

## A Low-Voltage, Low-Current, Digital-Driven MEMS Mirror for Low-Power LiDAR

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**Abstract**—Microelectromechanical (MEMS) mirrors have provided a fast and compact method to modulate light for mobile-scale projectors, LiDAR, and computational cameras. In this letter, we propose a new MEMS mirror design and its actuation method that is specifically built for low-voltage, low-current, and digital-driven IoT applications. The MEMS mirror specifically designed with direct actuation from the microcontroller was successfully fabricated and characterized. A full low-power LiDAR system based on the fabricated MEMS mirror was demonstrated, which was powered by a 9-V commercial battery.

**Index Terms**—Sensor-actuators, electrothermal actuator, LiDAR, microelectromechanical (MEMS) mirror.

### I. INTRODUCTION

The coming Internet-of-Things (IoT) revolution promises to dramatically change how humans and machines interact, through billions of tiny smart platforms. These are microplatforms that will appear in a variety of applications, particularly in intelligent buildings, smart homes, and infrastructure-embedded edge computing. In smart building applications, particularly, the challenge is to convert conventional “dumb” structures through the use of battery-powered, “peel-and-stick” sensors. For example, smart sensor-enabled heating, ventilation, and air-conditioning (HVAC) systems can control air flow by estimating and tracking the population distribution through visual sensors [1].

Light detection and ranging sensors (LiDAR) can contribute to novel compact and low power sensors, particularly where efficient imaging is required for monitoring people’s movement in buildings and controlling HVAC. The detection range needed is up to 10 m, which is achievable for most LiDAR. However, traditional LiDAR is power intensive. Motorized optomechanical LiDAR scanners are usually built with multiple channels of transmitters and receivers stacked vertically and rotated by a motor. The power consumptions for motorized LiDAR are usually around 10s of Watts, of which the motors consume a large part for rapid and wide-angle scanning. Low-power LiDAR are available on the market, such as the Hokuyo UST-10LX [2], which has a power consumption under 4 W because the motor is much smaller and lighter. However, this type of LiDAR only has a 1-D horizontal Field of View (FoV) that limits its detection area and application range. The relationship between the LiDAR power consumptions and their applications is shown in Fig. 1.

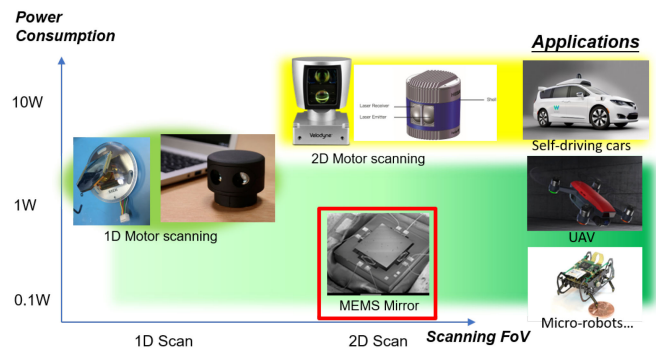


Fig. 1. LiDAR with different levels of power consumption and their applications.

Microelectromechanical (MEMS) mirrors are widely used in displays, optical medical imaging, and computational cameras [3]. In most cases, MEMS mirrors are much more power-efficient than motorized scanners, so they can fill the blank in Fig. 1 for their low-power consumptions and fast 2-D scanning capabilities. For power and actuate MEMS mirrors on IoT platforms, microcontrollers and driver circuits are often needed. Arduino Uno, MSP430 series, or the Raspberry Pi are the most popular microcontrollers for IoT applications. However, due to the limited analog-to-digital (ADC)/digital-to-analog (DAC) conversion resources and limited voltage or current levels on those microcontroller boards, additional driver circuits are often needed to actuate MEMS mirrors. Electromagnetically actuated MEMS mirrors usually require higher current and power than other types of MEMS mirrors [4]. Although the currents for electrostatically or piezoelectrically actuated MEMS mirrors are small, driver circuits with high voltages (50–150 V) are usually required and these driver circuits consume a considerable amount of power [5], [6]. For example, Arslan *et al.* demonstrated an electrostatic 1-D MEMS mirror with a

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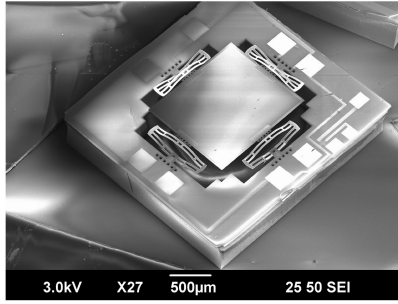


Fig. 2. SEM image of the fabricated MEMS mirror.

maximum  $76^\circ$  optical scan angle at 196 Vpp [5]. In addition, the power consumption of a dedicated MEMS driver's board for an electrostatic MEMS mirror is as much as 800 mW [7]. Resonant scanning can help to boost the scanning angle and reduce the power consumption. Koh *et al.* developed a 2-D electrothermal and electromagnetic hybrid-driven double-resonant scanning MEMS mirror with a low power consumption of 13 mW. However, resonant scanning MEMS mirrors for LiDAR usually require feedback control to monitor the scanning angles, which makes the systems more complicated and consumes more power [8]. In contrast, electrothermally actuated MEMS mirrors can achieve a wide scanning angle with a low voltage less than 5 V and a small current under 15 mA [9] for nonresonant scanning. Typically, multiple DACs plus power amplification circuits are used to actuate the electrothermal MEMS mirrors. However, DACs are not readily available on most of the economical microcontrollers.

In this letter, we have developed a low-voltage, low-power, digitally driven MEMS mirror, specifically designed for low-power, small-footprint IoT applications. Through properly designing the width and thickness of the Pt resistor embedded in the actuators, we have demonstrated that this MEMS mirror can be actuated directly by the digital outputs from an Arduino Uno board by using a special pulsewidth modulation (PWM) scheme. To the best of our knowledge, this is the first demonstration of driving MEMS mirrors with digital signals from a microcontroller without using any additional electronics. The MEMS mirror is integrated with an off-shelf time-of-flight (ToF) measurement engine to form a low-power 3-D LiDAR that can be placed on the ceiling of a room and can operate with a single 9 V battery, much like a smoke alarm.

## II. MEMS MIRROR

The employed MEMS mirror is based on electrothermal bimorph actuators that are made of the inverted-series-connected (ISC) bimorph actuation structure reported in [9]. Considering the 5-V digital output voltage and maximum 20-mA output current of the Arduino, the Pt resistive heater embedded in the electrothermal actuators of the MEMS mirror is redesigned to balance the actuation voltage and current by optimizing the width, thickness, and length of the Pt resistor, which are 12, 0.20, and 4400  $\mu\text{m}$ , respectively. This MEMS mirror uses  $\text{SiO}_2$  and Al as the two bimorph materials for the large difference of their coefficients of thermal expansion. The device fabrication process is similar to the one reported in [10]. Fig. 2 shows an SEM image of a fabricated device. The central mirror plate is 1.2 mm  $\times$  1.4 mm and is suspended by four ISC actuators for two-axis scanning. There are two sets of thermal isolation holes between the actuators and substrate and between the actuators and the mirror plate. These added thermal resistances increase the thermal actuation efficiency but at the price of slower response.

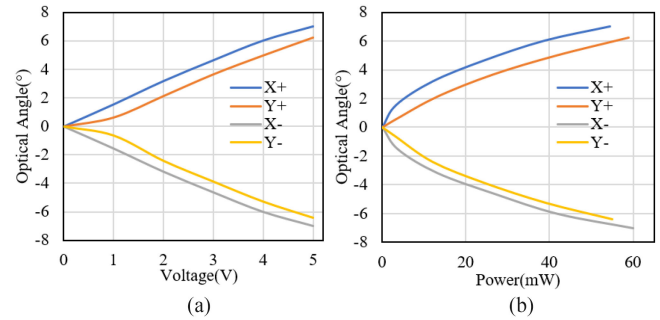


Fig. 3. Quasi-static optical scanning angle response of the MEMS mirror to (a) voltage and (b) power.

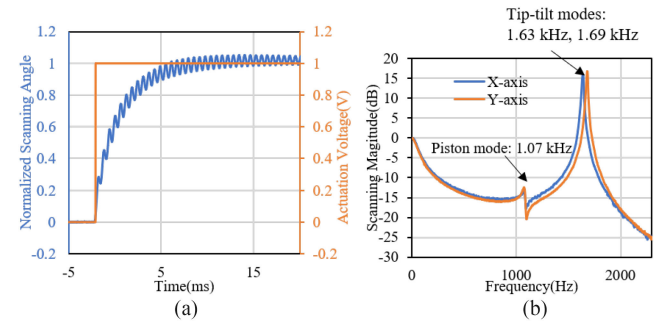


Fig. 4. (a) Step response time of the MEMS mirror (rising time = 5 ms). (b) Frequency response of the MEMS mirror. The 3 dB bandwidth is 70 Hz.

The measured quasi-static optical scanning angles of the MEMS mirror corresponding to various actuation voltages and input powers are plotted in Fig. 3(a) and (b), respectively. The optical scanning angle reached  $\pm 7^\circ$  in the horizontal direction at 5 V, or 55 mW, and  $\pm 6^\circ$  in the vertical direction at 5 V, or 59 mW. The step response of the MEMS mirror was smooth with no overshoot and very small ringing, as shown in Fig. 4(a). The corresponding rise time was 5 ms. The frequency response is shown in Fig. 4(b). The tip-tilt modes were at 1.63 and 1.69 kHz, respectively. There was a small separation between those two modes due to the fact that the side lengths of the mirror plate were slightly different. The reason for making such a design was to reduce the mechanical coupling between the two scanning axes. The 3-dB cutoff frequency  $f_{3\text{dB}}$  was around 70 Hz, which was the result of the thermal response.

## III. MEMS MIRROR ACTUATION

An Arduino Uno was selected to actuate the MEMS mirror because of its low cost and good compatibility. The Arduino Uno was also used to control the LiDAR system. The Arduino Uno had 16 digital IO pins, six of which can be used as the PWM outputs. The operating voltage of the Arduino Uno was 5 V with a maximum dc current output capability of 20 mA for each pin, which was sufficient to drive the electrothermal MEMS mirror to its maximum scan angle. By connecting the four actuators to four digital output pins of the Arduino Uno, the MEMS mirror was able to perform switching among nine points. However, this could only be used to measure those limited discrete points in the FoV.

MEMS mirrors usually require analog signals for nonresonant, continuous scanning. With the absence of DACs on the Arduino, PWM signals were explored to imitate analog signals for actuating MEMS mirrors. As can be seen from the resonant response in Fig. 4,

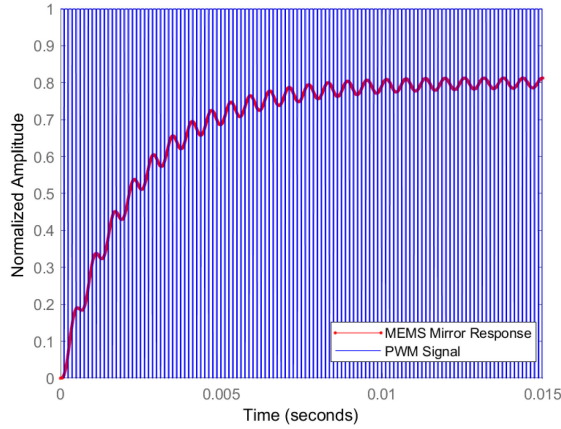


Fig. 5. Simulated responses of the MEMS mirror actuated by the PWM signal with a repetition rate of 15 kHz and a duty cycle of 80%. The time to stabilize is about 5 ms. The residue oscillation is about 2% after about 10 ms.

after exceeding the resonant frequencies, the frequency response had a 60 dB/Dec decay, so PWM signals with a modulation frequency much higher than the resonant frequency (around 1.7 kHz), e.g., 15 kHz, could be used to stably actuate the MEMS mirror for nonresonant scanning, which could eliminate the need of DACs.

The response of the electrothermal mirror under a PWM actuation signal will be analyzed in the following section. According to [11], the transfer function of the dynamic response of the MEMS mirror  $H_\Theta(s)$  can be expressed as

$$H_\Theta(s) = \frac{\frac{1}{\tau} \cdot \omega_n^2}{(s^2 + 2\omega_n\zeta s + \omega_n^2)(s + \frac{1}{\tau})} \quad (1)$$

where  $\tau$  is the thermal time constant,  $\omega_n$  is the natural resonant frequency of the mirror rotation, and  $\zeta$  is the damping ratio of the bimorph-mirror plate system. From the experimental data plotted in Fig. 4, the measured values of the following parameters can be extracted: the rise time  $t_r = 5$  ms, the rotation resonant frequency  $f_0 = 1.65$  kHz, and the quality factor  $Q = 80$ . Accordingly the following parameters can be calculated: the thermal time constants  $\tau = t_r / \ln 9 = 2.27$  ms, the rotation natural frequency  $\omega_n = 2\pi f_0$ , and the damping ratio  $\zeta = \frac{1}{2Q} = 0.006$ . Thus, the dynamic response  $H_\Theta(s)$  can be obtained by substituting the parameters into (1).

The mirror response to each pulse of the PWM signal is similar to the step response. Therefore, the oscillation and ringing is inevitable under a PWM actuation when the PWM frequency is close to the resonance frequency. Thus, to minimize the oscillation, the PWM frequency must be about one order of magnitude higher than the resonance frequency of the MEMS mirror to suppress the Q amplification effect. In this experiment, the frequency of the PWM was set to 15 kHz and the PWM signals are 8 bits, corresponding to the maximum pulsewidth of 66.7  $\mu$ s and the minimum pulsewidth of 0.26  $\mu$ s. Fig. 5 shows the simulated response  $H_\Theta(s)$  of the MEMS mirror actuated by the 15-kHz 8-bit PWM signal. The duty cycle of the PWM signal was set to 80%, and it took about 5 ms for the MEMS mirror to stabilize at 80% of the actuation range, as shown in Fig. 5. The residue oscillation was less than 2% after about 10 ms, which is negligible in most applications.

Fig. 6 shows a raster scanning pattern of the MEMS mirror actuated by four PWM signals generated by the Arduino. The synthesized drive signals for both axes from the PWM signals are sinusoidal waves. Thus, the mirror scans fast in the middle, causing the lines more separated in the middle. The scanning frequencies for the horizontal

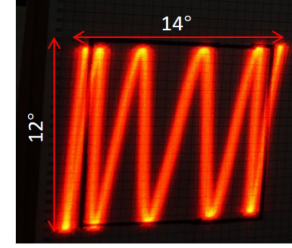


Fig. 6. Raster scanning pattern generated by the MEMS mirror actuated with an Arduino Uno.

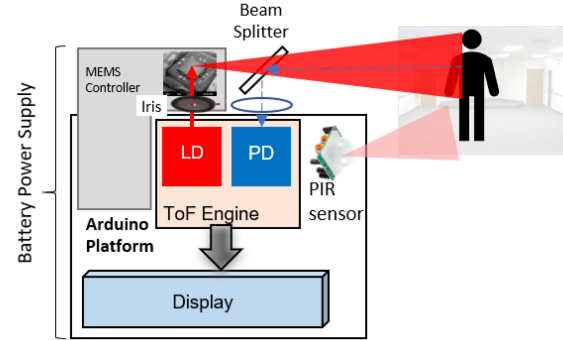


Fig. 7. Schematic of the low-power LiDAR with smart duty cycle scanning for extended battery life.

and vertical axes are 1 and 10 Hz, respectively. It can also be seen that the raster pattern has a slight distortion, which is believed to be caused by the small differences among the four actuators due to the fabrication process variations. The reliability and temperature stability of this type of electrothermal MEMS mirrors are also important issues, which has been studied extensively by Wang *et al.* [12].

#### IV. LOW-POWER MEMS LIDAR SYSTEM AND DEMONSTRATION

Fig. 7(a) shows the schematic of the low-power MEMS LiDAR system. A Lightware SF/02 ToF engine is employed. The laser from the ToF engine is incident to the MEMS mirror. As the transmission aperture and receiving aperture of the ToF engine point to the same direction, a beam splitter is added to direct the echo laser signals to the receiving aperture of the ToF engine. Since the ToF engine is for a range finder that has a narrow FoV, a convex lens with a numerical aperture of 0.25 is added in front of the receiving aperture to expand the receiving FoV of the ToF engine. The Arduino generates the PWM actuation signals for the MEMS mirror and reads the distance values from the ToF engine. The ToF engine outputs a peak laser power of 10 W and the wavelength is 905 nm. The LiDAR measurement results are shown in real time on a low-power OLED display. A Passive Infrared (PIR) sensor (Parallax, 555-28027) is used to detect human motion in the FoV of the LiDAR. The output of the PIR sensor changes from LOW to HIGH when it detects motion and changes back to LOW when the motion stops. So the MEMS mirror and the ToF engine can be automatically switched ON/OFF to save power. By adding the motion detection, the battery life can be extended by 3.5 times from 2 to 7 min under the normal operation condition. The power consumptions of all the components of the LiDAR are listed in Table 1, and the MEMS mirror itself only consumes a maximum power of 0.1 W. The whole LiDAR system can be powered with a 9 V battery. A portable LiDAR



TABLE 1. Power Consumptions of All the Components on the LiDAR

Components	Power Consumptions (W)
SF/02 Laser Range Finder	0.75
MEMS Mirror Max.	0.1
Arduino	0.86
OLED Screen	0.04 – 0.2
PIR Sensor	<0.001
Power Relay Module	0.8
Total	2.7

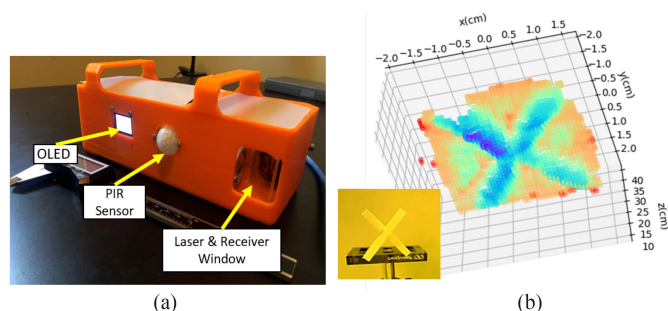


Fig. 8. (a) Low-power MEMS LiDAR in a portable enclosure. (b) LiDAR point cloud generated by the MEMS LiDAR scanning a paper cut at 25 cm and a background at 35 cm.

enclosure was designed and 3-D printed. Fig. 7(b) shows the portable LiDAR and its internal structures. The dimensions of the LiDAR are 21 cm  $\times$  9 cm  $\times$  6.5 cm. Note that the battery life is too short for practical applications. To extend the battery life for a significantly longer time, advanced low-power ASICs and power management must be developed, which is out of the scope of this letter.

The detection range of the LiDAR was from 3 to 35 cm with objects of 80% albedo. The error was 0.5 cm at 5 cm and gradually increased to 5 cm at 30 cm. The ToF measurement rate was 32 pt/s and the frame rate was 2 fps. The measured distances were correlated with a red-blue color map and displayed on the OLED screen with reduced resolution. The LiDAR and the OLED could operate autonomously on the battery power for alert and surveillance. Alternatively, the LiDAR data can also be transmitted to a computer and processed with more computational resources for more complicated tasks. In Fig. 8, the MEMS LiDAR scanned a scene with a paper cut at 25 cm and a ground at 35 cm at a lower frame rate of 0.1 fps. The high-resolution point cloud was generated using MATLAB on a PC with the measurement data of 10 frames. Note that the measured detection range is far from the required 10 m, but this work is only for the purpose of the proof of the concept. However, the detection range can be easily extended by properly choosing the laser source and photodetector and optimizing the receiving optics.

## V. CONCLUSION

A low-voltage, low-current, digital-driven electrothermal MEMS is developed in this letter. The electrothermal MEMS mirror is designed with a driving voltage from 0–5 V and low-current under 12 mA for nonresonant scanning. The mirror can be actuated directly by the digital outputs from a microcontroller in the form of PWM without the need of any additional driving circuits. All the features enabled by this electrothermal MEMS mirror are especially suitable for smart buildings. A low-power battery-powered 3-D LiDAR is built with the MEMS mirror with a maximum power consumption of 2.7 W. The LiDAR can actively turn the ToF engine and the MEMS mirror ON and OFF based on the motion of the target object in its FoV. The battery life is extended by 3.5 times. To further extend the battery life for practical uses, more studies are required to reduce the power consumption of the ToF engine.

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## REFERENCES

- [1] H. Han, Y. Jeon, S. Lim, W. Kim, and K. Chen, "New developments in illumination, heating and cooling technologies for energy-efficient buildings," *Energy*, vol. 35, no. 6, pp. 2647–2653, 2010.
- [2] M. Panicker, T. Mitha, K. Oak, A. M. Deshpande, and C. Ganguly, "Multisensor data fusion for an autonomous ground vehicle," in *Proc. Conf. Adv. Signal Process.*, 2016, pp. 507–512.
- [3] S. K. Nayar, V. Branzoi, and T. E. Boulton, "Programmable imaging: Towards a flexible camera," *Int. J. Comput. Vis.*, vol. 70, pp. 7–22, 2006.
- [4] L. Ye, G. Zhang, and Z. You, "Large-aperture KHz operating frequency ti-alloy based optical micro scanning mirror for LiDAR application," *Micromachines*, vol. 8, no. 4, p. 120, 2017.
- [5] A. Arslan, D. Brown, W. O. Davis, S. Holmstrom, S. K. Gokce, and H. Urey, "Comb-actuated resonant torsional microscanner with mechanical amplification," *J. Microelectromech. Syst.*, vol. 19, no. 4, pp. 936–943, 2010.
- [6] S. Gu-Stoppe et al., "A highly linear piezoelectric quasi-static MEMS mirror with mechanical tilt angles of larger than 10°," in *Proc. SPIE*, vol. 10931, 2019, Art. no. 1093102.
- [7] A. Kasturi et al., "Comparison of MEMS mirror LiDAR architectures," *Proc. SPIE*, vol. 11293, 2020, Art. no. 112930B.
- [8] K. H. Koh and C. Lee, "A two-dimensional MEMS scanning mirror using hybrid actuation mechanisms with low operation voltage," *J. Microelectromech. Syst.*, vol. 21, no. 5, pp. 1124–1135, 2012.
- [9] K. Jia, S. Pal, and H. Xie, "An electrothermal tip-tilt-piston micromirror based on folded dual s-shaped bimorphs," *J. Microelectromech. Syst.*, vol. 18, no. 5, pp. 1004–1015, 2009.
- [10] D. Wang, C. Watkins, S. Koppal, and H. Xie, "A compact omnidirectional laser scanner based on an electrothermal tripod MEMS mirror for LiDAR," in *Proc. 20th Int. Conf. Solid-State Sensors, Actuators Microsyst. Eurosensors XXXIII*, 2019, pp. 1526–1529.
- [11] M. Li, Q. Chen, Y. Liu, Y. Ding, and H. Xie, "Modelling and experimental verification of step response overshoot removal in electrothermally-actuated mems mirrors," *Micromachines*, vol. 8, no. 10, 2017, Art. no. 289.
- [12] P. Wang, Y. Liu, D. Wang, H. Liu, W. Liu, and H. Xie, "Stability study of an electrothermally-actuated MEMS mirror with al/sio2 bimorphs," *Micromachines*, vol. 10, no. 10, 2019, Art. no. 693.