Feature issue introduction: applications of adaptive optics

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Abstract: This feature issue of Optics Express follows the 2020 Imaging and Applied Optics Congress and comprises of articles on the development and use of adaptive optics across the broad range of domains in which the technique has been applied - including atmospheric correction, ophthalmology, vision science, microscopy, optical communications and beam control. This review provides a basic introduction to adaptive optics and a summary of the multidisciplinary articles included in this issue.

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1. Introduction

Adaptive optics is an area of optical research and application that has grown significantly in the last fifteen years as the cost and complexity of suitable beam shaping optics has fallen simultaneously with huge increases in computing power making control possible for more complicated systems. The method and concept are not, however, that new. Many have cited the first recorded use being in 215 BC when Archimedes directed a regiment of soldiers to polish their shields and lined them up individually to focus sunlight on a vessel [1] attacking Syracuse making perhaps the world’s first multiple element adjustable optic. According to the reports the vessel burst into flames but as described in Robert Tyson’s book [2] the details on the control loop to keep the light waves in phase by adjusting the shields is not known!

The start of what we might now recognize as adaptive optics is generally viewed as Babcock’s seminal 1953 paper, which proposed the use of deformable optical elements driven by a wavefront sensor for optical telescopes to compensate for aberrations caused by the atmosphere [3]. Research then progressed on two fronts, in the open scientific community, for use in ground-based telescopes for astronomy, and also by military researchers around the world. The advances made in the latter field became clear in the 1990’s as documents were declassified. The first diffraction limited image obtained on a 1.52 m telescope by Rousset and colleagues in 1989 [4] opened the way to a practical use of adaptive optics in astronomy. Adaptive optics systems are now in regular operation at all the major astronomical observatories. The use in optical communications then started to be explored before their application in areas such as retinal imaging and microscopy started to explode in research laboratories around the world from the middle of the 1990s.

2. Brief Introduction to Adaptive Optics

Before highlighting the papers in this feature issue, it is worth a brief review of the challenges and some of the solutions that adaptive optics have now helped to solve, and the specific features required within each area of research. Adaptive optics systems can be considered to fall into two classes of operation: open loop and closed loop. The method selected depends on a number of factors including the level of aberration being corrected, the temporal variation in the aberration,
the complexity that is practical and, frequently, the level of financial investment that may have
to be made. In a closed loop system the light reaches the wavefront sensor after the adaptive
optical element, thus the effect of the correction is ‘seen’ by the sensor. However, in an open
loop system the wavefront sensor sees the full wavefront error directly from the aberrated source.

Although wavefront sensors are used in many adaptive optics systems, they are not ubiquitous
and an image metric, e.g., a sharpness parameter as proposed by Muller & Buffington (1974)
[5], is frequently used in some fields in what is termed ‘sensorless adaptive optics’. Here, for
example, brightness or contrast present within the image is calculated as different wavefront
corrections are applied and an algorithm run to optimize the best shape for the best quality image.
The level of correction required is determined by continuously monitoring the image metric.
A variation of this method in an astronomical application can be used to estimate the profile
of the turbulence through which light is propagating. From this a wavefront correction can be
estimated and applied. The wavefront is not being sensed directly and it is now possible to use
machine learning to even predict what the upcoming aberration may be and apply the estimated
best correction in a totally open loop manner. The rate of change of aberration determines the
application of adaptive optics. The signal-to-noise ratio on the wavefront sensor, for successfully
closing the loop, is limited by the number of photons reaching the detector. The flux at the
detector is determined by both the brightness and the temporal sampling of the source. Compared
with applications in microscopy and ophthalmology, which require a response of up to around
100 Hz, correction of atmospheric turbulence typically requires a response of order of a kHz, and
thus short wavefront sensor exposures. This is leading to a new range of wavefront sensors with
the sensitivity and speed of response required, such as EM-CCDs.

In the field of ophthalmology, the wavefront errors vary more slowly. However, as the eye itself
is the final optical element in the system there are challenges to be met due to, e.g., movements of
the eye and scattering in the ocular media. In optical microscopy the aberrations are frequently
static or change very slowly and thus image-based metrics and sensorless adaptive optics are
generally the first approaches to be considered. In a static biological sample aberrations vary
spatially rather than temporally. Therefore, a look up table of pre-measured wavefront errors
can be generated and the correction applied as the sample is scanned. In addition, in biological
applications the general aim is normally to minimize the required light level to reduce the risk of
light toxicity.

Atmospheric correction can use either a natural or artificial source for wavefront sensing,
whether for imaging or for optical communications. For example, astronomical adaptive optics
uses laser guide stars to provide significant signal-to-noise ratio when no (or not sufficiently
bright) natural source is available. Additionally, constellations of laser guide stars can be used to
probe the turbulence profile of the atmosphere for wider field correction, in order to mitigate
anisoplanatism. Lasers are also used in the case of optical communications, where a laser beam
is typically propagated through the atmosphere over a horizontal path, e.g., between buildings
in a city, or over a vertical path for satellite links. Due to daytime operations, propagation
suffers from high turbulence and scintillation effects, even more in the case of horizontal path
propagation. However, a high-speed data communications link is expected. It is important to
note that there are environmental concerns associated when using lasers, especially those of
high power, and predictive modelling or other optimization methods are being pursued as a
lower-power alternative.

Adaptive optics has become strongly multidisciplinary in terms of its applications (atmospheric
correction, ophthalmology, vision science, microscopy, optical communications, beam control
etc.). The challenge now is the exchange of knowledge between the different fields. There
are multiple specialized conferences in each specific area of research, but the bi-annual OSA
Imaging Congress has hosted an adaptive optics session since 2005. At that time, only two of
the 50 or so presentations were in areas other than astronomy, namely retinal imaging. With the
development of increasing performance of components, adaptive optics has entered a wide variety of applications, including a significant growth in commercial application. This growth has been actively reflected by the presentations at the OSA Adaptive Optics topical meeting over the years and is illustrated by the publications in this feature issue from the June 2020 virtual meeting. This issue opens a window to current developments, with papers covering the breadth of research being undertaken in adaptive optics and also demonstrating the way that the methodology is now entering mainstream optics and photonics. The following is an overview of what is contained within this feature issue.

3. Highlights of this Feature Issue

Arguably the first ‘adaptive optics’ system was developed not by humankind but by biology – the focusing and control mechanism of the eye and brain. How apt that a major area of adaptive optics research studies the eye and visual system. Adaptive optics techniques for the eye were first developed in the 1990’s. Now, in 2020, adaptive optics is used in many different types of instrumentation for studying the eye – from visual simulators that are used to assess the impact of optical aberrations on vision, to various ‘flavors’ of retinal imaging systems that are advancing our understanding of early visual processing and enabling clinical studies with unprecedented resolution [6,7]. The papers included in this feature issue cover a number of the areas of research undertaken in the field today from Fernández et al.’s investigation of visual adaptation to the eye’s chromatic aberration [8] and Cooper and colleagues’ development of techniques for measuring retinal function on a cellular scale [9], to Bos et al.’s use of a liquid tunable lens to help restore a level of accommodation to people who have presbyopia [10]. These papers also address technical challenges that arise in ophthalmic adaptive optics imaging, such as the eye movement compensation methods explored by Li et al. [11] and the scattered light analysis presented by Sajdak et al. [12], and they contribute to well-characterized data sets, such as Reumueller and colleagues’ account of retinal cell density, which are valuable for understanding of what constitutes a normal, healthy retina [13].

In recent years one of the growth areas of adaptive optics has been in its application in optical microscopy. In particular in non-linear optical techniques where the size of the excitation spot plays a significant role in the size of the signal as well as the optical resolution that can be achieved. Lin et al. have now reported on the use of adaptive optics remote focusing in vivo using stimulated Raman Scattering as the contrast mechanism [14]. This has provided chemically specific volumetric imaging to observe drug movement through the skin. In another paper using two-photon excitation, Gao and colleagues have used a segmentation approach to correct for aberrations in optically cleared samples [15]. The clearing helps to remove the effects of scattering with the adaptive optics system correcting for the remaining aberrations caused by macroscopic refractive index miss-matches.

However, adaptive optics techniques, specifically in the case of digitally controlled phase conjugation, can be used to overcome some of the effects of light scattering and this has been applied by Mididoddi and a team from Exeter and Wuhan in a camera-based imaging system [16]. The approach also has the potential to be used in a single pixel configuration. This paper uses spatial light modulators to achieve the correction and Augusto Arias and a team from Spain have demonstrated a new way to use such devices with the potential for lower cost adaptive optics potentially leading to an even wider uptake of the technique perhaps even towards consumer products [17].

The use of adaptive optics is still most common in optical systems in which light propagates through the atmosphere. There is increasing use here for satellite-based imaging and also three-dimensional mapping systems. An example of this is demonstrated by Yang et al. (Landsatellite Remote Sensing Application Center in Being), who have used adaptive optics to correct for surface height profiling on ice sheets [18]. The fast development of free-space laser propagation
using adaptive optics is also here illustrated with a study in moderately scattering media where Galaktionov et al. from Moscow and Saint Petersburg institutions demonstrate experimentally the peak brightness increase of the far-field focal spot using a 48-electrode bimorph deformable mirror [19]. As for free space optical communications combined with wavefront sensorless AO, Segel and Gladysz from Fraunhofer IOSB propose to improve the convergence rate of a stochastic parallel-gradient-descent technique (initially proposed by Vorontsov and Sivokon [20]) using Karhunen-Loève modal decomposition [21]. In free-space quantum communications optical links, adaptive optics is employed to protect entanglement from degradation, an issue studied by Zhu et al. through a collaboration of several teams from Being [22].

Most adaptive optics systems correct solely for the phase of the wavefront, but the amplitude of the wavefront can also be distorted under strong turbulence conditions, an effect known as scintillation, i.e., the twinkling of starlight. The presence of scintillation can significantly impact measurements of phase errors requiring a different kind of wavefront sensor, Fresnel rather than Shack-Hartmann, as described by Crepp and his team from the University of Notre Dame [23]. The team from the Fraunhofer IOSB (Lechner et al.) have developed an adaptable Shack-Hartmann wavefront sensor that uses diffractive lenses displayed on a spatial light modulator as opposed to the traditional microlens array [24]. And another wavefront sensor approach has been investigated for a range of scintillation conditions, i.e., a digital holographic wavefront sensor proposed by Banet et al. for application to compensated beacon adaptive optics [25].

There are a number of papers regarding novel approaches to wavefront sensing, correction and control. One of these by Whang et al. [26] investigates a new approach to computing Zernike Coefficients using neural networks with image recognition to reduce the number of mathematical operations and improve efficiency. Another by Jiang et al. [27]) utilizes a static image-plane correction to improve the focus correction for 3D scanning, extending the defocusing range by around a factor of three. An event-based image sensor approach has been developed by Kong et al. [28] which makes use of a series of spatial-temporal events; data tagged with the location, timestamp and polarity triggered events, in conjunction with a Shack-Hartmann wavefront sensor for use with either low light-levels and/or high bandwidth cases. The correction of static and non-common path aberrations in an AO system is investigated in a paper by Knutsson et al. [29] who present a novel figure of merit, corresponding to the optical transfer function, and use a single value decomposition approach to optimize it. Temperature effects in deformable mirrors and new deformable mirror technology are investigated in two papers. In the first of these, Zheng et al. [30] mitigate the problematic effect of temperature-induced distortion with a stacked array piezoelectric deformable mirror operating at a substantial difference to its design temperatures. They have developed a hybrid connection structure deformable mirror which is relatively insensitive to these temperature variations in both simulations and experiments. Cao et al. [31] present a compression-bias mirror to overcome tensile stress and permitting enhanced dynamic range and low scattering. The curvature of the mirror is varied by adjusting its temperature. All AO systems require some control system and Kudryashov et al. [32] demonstrate the use of FPGAs for high frequency control, up to 1875 Hz, of an AO system for laser propagation, showing that the far field intensity pattern is close to the diffraction-limit.

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