to the above design, we assembled all components of the system through 3D printing. Figure 5 shows our proposed 3D imaging LIDAR vision system. And the parameter descriptions and values for the system are given in table 2.
Table 2. Parameter descriptions and values for 3D imaging LIDAR vision system.

| Parameter Description            | Value       |
|---------------------------------|-------------|
| laser wavelength                | 1064nm      |
| input beam diameter             | 0.5mm       |
| first positive lens focal length| 97.7mm      |
| PBS cube size                   | 10mm×10mm×10mm |
| MEMS mirror diameter            | 4.3mm       |
| max/min optical scan angle      | ±3°         |
| negative lens focal length      | -45mm       |
| second positive lens focal length| 10mm       |
| APD photosensitive diameter     | 800um       |
| FOV                             | 72°×72°     |
| system size                     | 160mm×140mm×40mm |

In our experiments, FPGA is used to drive MEMS mirror through DACs and precisely control the scan angle of it. Then we let the laser pass the system to the coordinate paper and find the center of the spot through the camera to measure the scanning angle. The experiment found that the scanning angle of this system is ±36° as expected by our theory.

Moreover, to verify the receiving ability of the system, we performed software simulations and experimental test on our system. First our system is built in the TracePro — an optical design software as shown in figure 6.

Figure 6. Simulation in TracePro.

We gradually increase the scanning angle of the MEMS mirror from 0° to 1.5° in steps of 0.25° for seven experiments. In every experiment, we set up three million parallel lights opposite to the incident direction at a distance of ten meters from the MEMS. Then we observe the received luminous flux of the APD surface. Figure 7 shows the experimental results, where \( \theta_1 \) is the scanning angle of the MEMS, \( \theta_2 \) is the corresponding detecting angle and \( \beta \) represents the luminous flux based on the luminous flux.
received at $\theta_1 = 0^\circ$. And the simulation results show that the received luminous flux is approximately equal at different detecting angles, which indicates that the system has almost the same receiving efficiency at different angles in the field of view. In addition, we let the parallel light incident at various angles within $-36^\circ$ to $+36^\circ$ and the reflected light can be received by the photodetector in each experiment, which further verifies that our system has the same size of the detecting FOV as the scanning FOV.

![Figure 7. Luminous flux diagram of the APD surface at different detecting angles in TracePro](image)

4. Conclusion

We propose a new type of 3D imaging LIDAR vision system based on MEMS and the co-aperture optical system. The co-aperture transceiver optical system with PBS as an optical isolating switch requires very few optical components, which makes the system very small and easy to manufacture. More importantly, with the cooperation of MEMS, it can be seen through experiments that scanning and detecting FOV of our system reach up to $72^\circ \times 72^\circ$ at voltages as low as $\pm 3$V. In addition, we innovatively use stray light as the starting signal to simplify the detection. This system characterized by compact structure and great performance, has broad application prospects in 3D imaging LIDAR.

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