Recent Developments in Adaptive Optics

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Abstract

Adaptive optics is having an increasing impact on imaging systems outside its historical role in astronomy and advanced military applications. Two such areas are confocal microscopy and ophthalmology. In this talk I shall summarise some of the advances made by adaptive optics in the past couple of years in these two application areas, and also briefly describe progress in the fabrication of deformable mirrors based on MOEMS technology.

Introduction

Figure 1 shows the schematic form of a classical closed-loop AO system for astronomy. There are three key sub-systems: the wavefront sensor, the deformable mirror and the control system. It is customary to think of these three sub-systems separately although in reality it is their combination, in closed-loop operation, that is of most importance. The purpose of an AO system in astronomy is to correct, in real time, the dynamic aberrations in this case caused by atmospheric turbulence.

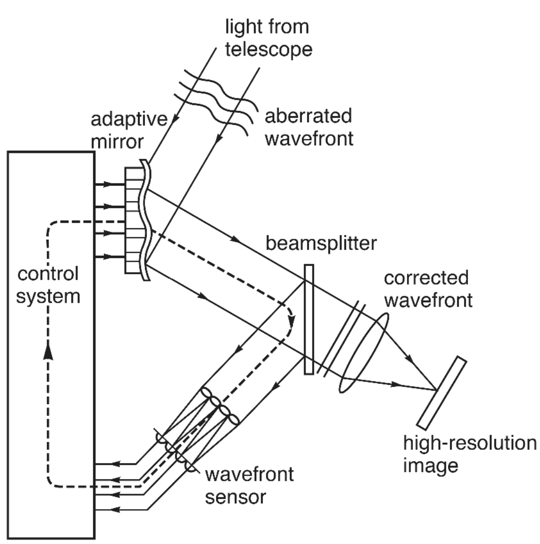

Figure 1. Schematic of an adaptive optics system for astronomy

MOEMS Deformable Mirrors

One area in which significant progress has been recently made is that of micro-optical-electrical-mechanical systems (MOEMS) for the fabrication of deformable mirrors. The group of Helmbrecht et al[2] at UC Berkeley have made discrete micromirrors with several microns of stroke that have piston and tip-tilt action (See Fig. 2). The largest device to date has only six mirrors but much larger arrays will be made in 2002.

A different process has been used by the group of Bifano,[3] yielding a continuous membrane surface in MOEMS technology. However, the stroke is lower, up to 2µm. Figure 3 shows a commercially available 140 actuator device using this technology.[4]

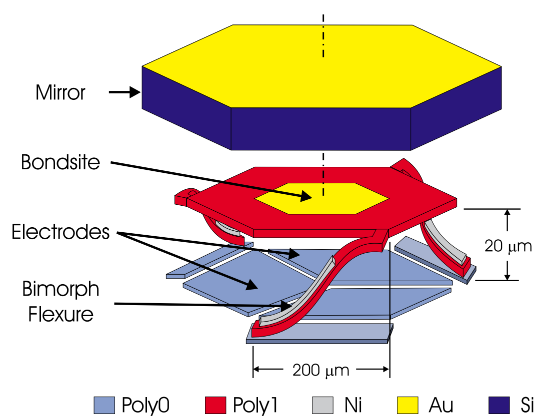

Figure 2. Tip, tilt and piston micro-mirror.[2]

Figure 3. 140 actuators MOEMS deformable mirror [4].

AO in Confocal Microscopy

In ordinary brightfield microscopy, a large area of the speciman is illuminated and a high numerical aperture objective forms an extended image. In contrast, in a confocal microscope, the object is illuminated by a point of light and this is re-imaged onto a pinhole behind which a detector is placed: to build up an image, the object is scanned over the probe of light (or *vice versa*). Because the pinhole is confocal to the illuminating probe, only a thin slice or section of the object is revealed, and by repeating the imaging process as a function of the focus position, a 3D image of the object can be obtained. Confocal microscopy enables 3D structures on a microscopic scale to be visualized.

The high transverse resolution of confocal microscopy is reduced if the illuminating probe is degraded in quality, and this happens as the probe passes through the object itself. Adaptive optics allows the quality of the probe to be maintained and therefore the high angular resolution to be maintained. In addition, more light passes through the pinhole and therefore the signal-to-noise ratio is maintained at a high value.

Figure 4 shows a breadboard set-up in our laboratory for evaluating the improvement made possible be adaptive optics. Note that both the ingoing and outcoming beams are reflected from the adaptive mirror.

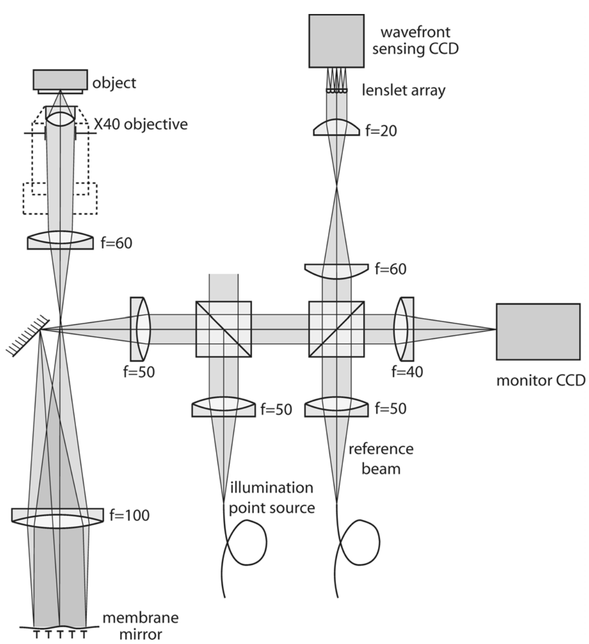

Figure 4. Schematic layout of a confocal microscope breadboard using adaptive optics

Figure 5 shows some sample results: the images are of the intensity in the pinhole plane. With no AO (top left), little light would pass through a pinhole (placed at the center of the image). With a simple scheme of wavefront sensing (top right), a more compact intensity distribution is seen, and more light would pass through the pinhole: a better wavefront sensing algorithm (lower picture) gives an even more compact intensity distribution.

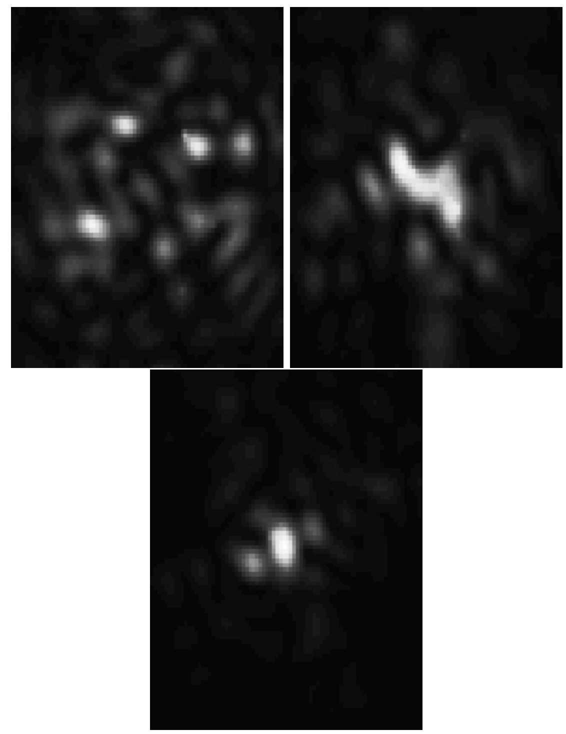

Figure 5. Intensity distribution in the confocal image plane. Top left: no AO. Top right: with AO, simple wavefront sensing. Lower: with AO, intensity weighted wavefront sensing

Ophthalmic Applications of AO

The wavefront sensor is one of the key parts of an AO system and in itself is useful as a stand alone instrument for assessing the optical performance of the eye. Figure 6 shows a schematic of a Shack-Hartmann wavefront sensor for the eye. One important application for this sensor is for the assessment of patients undergoing laser refractive surgery (e.g. Lasik) and a number of manufacturers have announced instruments in the past year (e.g. Ref. 5).

Following the pioneering paper by Roorda and Williams[6] showing *in vivo* imaging of the cone photoreceptors in the eye using open loop adaptive optics, three groups[7-9] have demonstrated closed loop operation in the past year, although diffraction-limited operation has not yet been achieved.

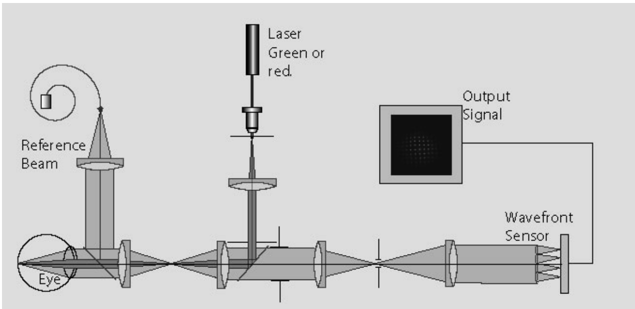

Figure 6 Wavefront sensing in the eye.

There is considerable current interest in this application of adaptive optics. Apart from improved retinal imaging by applying AO in a fundus camera or a laser scanning ophthalmoscope, there is also the possibility of enhancing vision, providing individuals with "super-vision". We can expect significant progress in this field in the coming years.

Acknowledgements

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References

1. J W Hardy, Adaptive Optics for Astronomical Telescopes, Oxford University Press, Optics, Oxford University Press, 1998.
2. M A Helmbrecht et al, “Micromirrors for Adaptive Optics Arrays”, in Transducers ’01, Proc. 11th International Conference on Solid State Sensors and Actuators, Munich, 2001, pp1290-1293.
3. T. Bifano, et al. "Compact adaptive optical compensation systems using continuous silicon deformable mirrors" SPIE's 46th Annual Meeting International Symposium on Optical Science and Technology,29 July - 3 August 2001,San Diego, CA, USA, High-Resolution Wavefront Control: Methods, Devices, and Applications III
4. Boston Micromachines Corporation, 108 Water Street, Watertown, MA 02472.
http://www.bostonmicromachines.com/
http://www.wavefrontsciences.com/
5. A Roorda and D R Williams, "The arrangement of the three cone classes in the living human eye", Nature 397 520-522 (1999)
6. E J Fernandez, I Iglesias and P Artal, "Closed-loop adaptive optics in the human eye", Opt. Lett. 26 746-748 (2001)
7. H Hofer et al, "Improvement in retinal image quality with dynamic correction of the eye's aberrations", Optics Express 8 631-643 (2001)
8. J-F Le Gargasson, M Glanc and P Lena, "Retinal imaging with adaptive optics", C R Acad Sci Paris, t2, Serie IV, 1131-1138 (2001)

Biography

Christopher Dainty is Pilkington Professor of Applied Optics and PPARC Senior Research Fellow at Imperial College, London. Prof Dainty has co-authored more than 100 peer-reviewed papers and approximately 150 conference publications. He is a Fellow of the Optical Society of America, SPIE and the UK Institute of Physics, and from 1990 to 1993 was President of the International Commission for Optics.