A compact 3D lidar based on an electrothermal two-axis MEMS scanner for small UAV

Dingkang Wang, Stephan Strassle, Aaron Stainsby, Yunkai Bai, Sanjeev Koppal, et al.

Dingkang Wang, Stephan Strassle, Aaron Stainsby, Yunkai Bai, Sanjeev Koppal, Huikai Xie, "A compact 3D lidar based on an electrothermal two-axis MEMS scanner for small UAV," Proc. SPIE 10636, Laser Radar Technology and Applications XXIII, 106360G (10 May 2018); doi: 10.1117/12.2304529

Event: SPIE Defense + Security, 2018, Orlando, Florida, United States

A Compact 3D LiDAR Based on an Electrothermal 2-axis MEMS Scanner for Small UAV

Dingkang Wang, Stephan Strassle, Aaron Stainsby, Yunkai Bai, Sanjeev Koppal, Huikai Xie*
Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA

ABSTRACT

This paper reports an electrothermal MEMS mirror-based LiDAR system. The MEMS mirror has a low driving voltage of 9 V and a large mirror aperture of 2 mm in diameter. The working range of this system is 80 to 250 cm with a distance resolution of 7.2 cm. The complete LiDAR prototype can fit into a small volume of 100 mm×100 mm×60 mm with the weight under 100 g. The use of such a MEMS mirror can greatly reduce the weight, size and power of LiDAR modules, making it possible for small UAVs to carry LiDAR for accurate navigation.

Keywords: MEMS Mirrors, LiDAR, laser range finder, UAV

1. INTRODUCTION

Small Unmanned Aerial Vehicles (UAVs) are finding more and more applications in search and rescue, exploration and surveillance [1][2]. The proper function of UAVs demands that they can acquire the depth information of the surrounding environment. 3D cameras have already been introduced for autonomous driving and flying. However, cameras may not be able to provide the true distance information, and the image quality will become poor at low illumination conditions.

Light detection and ranging (LiDAR) is a popular technology for autonomous vehicles [3]. A LiDAR scans a laser beam to the field of interest and measures the time-of-flight (ToF) to calculate the distance of each scanning point. A 3D point cloud can be built to provide the depth information of the surrounding environment. Laser range finders (LRFs) for single-point distance measurement have been commercialized with low cost, but 3D LiDAR are still quite expensive. The high cost of 3D LiDAR is due to the simultaneous requirements long range, large field of view (FoV), and high speed. In order to achieve a full 360° horizontal FoV and certain vertical FoV, multiple channels of transmitters and receivers are stacked vertically and rotated by a motorized stage, which drastically increases the cost and size. For example, LEDDAR's M16 uses sixteen individual transceiver units for a 9 ° vertical FoV[4]. IBEO's ALASCA LiDAR utilizes four laser channels for a vertical FoV of 3.2° [5]. Velodyne's latest model, VLS-128, stacks 128 lasers [6]. Such LiDAR systems are not power efficient and may be vulnerable to mechanical shock and wear. In addition, their vertical resolution is dependent on the number of transmitter and receiver channels, so high vertical resolution is always at the cost of high price and bulky structure. Furthermore, most of the LiDAR available on the market are significantly overweighed and oversized for applications in small UAVs.

To reduce the size and weight of LiDAR, microelectromechanical systems (MEMS) technology has been explored. Particularly, MEMS mirrors have been exploited extensively thanks to their advantages of small size, fast speed and low cost [7][8][9]. For a MEMS based LiDAR, both the size and weight are greatly reduced, and the horizontal and vertical scan can be much more easily realized, compared to motorized scanning LiDAR. For example, Moss *et al*. demonstrated a compact LiDAR system utilizing an electrostatic MEMS mirror with a 30°×40° FoV and 1.2 mm diameter, but this LiDAR still weighed 2.27 kg [7]. Most of reported MEMS LiDAR systems use electrostatically actuated MEMS mirrors, which can achieve high scanning speed, but typically have limited scanning range and require high voltage of in the order of 100 V. On the other hand, electrothermally-actuated MEMS mirrors can achieve large angle at low voltage [9][11][12], but they have not been used for LiDAR applications.

In this work, the feasibility of applying electrothermally actuated MEMS mirrors in a LiDAR system will be explored. The employed electrothermal mirror has a mirror plate of 2 mm in diameter. The paper is organized as follows. Section 2 introduces the architecture of the proposed MEMS LiDAR. Section 3 discusses the electrothermal MEMS scanner for the LiDAR. Section 4 presents the signal processing detail. Section 5 gives the experiment setup and measurement results.

*hkxie@ece.ufl.edu

Laser Radar Technology and Applications XXIII, edited by Monte D. Turner,
Gary W. Kamerman, Proc. of SPIE Vol. 10636, 106360G · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2304529

2. THE MEMS LIDAR ARCHITECTURE

The architecture of the MEMS LiDAR is shown in Figure 1. A Lightware OSLRF/01 1D laser range finder (LRF) [13]is used to measure the distance. The transmitter is an OSRAM 905 nm laser diode (LD) that can generate less than 30 ns short laser pulses. An iris is used to reduce the size of the laser beam and couple it to the MEMS mirror plate. The measurement range is 2.5 m with a ~20% reflective object based on the light power budget. The optical power received by the photodetector (PD) with a target distance of 2.5 m and laser peak power of 15 W is estimated to be $\geqslant$ 64 nW, which results in an SNR $\geqslant$ 12 dB for the PD.

The specifications of the Lightware OSLRF/01 Laser Range Finder are listed in Table 1. The laser beam spot diverges along its propagation path. The beam observed on the target at 1 m away is 4×6 mm^2. The laser range finder cannot automatically display the measured distance. Instead, two analogy pulses generated from the internal equivalent time sampling(ETS) circuit are used for deriving the ToF or the distance, which will be discussed in Section 4.

Table 1 Datasheet of Lightware OSLRF/01 Laser Range Finder.

Measurement Rate	41 Hz adjustable
Laser Peak Power	15 W
Laser Pulse Width(FWHM)	28 ns
Laser Wavelength	905 nm
Spectral width (FWHM)	10 nm
Plano-Convex Lens	25 mm Dia. 25mm FL
Field of View	~3°×3°

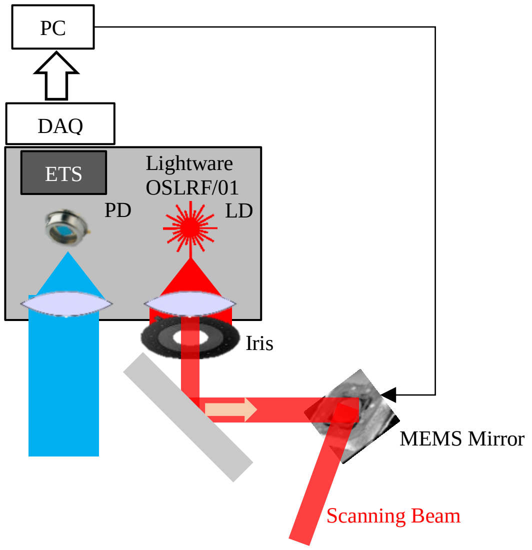

Figure 1. The schematic of the architecture of the MEMS LiDAR system.

3. MEMS SCANNER DESIGN AND CHARACTERISTICS

The 2-axis MEMS mirror utilized in this work is electrothermally-actuated and based on the inverted-series-connected (ISC) bimorph actuation structure reported in [9][11]. A single ISC bimorph actuator design is shown in Figure 2(a), which consists of three segments: inverted bimorph, overlap, and non-inverted bimorph, leading to zero tangential tip angle θ but with some lateral shift (LS) during vertical actuation. By connecting two ISC actuators in a folded fashion, both θ and LS are compensated. In this MEMS mirror, SiO_2 and Al are used as the two bimorph materials while Ti is used as the embedded heater material. The four actuators are arranged around the mirror and connected to the substrate for two-axis scan in both directions as shown in Figure 2(b).

An SEM picture of the fabricated MEMS mirror (WiO Tech, Wuxi, China) is shown in Figure 3(a). The measured static scan response is plotted in Figure 3(b), where an optical scan range of ±2.8° is obtained at 8.5 Vdc for both axes. The linear scan range is from 0.4° to 2.5°.

4. LIDAR SIGNAL ACQUISITION PROCESSING

4.1 Equivalent-time-sampling

High sampling rate in GS/s is usually required for high resolution ToF measurement, but this prebuilt LRF module features equivalent time sampling (ETS) circuits. This device does not contain a microprocessor to make the precise and ultra-fast calculations necessary for LIDAR measurements. Instead, ETS is an interesting solution for drawing out a nanosecond

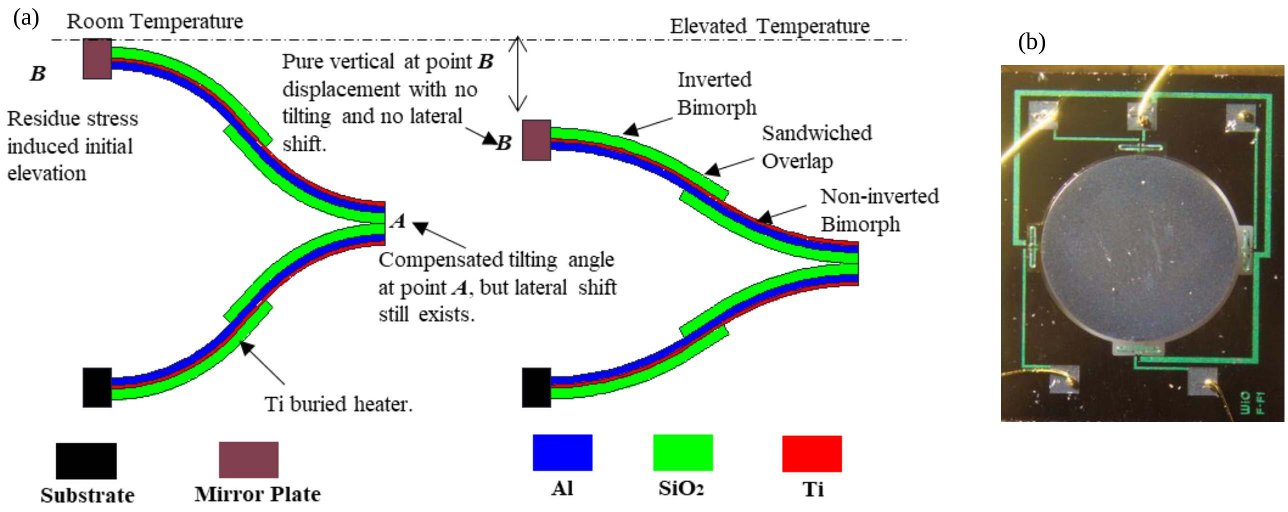

Figure 2 (a) Principle of the Al/SiO$_2$ ISC bimorph actuator. (b)A photo of the MEMS scanner.

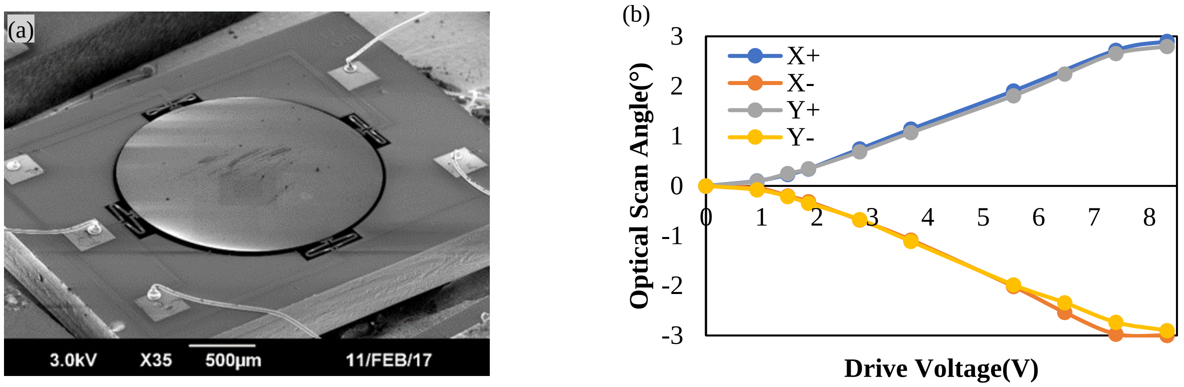

Figure 3 (a)An SEM of the fabricated MEMS scanner. (b) Static optical scan angle of the MEMS mirror.

pulse of signal into a millisecond long waveform. ETS is a method commonly used in oscilloscopes and electrical equipment that require extremely fast signal acquisition. ETS works by periodically sampling a new, distinct point on a repeating signal that comes in too fast to sample the whole signal in real time. ETS only works if the incoming signal is periodic in nature. By slowing down the original signal with ETS, a sampling rate of 16 kS/s is adequate to fully sample the ZERO (laser firing reference) and RETURN (signal detected) signals. Thus, fast ADC will not be required and most MCU development boards can be used in this LRF module.

The ZERO and RETURN signal from the LRF are sampled with a sampling rate of 50 kS/s. One pair of the signals is shown in Figure 4(a). ZERO is a periodic square wave reference signal for laser firing. RETURN is the signal of the detected laser pulse. Time-of-flight can be derived from comparing the time delay of the RETURN signal with respect to the ZERO signal. Figure 4(b) illustrates the signal process flow. It starts with processing the ZERO signal. The amplitude of the RETURN signal will change with the received optical power. Also, when the laser scans out of the acceptance angle of the receiver, the amplitude of the RETURN will drop rapidly to noise level. So those periods of weak or none RETURN signal are eliminated.

4.2 Walk error compensation

The challenging part of processing for the RETURN signal is how to minimize the walk error. Walk error is an intrinsic source of inaccuracies resulting from combining the following factors [14]:

- The detected pulse of light has a limited slope from its start until it reaches its peak of energy.
- Materials will reflect light with ratios varying between 0% and 100%.
- Pulse ToF measurement uses a single threshold to detect arrival of a signal.

The rising edge of the detected pulse of light is 5 ns, which is on the same order of the ToF to be measured. And the reflectivity of the target to be measured will vary a lot from 10% to 90%. The walk error will be significant if only a single threshold is used to measure the ToF.

A constant ratio of the peak power (voltage) of the RETURN pulse is used as the threshold for the RETURN pulse to compensate the walk error. And both the leading edge and trailing edge are weighted in finding the timestamp of the RETURN signal to minimize the jittering of single edge detection. The timestamp is between the leading edge and trailing edge and it is 1/3 closer to the leading edge. The ToF after the sequential equivalent time sampling (SETS) is the difference between the RETURN and ZERO timestamp. The actual distance can be derived from calibrating the slow down ToF:

$$Distance\ (\mathrm{cm}) = 95.2 * ToF(\mathrm{ms}) - 948.1(\mathrm{cm})$$

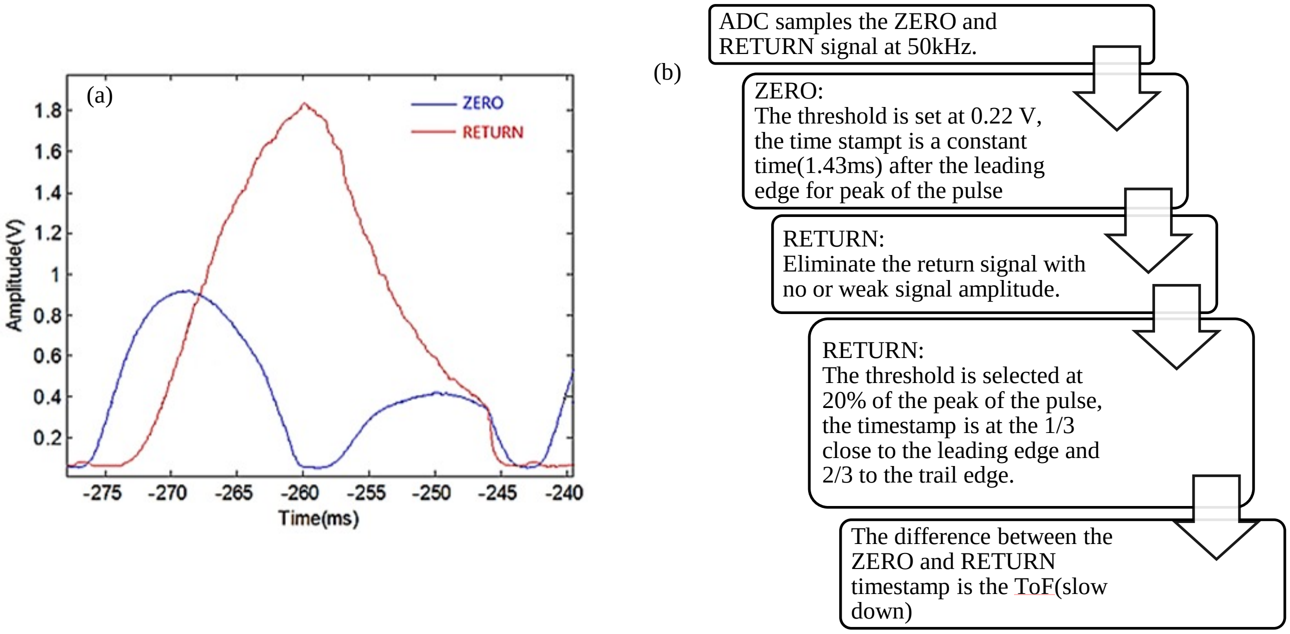

Figure 4. (a)One pair of sampled ZERO (laser firing reference) signal and RETURN (detected laser pulse) after ETS. (b) The signal process flow of the derivation of ToF from ZERO and RETURN.

5. LIDAR MEASUREMENT RESULT

A photograph of the assembly of the MEMS LiDAR on an optical bench is shown in Figure 5(a). A fully enclosed testing fixture has been designed in order to remove the need for an optical table resulting in a more compact and robust mechanical setup, as shown in Figure 5(b) and (c). By removing the necessity for an optical table, the new setup is more flexible when it comes to testing. The size of the enclosure is under 100 mm×100 mm×60 mm. In the future, this allows for the system to be tested in more real word conditions, or even mounted to a drone.

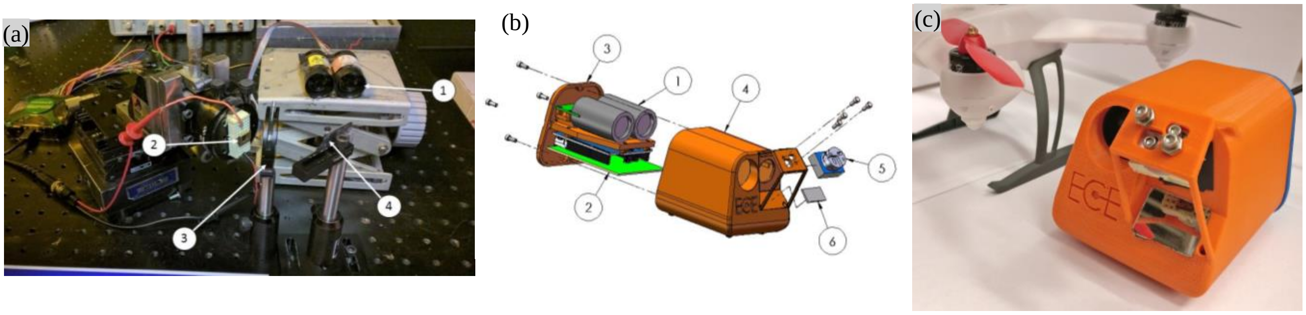

Figure 5. (a) Optical bench experimental setup: OSLRF-01 Module, 2: MEMS Mirror, 3: Iris, 4: 45°Angled Mirror. (b) CAD model of proposed Enclosure: 1. OSLRF-01 Module, 2. Printed Circuit Board, 3. Rear Cabling Enclosure, 4. Main Enclosure, 5. MEMS Alignment Stage, 6. 45° Angle Mirror. (c) The full enclosure of the LiDAR.

5. 1 Static distance test

This first test was performed to see how the LIDAR system would respond to a static object being placed at different distances to the LiDAR with same reflectivity and reflective angle. A cardboard box with a reflectivity of ~20% is used as the target object. Figure 6(a) shows the relationship between the ETS time of flight shift versus the object distance, starting at 100 cm and increasing to 250 cm.

5.2 Testing with static mirror and moving object

To explore the resolution of distance measurements, a four-point step made of carboard box was performed with the MEMS mirror at rest. A step test included different surface elevations for the LIDAR system to scan, which can be used to analyze how well the system can distinguish two adjacent distances. The LIDAR system was stationary while an object with varying step sizes moved through its scan area. These steps were of height 5 cm, 0 cm, 2.5 cm, 7.5 cm, 0 cm, 10 cm, and 5 cm, respectively. The results of this test are plotted in Figure 6(b). The standard deviation of the measured distance of each plane is 3.6 cm, resulting in a distance resolution of 7.2 cm.

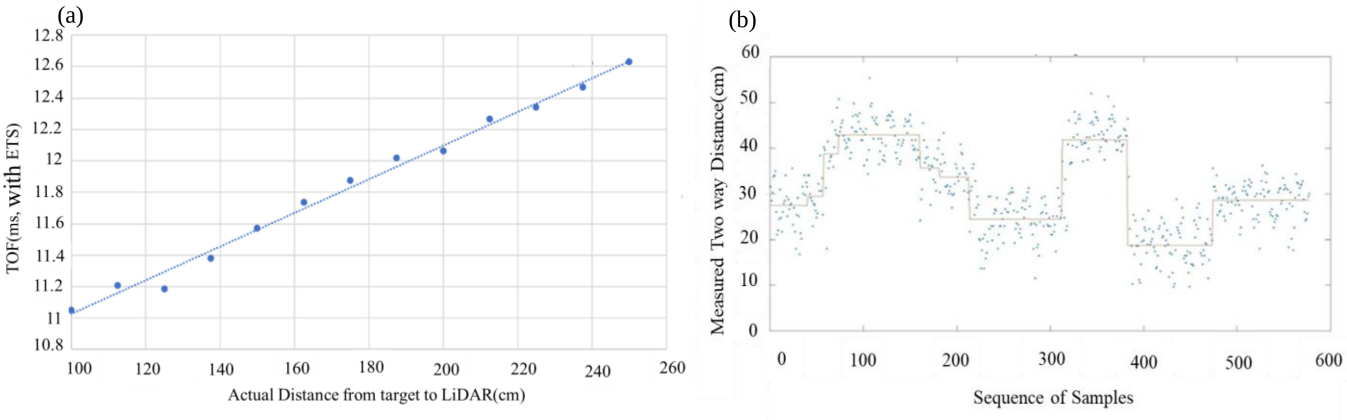

Figure 6: (a) Measured time of Flight with ETS verse true distance of target. (b) Measured Distance of moving object with step structure.

5.3 Testing with scanning mirror

To test the mirror scanning capability of more completed structures, a cardboard box corner was placed in front of the LiDAR to scan, as shown in Figure 7(a). The field of view of the receiver was only 3° because the lens of the photodiode was designed for 1D laser range finder. But we still managed to scan the mirror to the target and obtained 2D point clouds. The MEMS mirror was driven with 0.2 Hz triangular wave for 30 s to scan across the corner. The shape of the corner was reconstructed with some deformed points, as shown in Figure 7(b).

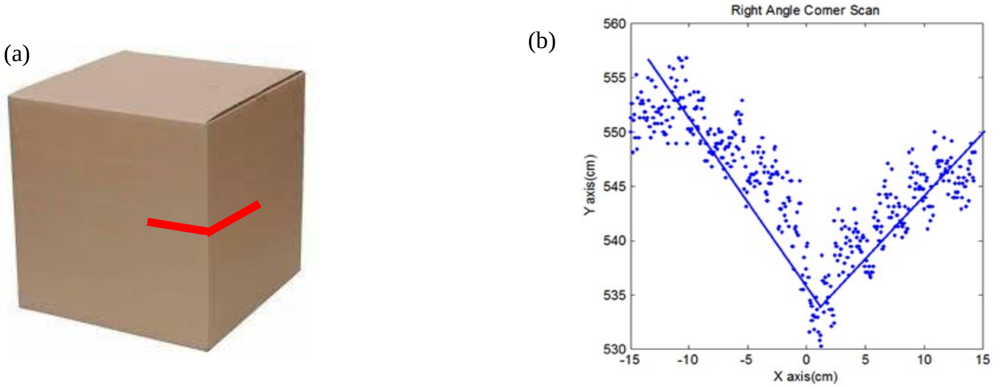

Figure 7: (a) The object to be measured, red line indicates the laser scanning line at the corner of the box. (b) The point clouds of scanning result.

6. DISCUSSION AND FURTHER WORKS

An electrothermal MEMS mirror-based LiDAR system for small UAV is reported in this paper. The small size is enabled by a 2-axis electrothermal MEMS mirror. The electrothermal MEMS mirror is applied in this LiDAR system for its advantage of low driving voltage and potentially large scanning FoV. The overall LiDAR system can fit into a dimension of 100 mm×100 mm×60 mm and its weight is under 100 g. The depth resolution of 7.2 cm is realized by this LiDAR.

There are some constraints due to the hardware limitations. The field of view of 3° by 3° is small, which is limited by the acceptance angle of the receiver. Also, we have only shown results on slow scan or slowly moving object because the employed equivalent time sampling cannot provide real-time fast data acquisition. Greater FoV and faster measurement rate are possible with improved optics and electronics. Furthermore, the maximum measurement range is less than 2.5 m because most of the laser power is wasted when coupling the laser onto the MEMS mirror; again, through a better optics design in the future, the measurement range will be extended.

The next generation of our MEMS LiDAR currently under development is more compatible with electrothermal MEMS mirrors. Faster measurement rate, real time signal analysis longer ranging distance and wider FoV is expected for this this LiDAR. It is based on time-to-digital conversion (TDC), which can detect ultra-short time delays (in the order of 50 ps) in real time. Meanwhile, the optics are custom designed, which can largely increase the SNR of the system.

ACKNOWLEDGE

This work was supported by the National Science Foundation under the award #1514154.

REFERENCES

[1] Federal Aviation Administration "Fact Sheet – Small Unmanned Aircraft Regulations (Part 107)," June 21, 2016, <https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20516>(June 21, 2016).

[2] Kennedy, C. and Rogers, J.I., "Virtuous drones?". The International Journal of Human Rights, 19(2), pp.211-227(2015).

[3] Geiger. A., Lenz, P. and Urtasun, R., "Are we ready for autonomous driving? The kitti vision benchmark suite," In Computer Vision and Pattern Recognition (CVPR), 2012 IEEE Conference on (pp. 3354-3361). IEEE.

[4] Hentschke, M., "Evaluation of altitude sensors for an application in a pulverization drone"(2017).

[5] Premebida, C., Ludwig, O. and Nunes, U., "LIDAR and vision-based pedestrian detection system," Journal of Field Robotics, 26(9), 696-711(2009).

[6] Chesworth, A.A. and Huddleston, J., "Precision optical components for lidar systems developed for autonomous vehicles." In Next-Generation Optical Communication: Components, Sub-Systems, and Systems VII (Vol. 10561, p. 105610J). International Society for Optics and Photonics (2018).

[7] Moss, R., Yuan, P., Bai, X., Quesada, E., Sudharsanan, R., Stann, B.L., Dammann, J.F., Giza, M.M. and Lawler, W.B., "Low-cost compact MEMS scanning ladar system for robotic applications," In Laser Radar Technology and Applications XVII (Vol. 8379, p. 837903). International Society for Optics and Photonics(2012).

[8] Milanović V., Kasturi A., Yang, J., Hu, F., "Closed-loop control of gimbal-less MEMS mirrors for increased bandwidth in LiDAR applications," In Laser Radar Technology and Applications XXII (Vol. 10191, p. 101910N). International Society for Optics and Photonics (2017).

[9] Wang. D., Zhang, X., Zhou, L., Liang, M., Zhang, D. and Xie, H., "An ultra-fast electrothermal micromirror with bimorph actuators made of copper/tungsten," Optical MEMS and Nanophotonics (OMN), 2017 International Conference on, 1-2(2017).

[10] Jia, K., Sagnik P. and Xie, H., "An electrothermal tip–tilt–piston micromirror based on folded dual S-shaped bimorphs." Journal of Microelectromechanical systems 18, no. 5,1004-1015(2009).

[11] Todd, S., Jain A., Qu H., Xie H., "A multi-degree-of-freedom micromirror utilizing inverted-series-connected bimorph actuators," Journal of Optics A: Pure and Applied Optics, 8(7), 352 (2006).

[12] Wang, D., Rojas, S., Shuping, A., Tasneem, Z., Koppal, S and Xie, H., "An integrated forward-view 2-axis mems scanner for compact 3d LiDAR," The 13th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems (IEEE-NEMS 2018), to be published

[13] Lightware "OSLRF-01 - Laser Rangefinder Manual – Rev 1.pdf," February 05, 2014, < http://www.lightware.co.za/shop2017/download/Documents/OSLRF-01%20-%20Laser%20Rangefinder%20Manual%20-%20Rev%201.pdf> (March 29, 2018).

[14] He, W., Sima, B., Chen, Y., Dai, H., Chen, Q. and Gu, G., "A correction method for range walk error in photon counting 3D imaging LIDAR". Optics Communications, 308, pp.211-217(2013).