Towards Fast and High-Resolution Adaptive Optics using Phase Light Modulators

John M. Bass*, Jeffrey Y. Chen*, Gregory M. Nero, Thomas L. Koch, Yushi Kaneda, Ivan B. Djordjevic, Florian Willomitzer, Yuzuru Takashima
Wyant College of Optical Sciences, University of Arizona, United States
*These authors contributed equally

Abstract: Adaptive optics systems traditionally use deformable mirrors with key resolution and speed limitations. We demonstrate first steps toward a high-resolution adaptive optics system using a recent Texas Instruments Phase Light Modulator capable of kHz speeds. © 2024 OSJ

Keywords: adaptive optics, phase light modulator, spatial light modulator, wavefront sensor, deformable mirror, Shack-Hartmann

1. Introduction

Adaptive optics (AO) systems are widely used in multiple fields to improve image and measurement qualities by removing wavefront aberrations. Areas of application include astronomy, vision science, microscopy, and free-space optical communication. The setups typically consist of an actuator-driven deformable mirror and a wavefront sensor. The wavefront sensor measures optical aberrations in an incoming wavefront, and the deformable mirror removes them based on this measurement [1].

However, deformable mirrors possess key trade-offs. Many have resolution limitations which restrict the wavefront correction quality, while some have speed limitations which lower effectiveness in extremely dynamic environments. These limitations become problematic when trying to correct for quickly-changing high-frequency aberrations which can be caused, i.e., by light propagating through living (moving) tissue in microscopy [2] or through atmospheric turbulence in low elevations [3]. Currently, to our knowledge, no device has hit the "holy grail" of extremely high-resolution wavefront correction at high speeds, for a low cost.

We believe a new class of MEMS-based devices, Texas Instruments piston-mode Phase Light Modulators (TI-PLMs), could fill this gap. These devices are extremely high resolution segmented mirrors, each containing a 1358x800 array of micromirrors with a pixel pitch of 10.8 microns. Each micromirror is electrostatically actuated by three electrodes underneath, which control the position. By addressing each electrode, a user can move each micromirror vertically at high speeds, with frame rates up to 5.7 kHz [4]. The specifications of the TI-PLM suggest that it could be a capable correction device for adaptive optics, at a reasonable cost. While the 0.67" diagonal of the device limits the etendue, the TI-PLM could deliver effective wavefront correction in fields where this is not a problem.

In this contribution, we will show the first-ever TI-PLM-based AO beam correction. Moreover, we will demonstrate the first considerations and experiments towards the field-implementation of a fully functional, high-speed adaptive optics system based on the TI-PLM. The final goal of this system is to demonstrate correction of extremely high-order Zernike modes at kHz speeds, for use in quickly-changing environments.

2. Methods

For a first proof-of-principle of TI-PLM-based AO beam correction, we designed the system shown in Fig. 1. The system first sends an expanded He-Ne laser beam through a space that contains an aberrating medium to simulate the effects of turbulence or distortion.

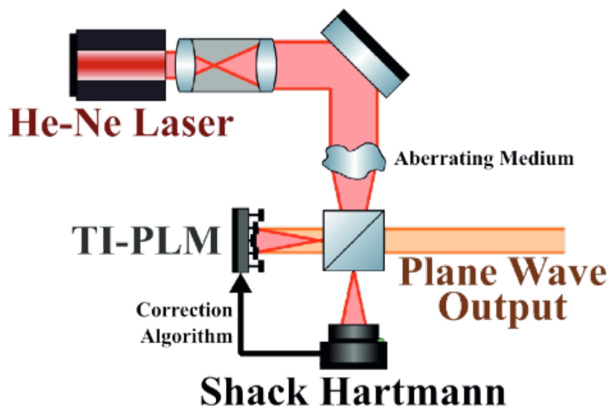

Fig. 1: Diagram of the TI-PLM AO System

After being aberrated the beam is sent through a beam splitter. A TI-PLM is placed on one output of this beam splitter, while a Shack-Hartmann wavefront sensor (Optocraft SHSCAM AR-S-150-GE) is placed an equal distance away at the other output. The wavefront sensor measures the shape of the incoming wavefront and outputs a vector of Zernike polynomial amplitudes to describe this shape.

Next, the vector of Zernike polynomial amplitudes is converted into a vector of micromirror positions, to correct the wavefront with the TI-PLM. To do this, we use a transfer matrix, that is created using a three-step process. First, we generate normalized images of each Zernike polynomial, with resolutions matching that of the TI-PLM. These images contain the required micromirror positions on the device that would be required to correct for each aberration. Next, we convert each image into a column vector, and finally combine each column vector to produce the transfer matrix. The rows of this trans-

Proc. of SPIE Vol. 13258 1325801-202
Paper presented at the 14th International Conference on Optics-Photonics Design & Fabrication, Tucson, July 10th-12th, 2024
Submitted: Feb. 13th 2024, Accepted: Apr. 4th 2024, Published in Abstract Digest: Aug. 15th, 2024 (https://doi.org/10.1117/12.3048202)

fer matrix correspond to micromirror positions, while the columns correspond to Zernike polynomials. By multiplying the vector of Zernike polynomial amplitudes by our transfer matrix, we obtain a vector of micromirror positions that would be required to correct an incoming beam.

3. Results

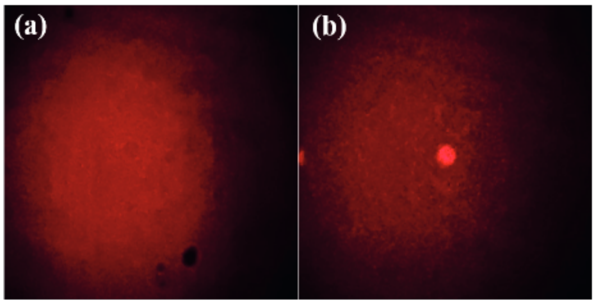

Fig. 2: Demonstration of TI-PLM AO system correcting for defocus and tilt aberrations. The output of the system is viewed on a screen (a) without AO enabled and (b) with AO enabled.

To test the system, we used a lens as an aberrating medium that we shifted along the transverse and longitudinal axes to generate tilt and defocus aberrations, respectively (see Fig. 1). We then used our system to correct for these aberrations.

Figure 2 shows this correction. Figure 2(a) shows the output of the system when AO correction was turned off; the output beam is clearly defocused and spread out. Figure 2(b) shows the system output when AO correction was then turned on; the central region of light is the corrected plane wave. By decreasing the speed of the system, we could observe the correction of aberrations frame by frame.

To test the AO correction accuracy, we measured the defocus at the output of the AO system using a shearing interferometer and measured tilt by checking the change in beam position at a long distance when the lens was shifted. We confirmed that both the tilt and defocus errors were successfully removed by the TI-PLM to create an on-axis plane wave.

4. Discussion and Conclusions

Our results demonstrate that a TI-PLM has huge potential to become an effective correction device for AO systems. This has the advantage of having over a million actuatable segments that can be updated at high speeds (up to 5.7 kHz) for a relatively low cost.

However, the solution is not without potential drawbacks: standard deformable mirrors correct the continuous spatial phase profile, while a TI-PLM only corrects the modulo 2-pi phase of a wavefront. This means that the TI-PLM can only correct relatively narrow bands of wavelengths at a time.

Even so, the TI-PLM could still enable new applications in situations that can employ monochromatic light, such as in retinal imaging, or microscopy. Our future work will focus on making the system to perform faster with higher-resolution corrections to be ultimately used in the field.

Acknowledgments
This paper was prepared by the named authors in collaboration with the National Center for Manufacturing Sciences (NCMS). The research effort and this paper is/was sponsored by the funding from U.S. Department of Defense. The content of this report does not necessarily reflect the position or policy of NCMS or the Government; no official endorsement should be inferred.

References

[1] K. M. Hampson, R. Turcotte, D. T. Miller, K. Kurokawa, J. R. Males, N. Ji, and M. J. Booth, "Adaptive optics for high-resolution imaging," *Nature reviews. Methods primers*, vol. 1, p. 68, 2021.

[2] Q. Zhang, Q. Hu, C. Berlage, P. Kner, B. Judkewitz, M. J. Booth, and N. Ji, "Adaptive optics for optical microscopy [invited].," *Biomedical optics express*, vol. 14 4, pp. 1732–1756, 2023.

[3] P. Liu, K. Kazaura, K. Wakamori, and M. Matsumoto, "Studies on c2n and its effects on free space optical communication system," in *8th Asia-Pacific Symposium on Information and Telecommunication Technologies*, pp. 1–6, 2010.

[4] T. A. Bartlett, W. C. McDonald, J. N. Hall, P. I. Oden, D. Doane, R. S. Ketchum, and T. Byrum, "Recent advances in the development of the Texas Instruments phase-only microelectromechanical systems (MEMS) spatial light modulator," in *Emerging Digital Micromirror Device Based Systems and Applications XIII* (J. Ehmke and B. L. Lee, eds.), vol. 11698, p. 116980O, International Society for Optics and Photonics, SPIE, 2021.

Paper presented at the 14th International Conference on Optics-Photonics Design & Fabrication, Tucson, July 10th-12th, 2024
Submitted: Feb. 13th 2024, Accepted: Apr. 4th 2024, Published in Abstract Digest: Aug. 15th, 2024 (https://doi.org/10.1117/12.3048202)