Adaptive Optics in Imaging

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Abstract

Adaptive optics (AO) is having an increasing impact on groundbased astronomy, providing telescopes on Earth with an angular resolution exceeding that of the Hubble Space Telescope. Such systems, however, cost millions of dollars and a different approach is required to the design of AO systems for application in medical imaging, industrial inspection or in consumer products. In this talk I shall review the progress made in astronomical adaptive optics, and then focus on our approach to low cost systems. Finally I shall describe some of the potential non-astronomical applications of adaptive optics.

Introduction

It is now 20 years since the first military systems using adaptive optics (AO) were built,[1] and 10 years since the first astronomical system was demonstrated.[2] Today, virtually all telescopes of diameter 4m or greater are equipped with adaptive optics, allowing them to achieve diffraction-limited angular resolution in the near infrared, despite the presence of atmospheric turbulence or "seeing". These systems cost several million dollars each, roughly the same as any sophisticated instrument on a large telescopes.

There are a number of potential applications for adaptive optics other than for astronomy or military uses. Some of these are:

- Intracavity laser correction
- Extracavity beam shaping
- Imaging of the retina
- Optometry
- Correction of spherical aberration
- Zoom lenses
- Confocal microscopy
- Free-space optical interconnects
- Ground-to-space optical communication
- Pulse shaping in lasers
- Submicron optical lithography
- 'Smart" binoculars
- Optical data storage
- Optical instrument manufacture and alignment
- Industrial inspection
- Laser materials processing

The challenge therefore is to design and construct low cost adaptive optics systems for the above applications.

Before describing our approach to this problem, we briefly discuss a few key issues in adaptive optics. 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. In a classical system, the usual argument is that the wavefront sensor is the most important element, since, if one cannot sense the distortion to be corrected, how can one apply the required correction? Figure 2 shows one of the most common wavefront sensors, the Shack-Hartmann sensor. This estimates the local wavefront slope by measuring the centroid of images formed by lenslets: this is potentially a very low cost wavefront sensor, and we are currently implementing this using a $20 lenslet array and a CMOS camera (similar to a WebCam). Other possible sensors include the curvature sensor[3] and the pyramid sensor.[4] In a low order system, one might in might dispense with a wavefront sensor altogether, and simply maximize the image sharpness[5]: perhaps a wavefront sensor is not essential, after all.

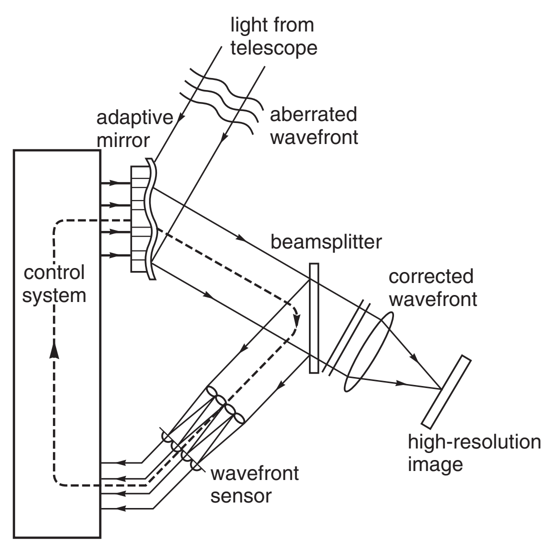

Figure 1. Schematic of an adaptive optics system for astronomy

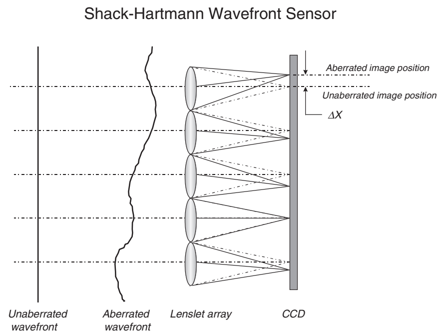

Figure 2. The Shack-Hartmann wavefront sensor.

A second issue in adaptive optics is that of angular isoplanatism. This is illustrated in Fig. 3 for the astronomical case: it is clear from this figure that the wavefront distortion experienced by two points in the field of view is different, and therefore different corrections have to be applied across the field-of-view. This is not possible with a single deformable mirror and the best that can be done is to correct one point and a limited field around that point called the isoplanatic patch. Unfortunately, the isoplanatic patch can be rather small, perhaps only a few arc seconds (1 arc sec is 5 µrad). This is a very major limitation of adaptive optics for imaging and the only way to overcome it is to use several deformable mirrors conjugated to different locations of the turbulence, so-called multi-conjugate AO (MCAO). This is the current “hot topic” in astronomical AO at the present time and MCAO systems are being designed for the World’s largest telescopes.

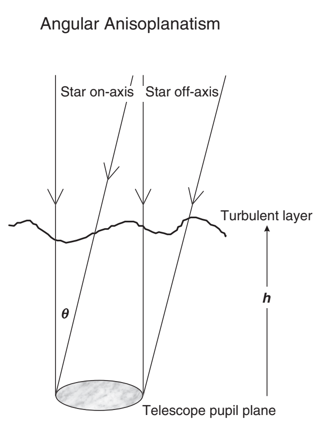

Figure 3. Angular anisoplanatism in astronomical AO.

A Low Cost AO Breadboard

In order to explore the scope for building low cost AO systems, our group has constructed two systems to date, the main difference between them being the physical size and the details of the control system. Here we briefly describe the first system (see [6] for further details and a movie of the AO process).

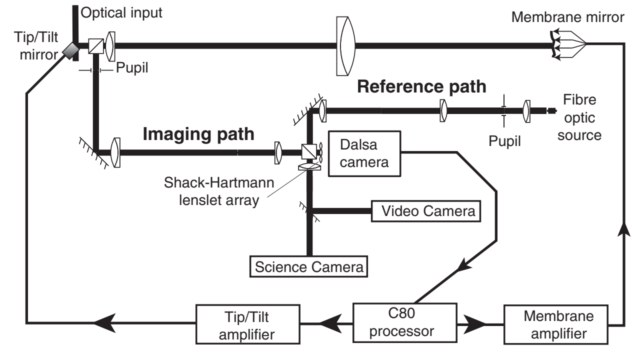

Figure 4. Schematic diagram of a breadboard layout for a low cost adaptive optics system.

Figure 4 shows the system layout. The whole system occupies a 60 by 150cm breadboard (60 by 60cm in the second system) and is designed as a testbed for a number of wavefront sensors and deformable mirrors. For the results shown in this paper, we used a 37-element membrane mirror from OKO Technologies[7] and a 5 by 5 Shack-Hartmann sensor with a Dalsa, Inc 128 by 128 pixel CCD camera as detector. This camera has a maximum frame rate of 780 frames per second, and this is our typical open-loop bandwidth.

The control system of the first system, as originally implemented, is shown in Figure 5. A Texas C80 digital signal processor (DSP) was used for the computations of the Shack-Hartmann centroids and for the control loop. The DSP was provided on a PC plug-in card, and in principle controlled the whole AO process over the PCI-bus. Initially, however, we had to rely on the host PC to direct the signals to the deformable mirror, and it is only recently that we have by-passed the PC altogether using a PCI I-O D-to-A card. This control system is easily able to maintain an open loop frame rate of 780fps, and we estimate that the maximum frame rate would be ≈3000fps. However, the use of commercial framegrabbers means that there is an unknown time delay in the system (probably ≈2 frames), thus lowering the bandwidth in closed-loop operation.

In our second breadboard system, all the control is accomplished by a Pentium 500MHz processor under the Linux operating system, and again we can achieve an open-loop frame rate of 780fps comfortably.

The details of the spatial and temporal control system are provided in Ref. [6]. We use a simple least squares approach for the spatial control, discarding higher order modes that cannot be corrected by the system. For temporal control, a simple integrator is used.

In order to test the system we use an optical wavefront generator as described in Ref [8]. Typically we generate single layer pseudo-Kolmogorov turbulence, with a (“wind”) velocity v and Fried parameter r_0: the tip-tilt signal produced by this generator is less than that expected for Kolmogorov turbulence with an infinite outer scale, and in the results shown below we did not need to use a separate tip-tilt mirror.

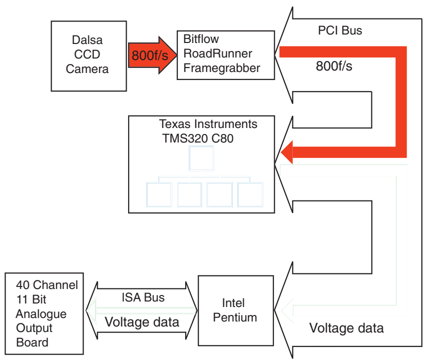

Figure 5. Schematic of control system

A sample result is shown in Figure 6: for this figure, the open loop frame rate was 270Hz, $D/r_0 \approx 7.5$ and $v/r_0 \approx 5$Hz. The maximum Strehl ratio was approximately 0.4 in this case, compared to a value for the reference arm of approximately 0.8: we have not carried out detailed modeling of our system, but this Strehl is of the same order-of-magnitude that we would expect for this value of D/r_0 and a 37-element membrane mirror.

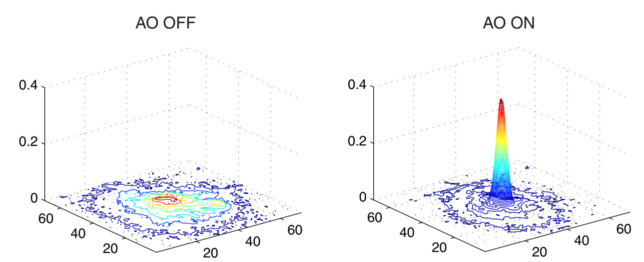

Figure 6. Adaptive imaging of a point source viewed through optically simulated turbulence with $D/r_0 \approx 7.5$ (from Ref [6]).

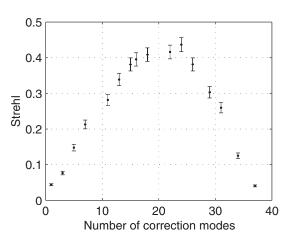

Figure 7. Strehl ratio as a function of the number of modes used in the control loop. (from Ref [6])

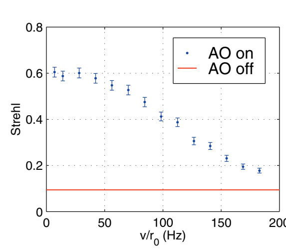

Figure 8. Strehl ratio as a function of the "wind speed" parameter v/r_0 for $D/r_0 \approx 5$. (from Ref [6])

Figures 7 and 8 provide a more quantitative description of the performance of the system. Figure 7 shows the effect of discarding higher order modes, for a value of D/r_0 of 7.5. We typically find that it is optimum to retain 20-25 modes in this system.

Figure 8 shows the temporal behaviour for an 780Hz frame rate and $D/r_0 \approx 5$. There is still a good Strehl ratio at value of $v/r_0 \approx 100$Hz, corresponding to a wind speed of $50ms^{-1}$ for a value of $r_0 \approx 0.5$m (typical of a good observing site in the near IR).

Conclusions and Discussion

Work by ourselves and others (e.g. [9,10]) has shown that experimental breadboard AO systems can be built for relatively low cost ($20-$30K) and this will open up applications in vision and ophthalmology, microscopy and optical communications. Beyond this, we need to identify applications that involve larger scale production; these applications might justify the development of very low cost deformable mirrors (or refractive correctors such as liquid crystals) and wavefront sensors. It is quite possible to envisage that an AO system of moderate spatial complexity (≈50 degrees of freedom) and temporal response (≈100Hz) could be built for <$10, provided the number of units made is sufficiently large.

Acknowledgements

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Biography

Christopher Dainty is currently Pilkington Professor of Applied Optics at Imperial College, London. From 1978 to 1983, he was Associate Professor of Optics at The Institute of Optics, University of Rochester, NY. 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.