Journal of Micromechanics and Microengineering

A position sensing method for 2D scanning mirrors

To cite this article: Behrad Ghazinouri *et al* 2022 *J. Micromech. Microeng.* **32** 045007

OPEN ACCESS
IOP Publishing
Journal of Micromechanics and Microengineering
J. Micromech. Microeng. **32** (2022) 045007 (7pp)
https://doi.org/10.1088/1361-6439/ac58df

A position sensing method for 2D scanning mirrors

Behrad Ghazinouri, Siyuan He and Trevor S Tai

Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Canada

E-mail: s2he@ryerson.ca

Received 23 October 2021, revised 23 January 2022
Accepted for publication 25 February 2022
Published 9 March 2022

Abstract

This paper presents a cost-effective position sensing method for 2D scanning mirrors. The method uses only one 1D PSD (position sensitive detector) located at the backside of the 2D scanning mirror plate to retrieve the 2D rotation angle about the two axes separately in real time. Any 2D scanning mirror with resonant vibration about one axis and quasi-static vibration such as sinusoidal, saw tooth, triangular oscillation about the other axis can use this method. The two vibration axes are orthogonal to each other to form the scanning patterns, which are most desired in scanning 3D LiDAR systems. 3D scanning LiDAR is the targeted application for this research. The method uses timing measurement to measure the resonant vibration angle and Lagrange interpolation polynomial approximation to retrieve the quasi-static vibration angle. A prototype has been built to measure the 2D rotation angle of a 2D micromirror. The measured angle using the proposed method was verified using a 2D PSD. The largest errors for the vertical/horizontal angles were 9.6% and 5.36% respectively. The position sensing mechanism is also integrated to a scanning 2D micromirror based LiDAR system to demonstrate it as real time capability.

Keywords: 2D scanning micromirror, position sensing, 1D PSD, micromirror LiDAR

(Some figures may appear in colour only in the online journal)

1. Introduction

Motors have been the dominant laser steering mechanism for many optical systems such as the laser vector display, LiDAR (light detection and ranging), etc. MEMS (micro electromechanical system) mirrors offer a smaller and more cost-effective steering system and subsequently there is a growing interest in the market for this, which is the so called solid-state steering mechanism (actually it is more appropriate to be named as 'semi-solid-state steering' since there is still mechanical oscillation part, i.e. the scanning micromirror). In order to achieve 3D scanning (e.g. cover the whole environment in LiDAR application), two orthogonal scanning axes are required for a 2D MEMS mirror, where the mirror plate rotates about two orthogonal axes [1, 2], i.e. resonant vibration about one axis and quasi-static vibration about the other. Knowing the rotation angles of the MEMS micromirror about the two orthogonal axes at any time is critical for any 2D scanning micromirror based system. For example, only when the 2D scanning angle can be accurately obtained the 2D scanning micromirror based LIDAR can retrieve the 3D map accurately.

Various methods have been developed to measure the 2D rotation angle of 2D scanning micromirrors such as the capacitive sensing method [3], piezo-resistors based method [4], electromagnetic internal sensing method [5–7] and optical feedback method [8, 9]. Capacitive sense method is mainly used for electrostatically driven micromirrors, in which the interference between the driving signal and the sensing signal is a serious challenge [3]. Piezo-resistors method requires piezoresistive materials integrated to the torsion beams of the

2D micromirror, that increases the manufacturing complexity. In addition, this method suffers from temperature instability due to the use of piezoresistive material [10]. The electromagnetic internal sensing method uses a separate coil in electromagnetically actuated micromirrors to sense the current induced by the mirror plate's rotation. However, it is difficult to separate rotation angles about two axes. Therefore, it is only suitable for 1D micromirrors (i.e. rotation about only one axis), rather than 2D micromirrors (rotate about two axes). Moreover, this method requires extra space and separate path for the sensing coil [6]. The optical feedback method has the advantage of the angle measurement being independent of the driving mechanism since it either uses 2D PSD (position sensitive detector) with a laser beam positioned externally [11, 12], or a quadrant photodiode at the backside of the 2D mirror plate [9]. Quadrant photodiodes are commonly used as tracking and centering devices, in order to be used as a position sensor, its transfer characteristics needs to be linearized [13]. Nonlinearity specially at high deflection angles is one of the main issues [9] which makes the calibration complicated. In one case, Baumgart *et al* [9] used a quadrant photodiode with a hole in the middle which is a rare type of quadrant photodiode to reduce the size of the device. In another approach, Tortschanoff *et al* [14–16] used two cross orthogonal laser beams. Each reflected one beam passing a cylindrical mirror to be compressed and sent onto the photodiodes such as to reduce the complexity of dividing one 2D pattern into two separate 1D patterns to implement the timing measurement method to retrieve the two rotation angles. Kimoto *et al* [17] also used the timing measurement method in their 3D LiDAR sensor to adjust the amplitude of a 1D resonant mirror. The timing measurement method works best only for resonance vibration at which the micromirror's oscillation is pure sinusoidal. In many 2D micromirror based applications such as LiDAR systems, the micromirror is required to oscillate at resonant frequency about one axis while oscillate following quasi-static waves (such as triangular, saw-tooth) trajectory about the other axis, in which timing measurement method does not work anymore. The optical based 2D micromirror's angle measurement method is attractive due to its independence of the steering mechanism. However, this method could need very high cost if 2D PSD is used and suffer from the complex linearization and calibration in the case of using quadrant photo diodes.

This paper proposes a method of measuring the 2D micromirror's rotation about two axes using only one 1D PSD such as to significantly lower the cost in comparison to the 2D PSD method (e.g. 100 US$ versus 750 US$ for low quantity) with the advantage of optical measurement, i.e. measurement signal independent of the driving signal.

This method is suitable for any 2D scanning mirror with the resonant vibration about one axis and the quasi-static vibration about the other axis. Since only 1D PSD used instead of 2D PSD, the cost is greatly reduced. Moreover, the sensing mechanism is very compact and requires only very simple signal processing. Using the 1D PSD to retrieve 2D micromirror' rotation angles about two axes, the resonant vibration angle is obtained using timing measurement method and the quasi-static vibration angle is obtained based on the method of Lagrange interpolation polynomial approximation.

2. Method and principles

2.1. 2D micromirror scanning manner

The following assumption is used in explaining the principle of the 2D micromirror rotation angle measurement using one 1D PSD. The 2D micromirror resonates in the horizontal direction (hereafter it is referred to as the fast axis scanning) and its quasi-static vibration is in the vertical direction (hereafter it is referred to as the slow axis scanning). This scanning mode is the most popular scanning manner needed in 2D micromirror based LiDAR systems. The horizontal scan is resonant sinusoidal vibration and the vertical oscillation is quasi-static, which could follow a triangular or saw tooth wave trajectory as illustrated in figure 1, where the frequency ratio between the horizontal and vertical oscillation is 9.

2.2. Position sensing mechanism

As it is shown in figures 2 and 3, the 1D PSD surface is parallel to the 2D mirror surface with its longitudinal direction along the 2D micromirror's vertical direction (z-axis shown in figure 3). The laser beam is perpendicular to the 2D mirror's back side surface.

As shown in figure 3, an x,y,z coordinate system is established at the center of the 2D mirror with the 1D PSD's surface parallel to the x-z plane and the laser beam is along the y-axis with a distance of $\boldsymbol{b}$ to the mirror's back side surface. The 1D PSD's center longitudinal line is offset the y-axis by $\boldsymbol{a}$, i.e. $-a$ as the x-axis coordinate. Therefore, each point of the laser beam hitting on the 1D PSD surface (on the longitudinal central line) at time $\boldsymbol{t}$ has the coordinates of **[-a b z]**.

The angle between the incident laser beam and lines connecting points on PSD and the origin can be discomposed into two parts, angle parallel to the x–y plane, i.e. θ_i, and angle parallel to the y–z plane, i.e. ψ_i. When the 2D mirror oscillates, θ represents 2D mirror's vibration horizontally about the z-axis, and ψ represents the vertical oscillation about x-axis. Thus, the proposed 2D micromirror angle measurement method in this paper is to obtain the θ and ψ at any time through the 1D PSD readings.

According to figure 3, $\theta_i = \tan^{-1}\left(\frac{-a}{b}\right)$ and $\psi_i = \tan^{-1}\left(\frac{z}{b}\right)$, where a, b are constants after the setup is fixed with z varying when the 2D mirror vibrations.

3. Calculation of fast-axis angle (θ)

Figure 4 shows the scanning pattern on the 1D PSD surface. Points, **(1), (2)** and **(3)** are points at which the laser beam hits the PSD window consecutively at the central longitudinal line at the time of t_1, t_2, t_3 respectively. Figure 5 is the signal from the PSD, in which the horizontal axis is time and the vertical

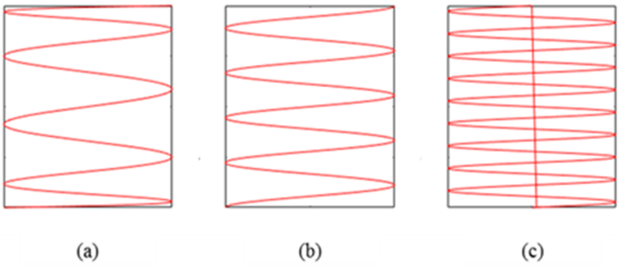


Figure 1. 2D micromirror scanning patterns with horizontal sinusoidal vibration and the quasi-static vertical scanning following (a) sinusoidal, or (b) triangular or (c) saw tooth wave trajectory.

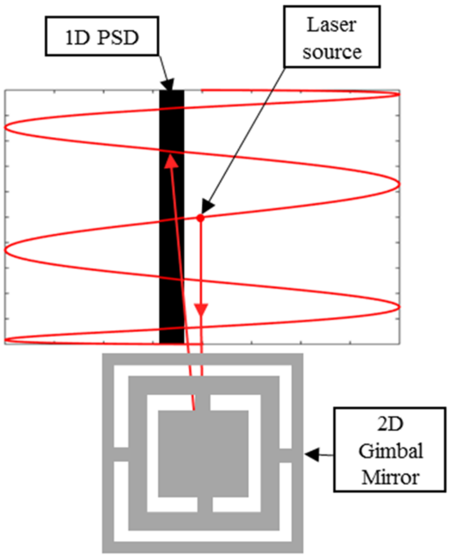


Figure 2. The 1D PSD and the 2D micromirror.

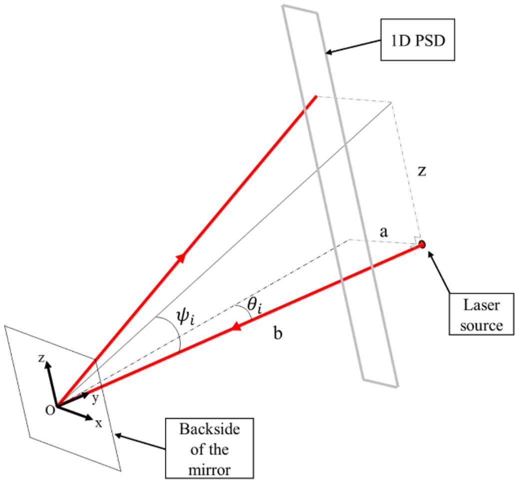


Figure 3. Coordinate and variables of the angle measurement mechanism.

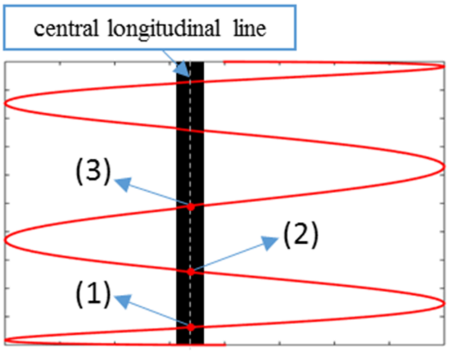


Figure 4. Laser scanning pattern on the 1D PSD surface.

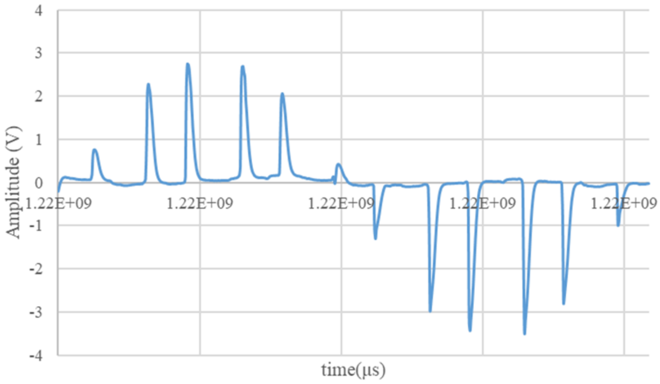


Figure 5. Received signal from 1D PSD.

axis is amplified PSD output voltage corresponding to the longitudinal distance in the PSD window. From the 1D PSD signal (figure 5 shows an example readings) vertical coordination '**z**' and time difference between sequential hits '$\mathbf{\Delta t}$' are obtained. From t_1 to t_3 the mirror has done a complete cycle around fast axis and since the time difference between t_3 and t_1 can be measured such that the vibration frequency can be calculated using equation (1):

$$f_1 = 1/(t_3 - t_1). \tag{1}$$

θ represents 2D mirror's vibration horizontally about the z-axis which is resonant, and the equation of motion is sinusoidal as shown in equation (2):

$$\theta\left(t\right) = \theta_{\max}\sin\left(2\pi f_1 t\right), \tag{2}$$

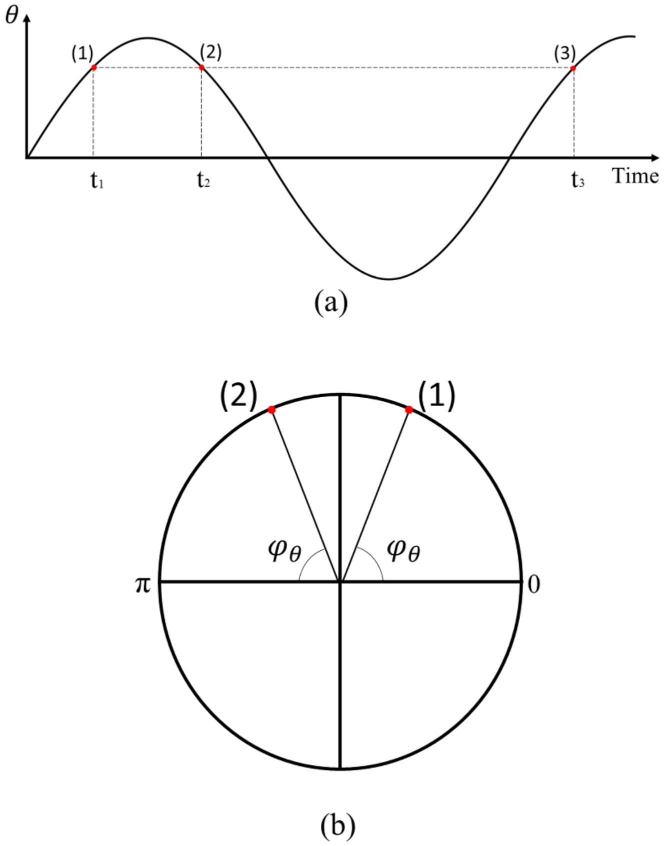
where $\theta_{\max}$,f_1, are maximum angle and the frequency of vibration horizontally respectively.

However, the reference time $t = 0$ s cannot be extracted from the PSD signal. Thus, the t_1 is considered as the reference time and the phase is represented using φ_θ. Thus equation (2) can be rewritten as equation (3) [18]:

$$\theta\left(t\right) = \theta_{\max}\sin\left(2\pi f_1\left(t - t_1\right) + \varphi_\theta\right). \tag{3}$$

It was mentioned that the horizontal vibration angle at t_1, t_2 and t_3 is constant and is equal to $tan^{-1}\left(\frac{-a}{b}\right)$.(see figure 3).

Based on the trigonometry circle in figure 6(b), phase of point **(1)** is φ_θ and phase of point **(2)** is $\pi - \varphi_\theta$. The φ_θ can be retrieved by having the time difference between these two



(a)

(b)

Figure 6. (a) Sinusoidal diagram of horizontal motion and (b) trigonometry circle of the motion.

points and the frequency. It can be expressed as equation (4) [18]:

$$\varphi_\theta = \pi\left(0.5 - (t_2 - t_1) f_1\right). \tag{4}$$

The maximum angle $\theta_{\max}$ can be derived from equation (3) and figure 3 as:

$$\theta_{\max} = \frac{\tan^{-1}\left(\frac{-a}{b}\right)}{\sin\left(\varphi_\theta\right)}. \tag{5}$$

Therefore after 3 hits of the laser beam on the PSD, the horizontal angle at any time t can be obtained according to equations (3–5).

4. Calculation of the slow-axis angle (ψ)

Timing measurement method works best for near resonant rotating because the rotation response of the mirror is sinusoidal and subsequently the response is predictable based on time. Although the driving signal is sinusoidal, it was observed that the slow-axis rotation response of the mirror is not standard sinusoidal since it is quasi-static driving. As a result, for the slow-axis scanning timing method was not accurate to measurement the rotation angle. Fortunately, it is possible to take advantage of the fact that shape of the 1D PSD output signal can be used to retrieve the vertical oscillation angle (figure 5). From the data generated by the consecutive hits on the 1D PSD, the scanning mirror's vertical vibration angle can be predicted using proper interpolation methods.

For sinusoidal interpolation, normally Taylor polynomial approximations is being used but it was observed that the Lagrange interpolating polynomial [19] gives more accurate approximation in this case of non-standard sinusoidal vibration in comparison to Taylor polynomial approximation which requires a very high degree of polynomial approximation and consequently cannot achieve real-time measurement. The Lagrange interpolating polynomial of degree 2 as shown in equations (6) and (7) are used to calculate vertical angle ψ [19]:

$$\psi(t) = \sum_{j=1}^{3} \psi_j(t), \tag{6}$$

where,

$$\psi_j(t) = \tan^{-1}\left(\frac{z_j}{b}\right) \prod_{\substack{k=1 \\ k \neq j}}^{3} \frac{t - t_k}{t_j - t_k}. \tag{7}$$

After three hits of the laser beam on the 1D PSD are measured, the vertical angle at any time t can be obtained according to equations (6) and (7).

5. Prototype and experimental verification

Figure 7 shows the prototype setup of using 1D PSD to measure the 2D scanning mirror's rotation angle. The 1D PSD is mounted at the back side of the 2D mirror and a 2D PSD mounted in front of the 2D mirror, which is for verification. The 2D scanning mirror is a FPCB 2D micromirror, which is described in [19]. The horizontal vibration of the 2D mirror is resonance at 140 Hz while the vertical vibration is quasi-static at 28 Hz with the driving signal of sinusoidal wave.

Figure 8 shows signals from the 2D PSD and 1D PSD as well as the angles retrieved using equations (6) and (7). Frequency ratio between the horizontal resonant frequency and the vertical quasi-static is 5 and the number of hitting points on the 1D PSD is low but the Lagrange interpolating polynomial gives out a smooth and precise result. The result from the 2D PSD contains environmental noise. Moreover, the 2D PSD signal has small jumps on the negative portion of the sensor. Although our mirror is almost crosstalk-free, these jumps could be due to a minor cross talk between the two axes of oscillation. The Higher frequency ratio results in more scanning lines of each frame and consequently more hitting points on the PSD which results in a more accurate interpolation.

Since the methods that we use for both directions are based on interpolation, thus result is noise free. However,

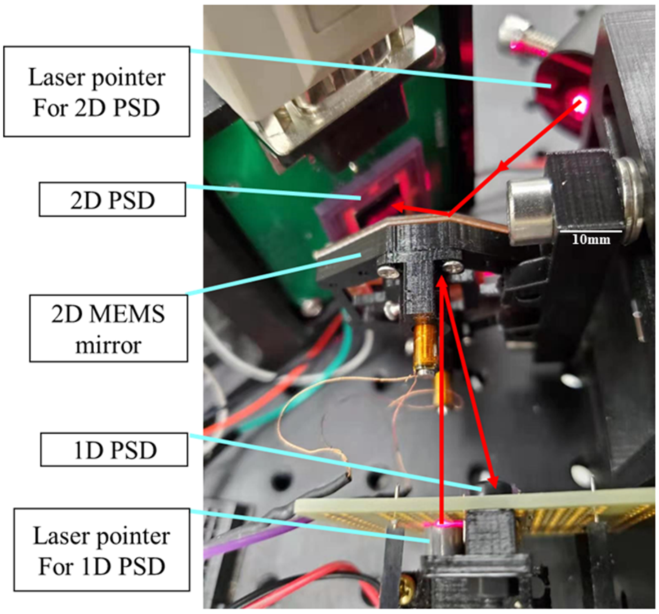


Figure 7. Prototype of 1D PSD measuring a 2D scanning mirror's rotation angle.

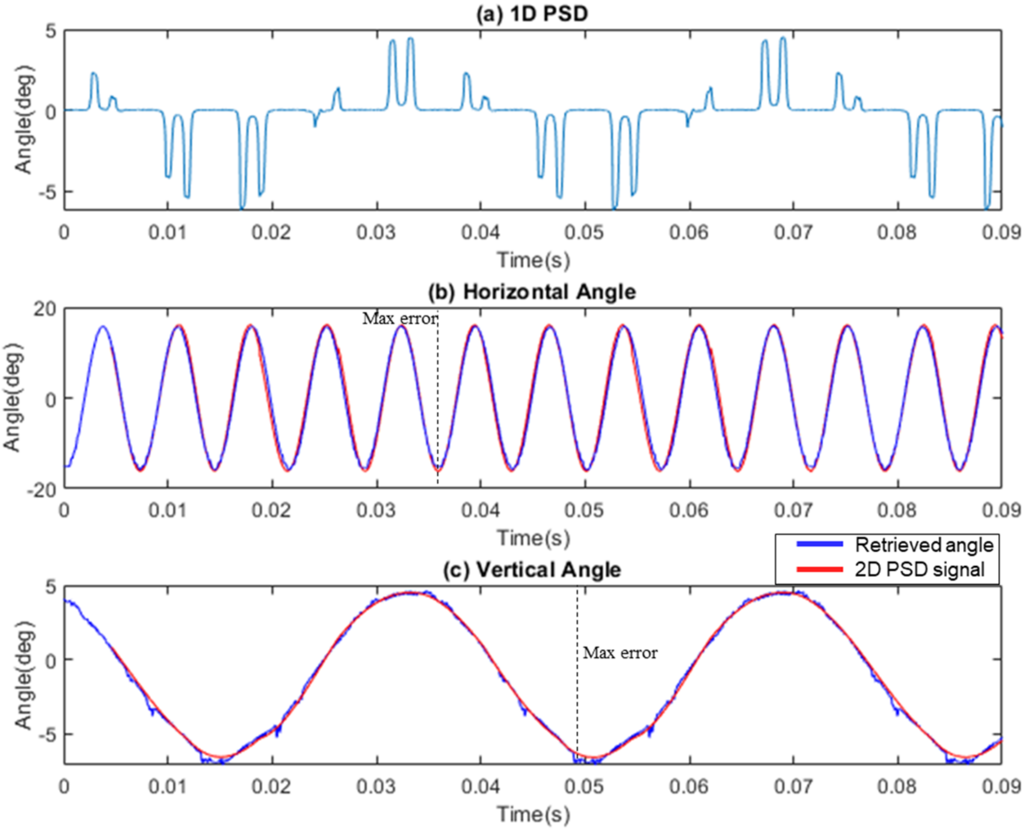


Figure 8. (a) Signal from the 1D PSD, (b) retrieved horizontal angle vs. 2D PSD signal, (c) retrieved vertical angle vs. 2D PSD signal.

the result from the 2D PSD which shows the real world's signal and contains environmental noises. Moreover, the 2D PSD signal has small jumps/spikes on the negative portion of the sensor. Although our mirror is almost crosstalk-free, these jumps could be due to a minor cross talk between the two axes of oscillation. That is why the results of 2D PSD looks noisier than the result from the method proposed in the paper.

The comparison between the retrieved angles using the proposed method and the measured angles using the 2D PSD is

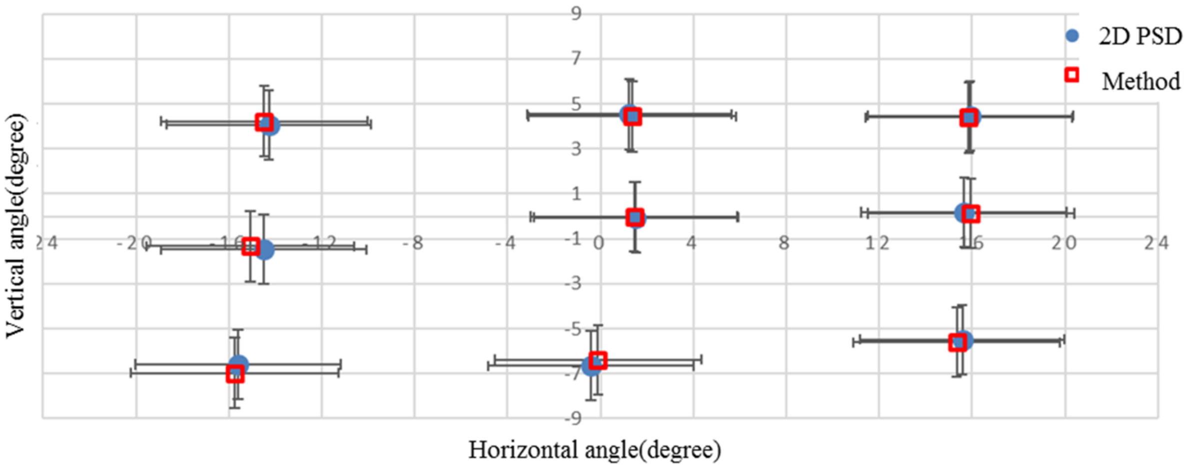


Figure 9. Comparison between the angles retrieved using the method proposed in this paper and the measured angles using the 2D PSD (blue color points are angles measured using 2D PSD, red color points are angles retrieved using 1D PSD based method proposed in the paper).

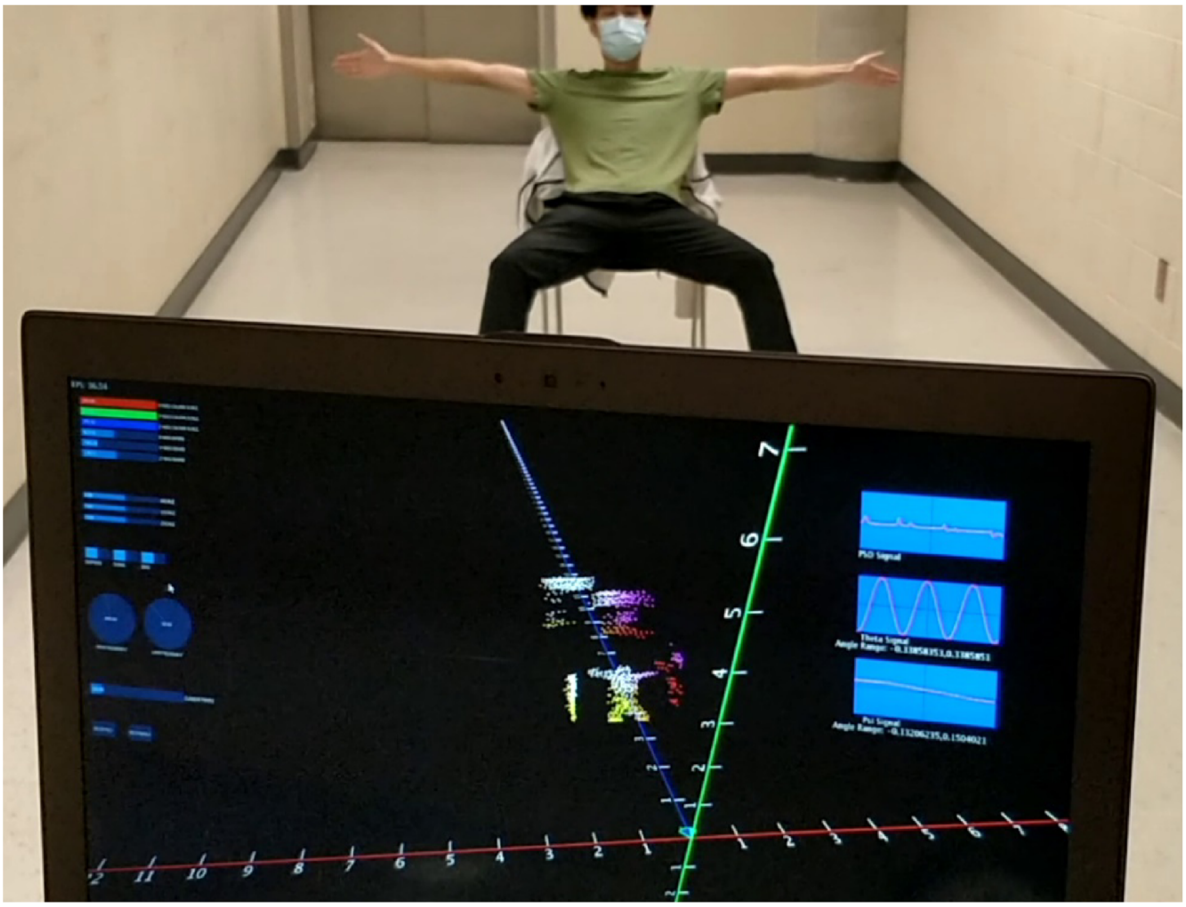


Figure 10. 3D point cloud of the environment Horizontal frequency: 150 Hz, vertical frequency: 2 Hz.

presented in figure 9, where 9 points are compared. The largest error for the oscillation vertical angle is 9.6% and 5.36% for the horizontal vibration angle. Decreasing crosstalk and increasing the ratio of the scanning frequencies will reduce the error. Figure 7 illustrates that the measured maximum horizontal scanning angle is limited by the size of the 2D PSD sensing surface and the distance between the 2D PSD and the mirror. However, the 1D PSD angle measurement method proposed in this paper is not limited by the mirror's maximum horizontal scanning angle.

6. Application of the proposed method of using 1D PSD to measure 2D scanning mirror's angle to a 3D LiDAR system

In order to implement the proposed method in real time, the prototype is applied to a 3D LiDAR system, in which the software package of Processing 3 is used as the development environment and for communication, Teensy Board 3.6 microcontroller, a single-point LiDAR, i.e. Benewake TF03-180 at 10 kHz frame rate, as well as an FPCB 2D micromirror [19] were used. First a peak finder algorithm is implemented. Then the peaks are split into three groups, which are considered as the 3 hits of the laser beam on the 1D PSD sensing surface at t_1, t_2 and t_3 and used as the input to the method proposed in this paper. Both horizontal and vertical vibration angles ψ and θ are retrieved using equations (6) and (7) The execution time of the algorithm was measured to be 70–100 microseconds for each pack of 5000 points in Processing 3. The 3D LiDAR's is used to scanned human body as shown in figure 10, which also shows the measured point cloud.

7. Conclusion

A novel angle measurement method for 2D scanning mirrors has been presented. The method principle was introduced and a prototype has been built with experiments conducted to verify the proposed method. In addition, the proposed method was implemented in a 3D scanning LiDAR system to illustrate its capability of achieving real-time measurement and it can be used in practical applications with the advantages of low cost and compact size over other reported methods of measuring the 2D scanning mirrors' angle.

Acknowledgment

This research is under the support of Mitacs Accelerate Program (Mitacs IT 13556).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iD

Siyuan He https://orcid.org/0000-0002-6954-1206

References

[1] Wang D, Watkins C and Xie H 2020 MEMS Mirrors for LiDAR: a review *Micromachines* **11** 456

[2] Kang S-Y, Park J-H and Ji C-H 2020 Design optimization of a 6.4 mm-diameter electromagnetic 2D scanning micromirror *Opt. Express* **28** 31272–86

[3] Cagdaser B *et al* 2004 Capacitive sense feedback control for MEMS beam steering mirrors *Proc. 2004 Solid-State Sensor and Actuator Workshop* pp 348–51

[4] Grahmann J, Conrad H, Sandner T, Klose T and Schenk H 2009 Integrated position sensing for 2D microscanning mirrors using the SOI device layer as the piezoresistive mechanical-elastic transformer *MOEMS and Miniaturized Systems VIII* vol 7208 (International Society for Optics and Photonics) p 720808

[5] Lei H, Wen Q, Yu F, Zhou Y and Wen Z 2018 FR4-based electromagnetic scanning micromirror integrated with angle sensor *Micromachines* **9** 214

[6] Wen Q *et al* 2018 Investigation of electromagnetic angle sensor integrated in FR4-based scanning micromirror *Appl. Sci.* **8** 2412

[7] Zhou Y, Wen Q, Wen Z, Huang J and Chang F 2017 An electromagnetic scanning mirror integrated with blazed grating and angle sensor for a near infrared micro spectrometer *J. Micromech. Microeng.* **27** 125009

[8] Tortschanoff A *et al* 2012 Optical position feedback for electrostatically driven MOEMS scanners *MOEMS and Miniaturized Systems XI* vol 8252 (International Society for Optics and Photonics) p 82520S

[9] Baumgart M, Lenzhofer M, Kremer M and Tortschanoff A 2015 Integrated packaging of 2D MOEMS mirrors with optical position feedback *MOEMS and Miniaturized Systems XIV* vol 9375 (International Society for Optics and Photonics) p 93750R

[10] Liu Y, Wang H, Zhao W, Qin H and Fang X 2016 Thermal-performance instability in piezoresistive sensors: inducement and improvement *Sensors* **16** 1984

[11] Duan C, Wang W, Zhang X, Zhou L, Pozzi A and Xie H 2016 A self-aligned 45-tilted two-axis scanning micromirror for side-view imaging *J. Microelectromech. Syst.* **25** 799–811

[12] Wang D, Watkins C, Koppal S and Xie H 2019 A silicon optical bench with vertically-oriented micromirrors for active beam steering *Sens. Actuators* A **298** 111586

[13] Mäkynen A 2000 *Position-Sensitive Devices and Sensor Systems for Optical Tracking and Displacement Sensing Application* (Oulu, Finland: Faculty of Technology, University of Oulu)

[14] Tortschanoff A *et al* 2011 Optical position feedback and phase control of resonant 1D and 2D MOEMS-scanners *MOEMS and Miniaturized Systems X* vol 7930 (International Society for Optics and Photonics) p 79300S

[15] Tortschanoff A, Sandner T and Kenda A 2012 Design of an optical position detection unit for fast 2D-MOEMS scanners *Optical Systems Design 2012* vol **8550** (Barcelona, Spain: CCIB—Centre Convencions Internacional Barcelona) pp 85501F

[16] Tortschanoff A, Frank A, Wildenhain M, Sandner T, Schenk H and Kenda A 2010 Position feedback and phase control of resonant MOEMS-mirrors with one and two axes *Proc. Eng.* **5** 689–92

[17] Kimoto K, Asada N, Mori T, Hara Y and Ohya A 2014 Development of small size 3D LIDAR *2014 IEEE Int. Conf. on Robotics and Automation (ICRA)* (IEEE) pp 4620–6

[18] Tortschanoff A *et al* 2010 Position encoding and phase control of resonant MOEMS mirrors *Sens. Actuators* A **162** 235–40

[19] Davis P J 1975 *Interpolation and Approximation* (Cannada: General Publishing Company)