Optics and Photonics Journal, 2021, 11, 265-272
https://www.scirp.org/journal/opj
ISSN Online: 2160-889X
ISSN Print: 2160-8881

A Compact MEMS-Based Optical Scanning System with Large Field of View for Lidars

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How to cite this paper: Wang, Y.J. and Chen, L.G. (2021) A Compact MEMS-Based Optical Scanning System with Large Field of View for Lidars. *Optics and Photonics Journal*, **11**, 265-272.
https://doi.org/10.4236/opj.2021.118016

Received: November 5, 2020
Accepted: July 31, 2021
Published: August 3, 2021

Abstract

In this work, a design of a compact optical MEMS-based lidar scanning system with a large field of view (FOV) and small distortion is presented. The scanning system applies an off-axis structure and the length of the system can be reduced to about 10 cm in an optimized way. Simulation results show that a large FOV is achieved under a uniform scanning scheme. In addition, the spot size less than 20 cm at distance of 100 m is also realized. The optical scanning system can be used for the vehicle-mounted Lidar.

Keywords

MEMS Mirror, Lidar Scanning System, Beam Steering, Optical Design

1. Introduction

With the emerging needs for high-resolution light detection and ranging (LIDAR) technologies in advanced driving assistance systems (ADASs), a new generation 3D image lidar system that takes advantage of a micro-electro-mechanical-system (MEMS) scanner approach has been investigated widely [1] [2]. In this lidar system, the MEMS scanning mirror is considered as key component because of its huge advantages, including fast scanning speed, low weight, flexibility, low power consumption [3]. However, a MEMS mirror has a drawback, that the mechanical tilt angle is small and is usually limited to a few or 10 degrees, which is obviously not enough for a 3D imaging lidar system.

To solve the limitations of the scanning system based on MEMS mirror, researchers have proposed several solutions that can offer large scanning area. A system with three laser diodes has been reported for 3D image lidar [4] [5]. The optical beam and mirror are changed by switching different laser diodes. The FOV has been extended by three times up to 45˚. However, multiple laser diodes can increase the cost of lidars. The more explorations and efforts in scan FOV extending are focusing on the additional lens. Researchers proposed a method to use a telescope-type optical angle amplification system [6]. The scan angle was amplified by putting two lenses, a positive one and a negative one, in front and back of the MEMS mirror, respectively. The optical FOV increases to 40˚. However, the emergent beams in this system are divergent. For target in long distance from the source, beams with high divergence can lead to large spots. And it can cause low image resolution and less received energy for a photo detector. An improved system was presented recently to solve the problems by adding an *f*-theta lens group and a wide-angle lens group into the MEMS-based scanner [7]. But too many lenses are used, making it bulky as a MEMS-based Lidar scanner.

This paper presents a design of compact scanning system with a large scan field of view (FOV) for 3D image lidars. An Off-axis Parabolic (OAP) mirror is utilized to decrease the volume of the system. In addition, the spot size and emergent beam angle are investigated by applying physical optics propagation modeling and ray tracing modeling.

2. Design and Simulation

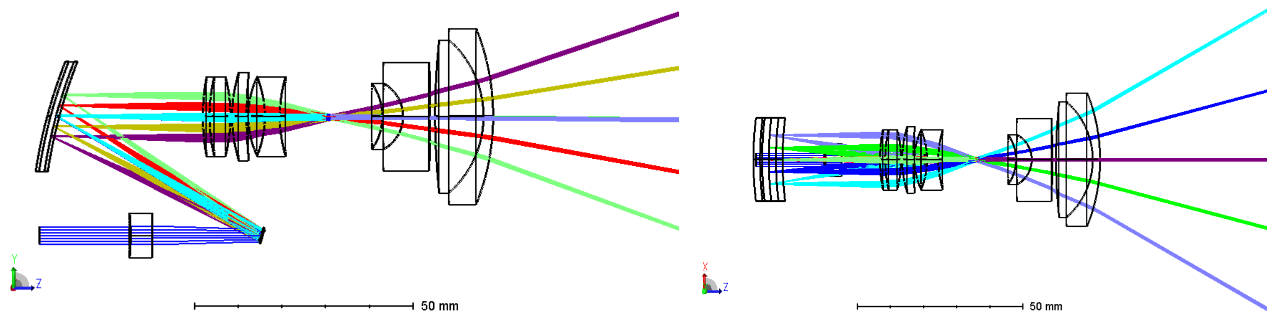
2.1. System Design

The proposed system consists of a positive lens, followed by a MEMS mirror, an OAP mirror and a wide-angle lens group. And the design is implemented in Zemax Optical Studio, which is a powerful tool for designing and analyzing all kinds of optical systems. As shown in **Figure 1**, the laser beam first passes through a pre-positive focusing lens to a two-axis MEMS mirror. With a mechanical tilt angle of the MEMS mirror, the beam is reflected into twice of tilt angular field. Then the beam travels through an OAP mirror and wide-angle lens group. The constant power image spot moves uniformly in large scan field.

In simulation, the wavelength used in the system is 905 nm. It is one of the most popular lidar wavelengths in autonomous vehicle applications because of low cost and high safety threshold for human eyes. The initial beam for the system is defined to be Gaussian TEM_{00} with the waist of 2 mm in physical optics model. Such beam can be easily obtained in reality and able to focus on a single two-axis MEMS mirror by the pre-positive lens. The main parameters of the MEMS mirror produced by Mirrorcle Technologies inc. are listed in **Table 1**. In drive system, different actuation voltages are applied in two axes respectively.

Table 1. Parameters of the MEMS mirror from mirrorcle technologies inc.

Parameter	Value
Mirror Type and Size	Bonded mirror of 4.2 mm diameter
Maximum Angle—X axis [degree]	5.1984
Maximum Angle—Y axis [degree]	5.2577



(a) (b)

Figure 1. The scheme of the scanning system. (a) Front view of the system; (b) Top view of the system.

And the mechanical tilt angles of the MEMS mirror are different as well, which are ±2.5˚ in vertical direction and ±4˚ in horizontal direction. As a result, the system is able to scan in a rectangular FOV.

The design of the OAP mirror and wide-angle lens group are key parts to realize scan angle linear extension, which are presented following.

2.2. Design of Off-Axis Parabolic Mirror

A parabolic mirror has the ability to take light from a point source placed at focal point and create a collimated beam without introducing spherical aberration. Moreover, unlike a complete parabolic mirror, the OAP mirror which is a portion of a parent parabolic mirror has more interactive space around the focal point without obstructing the incoming beam.

The principle of the OAP mirror is shown in **Figure 2**. The equation describing a parabola surface is given by:

$$-2Rz + y^2 = 0 \tag{1}$$

where R is radius of curvature of the parabola surface. It equals two times of parent focal length of the OAP mirror. The parameters and value used in design are shown in **Table 2**.

As mentioned above, the laser beam projects into an angular field with angle θ (angle between the beam and chief ray). After being reflected by the OAP mirror, the laser can be converted into parallel beam. The beam angle θ leads to a displacement of the parallel beam h. We consider that the displacement h has an approximately linear relationship to the beam angle θ.

2.3. Design of Wide-Angle Lens Group

The scan field for the wide-angle lens group is set to ±30˚. To achieve this target, a wide-angle lens group is designed as shown in **Figure 3**. Such a lens system has a front lens group of a positive refractive power and a rear lens group of a negative refractive power.

The lens group is based on a sample lens from ZEBASE library (F002). The sample lens is optimized with surface curvatures as variables for the best spot performance while the scan FOV is maintained. Then variables such as glass

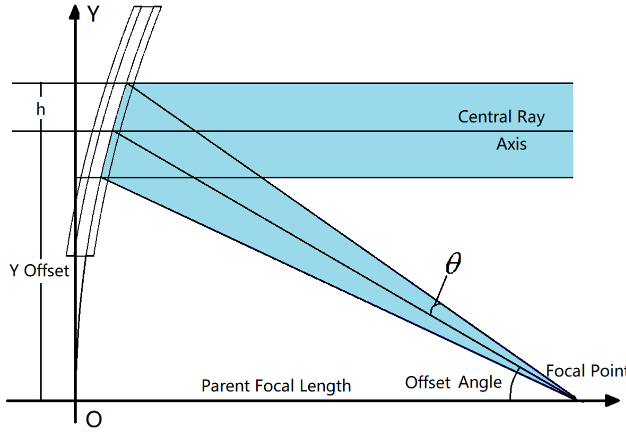


Figure 2. Diagram of off-axis parabolic mirror.

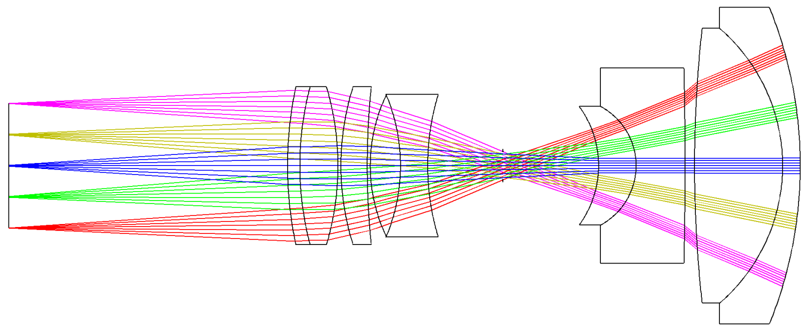


Figure 3. Graph of wide-angle lens group.

Table 2. Parameters of the off-axis parabolic mirror.

Parameters	Value
Effective Focal Length (mm)	101.6
Parent Focal Length (mm)	50.8
Diameter (mm)	25
Off-Set angle (degree)	30
Y Offset(mm)	27.6

type, surface separation and *f*-theta constrain are added to achieve much better scanning performance. The data for an optimized wide-angle lens group are shown in **Table 3**.

The effective focal length of the lens group is equal to 14.05 mm. The emergent angle θ_o (rad) from the wide-angle beam and incident parallel beam with displacement *h* satisfy:

$$\theta_o = h/f \quad (2)$$

Low *f*-theta distortion is critical in lens systems requiring linearly scaled dimensional fidelity. To get a better scan field performance, the goal of *f*-theta distortion for the wide-angle lens is set to be lower than 0.5%. As **Figure 4**

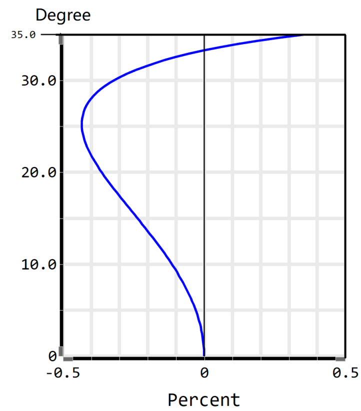


Figure 4. *f*-theta distortion of the optimized wide-angle lens group.

Table 3. Design data of the wide-angle inverted telephoto lens group.

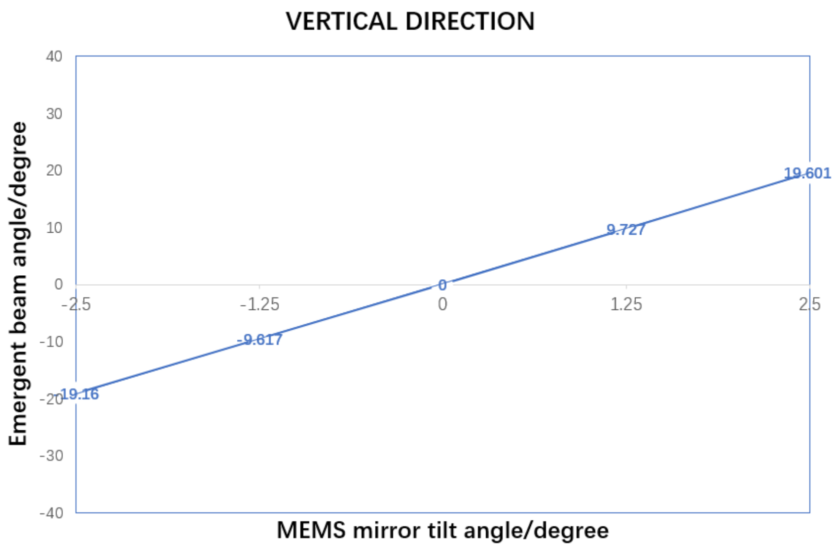
Surface No.	Radius of Curvature/mm	Surface Separation/mm	Glass Type	Diameter/mm
1	−48.131	35.000		10
2	−34.439	1.542	LAF2	10
3	35.413	4.775	PSK3	10
4	−35.553	0.381		10
5	−98.824	3.302	LAN12	10
6	−20.874	0.381		9
7	23.310	3.785	SK16	9
8	−31.375	3.420	SF1	9
9	12.757	21.444		7.5
10	8.537	4.710	K7	7.5
11	530.664	6.147	SF3	12.367
12	−159.640	1.194		17.367
13	23.023	11.049	PSK3	17.367
14	53.589	2.210	LAF2	20

shown, the maximum *f*-theta distortion is 0.43% after optimized in 30 degrees field.

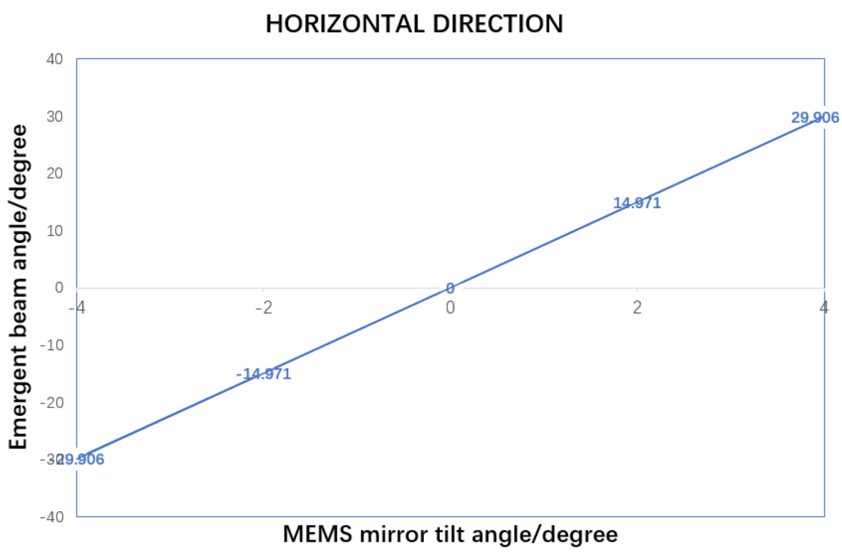
3. Results and Discussions

As a lidar scanning system for autonomous vehicle applications, the optical performances are determined by FOV, scan linearity and spot size in long distance.

By tracing the single ray with maximum MEMS mirror tilt angle, the corresponding emergent beam angle is obtained in image space. Results show that the nearly uniform scanning in a 59.8˚ × 38.8˚ FOV is realized. **Figure 5** shows the linear relationship between tilt angle and emergent beam angle. The amplification factors of the scan angles are 3.7375 in horizontal direction and 3.88 in vertical direction, respectively.



(a)



(b)

Figure 5. The relationships between tilt angles and emergent angles. (a): vertical direction (b): horizontal direction.

The size of beam is related to the received energy and affects the spatial resolution of the target in the 3D image lidar system. A large size of beam may result in not enough energy for the photo detector in receive side. The angular resolution for two adjacent circles with 17 cm diameter at a distance of 100 m is 0.1˚. **Figure 6** is the spot patterns of the optimized system at distance of 100 m. The spots are the cases corresponding different MEMS mirror mechanical tilt angles and different scan angles in the FOV. As shown in the figure, the patterns of the beam spots are less deformation except some spots in the corner of the FOV. And the diameter of the spot varies from 16.2 cm to 19.8 cm over FOV. The results indicate that the spot performance is good to a lidar scanning system for a distance of 100 m.

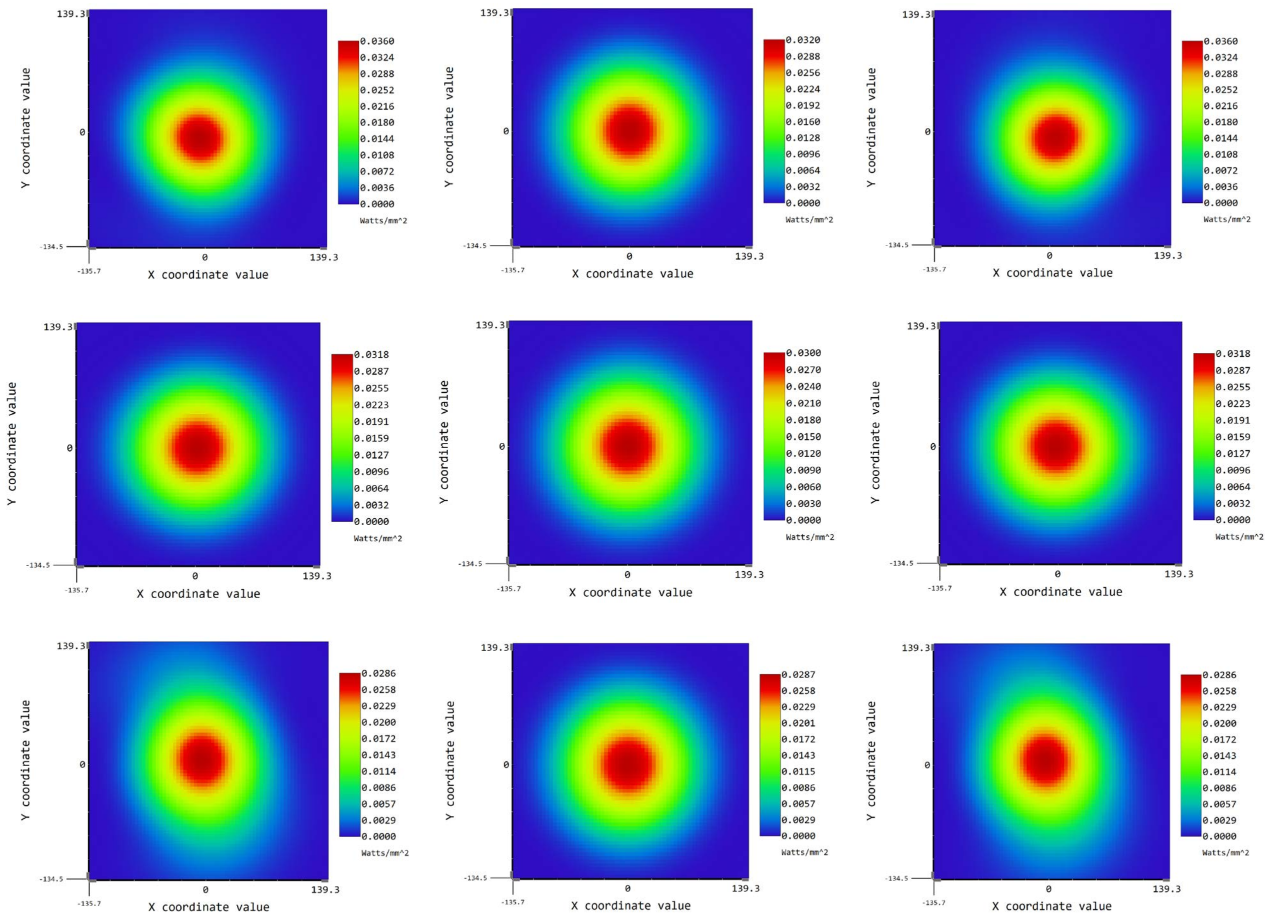


Figure 6. Beam spot patterns with different MEMS mirror tilt angle at a distance of 100 m away. The scale is 275 mm. The three line from the upper left to lower right are the cases corresponding the tilt angles (2.5˚, −4˚), (2.5˚, 0˚), (2.5˚, 4˚), (0˚, −4˚), (0˚, 0˚), (0˚, 4˚), (−2.5˚, −4˚), (−2.5˚, 0˚), (−2.5˚, 4˚), respectively.

4. Conclusions

A new optical scanning system based on two-axis MEMS mirror has been designed for 3D image lidars. The scan angle is linearly extended by adding an OAP mirror and a wide-angle lens group.

The optical performances of the scanning system in scan angles and beam spots are discussed. The system can uniformly scan in a large rectangular FOV (59.8˚ × 38.8˚). The spot size is investigated in physical optics propagation modeling, which varies from 16.2 cm to 19.8 cm at a distance of 100 m. Due to the application of the OAP mirror, the system can fold up to a smaller size. The proposed scanning system has great potential in vehicle-mounted 3D image lidars.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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