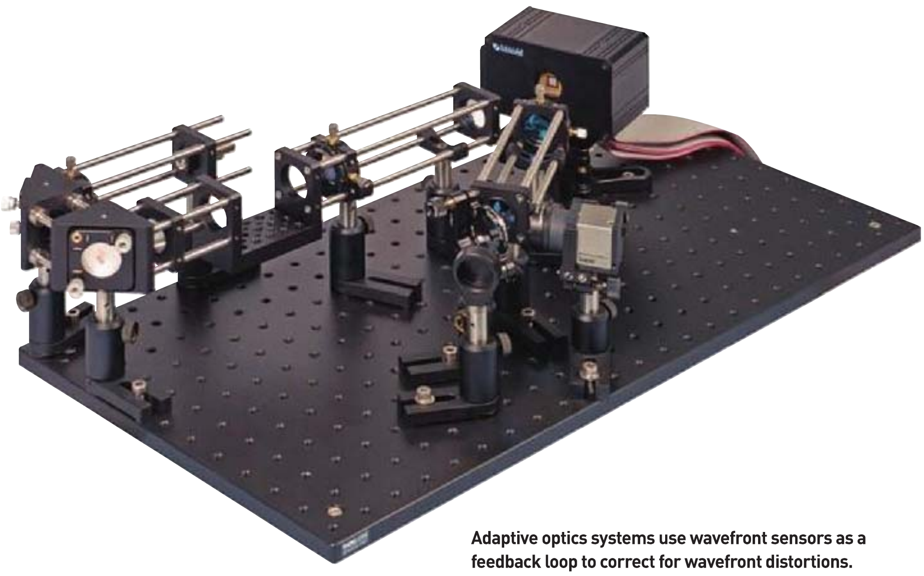
Insights into sight



Adaptive optics systems use wavefront sensors as a feedback loop to correct for wavefront distortions. Image courtesy of Thorlabs

Our eyes are not perfect optical systems, so in order to study them, researchers are utilising wavefront sensing techniques, as **Greg Blackman** discovers

Seeing is said to be believing and for us humans this is certainly the case, with 80 per cent of information received by the brain coming from the eyes. Our eyes are one of the most complex organs we have, allowing us to navigate in moonlight or bright sunlight.

While our eyes are good for gathering visual information, they are flawed as optical systems, making them difficult to study. 'The eye is adequate to look out through, but it's poor for looking into,' says Peter West of UK company 4D Optics. 'For imaging the retina, the resolution is limited by aberrations caused by the eye itself.'

4D Optics conducts research on correcting aberrations to image photoreceptor cells in the retina, in particular to develop instrumentation that could be used in clinical trials on diseases like age-related macular degeneration (AMD). The work is carried out with a major eye hospital.

Just like any optical system, distortions in the wavefront of light passing through the eye can be measured with a wavefront sensor. This provides information on the degree of aberration, which, when combined with adaptive optics, can be corrected for and a higher quality image produced.

There are two main analytical properties of a wavefront: the phase and the amplitude. A wavefront intensity analyser can measure the amplitude of light, but this article, however, is mainly concerned with analysing the phase, typically using a wavefront sensor.

A common type of wavefront sensor is the Shack-Hartmann sensor. Developed by Johannes Hartmann around 1900 and then improved upon by Roland Shack in the late 1960s, it uses a lenslet array to generate a spotfield, which is focused onto a photon sensor. The direction of light passing through each of the sample points is measured. The positions of the points of the foci are compared against spatially resolved patterns to gain a measurement of the wavefront and any distortions caused by imperfections in the optical system.

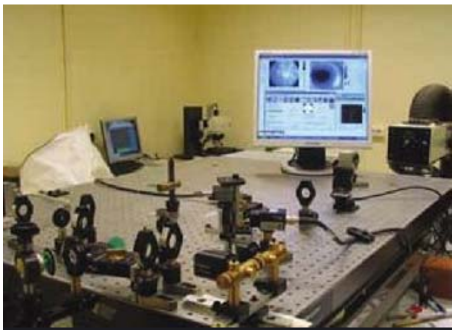
4D Optics is not using Shack-Hartmann analysis, but curvature sensing. This involves measuring two samples along a propagating wavefront to identify the phase. 'It's a fearsomely complex piece of mathematics,' West says. The instrument uses digital wavefront cameras and software from PhaseView to recover the phase from the intensity samples and measure aberrations in the wavefront. These aberrations are then corrected using a Hamamatsu spatial light modulator (SLM).

West says the technique shows promise for producing much higher resolution measurements of aberrations in the eye than techniques based around Shack-Hartmann analysis – PhaseView's cameras offer around 10 times higher resolution than standard Shack-Hartmann sensors.

The sensing technology is also fast. 'The eye is subject to tiny movements at up to 30 to 40Hz,' says West. 'If you want to see those movements, the sample frequency has to be at 60Hz.' This is achievable with one of PhaseView's sensors.

West says the technique has clinical potential for the manufacture of custom correcting wavefront contact lenses and intraocular lenses (IOLs), as well as for studying the tear film, a film of tears spread across the cornea each time we blink: 'The blinking mechanism is of great interest, in that there are a range of eye diseases that result in dry eyes.'

'The great advantage of PhaseView's technology is that it makes curvature sensing a viable technique,' states West. 'Curvature sensing has been used for a long time in astronomy, which is why we started looking at it for ophthalmology. Astronomers, however, can image for quite a long time, which is not possible in ophthalmic investigations. Even when the eye is apparently still, it's moving; you're making dozens of microsaccades a minute and there is drift and tremors. All of these are at the microscopic



The adaptive optics system at the Visual Optics and Biophotonics laboratory, Spanish Council for Scientific Research (CSIC) is being used to gain a better understanding of basic mechanisms of the visual system

scale at which we're interested in imaging. The measurement has to be made and corrected fairly quickly to overcome the movements.'

20/20 vision

At the Visual Optics and Biophotonics laboratory at the Spanish Council for Scientific Research (CSIC) in Madrid, researchers are using ray tracing and Shack-Hartmann aberrometry to gain a better understanding of mechanisms of the visual system, such as the limits to spatial vision.

Ray tracing is an alternative wavefront analysis method to Shack-Hartmann. It is a sequential technique in which rays of light are shone through the pupil and the level of displacement is estimated with respect to a central ray at the plane of the retina. This is ingoing aberrometry, in the sense that aberrations are measured as the wavefront travels into the eye. The laboratory is using ray tracing to understand how aberrations in the eye alter with factors like refractive error, accommodation or ageing.

Ray tracing has the advantage of having a high dynamic range, allowing large wavefront aberrations to be measured. There is also no crossing over of light points to other areas in the system, as can occur with Shack-Hartmann, because every spot is separated in time. However, it is slower than a Shack-Hartmann system, which provides all the information in one snapshot.

'We're using the high dynamic range of ray tracing for clinical cases like cornea pathologies or highly aberrated eyes,' says Professor Susana Marcos, head of the laboratory. 'Having the real-time capability of the Shack-Hartmann system is very valuable for other applications involving dynamic measurements and accommodation or real-time correction of aberrations.'

The laboratory uses a Haso Shack-Hartmann sensor from Imagine Eyes for studies measuring dynamically ocular aberrations as a function of the accommodative demand, i.e. stimulating accommodation through forcing the subject to focus dynamically on near and far objects and looking at how the aberrations in the eye change, and what the accommodative response is.

Imagine Eyes, based in Orsay, France, provides aberrometers and adaptive optics for ophthalmic applications. The Haso system used in the lab is capable of running at 50Hz, although in the laboratory's experimental setup, the sensor runs at 15Hz. 'Several other studies in our laboratory deal with how the eye's ability to resolve objects is affected by the correction or presence of aberrations,' says Marcos. 'In this system, we're using an adaptive optics deformable mirror in combination with Imagine Eyes' Haso Shack-Hartmann sensor. We also have a psychophysical channel – a monitor that projects stimuli that the subject sees throughout the setup. We correct the aberrations of the subject with the adaptive optics mirror and evaluate any improvements in visual acuity (at different contrasts and luminances) or visual performance, including recognition of faces and facial expressions, as well as how much the subject's impression of sharpness is modified.'

The research has implications for refractive corrections and for treatment of different conditions of the eye. 'An aim of refractive surgery or future generations of intraocular or contact lenses is the correction of low order aberrations, such as defocus or astigmatism, but also other higher aberrations of the eye,' says Marcos. 'With this equipment, we can simulate a perfect refractive procedure and measure what the implications would be for the subject's vision.'

'The hypothesis is that by correcting higher aberrations of the eye – those aberrations measured with wavefront sensing – you could improve vision,' continues Marcos. 'But this has to be tested and this is one of the aims of these experiments.'

Adaptive optics

Researchers at 4D Optics and the laboratory at CSIC are using wavefront sensing in combination with adaptive optics – the sensor detects any aberrations in the incident light and the optics correct for those distortions to gain a better image.

John Taranto of Thorlabs says: 'The benefit of using a wavefront sensor as a feedback mechanism is that, in theory, only one measurement is required, from which the voltage map can be determined and used to make the correction in the mirror. Therefore, potentially, a correction can be made every time the sensor makes a measurement.'

Thorlabs provides measurement and control solutions for the photonics industry, including wavefront sensors. The company's AO kit is based on a Shack-Hartmann wavefront sensor and ➤

Boston Micromachines' deformable mirrors. It has also recently released a sensor incorporating a CMOS detector capable of measuring wavefronts at frame rates up to 450Hz.

The ability to close the loop between sensing and correction quickly is one of the big challenges Michael Feinberg, director of product marketing at Boston Micromachines, identifies for engineering high-quality adaptive optics systems: 'The speed of the sensor is a limiting factor in many AO systems.'

As an alternative to sensor-based AO systems, the phase of light can also be measured with a metric-based analysis, in which a property such as contrast or intensity is used to quantify how far in or out of phase the wavefront is. A hill-climbing algorithm is used to manipulate the mirror or corrector, perturbing it in one direction and then the other to determine whether the metric has got better or worse. 'A sensorless technique would typically be used in light-starved environments,' notes Feinberg.

Boston Micromachines is about to release a sensorless AO kit, called the wavefront sensorless AO demonstrator. This uses a photodetector and Boston Micromachines' deformable mirror.

Intraocular lenses

Intraocular lenses (IOLs) are implants in the eye, typically used to replace the crystalline lens in cataract surgery or in other refractive surgery. Designs of IOLs are becoming increasingly complex, as Dr Iris Erichsen of Trioptics explains: 'In the past, IOLs were spherical with only one radius of curvature. Now multifocal IOLs are being designed. These have several zones on the lens with different radiuses of curvature, enabling the patient to see objects nearby and far away. There are now many different multifocal designs.'

Trioptics manufactures both Shack-Hartmann sensors and interferometers. Its OptiSpheric instrument, which has a reticule through which the magnified image is measured to provide information on the focal length of the lens, is designed to satisfy the ISO standard for IOL characterisation. It also has the advantage of being able to measure the properties of a lens in different focal planes as the detector operates directly in the image plane. 'Using a Shack-Hartmann or any wavefront sensor, it's hard to separate the image planes as these sensors only measure a single wavefront,' says Erichsen.

But Erichsen notes that the big advantage of Shack-Hartmann sensors compared to the OptiSpheric system is that the lateral resolution is lost when imaging over the full aperture of a lens with OptiSpheric: 'The system always measures objects in infinity, whereas, with a wavefront sensor, the measurement is made in the exit pupil of the system. Therefore, a 2D image of the complete lens is recorded and, for example, if there is a defect at the edge of the lens, it can be seen.'

In principle, interferometry can be more accurate than Shack-Hartmann wavefront sensors

Compared to an interferometer, the repeatability and speed of wavefront sensors is particularly important for ophthalmic applications like testing contact lenses and IOLs, says Dr Johannes Pfund, managing partner at optical metrology company Optocraft: 'In principle, interferometry can be more accurate than Shack-Hartmann wavefront sensors and is the technique of choice in, say, semiconductor inspection, but generally not in ophthalmology.'

Interferometry is typically slower, requiring a number of measurements compared to a Shack-Hartmann sensor that gathers all the information in a single shot. However, there is interferometry equipment suitable for testing IOLs. Phasics' (Palaiseau, France) SID4 sensors, which operate via four-wave lateral shearing interferometry, are used in contact lens or IOL characterisation.

'Particularly for IOL measurements, the dedicated system provides a complete and fast analysis of all the important IOL parameters (aberrations, MTF, power map, etc) in accordance with ISO standards,' comments Raphaël Serra, sales manager at Phasics. 'The advantage of this system is that, thanks to the high resolution of the phase map and the intensity map, we can obtain a very precise quality analysis of the IOL in only one measurement.'

The technique records the interference pattern from four identical waves, replicated from the incident beam with a 2D diffraction grating. Any aberrations in the beam result in distortions in the interference grid, which can then be measured.

IOLs of the future

Wavefront sensing is playing an important role in developing new IOL designs. Professor Marcos at CSIC is testing IOL designs for presbyopic corrective procedures in which an optimal aberration pattern is determined using wavefront sensing and adaptive optics prior to manufacturing the lens. Presbyopia is the loss of accommodation as the eye ages, corrections for which involve multifocal IOLs that induce aberrations to extend the depth of focus of the eye. Marcos says that by using the AO setup, new lenses can be designed and tested before being manufactured.