Smart optics means much more than adaptive optics on telescopes: these new technologies are changing the way space instruments are built and operated and are bringing new technologies into everyday life in the form of cheaper, lighter and more robust optical systems. Steve Welch, Peter Doel, Alan Greenaway and Gordon Love summarize the work of the Smart Optics Faraday Partnership in the UK.

Smart optics technologies
In this simple description, smart optics depends on two technologies:

- A wavefront modulator, which can modify the shape of an incoming wavefront (thus changing its phase). Examples include deformable mirrors and liquid-crystal lenses.
- A wavefront sensor, which can estimate the shape of the wavefront. These use, for example, lenslet arrays and phase-diversity measurements.

These two essential building blocks are linked together in an AO system through a control loop to modify the incoming wavefronts, but the basic technologies of the wavefront modulators and the wavefront sensors have other “smart” applications that do not necessarily require linkages. In the following sections we will consider briefly some of the approaches used, first in wavefront modulation and then in wavefront sensing, with particular emphasis on developments that are supported through the Smart Optics Faraday Partnership in the UK and their application beyond terrestrial astronomy.

Deformable mirror technology
In present telescope AO systems the most commonly used wavefront modulator is a deformable mirror. Many types are in use, with such technology as thin glass facesheets deformed by piezoelectric actuators; bimorph mirrors made of thin slabs of piezoelectric material; and membrane mirrors that depend on electrostatic distortion of a thin metallic membrane. These mirrors range from a few centimetres to a few tens of centimetres across.

A recent innovation in deformable mirrors has been the development of micro-mirrors manufactured using Micro-Electro Mechanical Systems (MEMS) technology. The mirror is made using techniques developed from silicon chip production, where micro-electromechanical actuators are produced on a silicon wafer using photo-lithography and etching. This technology has already found uses in the optical switching and projection markets and has the potential to produce mirrors with thousands of tiny actuators at relatively low cost. MEMS devices are still under significant development, particularly with respect to the position sensing of individual mirrors. Techniques being explored include the use of a capacitive divider formed between the mirror and two sensing electrodes underneath it. As the mirror moves, one capacitor value increases and one decreases; the differential capacitance determines the exact tilt of the mirror. This position sensing is important for areas outside optical switching. On a larger scale there is interest in developing deformable mirrors several metres across for the next generation of 50–100 m class optical telescopes. In Europe there are two main telescope projects in progress, the EURO-50 50 m telescope and the ESO OWL 100 m telescope, which both have large adaptive mirrors in their baseline designs. Of particular note is the EURO-50 programme that proposes a 4000-actuator, 4 m diameter adaptive secondary mirror. The choice of substrate for such a mirror is important. Current research into large adaptive mirror technology has focused on conventional materials, such as glass (Burge et al. 2001) or nickel-coated aluminium. Both of these have their limitations because of their relatively high mass and, for glass, susceptibility to brittle fracture. Carbon fibre composite materials offer an interesting way forward, allowing lower mass, with high stiffness and thermal stability.

Mass is also a reason for the utility of AO far beyond the specific case of correcting for atmospheric turbulence. Deformable mirror technology can be used to produce lightweight optical systems with high imaging performance. This has applications in space and aviation systems where mass is a major cost driver. Although the operational environment of a spacecraft is relatively benign, mechanically speaking, the launch trauma is significant; the steps taken to mitigate this in the traditional design of the optics and structure add significant mass to the system. A deformable mirror could not only be lighter but, because it would be able to correct for thermal distortions and alignment errors once in orbit, could achieve a much higher imaging performance while relaxing the satellite design constraints, and hence reducing overall cost.

Adaptive liquid-crystal lenses
As well as deformable mirrors, lenses that can alter their shape or their effect on the phase
ronomy and space

pattern of an incoming wavefront have a place in smart optics. A lens is a fundamental optical component, with virtually limitless applications, but a particular attraction of a “solid state” variable lens is its potential for lightness and reliability. A compound lens system that could zoom and focus without any moving parts would be ideal for a lightweight, compact, reliable camera for a planetary lander, such as that needed for the Mercury-bound Bepi-Columbo mission, the proposed UK SIMONE mission to a near-Earth object, or subsequent Mars or other solar-system missions. A liquid-crystal element, as a potentially low-cost device, has applications on the ground, too, including CCTV, consumer products and machine vision.

There is a long history of research into tunable lenses based on, for example, piezoelectricity or acousto-optics (Shibaguchi and Funato 1992). Water-filled systems have also been proposed and used (see examples at www.adaptive-eye-care.com). Liquid crystal (LC) phase devices have, however, proved to be the most promising type of solid-state technology because of the relatively large changes of refractive index that are achievable for low voltages. LC lenses exploit the same relationship between electric field and refractive-index as liquid crystal displays. There are various ways of producing a switchable liquid-crystal lens, which I summarize here. Using a standard array of LC phase modulators allows the construction of a pixelated lens (Laude 1998), whereby the phase profile is produced by a step-like approximation. However, more than 10^4 data values (pixels) are needed to produce a lens. Another class of lenses uses patterned holed electrodes (Homma et al. 1999) whereby fringing fields are used to define the phase profile over a small hole in the LC electrode. This is a simple approach to lens construction, but it can only be used to produce micro-lenses (approximately tens of microns in diameter). The combination of an LC layer with a fixed lens (Hain et al. 2001) allows the construction of lenses with small f-ratios, but the lens construction and LC alignment is harder than using the modal principle used here. A similar technique uses an array of fixed micro-lenses (Commander et al. 2000), but these are not suitable for use in macro-optics systems. LC Fresnel lenses (Williams et al. 1989) have very short focal lengths, but also the usual problems of multiple foci and poor off-axis performance.

An alternative technique for controlling liquid crystal called “modal addressing” has been developed at the University of Durham (Naumov et al. 1999, Loktev et al. 2000). The key advantage is that the liquid crystal can be controlled without pixels over a large area, and therefore a low-order phase structure can be produced simply and easily. A liquid-crystal lens is nearly identical to a conventional liquid-crystal cell (with only one “pixel”). The difference is that one of the electrodes has a very high resistance (~MΩ/square). As shown in figure 2(a) it consists of a thin LC layer (~20 µm) between glass plates coated with electrodes. The electrical analogue of this circuit, in figure 2(c), is similar to a transmission line, or an array of RC filters. If an oscillating voltage is applied to each then the voltage in the centre of the cell will be less than the supply voltages at the edges. By carefully controlling the electrical parameters, a voltage and hence phase profile can be produced which is lens-like. The precise shape of the lens depends on the cell parameters and the amplitude, frequency and spectral content of the applied voltages.
LC lenses produced in this way are currently 5 mm in diameter and have focal lengths from infinity down to about 50 cm. Interestingly, lenses with astigmatism and spherical aberration can be produced (for aberration correction). The major disadvantage of this type of lens is its relative weakness, and current work is investigating methods for increasing the optical power.

A powerful application area for these devices is in CCTV, where there is need for improved image quality and for feedback between image-processing software and the optics. It is expected that developments of compound systems using liquid-crystal lenses together with other lenses will benefit both this market and the space market.

Wavefront sensors

In AO the role of the wavefront sensor is to estimate the aberrations to which the measured wavefront has been subjected. Ideally, this estimate would be obtained without any a priori knowledge of the input wavefront and would work equally well with radiation from coherently illuminated and from incoherently illuminated (or self-luminous) scenes.

Detection techniques available for use with signals at optical and higher frequencies are energy-sensitive and do not preserve the phase of the input complex field. It is the relative phase across a wavefront that contains information about both the object structure (image) to be reconstructed and the aberrations to which the radiation has been subjected. Wavefront-sensing techniques therefore form part of the general class of techniques for phase reconstruction from energy (intensity) measurements, which occur in X-ray diffraction, nuclear scattering, microscopy, aperture synthesis and optical imaging.

The wavefront sensor generally characterizes the wavefront shape by estimating phase as a function of position on the wavefront. Imaging and other non-interferometric optical methods are insensitive to overall phase changes and the wavefront position is the deviation of the test wavefront from a plane wave. In AO these deviations are then corrected (or mitigated) by a wavefront modulator that is programmed to impose equal and opposite distortions on the wavefront.

Wavefront sensors in AO systems need not, in general, be combined with algorithms that reconstruct the wavefront shape. Most wavefront sensors can be operated so that the output (control signal) from the wavefront sensor is null when the wavefront is a plane wave. In this case the wavefront sensor is required to indicate where, and preferably in what direction, the wavefront modulator should change the wavefront shape. But such wavefront sensors have wider applications. The deviation of wavefront shape from the known shape of a probe wavefront can be used to characterize the profile of optical components and other surfaces and to characterize inhomogeneities in the refractive index of materials. Further, the measured curvature and relative inclination of an input wavefront can be used to estimate the distance and the bearing of a source. Finally, measurement of the shape of a wavefront after passage through an optical system provides a powerful diagnostic of system quality.

Our purpose here is to review briefly the approaches used to estimate the deviation from a plane wave of wavefronts in optical systems such as high-angular resolution imaging through large-aperture astronomical telescopes.

Shack–Hartmann wavefront sensors

The Shack–Hartmann wavefront sensor is widely and successfully used, notably in terrestrial astronomy (Shack and Platt 1971). The basis of this method is the approximation of the shape of the wavefront by a set of straight-line segments (tilted planes in three dimensions) shown schematically in figure 3. Each segment characterizes the local slope of the wavefront. The segment positions are defined by a lenslet array through which the radiation passes. This is a modification of the Hartmann mask, using lenses for better performance with faint sources.

The Shack–Hartmann sensor is photometrically efficient and, because each lenslet can be achromatic, is suitable for broadband operation if the wavefront shape is independent of colour. The scheme generally uses a single, spatially-resolved detector and allocates only a few pixels for the measurement of the image formed through each lenslet. This is sufficient to determine the centroid of each image with suitable precision. The operation is usually described in terms of an integration of the two-dimensional slope data in order to reconstruct the wavefront, but the sensor can be operated as a null sensor.

Used as a null sensor, a deformable mirror in an AO system is driven to maintain the position of the image formed through each lenslet in the appropriate (and carefully calibrated) axial location for that lens. If the illumination source is a compact object, such as a star, the image centroid is well defined and easy to determine. But if the scene observed is extended and does not have point-object components, the relative tilts of the images through each lenslet must be evaluated from cross-correlations between the images formed through each lenslet (Rao et al. 2002). Evaluation of such correlations requires more pixels in each image and substantially more computational effort and/or power. In addition, this highly successful technique can readily be combined with a wavefront curvature approach in order to provide a better estimate of wavefront shape (Paterson and Dainty 2000).

Phase-diversity and curvature sensors

These techniques depend on comparisons between phases in adjacent areas in the image or objective plane of an optical system. The principle of the phase-diversity technique is that the propagation of a wavefront can be described using the Intensity Transport Equation (ITE) (Gonsalves 1982). Phase diversity is normally implemented in the image plane, using two images recorded under different defocus conditions to reconstruct the wavefront. The algorithm has also been implemented in the plane of the objective lens of the imaging system (Wood and Greenaway in press), where it is similar to the curvature-sensing method (Roddier 1988).

The wavefront-curvature method has been implemented using a vibrating membrane mirror to obtain the intensity distribution on either side of the measurement plane. Recent implementations of the phase-diversity approach have used Diffractive Optical Elements (DOEs) known as IMPs (IMP is a trademark of QinetiQ Ltd), where it is similar to the curvature-sensing method (Roddier 1988). The wavefront-curvature method has been implemented using a vibrating membrane mirror to obtain the intensity distribution on either side of the measurement plane. Recent implementations of the phase-diversity approach have used Diffractive Optical Elements (DOEs) known as IMPs (IMP is a trademark of QinetiQ Ltd), where it is similar to the curvature-sensing method (Roddier 1988). The wavefront-curvature method has been implemented using a vibrating membrane mirror to obtain the intensity distribution on either side of the measurement plane. The dominant disadvantage of this type of lens is its relative weakness, and current work is investigating methods for increasing the optical power.

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implementations of adaptive optics – in Earth-imaging satellites – by the US Air Force. These interferometers can be made robust and reliable, but a shear of the wavefront is required in two directions in order to reconstruct a wavefront over a two-dimensional plane. The shape of the wavefront can be reconstructed from distortions of the fringe pattern, which is dependent on the phase difference between the wavefront measured over the shear distance. The fringe contrast recorded depends on the size of the object and falls quickly with well-resolved objects. Despite its early success, the shearing interferometer has now given way to the Shack–Hartmann sensor for most AO applications.

Wavefront sensing can also be used as an enabling technology in metrology, for:

- determination of surface shape (using a reflected beam) in optical metrology;
- measurement of inhomogeneity in transparent materials;
- measurement of the thickness and parallelism of transparent laminate structures;
- determination of distance through measurement of wavefront curvature;
- measurement of properties of optical components and complete optical assemblies;
- validation of the performance of optical signal processing filters.

Summary

Smart optics technologies offer exciting possibilities in a diversity of application areas for both space- and ground-based astronomy, but also in metrology, microscopy and communications, among others. Applications can both meet existing needs with cheaper solutions or solutions with improved performance, and make new activities possible.

Smart optics is particularly attractive for space applications, where it may be used to reduce the mass of optical instruments; launch costs relate directly to payload mass, so that larger aperture instruments or lower-cost missions can be flown. Mass savings are achieved by using smart optics to correct for alignment errors in a lightweight optical system after launch, or to correct for thermally introduced optical aberrations in flight. These techniques will be part of the operation of the James Webb Space Telescope (JWST), NASA's Next Generation Space Telescope. The JWST's primary mirror will be about 6 m in size, segmented so that it can fit into the launch craft. Once deployed, the mirror segments must be aligned to an accuracy of a few tens of nanometers. This exacting tolerance will be met by a combination of smart materials and smart control of the optics (www.nsstc.nasa.gov/Hardware/text/WCT.html). Smart optics may also improve reliability by replacing motorized adjustable optics with solid-state devices, such as modally adjustable liquid-crystal lenses. The pedigree of LC devices in space has yet to be established, but they show great potential.

With further developments in wavefront-sensing techniques that don’t require a point source, will come significant improvements in resolution of planetary surface details from orbit. Smart optics could simplify the pre-launch alignment requirements for Earth and planetary remote sensing, possibly within the framework of ESA’s Aurora programme. Even with “traditional” remote-sensing optics, the potential for post-launch alignment is attractive, especially for multi-angle systems.

Using narrow-beam optical wavelengths for inter-spacecraft communications will both increase the available bandwidth and eliminate the problems that inter-modulation products bring to the radio frequency background. Formation flying by multiple spacecraft (e.g. in forthcoming missions LISA and XEUS, sci.esa.int) will be possible to greater accuracy using optical wavelengths. AO techniques for beam-steering are desirable here owing to the potential to eliminate moving parts.

Steve Welch (sja@msdl.ucl.ac.uk) is an associate director of the Smart Optics Faraday Partnership, Mullard Space Science Laboratory. Alan Greenaway (a.h.greenaway@fsl.ac.uk) is Professor at the School of Engineering and Physical Sciences, Heriot-Watt University and is Principal Investigator on the OMAM project. Peter Doel (apd@star.ucl.ac.uk) is Head of Adaptive Optics at the Optical Science Laboratory, UCL and Principal Investigator on a PPAC-funded project developing a carbon-fibre deformable mirror. Gordon Lowe (g.d.lowe@durham.ac.uk) is a lecturer in the Astronomical Instrumentation Group at the University of Durham, and Principal Investigator on a PPAC and EPSRC project developing a liquid-crystal lens system for space use.

References


Wavefront-shearing interferometers

These devices were used in the first successful implementations of adaptive optics – in Earth-