

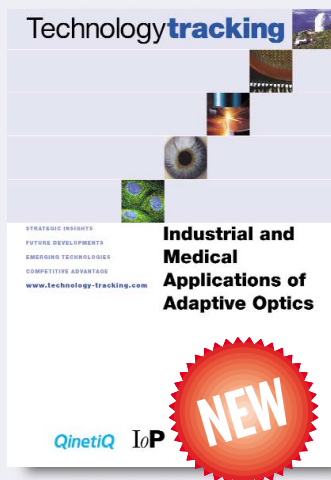
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Industrial and Medical Applications of Adaptive Optics

Industrial and Medical Applications of Adaptive Optics examines the need for adaptive optics in a range of current and emerging applications; explains how the technology works; discusses the criteria for selecting particular component technologies; and explores the strategic opportunities for adaptive optics in the commercial market-place.

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FOR DECISION MAKERS

Adaptive optics: how to unleash its commercial potential

"The next five years will go a long way to determining whether adaptive optics will become a mainstream technology with credible and sustainable growth prospects."

Professor Alan Greenaway and Dr James Burnett

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Industrial and Medical Applications of Adaptive Optics reveals that some companies are already taking action to capitalize on the power of adaptive optics technology. Patent activity has risen dramatically, with the number of patent applications more than doubling between 2001 and 2003. R&D activity is also on the increase, with the number of active researchers in the field almost doubling in the last year alone.

These figures indicate a sector that is poised to make the transition into the mainstream optics market-place. Key applications include laser materials processing, ophthalmology, free-space optical communications, metrology and 3D imaging. But that's not all. This report also reviews emerging applications in display and laser scanning; femtosecond laser pulses; laser fusion; lightweight optics; signal processing; robotic vision; cornea assessment; and the compensation of turbulence-induced effects.

Analyse the challenges that need to be addressed

Industrial and Medical Applications of Adaptive Optics provides an in-depth analysis of the commercial and technical challenges that are being addressed to transform adaptive optics into a low-cost user-friendly technology with serious growth prospects:

- **From academia to industry:** The development of adaptive optics systems remains largely the preserve of research groups, but start-up firms are now launching commercial products based on adaptive optics. Two major initiatives – the Smart Optics Faraday Partnership in the UK and the Center for Adaptive Optics in the US – are also working to foster relationships between industry and academia.
- **From DIY to plug-and-play:** Adaptive optics has a history of one-off developments for particular applications, but researchers are now working with industrial partners to develop plug-and-play systems based on standard components that can be readily interchanged by non-expert staff.
- **From large systems to low-cost compact packages:** More work is needed to reduce the size and cost of systems and components. Integrated wavefront sensors in wafer-sized packages and the development of more compact wavefront modulators remain the key priorities.
- **From small-scale production to commercial supply:** Although some devices are available off-the-shelf, low manufacturing volumes lead to erratic component supply, poor yields and high prices. This situation would change dramatically if large optical companies were to introduce adaptive optics technology into their catalogues.

Introduction – key trends highlighted and analysed.

CHAPTER 1: INTRODUCTION

Optical systems are central to our understanding of the world around us. Our perceptions of what we see, what is happening in the world, and our position in the universe are dictated by what we can see. Any technology that allows us to see better – that improves our vision, allows a clearer picture of our surroundings, or gives us a better view of the cosmos – fundamentally changes our perception of the world around us. Herein lies the power of adaptive optics.

Adaptive optics (AO) offers a means to overcome the principal limitation of optical systems: the need to compensate for image distortions generated at the interface between the system and the real world. AO achieves this compensation dynamically and in real time, and the benefits this brings in terms of image quality – spatial resolution and contrast – can be exploited in a range of industrial and medical applications.

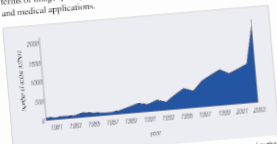


Figure 1.5. Number of active researchers in adaptive optics measured by named authors on open literature publications.

As well as improving image quality, AO can be exploited to alter the characteristics of an optical system. The purpose here is not to compensate for optical distortions, but rather to modify the optical properties to achieve a particular result, such as accurate focus control of a laser beam. Many of the emerging applications for AO technology, such as laser materials processing and the generation of femtosecond laser pulses, exploit this capability.

1.1 The power of adaptive optics

An insight into the strength of AO is given by its ability to compensate for the distortions that frequently arise in optical systems. Under ideal circumstances, the resolution of an optical system is generally limited by the diffraction of light waves. This so-called "diffraction limit" is a function of the wavelength of the light and the input aperture of the optical system, while the system's resolution is directly proportional to the inverse of its optical aperture. For example, the fully dilated human eye should be able to separate objects as close as 9×10^{-5} rad (equivalent to 1 mm at a distance of 10 m), and large ground-based telescopes, such as the Keck Telescope on Mauna Kea, Hawaii, should be able to resolve objects as close as 6×10^{-6} rad.

CHAPTER 4: APPLICATIONS

Table 4.1. Summary of AO applications

Application category	Maturity range			Technologies			Section
	Mature	conceptual	AO	Active	WFS	WFM	
Laser applications							
Intra cavity laser – beam shape	●	●		✓			LO 1.1.1
Extracavity laser – pulse shape	●	●		✓			LO 4.1.2
Intra cavity laser – wavefront shape	●	●	?	✓			LO 4.1.3
Laser materials processing	●	●		✓	LO		LO 4.1.4
Laser focus quality	●	●		✓	PO	LO	LO 4.1.5
Display and laser-scanning	●	●		✓			LO 4.1.6
Laser communications	●	●		✓	LO	LO	LO 4.1.7
Laser fusion	●	●		✓	?	LO	LO 4.1.8
Ophthalmology							
Vision assessment	●	●				LO	LO 4.2.3
Retinal imaging	●	●		✓		LO	LO 4.2.2
Corneal assessment	●	●				LO	LO 4.2.1
Cornea assessment	●	●				LO	LO 4.2.4
Industrial inspection							
Monitors	●	●				HI-LO	HI-LO 4.3.1
Signal processing	●	●		✓		HI	HI 4.3.2
Robotic vision	●	●		✓		HI	HI 4.3.3
Imaging applications							
Light-weighted optics	●	●	?	✓	?	LO	LO 4.4.1
Compensation of turbulence effects	●	●		✓		HI	HI 4.4.2
Compensation of low-quality optics	●	●		✓		LO	LO 4.4.3
Wide-field applications	●	●		✓		HI	HI 4.4.4
3D imaging							
As fibre applications (TE)	●	●		✓		LO	LO 4.5.1
Confocal microscopy (TE)	●	●		✓		LO	LO 4.5.2
Optical data storage (TE)	●	●		✓		LO	LO 4.5.3
Defence applications							
Adaptive	●	●		✓		HI	HI 4.6

Maturity range is indicated by colour as follows: mature (green); prototype (yellow); conceptual (orange); active (red). The range of technologies required is indicated by using one of complete AO system (WFM), WFS and control loop, use of WFS only, and use of WFM only. HI indicates high-order systems with many degrees of freedom; LO indicates low-order systems with low degrees of freedom; HI-LO indicates multiple order systems. ? indicates a possible need in some circumstances to go use of a wavefront sensor to measure cavity optics in a high-power pulsed laser with very low duty cycle.

Adaptive optics is now a well-established technique in astronomy and defence, and there is now growing interest in applying AO technologies to a variety of industrial and medical applications. Some are more advanced than others, with applications in ophthalmology, laser materials processing and metrology leading the way in terms of commercial development. In addition, many of the emerging applications rely on one of the component technologies developed for AO rather than a complete system.

Applications – the key commercial applications are reviewed.

Market prospects – AO must now make the transition from one-off design to mass-market appeal.

CHAPTER 5: MARKET PROSPECTS

Adaptive optics is now emerging as a powerful and flexible optical technology that has the potential to play a crucial role in a range of industrial and medical applications. While the technology owes its strength to big-budget programmes in defence and astronomy, AO must now make the transition from the production of customized high-value systems to the manufacture of low-cost standard components that can be looked together by non-specialist staff.

We believe that this transition from one-off design to mass-market appeal must take place within the next five years if AO is ever to become a commercial success with credible and sustainable growth prospects. Fortunately, there are signs that this will happen: the AO community is working to develop start-up firms are beginning to launch commercial products based on AO. But much more work is needed to deliver on the promise of AO for mass-market applications.

Four main areas must be addressed for AO to become a mainstream commercial technology, each of which will be discussed in more detail below.

- **From academia to industry:** AO development remains largely the preserve of university research groups. But start-up firms are starting to commercialize the technology, and major initiatives are working to foster relationships between industry and academia.
- **From DIY to plug-and-play:** AO has a history of one-off developments for particular applications. AO researchers are now working with industrial partners to develop plug-and-play systems based on standard components that can be readily interchanged to suit the needs of a particular market.
- **From large systems to low-cost compact packages:** More work is needed to reduce the size and cost of AO systems and components. Integrated Shack-Hartmann sensors in wafer-sized packages and the development of more compact wavefront modulators remain the key priorities.
- **From small-scale production to commercial supply:** Off-the-shelf AO devices are currently produced in low volumes, which leads to high prices and erratic component supply. This situation would change dramatically if large optical companies were to introduce AO technology into their catalogues.

5.1 From academia to industry

Most development of AO technology and its applications is currently being driven by academic research groups. But that situation is now starting to change.

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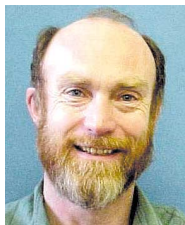
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QinetiQ is Europe's largest independent science and technology organization with more than 9000 staff. Its work in optics and electronics dates from the 1940s. Much of the UK's defence-related research in both radar and electro-optics was focused at *QinetiQ* (then known as the Royal Signals and Radar Establishment and later incorporated into the Defence Evaluation and Research Agency).

About the authors



Alan Greenaway took a chair in physics at Heriot-Watt University in 2000, where his research interests continue to focus on adaptive optics. Prior to that, Alan worked for 19 years at *QinetiQ* on a range of optics-related problems and invented a 3D imaging technique based on adaptive optics that is now being exploited in commercial products. He remains an honorary senior DERA fellow and is also an honorary professor at Cardiff University.



James Burnett has worked at *QinetiQ* for 15 years, where his work has included the successful demonstration of an adaptive optics system. James was also a key researcher in optical-fibre interferometer sensing techniques for 10 years. James has published over 30 scientific papers and holds three granted US patents.

150 pages of incisive information and emerging applications

CHAPTER 1: Introduction

As well as tracing the evolution of adaptive optics and its applications, this chapter analyses growing development activity in adaptive optics in terms of papers published and patents filed by commercial organizations.

CHAPTER 2: Technology overview

Back to basics: how adaptive optics can correct for optical aberrations, and the main types of adaptive optics systems.

CHAPTER 3: System design

Providing a clear overview of the main component technologies, this section provides guidance on the cost and capabilities of the most common wavefront modulators and wavefront sensors.

CHAPTER 4: Applications

From laser-beam delivery systems to ophthalmology and 3D imaging, this chapter delivers an informed assessment of the prospects of adaptive optics in a range of current and emerging applications.

CHAPTER 5: Market prospects

This section delivers an in-depth analysis of the commercial status of adaptive optics technology and the barriers that must be overcome for it to become a mainstream optical technology.

CHAPTER 6: Wavefront modulator technologies

A comprehensive review of the latest advances in wavefront modulators.

CHAPTER 7: Wavefront sensing technologies

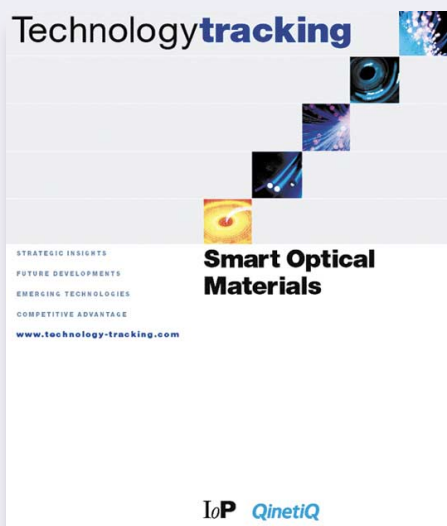
A clear and complete description of the techniques used to measure the optical wavefront.

CHAPTER 8: Closed-loop control systems for adaptive optics

A discussion of the challenges associated with building control systems for specific adaptive optics applications.

PLUS six appendices providing valuable sources of further information, including informed profiles of organizations actively developing adaptive optics technology; an extensive glossary; and a comprehensive listing of publications and professional bodies that provide further information on adaptive optics.

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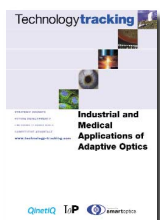
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