SIGNIFICANTLY ENHANCED BANDWIDTH OF A DUAL-AXIS PIEZOELECTRIC QUASI-STATIC MEMS MIRROR FOR MINIATURIZED LASER TRACKING

Anna Li[1,2], Hao Huang[1,2], Yongquan Su[1,3], Cheng Zhang[1,2], Jiachang Zhang [1,2], Yonggui Zhang [1], Lihao Wang [1,4], Yichen Liu [1,3], Yang Wang [1,2], and Zhenyu Wu[1,2,3,4,5]

[1] Shanghai Institute of Microsystem and Information Technology, CHINA
[2]University of Chinese Academy of Sciences, CHINA
[3]Shanghai Industrial μTechnology Research Institute, CHINA
[4]Shanghai MExpert Technologies Co., Ltd, CHINA and
[5]Shanghai University, CHINA

ABSTRACT

A large working bandwidth is the key to attaining real-time tracking and positioning of the target of a laser tracking system. This paper introduces a dual-axis piezoelectric quasi-static MEMS mirror, proposed for the first time in laser tracking. The bandwidth of the MEMS mirror is enhanced through structural optimization and control algorithms. The lightweight design results in a high resonant frequency of 1011.25 Hz. Optimization of the feedforward algorithm reduces the settle time from 2 s to 0.5 ms, significantly increasing the vector scan frame rate from 0.2 fps to 5.6 fps, thereby enhancing bandwidth to 2000 Hz. While the closed-loop control combined with filtering and PID algorithm can improve system reliability. Therefore, the dual-axis quasi-static piezoelectric MEMS mirror ultimately achieves to fast and stable for laser tracking.

KEYWORDS

MEMS mirror, piezoelectric, quasi-Static, bandwidth, laser tracking, feedforward control, PID

INTRODUCTION

The small size and rapid response of MEMS mirrors make them vital in laser tracking systems, particularly for beam pointing and deflection. Electrostatic MEMS mirrors controlled by the high-order Bessel filter and PID [1] are frequently utilized in laser tracking [2]. However, despite piezoelectric MEMS mirrors with high linearity and reliability of piezoelectric [3], they have not yet been applied to laser tracking. In recent research, Gu's team proposed a piezoelectric MEMS mirror with a large deflection angle, but low resonant frequency and narrow operating bandwidth [4]. In order to achieve fast and accurate tracking of moving targets, there is an urgent need for a piezoelectric MEMS mirror with a large bandwidth when operating in quasi-static mode.

DESIGN OF NEW STRUCTURAL OF THE MEMS MIRROR

The stiffness and resonant frequency of a MEMS mirror can be formulated as:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \tag{1}$$

$$K = \frac{AE}{L} = \frac{hdE}{L} \tag{2}$$

Particularly, K is the stiffness, f is the resonant frequency, m is the mass of a MEMS mirror, E is the elastic modulus, h, d, and l represent the thickness, width, and length of the movable part, respectively. It can be concluded that reducing the mirror mass will increase the resonant frequency. In addition, reducing the thickness of the top silicon can lower the stiffness, thereby increasing the turning angle of the MEMS mirror.

By finite element analysis, calculate and compare the changes in resonant frequency of the device caused by different mirror sizes and thickness of top silicon, as shown in Figure 1. To meet the application requirements of laser tracking, it was ultimately decided to choose a mirror diameter of 3mm and the top silicon thickness of 40 um. A dual-axis quasi-static MEMS mirror based on AlScN piezoelectric material [5, 6] is shown in Figure 2.

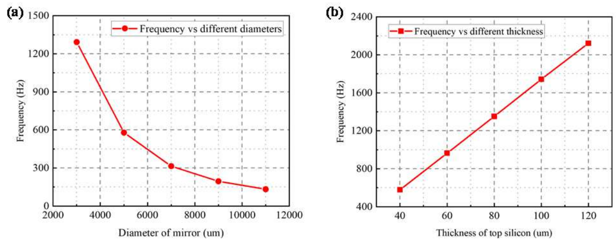

Figure 1. Simulation results of the MEMS mirror: (a) Frequency vs different mirror diameters; (b) Frequency vs different thickness of top silicon.

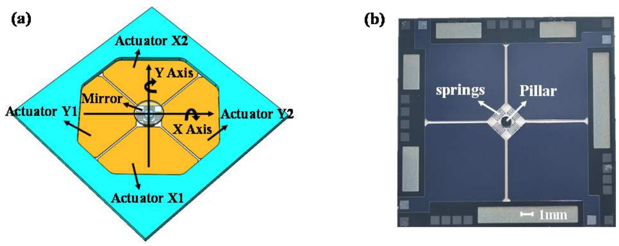

Figure 2. (a) The structure of the MEMS mirror in the top view; (b) The photograph of the MEMS mirror.

DESIGN OF CONTROL ALGORITHMS FOR THE MEMS MIRROR

Feedforward algorithm for open-loop control

Based on POSICAST control [7] principle and the under damping characteristics of the MEMS mirror [8], the oscillation of the mirror under high-frequency excitation is suppressed to achieve fast stability [9]. The first algorithm design is a two-step feedforward control as shown in formula (3). With two-step control, the MEMS mirror reaches the target output at t_p, which represents half of the natural oscillation period of the mirror. The second algorithm design is a three-step feedforward control [10], adding two intermediate steps to reach the target output in $\frac{2}{3}t_p$, as shown in formula (4). It can be seen that the "three-step" control reaches the target voltage faster than the "two-step " control.

$$V_x = \begin{cases} V_0 & t \le 0 \\ V_0 + \dfrac{V' + V_0}{2} & 0 < t < t_p \\ V' & t \ge t_p \end{cases} \tag{3}$$

$$V_x = \begin{cases} V_0 & t \le 0 \\ V_0 + 0.98\left(V' - V_0\right) & 0 < t \le \frac{1}{3}t_p \\ V_0 + 0.02\left(V' - V_0\right) & \frac{1}{3}t_p < t \le \frac{2}{3}t_p \\ V' & t \ge t_p \end{cases} \tag{4}$$

PID algorithm for closed-loop control

Based on the PID control principle [11], a combination of proportional, integral, and derivative algorithms is used to correct the deviation between the output of the MEMS mirror and the target. This results in a stable target state for the output of the MEMS mirror. The closed-loop control system designed based on PID algorithm is illustrated in Figure 3. To achieve the optimal closed-loop control effect, the proportional, integral, and derivative constants, KP, KI, and KD, are adjusted to the controlled, the MEMS mirror.

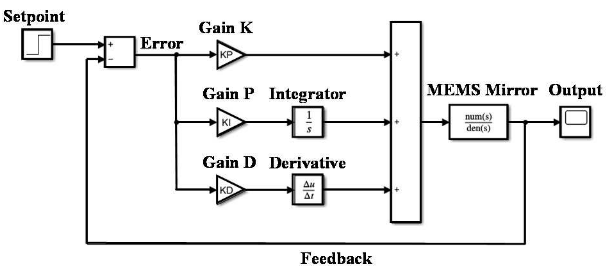

Figure 3. Schematic diagram of closed-loop control system based on PID algorithm.

EXPERIMENT RESULTS

The spectrum curve of the MEMS mirror was obtained by a Laser Doppler Velocimeter (LDV) instrument (Polytec MSA 500) [9], as shown in Figure 4 (a). The resonant frequencies of the X-axis and Y-axis are close, at 1004.69 Hz and 1011.25 Hz, respectively.

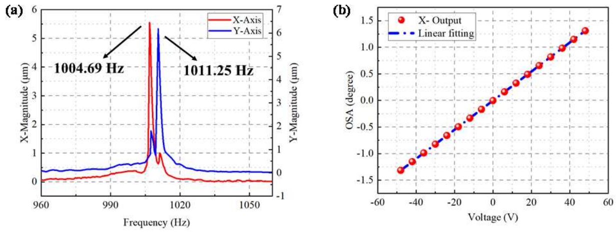

Figure 4. (a) Frequency spectrum of the MEMS mirror; (b) Optical scanning angle of the MEMS mirror with driving voltage.

An angle characterization system for MEMS mirrors has been set up in Figure 5. The laser source generates laser, which is then directed onto the mirror through a collimator and aperture, and the laser is reflected onto a position detector (PSD). The control signal from the computer drives the MEMS mirror through the circuit board, causing a change in the reflection position of the laser. To obtain the motion of the MEMS mirror, the computer monitors the laser position signal of PSD in real time through the data acquisition module.

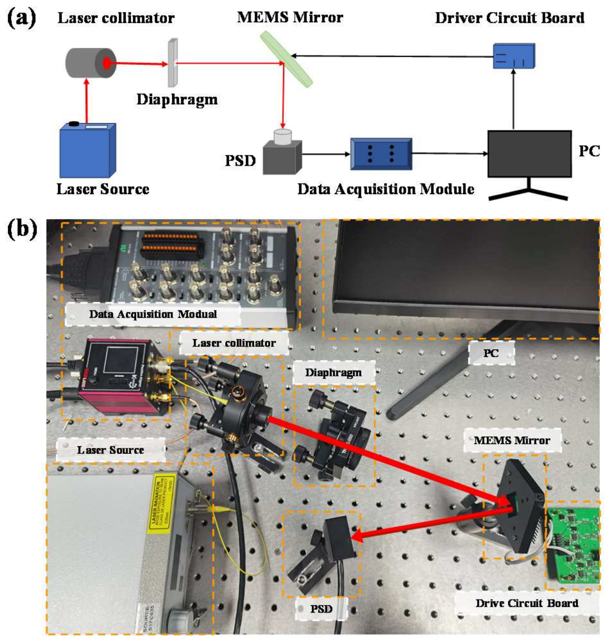

Figure 5. Angle characterization system of MEMS mirrors: (a) Schematic diagram; (b) Image of all components.

The static response characteristics of MEMS mirrors are obtained, utilizing the characterization system shown in Figure 5. As shown in Figure 4 (b), the sensitivity of the MEMS mirror is measured to be 0.017015 deg/V, and it exhibits a nonlinear error of 0.0888%. This high linearity enhances the controllability of the MEMS mirror.

Input step voltage signals to the MEMS mirror and compare the control effects of different feedforward algorithms. The experiment results are shown in Figure 6. The stability margin is defined as ± 5%. Without algorithmic control, the settle time of the MEMS mirror is about 2 s, and the operating bandwidth is 0.5 Hz. Before the stabilization of the MEMS mirror, there were significant oscillations and crosstalk phenomena between the two pairs of axes. The feedforward control result of the

" two-step " is illustrated in Figure 6 (a), where the settle time is shortened to 2 ms, achieving a control bandwidth of 500Hz. Furthermore, the feedforward control result of the " three-step " is illustrated in Figure 6 (b), where the settle time is shortened to 0.5 ms and the control bandwidth is increased to 2000 Hz.

Input a vector spiral shape consisting of 512 points, and compare the scanning effect of the MEMS mirror. The experiment results are shown in Figure 7. Without algorithmic control, severe distortion occurs in scanned graphics at very low frame rates, 0.6 fps. Based on the feedforward algorithms, the results fit well with the input graphics, with a maximum frame rate of 3.8 fps under the "two-step" control and 5.6 fps under the "three-step" control.

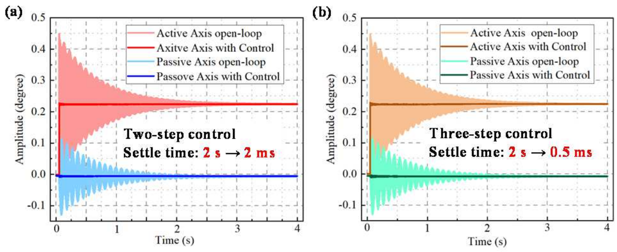

Figure 6. Comparison of step response effects of open-loop control of the MEMS mirror with: (a) two–step control; (b) three–step control.

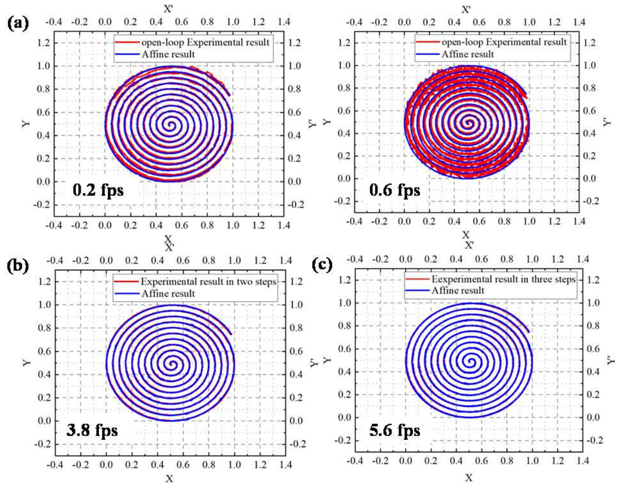

Figure 7. Vector scanning results of the MEMS mirror: (a) without feedforward control at different frame rate; (b) with two-steps control at 3.8 fps; (c) with three-steps control at 5.6 fps.

The experiment results show that the feedforward control can effectively shorten the settle time of the MEMS mirror and improve the working bandwidth when the input signal changes rapidly. Moreover, comparing the control effects of the two feedforward algorithms, the "three-step" has the shorter settle time of 0.5 ms. It is more suitable for large bandwidth control of MEMS mirrors, with a maximum working bandwidth of 2000Hz.

Based on the PID control algorithm from Section 3, a step voltage signal was input to the MEMS mirror. The experiment results are shown in Figure 8 (a). The response signal of the MEMS mirror does not exhibit long-term oscillation, with the settle time of 12 ms and a maximum working bandwidth of 83 Hz. Furthermore, a 200Hz triangle wave signal was input into the MEMS mirror, and the experiment results are shown in Figure 8 (b). Without algorithmic control, the response signal is superimposed with the oscillation of the MEMS mirror itself, resulting in severe waveform distortion. With the closed-loop control of PID algorithm, the response signal maintains a good triangle waveform.

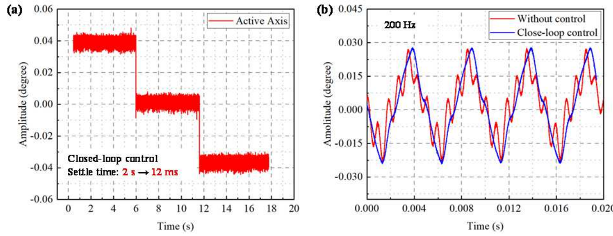

Figure 8. Closed-loop control effect of the MEMS mirror: (a) Step response; (b) 200 Hz triangle wave.

Comparing the experiment results of open-loop control and closed-loop control, it can be seen that the feedforward control of "three-step " has the shortest settle time and maximizes the working bandwidth of the MEMS mirror, making it applicable to laser fast tracking systems. Finally, Table 1 summarizes the comparison of MEMS mirrors' performance between this study and other reports.

At present, the MEMS mirror has been applied in a laser tracking system designed by our group. The working principle of the laser tracking system is shown in Figure 9. The control system controls the scanning of the MEMS mirror to search for the target, and the wide-angle lens increases the field of view of the MEMS mirror. The laser reflected by the target is received by the detector and fed back to the control system. The control system calculates the position of the target and then controls the MEMS mirror to point and track the target. The motion trajectory of the target can be displayed in real-time on the monitoring screen.

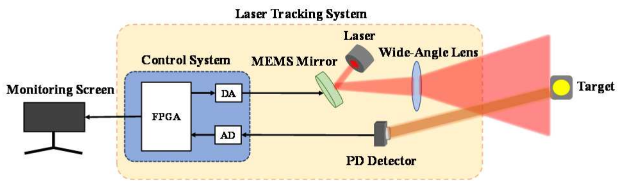

Figure 9. Schematic diagram of the MEMS laser tracking system.

The comparison of tracking effects is shown in Figure 10 (a) and (b). Through the control of feedforward algorithm, the laser reflected by the MEMS mirror locks onto the target in a stable scanning pattern and follows the movement. Real-time tracking of moving unmanned aerial vehicles in air can be achieved by the miniaturized tracking system based on this MEMS mirror.

Table 1. Comparison of MEMS Mirrors

Reference	Drive Mode	Mirror Diameter	Resonant Frequency (Hz)	Q Factor	Maximum Angle (degree)	Bandwidth (Hz)
[1]	Electrostatic	2 mm	1314	75	±10	3500
[4]	Piezoelectric	5 mm	231	50	±5	12.5
This work	**Piezoelectric**	**3 mm**	**1011**	**321**	**±2.04**	**2000**

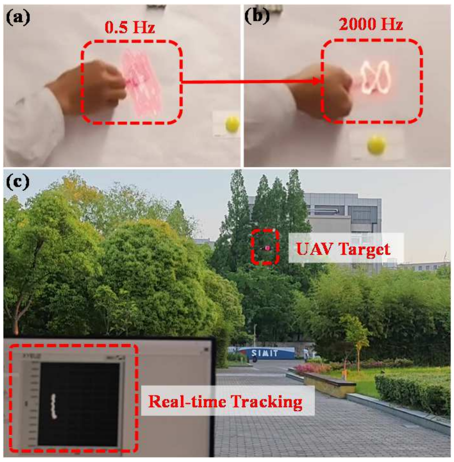

Figure 10. Laser tracking demonstration results: (a) without control; (b) with control; (c) UAV laser tracking.

CONCLUSIONS

In this study, the work bandwidth of a dual-axis piezoelectric quasi-static MEMS mirror is enhanced for rapid target tracking and aiming in a miniaturized laser system. Structural optimizations increased the resonant frequencies to 1004.69 Hz of X-axis and 1011.25 Hz of Y-axis. Performance comparisons between open-loop and closed-loop control revealed that the "three-step" feedforward control achieved a minimum settle time of 0.5 ms and a maximum bandwidth of 2000 Hz. This MEMS mirror has been successfully integrated into our custom miniaturized laser tracking system, allowing for real-time target tracking through feedforward control.

ACKNOWLEDGEMENTS

This work is supported by the National Key R&D Program of China (2021YFB3202500), the Shanghai Municipal Science and Technology Commission (HCXBCY-2021-044), " Science and Technology Innovation Action Plan" Daystar Project 23YF1445100 and the National Key R&D Program of China under Grant (No. 2023YFB3209900).

REFERENCES

[1] MILANOVIĆ V, KASTURI A, YANG J, et al. Closed-loop control of gimbal-less MEMS mirrors for increased bandwidth in LiDAR applications, F, 2017 [C].
[2] DANIEL L, VELJKO M, ABHISHEK K, et al. Optical MEMS enable next generation solutions for robot vision and human-robot interaction, F, 2022 [C].
[3] HAO Z, YANG W, LIHAO W, et al."Process Control Monitor (PCM) for Simultaneous Determination of the Piezoelectric Coefficients d31 and d33 of AlN and AlScN Thin Films,"Micromachines,vol 13,no 4, 581-,2022.
[4] GU-STOPPEL S, SENGER F, WEN L, et al. A design and manufacturing platform for AlScN based highly linear quasi-static MEMS mirrors with large optical apertures; proceedings of the OPTO, F, 2021 [C].
[5] LIU Y C, WANG L H, SU Y Q, et al."AlScN Piezoelectric MEMS Mirrors with Large Field of View for LiDAR Application,"Micromachines,vol 13,no 9,2022.
[6] ZHU W, SU Y, GAO S, et al."Electrical aging of a piezoelectric MEMS fast steering mirror and its impact on reliability,"Sensors and Actuators A: Physical,vol 376,no 115589,2024.
[7] GONZALEZ E A, HUNG J Y, DORCAK L, et al."Posicast control of a class of fractional-order processes,"Cent. Eur. J. Phys,vol 11,no 6, 868-80,2013.
[8] YU Z, WANG L, WANG Y, et al."Control of a MEMS Fast Steering Mirror With Improved Quasi-Static Performance,"IEEE Access,vol 11,no 95307-14,2023.
[9] LI A, HUANG H, ZHANG P, et al."Determination of Crosstalk in a Dual-Axis Piezoelectric MEMS Mirror and Suppression With Feedforward Algorithms,"IEEE Sensors Journal,vol 24,no 20, 32272-82,2024.
[10] C P, J J, A S, et al."Extreme angle, tip-tilt MEMS micromirror enabling full hemispheric, quasi-static optical coverage,"Opt. Express,vol 27,no 11, 15318-26,2019.
[11] PID Controller Design Approaches - Theory, Tuning and Application to Frontier Areas [M]. INTECH Open Access Publisher.

CONTACT

*Yang Wang, tel: +86-21-69075572; wangyang@mail.sim.ac.cn
*Zhenyu Wu, tel: +86-21-69075572; zhenyu.wu@mail.sim.ac.cn