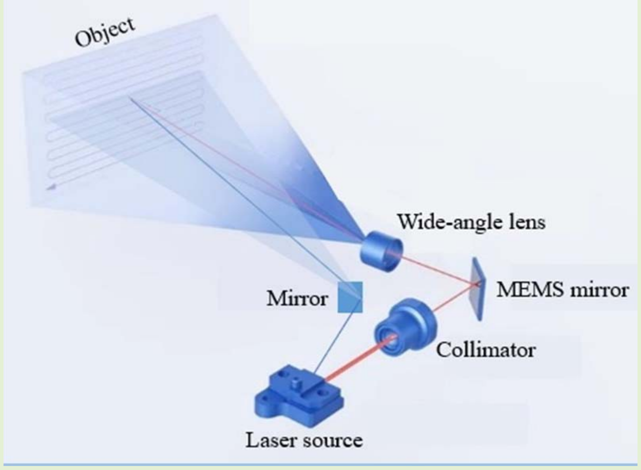
Design and Realization of Wide Field-of-View 3D MEMS LiDAR

Chia-Hsing Lin, Hao-Sheng Zhang, Chia-Ping Lin, and Guo-Dung J. Su



***Abstract*—Light detection and ranging (LiDAR) sensors are promising for automated transportation to detect the surrounding environment. However, most LiDAR solutions are complex and bulky. By designing a MEMS-mirror-based LiDAR, we can improve the volume constraints, but MEMS mirrors could limit scanning angles. In this work, we simulated and demonstrated a MEMS LiDAR system to solve the current obstacles. Combining a MEMS mirror and a wide-angle lens into the system, small-volume and large field-of-view (FOV) LiDAR systems can be realized. We use ray tracing optical simulation software to design a pair of aspherical lenses to expand the scanning angle. After the laser beam passes through the wide-angle lens, the FOV can be increased to 104 degrees. The distortion of the wide-angle lens is controlled below 3%, making the scanned image precise to the actual situation. In order to experimentally demonstrate the small-volume MEMS scanning LiDAR, a modular laser rangefinder is used with a MEMS mirror. The entire system of the LiDAR scanner is around 15 cm × 5 cm × 2.5 cm. In the natural light environment for wide-angle LiDAR measurement, the maximum error is less than 2%. Finally, an image processing program is written to convert the scanned data into a 3D point cloud image, and the generated image proves the complete function of the proposed LiDAR.**

***Index Terms*—LiDAR, wide-angle scanning, time of flight, optical system design, portable, MEMS mirror, point cloud diagram.**

I. Introduction

It is essential to acquire 3D images for autonomous driving. The straightforward step is to use stereo cameras like human eyes. However, cameras have limitations in the fixed resolution of the camera and relatively limited depth recognition capabilities [1], [2]. Besides, it is challenging to detect 3D information without high-quality images and accurate distance information [3], [4]. Furthermore, the camera's most obvious limitation is the lighting, which means that the camera cannot obtain reliable data from relatively or completely dark scenes or objects. The rapid development of light detection and ranging (LiDAR) sensors could provide high image resolution, high range accuracy, and a high frame rate. LiDAR sensors are widely used in military and civilian applications, such as laser ranging, battlefield environment recognition, terrain scanning, and monitoring. In recent years, the design architecture of LiDAR was initially based on the traditional rotating scanning motors for ranging. On the other hand, MEMS-based 3D imaging lidar scanning mirror has unrivaled advantages in terms of size, speed, and cost over motor types of laser scanners, making them ideal for a broader range of applications. The compact system using MEMS mirrors demonstrated by Moss *et al.* has excellent performance parameters [5], but it is still significantly "overweight" and "oversized" for autonomous driving applications [6]. For ADAS applications, size, weight, and power are not significant factors compared to the reliability, FOV, and scanning rate. Meanwhile, for mobile robotic platforms (UAV or UGV), the size, power, and weight are determining constraints. At present, the LiDAR system still has many shortcomings for the autonomous driving market. The scanning angle is limited, the power consumption is large and expensive [7], [8]; therefore, improvement is desirable. Lee and Wang added the f-theta lens and achieved the linear scan [9], [10]. However, many lenses are used, and this approach reduces the output of light energy. They expanded the angle by 2.45 times but did not analyze the target plane spot size factor with larger magnification.

Manuscript received September 24, 2021; accepted November 1, 2021. Date of publication November 9, 2021; date of current version December 29, 2021. This work was supported by the Ministry of Science and Technology under Grant 109-2221-E-002 -187-MY2. The associate editor coordinating the review of this article and approving it for publication was Prof. Hsin-Ying Lee. *(Corresponding author: Guo-Dung J. Su.)*

Chia-Hsing Lin was with the Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 10617, Taiwan. He is now with Taiwan Semiconductor Manufacturing Company, Ltd. (TSMC), Hsinchu 300, Taiwan.

Hao-Sheng Zhang, Chia-Ping Lin, and Guo-Dung J. Su are with the Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 10617, Taiwan (e-mail: gdjsu@ntu.edu.tw).

Digital Object Identifier 10.1109/JSEN.2021.3127045

We decided to use scanning LiDAR based on MEMS mirrors to scanning and ranging[1]. However, the mechanical tilt angle of a MEMS mirror is usually less than 20°. For a dual-axis MEMS mirror, the tilt angle could be even smaller. It is not enough for 3D imaging lidar systems. Therefore, we design a wide-angle lens for a MEMS LiDAR transmitter to collimate the light to the entire scene to illuminate the object. We propose a system that uses a MEMS mirror as a LiDAR 3D scanning device, which successfully reduces the size and power consumption and achieves large-angle scanning through a customized wide-angle lens. As far as we know, this is the first demonstration of using LiDAR with a MEMS scanning mechanism to achieve an optical scan range of 104° without using other electronic equipment. The MEMS mirror is integrated with an off-the-shelf time-of-flight (TOF) measurement engine to form a low-power 3D LiDAR. Finally, an in-house image processing program is used to convert the scanned data into a 3D point cloud image, and the generated image proves the complete function of a LiDAR system.

II. DESIGN AND SIMULATION OF THE WIDE-ANGLE MEMS LIDAR SYSTEM

A. System Structure

The LiDAR system is composed of four parts: (1) laser diode collimator used to collimate the emitted light of the laser light source, (2) laser scanning system containing a MEMS mirror to deflect the laser light, (3) wide-angle scanning lens installed in front of the MEMS mirror to expand the scanning angle, and (4) a photodiode so that the reflected light signal at a larger angle can be detected. As shown in Fig. 1, the light source from the laser diode is collimated by the collimator and then coupled to the MEMS mirror. After being deflected by the dual-axis MEMS mirror, a small range of a 2D scene can scan. However, because the MEMS mirror's deflection angle is small, the laser scanning light cannot cover the desired scanning range. Therefore, we designed a set of wide-angle scanning lenses to be installed after the MEMS mirror. Finally, to allow the optical signal of the entire scanning range to enter the receiver, a single-pixel photodiode is adopted. This method allows us to have a simple, lightweight, and wide-angle LiDAR system. The optical simulation architecture of the entire LiDAR system is shown in Fig. 1. The optical propagation simulation in the system is based on the geometric optics theory, and the optical lens meets the system requirements. The entire system is constructed using OpticStudio® (Zemax, LLC) optical simulation software and uses ray tracing optimization functions to improve the system's optical lens quality.

B. Wide-Angle Scanning Lens

Because the MEMS mirror's mechanical tilt angle is +/−6 degrees, which means +/−12 degrees optically, therefore, there are 24 degrees of the total optical scan range. We add a wide-angle scanning lens behind it to improve the optical scan range. The traditional feasible method is adding an angle expansion optical system to the scanning system, consisting of a positive lens behind the MEMS mirror and a negative lens behind it. However, this traditional lens set has two disadvantages: (1) the emitted light beam's divergence angle is too large. Although for short-distance targets, a large laser divergence angle will not significantly impact scanning, when used for targets tens of meters or hundreds of meters, the outgoing beam's spot size will become more significant. The energy per unit area rapidly reduces, causing the returned laser signal to be too small. The signal-to-noise ratio is too low to be received by the detector. (2) The expanded scanning angle is limited (usually less than 50 degrees). If the FOV increases, the distortion will become very serious. Therefore, we use the free-form surface technology to design the wide-angle lens's surface shape into different regions. We designed a wide-angle lens with this technology that can expand the scanning range four times and controlled the maximum distortion value within 3%, as shown in Fig. 2. It allows our wide-angle LiDAR system to achieve precise and large-angle scanning without curvature of field.

When designing the lens, we introduce the concept of a free-form surface, cut the lens's surface into many regions, and independently adjust each area's surface structure—the lens surface design using an aspheric formula, as shown

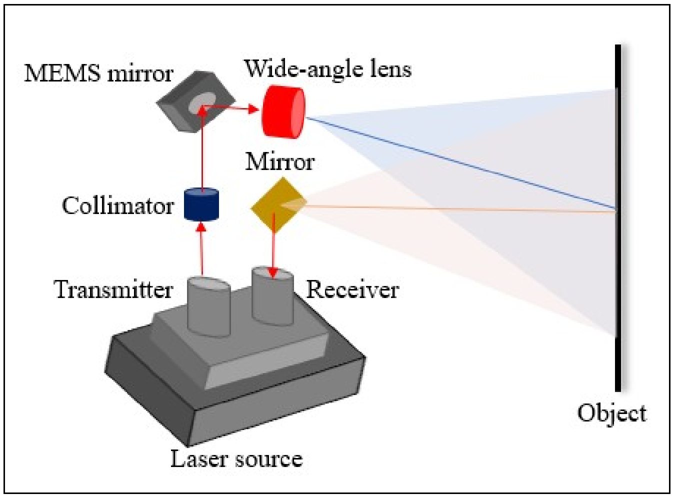


Fig. 1. Schematic diagram of the optical system of the MEMS-based wide-angle TOF LiDAR.

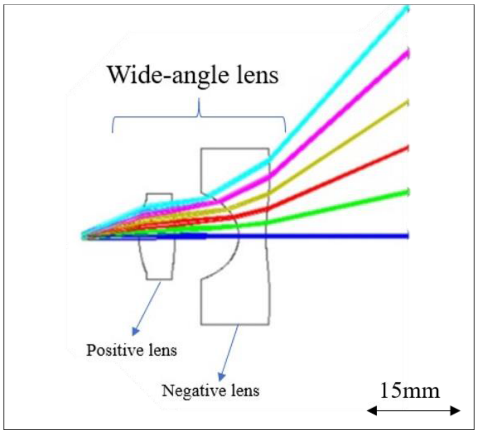
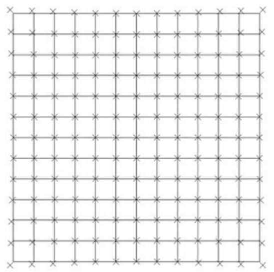


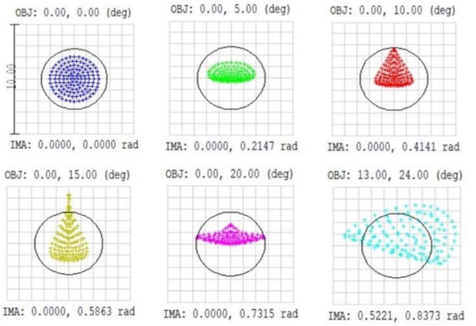
Fig. 2. In the simulated 3D layout of the wide-angle lens, each line of different colors represents the incident light differently. The wide-angle lens system we designed is a combination of a positive lens and a negative lens. The detailed structure of the lens surface is adjusted in different regions to improve the quality of the laser beam in each scanning area. The optical field-of-view of the wide-angle lens group is 104 degrees.



Grid Distortion

- Field: Maximum 104 degrees
- Incident angle: Maximum 24 degrees
- Maximum distortion: 2.7750%
- Wavelength: 0.9050 μm

Fig. 3. The grid distortion of the wide-angle lens group simulation result done by Zemax. It must be noted that the value of the field represents the oblique angle, not the x-axis or y-axis. The optical scan range of the wide-angle lens group we designed is 104 degrees.



Spot Diagram

- Units are mr.
- Airy Radius: 2.752 mr
- Surface: IMA
- Wavelength: 905 nm

Field	1	2	3	4	5	6
RMS radius	1.498	1.067	1.194	1.785	1.428	2.835
GEO radius	2.027	1.883	2.581	4.265	2.718	4.819

Fig. 4. Spot size with different scan angles in the target plane perpendicular to the optical axis at a distance of about 100 m. The scale is ten microrads, where the two lines from the upper left to lower right are the cases corresponding to the scan angle being (0°,0°), (0°,5°), (0°,10°), (0°,15°); (0°,20°), and (13°,24°), respectively.

in Eq.(1).

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum a_i r^{2i} \tag{1}$$

where c is base curvature, k is the conic constant, r is the radial coordinate measured perpendicular from the axis. This formula is a binary function with many higher-order terms. By adjusting the higher-order term's coefficient, the shape of the surface can adjust to our needs. With this design, we can get a wide-angle LiDAR that can scan long distances without severe distortion. The grid distortion is illustrated in Fig. 3 with less than 3% distortion.

The spot sizes of different angles are shown in Fig. 4. The two lines from the upper left to lower right are the cases corresponding to the scan angle being (0°,0°), (0°,5°), (0°,10°), (0°,15°), (0°,20°), and (13°,24°), respectively. The angles listed above are incident angles in OpticStudio® simulation in Fig. 2. The light spot's size gradually increases with the angle, but they are all smaller than the airy disk, which meets the design requirements. We propose a MEMS-based 3D uniform scanning method, which achieves the design goal through only one positive lens and one negative lens. This wide-angle lens group's optical scan range is 104 degrees, and the distortion is less than 3%. Our design achieves a reduction in size and weight and reduces the number of optical components, making the entire LiDAR easier to assemble and increasing the entire system's durability. It dramatically reduces the manufacturing cost of LiDAR and gives it more opportunities to be applied to many emerging applications [11].

III. EXPERIMENTAL SETUP AND DATA PROCESSING

To demonstrate the scanning capabilities of our designed MEMS LiDAR and the effectiveness of the wide-angle lens, we modified the mechanical structure of the single-point laser rangefinder and added a MEMS mirror along with a wide-angle lens to successfully set up a LiDAR with a scanning angle of 104 degrees. The ranging unit uses a Garmin LiDAR lite v.3 TOF engine. Time of flight (ToF) is a measurement of the time it takes for an object to travel a certain distance in a space environment. We chose Garmin Lidar Lite v.3 for prototype development because of its small overall size, fast scanning rate, and its transmitting and receiving ends are at the exact location, which is highly convenient and does not require additional consideration of scattered light reception. This device has a 2-wire, I2C-compatible serial interface. It can be connected to an I2C bus as a slave device, under the control of an I2C master device. It supports 400 kHz Fast Mode data transfer. The I2C bus operates internally at 3.3 Vdc. An internal level shifter allows the bus to run at a maximum of 5 Vdc, and 3k ohm pull-up resistors ensure this functionality, allowing for a simple connection to the I2C host. The device has a 7-bit slave address with the default value of 0 × 62, and the elective eight bits I2C address is 0×64 write and 0 × C5. The device initiates the measurement by performing a series of acquisitions. Each acquisition is the transmission of the primary laser signal, while the return signal is recorded on the receiver. If there is a signal match, the result is stored in the memory as a related record. The device integrates the acquisition until the signal peak value in the relevant record reaches its maximum value. If the returned signal is not strong enough for integration, the device will stop at the predetermined maximum acquisition count. The signal strength is calculated according to the signal record peak's size, and the effective signal threshold is calculated according to the noise floor.

The laser light from the TOF engine is incident on the MEMS mirror, and the reflection of the MEMS mirror scans the target. Since the FOV of the TOF engine is small, we added a wide-angle lens we designed after the MEMS mirror to increase the scanning angle. Furthermore, through the point-cloud diagram image processing program we developed, the scanned data is converted into an image that can express depth information. By doing this, there are no large-scale experimental instruments in the system we designed, and the power control and signal processing systems of all equipment are small IC circuit boards. Moreover, because of our experimental architecture design, the required power consumption is efficient, the weight is also very light, and it can be moved around very conveniently, so the MEMS LiDAR system we designed is full of feasibility in the ADAS market.

Both the laser transmitter module and the optical signal receiver module are modified using laser rangefinders, but because the size of the laser beam is different from the MEMS mirror, we added a set of telescope structures

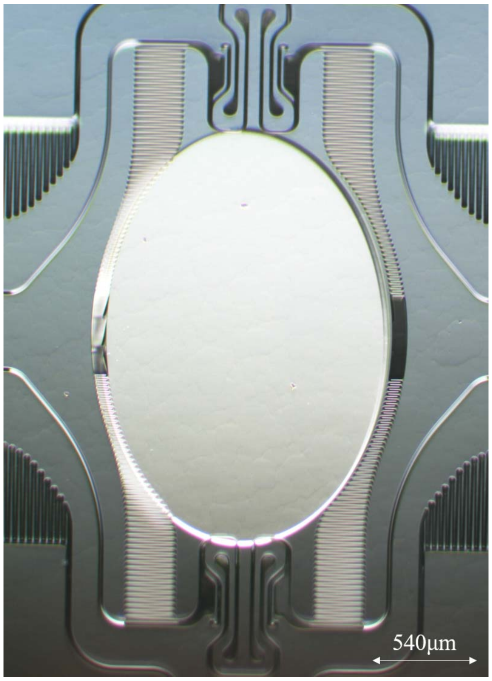


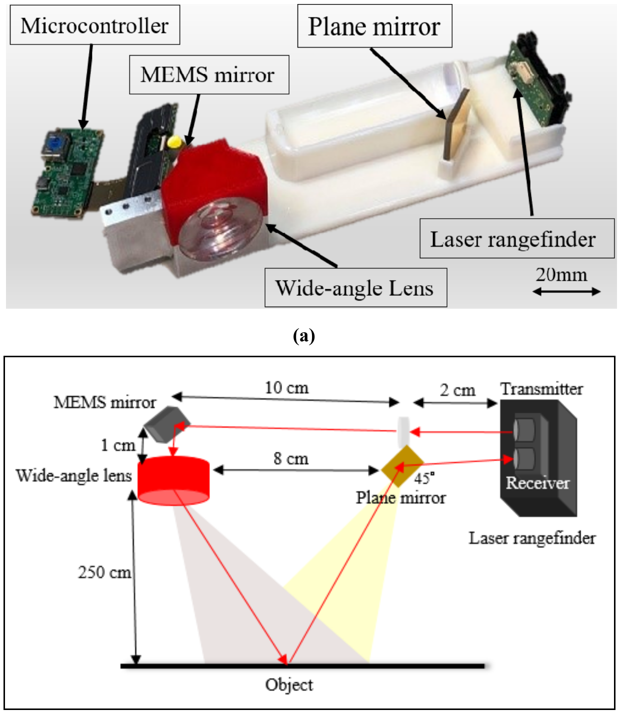
Fig. 5. The internal structure of the MEMS mirror. The laser beam is first adjusted by the beam expander, reflected by the MEMS mirror, and then passed through the wide-angle lens to increase the scanning angle.

(Thorlabs LA1251-B, LC2969- B) so that the laser light can be irradiated entirely on the mirror. Regarding the scanning system, we use a MEMS mirror (UM-6002G) produced by UltiMEMS, as shown in Fig. 5.

The SEM image of the MEMS mirror shows the details of the comb-drive actuators and the ellipsoid shape reflecting surface to accommodate oblique incident light. This MEMS mirror is a package in the form of an EV-kit, and a drive circuit board controls its movement. The laser rangefinder uses the Arduino Uno as the control circuit. By writing the Arduino language, the LiDAR-lite laser's pulse frequency of 500 Hz and the receiving frequency of the light signal is controlled, and the depth information of each point in the space is received on the Arduino control system. The complete setup is shown in Fig. 6.

Because the laser light transmitting and receiving module in the LiDAR system is modified using an off-the-shelf laser rangefinder, and the beam size at the transmitting end, the receiving end structure must also be modified to allow large-angle light to enter the photodetector. If we remove the lens and the housing in front of the receiving end, it could receive large-angle light signals[12]. As shown in Fig. 7, although the original receiver lens can increase the detection range of LiDAR because it could improve the receiving ability of weak reflected light signals, it has a limited receiving angle. In order to prove the design of a large FOV MEMS LiDAR, we decide to use a bare photodiode without any lens [13]. The distance measuring range of our LiDAR system is limited to 250 cm. After experiments, our wide-angle LiDAR system can scan at an optical field-of-view of 104 degrees and finally generate a 3D point cloud image through an in-house image processing program.

In Table I, we have consolidated the weight of each part of the wide-angle LiDAR system we designed. Our system weighs only 267 grams, which is very lightweight and has a potential for wide application.



(a)

(b)

Fig. 6. (a). A wide-angle MEMS LiDAR system modified from a laser rangefinder. The laser beam is first adjusted by the beam expander, reflected by the MEMS mirror, and then passed through the wide-angle lens to increase the scanning angle. (b). The design diagram of the wide-angle MEMS LiDAR prototype. The distance between MEMS mirror and wide-angle lens is 1 cm. The separation distance between lens and lidar module is about 12 cm. The rotation angle of the plane mirror is about 45 degrees. The total measurement distance between an object and a wide-angle lens is 250 cm. Furthermore, the direction and path of the laser ray (reflected light) are illustrated in the drawing, indicated by a red line.

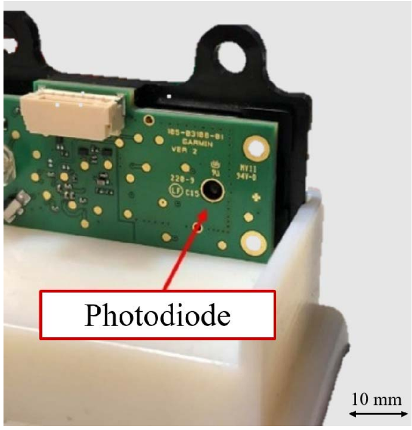


Fig. 7. Receiver without a lens. Although the receiver lens can increase the detection range of LiDAR, it can increase the receiving ability of weak reflected light signals, but it severely limits the system's light signal receiving angle. If the receiver lens is removed, the limitation on the optical signal's receiving angle can be lifted.

IV. GENERATION POINT-CLOUD DIAGRAM

We designed the wide-angle LiDAR based on the TOF principle and used the beam's flight time to calculate the distance between the object and the light source. By adding a MEMS mirror and a wide-angle lens to the one-dimensional

TABLE I
THE TABLE SHOWS THE WEIGHT OF EACH PART OF THE WIDE-ANGLE LIDAR AND THE SIZE OF THE ENTIRE SYSTEM

Item	Weight	Specification
Laser rangefinder	22 g	Garmin lidar lite v.3
Beam expander lens group	29 g	Thorlabs stock lens
MEMs system	33 g	Ultimems Inc.
Wide-angle lens	37 g	Material Is PMMA
Micro-controller	25 g	Arduino Uno
System shell	121 g	Print by 3D printer
Whole system	267 g	150×50×25 (mm)

Fig. 8. We made an “NTU” card and scanned it with LiDAR to compare the difference before and after the wide-angle lens was added. The results of the scan are shown in the figure below.

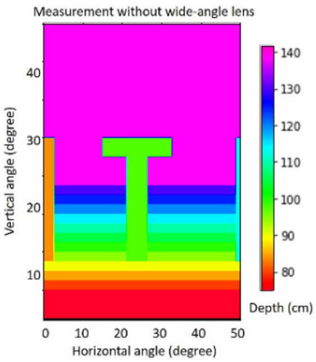


Fig. 9. The scan result of a MEMS Lidar system without the wide-angle lens.

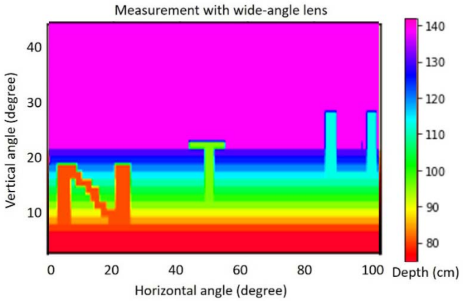


Fig. 10. The scan result of adding a wide-angle lens. In this scan, the maximum horizontal angle could reach 104 degrees.

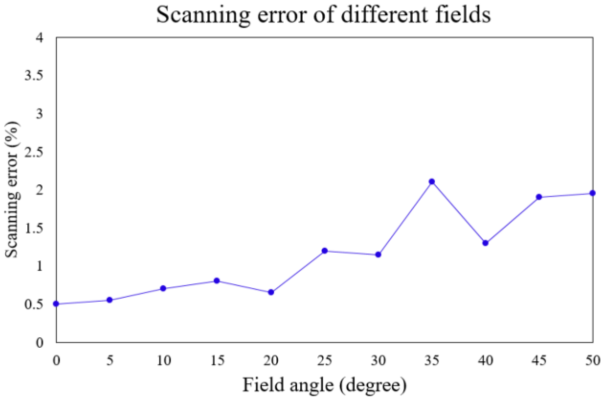


Fig. 11. For the measurement error of each angle, the target is set at 2.5 meters away. Because the wide-angle lens is axisymmetric, we measured 0 degrees to 50 degrees. At large angles, because the beam diameter is large and the incident angle of the light beam received by the photodetector is large, the intensity of the light signal per unit area is low, so the error is more significant. However, the maximum error value is within 2 %, which has almost no effect on the image quality of the point cloud.

single-point laser range module, we could achieve small size and high-performance LiDAR scan system. By scanning our wide-angle LiDAR system, the depth relationship of each position in space can be captured on the computer. However, if only the distance between each object’s position in the space can be obtained, only a large number of digits will be displayed. Therefore, we developed an image processing program by ourselves, which was written in Python$^{\text{TM}}$ language, to convert collected digits into an image. As shown in Fig. 8, we made the abbreviation “NTU” of National Taiwan University and scanned it with a wide-angle LiDAR to compare the difference before and after adding a wide-angle lens. The scan result of the LiDAR system is to use the display window in the Arduino control program to read the spatial information and export it into a file in the form of text. These files with only digital information are imported into the image processing program and combined into one picture, showing depth information using color. Our system limits the number of points detected due to the limitation of the ranging module’s performance. In Fig. 9, there are 1000 distance data points in the vertical direction and one data array every degree in the horizontal direction before the wide-angle lens set is applied. The scan range is only 50 degrees horizontally. In Fig. 10, we adjusted the MEMS mirror’s fast axis to be parallel to the ground so that the horizontal field-of-view of the scanning range reached 104 degrees after we applied the wide-angle lens. From the results of the scan, it is known that the field-of-view of LiDAR with a wide-angle lens is increased accordingly. The recorded image in Fig. 10 does not show severe distortion as predicted in Fig. 3.

We summarize each angle’s scanning result error in Fig. 11, and the target was set at 250 cm away when we performed this measurement. Because the wide-angle lens is axisymmetric, we measured the scan error from 0 degrees to 50 degrees. Here we define scanning error $\Delta h \equiv h' - h$, where h' is the experimental measurement result value and h is the actual distance. After the calculation, the Δh generated is divided by the target’s actual distance to obtain the scanning error expressed as a percentage. From the measurement results, we know that our LiDAR system’s measurement error is less than 2 %, which corresponding to a max error of 4.1 cm when

TABLE II
THE REQUIREMENTS FOR MEMS MIRRORS FOR DIFFERENT LIDAR SYSTEMS

	[9]	[10]	[11]	[14]	Our work
FOV	40° x 40°	60° x 60°	30° x 30°	52° x 26°	104° x 45°
Mirror size (mm)	1.7 x 1.7	3.6 x 3.6	5.0 x 5.0	3.6 x 3.6	1.0 x 1.2
Max mechanical tilt angle	±8°	±5°	±5°	±6.55°	±10°
Whole system volume				15(cm) x 22(cm) x 20(cm)	15(cm) x 5(cm) x 2.5(cm)

the object is 250 cm far at 50 degrees. The target object we measured is thick cardboard, and its reflectance is a uniform material, which does not scatter light. Therefore, it assures good quality-images.

V. DISCUSSIONS AND CONCLUSION

We have proposed an optical system design for a LiDAR scanning system based on a MEMS mirror and wide-angle lens to make a small and lightweight MEMS LiDAR. In Table II, we make a comparison table for the performance of MEMS mirrors in LiDAR systems. The LiDAR system design in our work has a large FOV compared with the other references below in Table II. Although our MEMS mirror size is the smallest, the scanning angle range is more extensive due to the wide-angle lens design. The entire system's weight is less than 270g, and the volume is 15 cm × 5 cm × 2.5 cm. Our overall system volume is smaller than others.

We experimentally demonstrated a wide-angle LiDAR with a FOV of 104 degrees. We use ray-tracing software to design a wide-angle scanning lens that can magnify the MEMS mirror's scanning angle to 104 degrees, and the distortion is less than 3%. It is worth mentioning that the use of a MEMS mirror and a wide-angle lens on the scanning device can achieve a smaller size and faster scanning speed, with high efficiency, large field of view, simple structure, low power consumption, and lightweight, which means that the 3D image LiDAR has high potentials. As mentioned above, the maximum error is the actual distance of the experimental measurement result of 4.1 cm divided by the actual distance of the target object of 250 cm to obtain the scanning error expressed as a percentage. Its value is about 1.64%, which is significantly less than 2%. In the natural light environment for wide-angle LiDAR measurement and analysis, the maximum error is less than 2%. Through the TOF calculation method, we developed an image processing program to generate point cloud images. Finally, the image processing program is used to convert the scanned data into a 3D point cloud image, and the generated image proved the complete function of LiDAR.

In the future, our proposed work is expected to improve the accuracy of the overall measurement data and speed up the scanning frequency, thereby increasing the optical scan range and reducing measurement errors. The wide-angle 3D MEMS LiDAR is a potential application for automatic sensing technology. It could be potentially applied to indoor autonomous delivery vehicles, mobile robotic devices, or self-guidance drones.

TABLE III
THE PROTOTYPE OF LASER OPTICAL SENSOR

	LIDAR-LITE V3
Dimension	2(cm) x 4.8(cm) x 4(cm)
Range(min-max)	0-40(m) Laser Emitter
Accuracy	+/- 2.5(cm) at distances greater than 1(m)
Laser Wavelength	905(nm)
Optical Aperture	12.5(mm)
Scan rate	1–500(Hz)
Cost	~ US$ 175.00
Weight	22(g)
Power	4.75–5(V) DC; 6(V) Max

APPENDIX

This is the LIDAR-Lite v3, a compact, high-performance optical distance measurement sensor from Garmin™. Small in form and light in weight with a low power consumption of less than 130 mA during an acquisition. The LIDAR-Lite v3 is the ideal solution for drone, robot, or unmanned vehicle applications.

REFERENCES

[1] D. Wang, C. Watkins, and H. Xie, "MEMS mirrors for LiDAR: A review," *Micromachines*, vol. 11, no. 5, p. 456, Apr. 2020, doi: 10.3390/MI11050456.

[2] T. Raj, F. H. Hashim, A. B. Huddin, M. F. Ibrahim, and A. Hussain, "A survey on LiDAR scanning mechanisms," *Electronics*, vol. 9, no. 5, p. 741, Apr. 2020, doi: 10.3390/electronics9050741.

[3] S. Royo and M. Ballesta-Garcia, "An overview of LiDAR imaging systems for autonomous vehicles," *Appl. Sci.*, vol. 9, no. 19, p. 4093, Sep. 2019, doi: 10.3390/app9194093.

[4] S.-H. Chung, S.-W. Lee, S.-K. Lee, and J.-H. Park, "LiDAR system with electromagnetic two-axis scanning micromirror based on indirect time-of-flight method," *Micro Nano Syst. Lett.*, vol. 7, no. 1, pp. 4–8, Dec. 2019, doi: 10.1186/s40486-019-0082-9.

[5] R. Moss *et al.*, "Low-cost compact MEMS scanning ladar system for robotic applications," *Proc. SPIE*, vol. 8379, May 2012, Art. no. 837903, doi: 10.1117/12.919804.

[6] *SpectroScan 3D MEMS LiDAR System Model MLS 201*, Spectrolab, Sylmar, CA, USA, 2016.

[7] F. Schwarz *et al.*, "Resonant 1D MEMS mirror with a total optical scan angle of 180° for automotive LiDAR," *Proc. SPIE*, vol. 11293, Feb. 2020, Art. no. 1129309, doi: 10.1117/12.2546035.

[8] D. Wang, H. Xie, L. Thomas, S. Koppal, and Y. Ding, "A low-voltage, low-current, digital-driven MEMS mirror for low-power LiDAR," *IEEE Sensors Lett.*, vol. 4, no. 8, pp. 27–30, Jul. 2020.

[9] X. Lee and C. Wang, "Optical design for uniform scanning in MEMS-based 3D imaging LiDAR," *Appl. Opt.*, vol. 54, no. 9, p. 2219, Mar. 2015, doi: 10.1364/ao.54.002219.

[10] X. Lee, C. Wang, Z. Luo, and S. Li, "Optical design of a new folding scanning system in MEMS-based LiDAR," *Opt. Laser Technol.*, vol. 125, May 2020, Art. no. 106013, doi: 10.1016/j.optlastec.2019.106013.

[11] C. Zhu, M. J. Hobbs, M. P. Grainger, and J. R. Willmott, "Design and realization of a wide field of view infrared scanning system with an integrated micro-electromechanical system mirror," *Appl. Opt.*, vol. 57, no. 36, p. 10449, Dec. 2018, doi: 10.1364/ao.57.010449.

[12] A. Kasturi, V. Milanovic, B. H. Atwood, and J. Yang, "UAV-borne LiDAR with MEMS mirror-based scanning capability," *Proc. SPIE*, vol. 9832, May 2016, Art. no. 98320M, doi: 10.1117/12.2224285.

[13] A. McCarthy *et al.*, "Kilometer-range depth imaging at 1550 nm wavelength using an InGaAs/InP single-photon avalanche diode detector," *Opt. Exp.*, vol. 21, no. 19, p. 22098, Sep. 2013, doi: 10.1364/oe.21.022098.

[14] P. K. Choudhury and C.-H. Lee, "Simultaneous enhancement of scanning area and imaging speed for a MEMS mirror based high resolution LiDAR," *IEEE Access*, vol. 8, pp. 52113–52120, 2020, doi: 10.1109/ACCESS.2020.2979326.