Proceedings of the
First Annual Meeting of the
Smart Optics Systems Programme

Preface

The Smart Optics Systems (SOS) program sponsored by the Dutch National Science Foundation STW aims at developing, integrating and validating the use of optical components, such as deformable mirrors, wavefront sensors, etc. acceptable on a wide industrial scale. The program aims at achieving this goal in two ways. First, it aims at developing technology for a dramatic improvement in the quality of optical instruments. Second, it will result in a new and optimized integrated design that will allow for an integration of the design of smart optics systems taking the use and constraints of the imaging equipment into account.

In such an integrated design approach, taking into consideration from the onset of the design of the imaging equipment the capabilities of e.g. feedback control has the potential of revolutionizing the overall design. Such integrated approach may lead to similar breakthroughs as was manifested in the last century by the introduction of the operational amplifier. Here feedback control enabled the production of high performance components from low quality and low cost physical open-loop components.

In addition to the methodological improvement anticipated by the program, the goal is pursued in two organization manners. First in the definition of six multi-disciplinary research projects where researchers with a different technological expertise work intensively together on a common imaging demonstrator. A second way to disseminate the knowledge and the experience between the researchers actively involved in the program on one hand and between these researchers and external experts on the other hand is enabled by the organization of program meetings on an annual basis.

These proceedings presents the activity report of the first annual meeting of the Smart Optics Systems STW perspective Program. In the proceedings the progress on the following six projects is reported:

1. Integrated High-resolution Observing through Turbulence
2. Smart Microscopy of Biological Tissues
3. Integrated Smart Microscopy
4. Waveguide-based External Cavity Semiconductor Laser
5. Smart Multilayer Interactive Optics for Lithography at Extreme UV wavelengths
6. Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems

For the first annual meeting 2 keynote speakers will present there vision on the research challenges in smart optics systems. These are:

1. Prof. Pablo Artal (Professor of Optics at the University of Murcia, Spain)
2. Dr. Nicholas Devaney (Applied Optics group, School of Physics, National University of Ireland, Galway)

In addition a number of expert guests are invited to share their view during the discussions of the projects. These experts are:

1. Dr. Jean-Marc Conan (senior research scientist at Onera, France)

2. Dr. Anton van Dijsseldonk (senior researcher scientist at ASML, the Netherlands)
3. Dr. Martin J Booth (EPSRC Advanced Research Fellow, Dept of Engineering Science, University of Oxford)
4. Prof. Dr. Ulrich Wittrock (Fachhochschule M´unster, Germany)
5. Prof. Alan Greenaway, (Honorary Professor of Physics at Cardiff University)
6. Prof. Austin Roorda (University of Berkeley, US)

The meeting is held in Scheveningen on June 14th, 2010.

On behalf of the organization committee we look forward towards an interesting day of discussion, exchange of ideas and stimulation towards future new and bright ideas.

Prof. Michel Verhaegen
Program Leader SOS

Contents

Program

Morning sessions

8.30	Welcome with coffee / tea		
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10.15	Coffee break		
10.30	Project: Integrated High-Resolution Observing through Turbulence	Prof. Christoph Keller	Introduction to the project
10.40		Dr. Visa Korkiakoski	Jointly optimizing adaptive optics control and post-facto image reconstruction techniques
11.05		Federico Pinchetti	Integrated High Resolution Observing through Turbulence
11.30	Project: Smart Microscopy of Biological Tissues	Prof. Hans Gerritsen	Introduction to the project
11.40		Tim van Werkhoven	Smart microscope — Implementing adaptive optics in advanced scanning microscopes
12.05		Jacopo Antonello	Intensity maximisation for Sensorless Adaptive Optics
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Afternoon sessions

12.45	Lunch		
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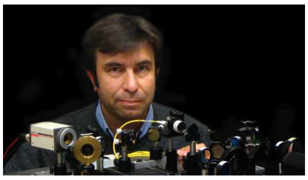
Keynote lectures

Pablo Artal — History and Future of Adaptive Optics for Vision



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Pablo Artal was born in Zaragoza (Spain) in 1961. He received his M.Sc. degree in Physics from the University of Zaragoza, Spain, and the Ph.D. degree in Physics (Optics) from the University Complutense of Madrid in 1988. He was a post-doctoral fellow at the Institut d'Optique, Orsay, France in 1989-90 and a senior researcher at the Instituto de Optica (CSIC) in Madrid from 1990 to 1994. Since 1994, he is full Professor of Optics at the University of Murcia, Spain. He spent several periods doing collaborative research in laboratories in Europe, Australia and USA. Prof. Artal was secretary of the Spanish Optical Society (SEDO) from 1990 to 1994; associated Dean of the University of Murcia Science Faculty from 1994 to 2000 and Director of the Physics Department at Murcia University from 2001 to 2003. From 2004 to 2007 he was in charge of the reviewing grant panel in Physics at the Spanish Ministry of Science. Since 2006 is the director of the Center for Research in Optics and Nanophysics at Murcia University. He is a member of SEDO, EOS, ARVO and SPIE. He was elected fellow member of the Optical Society of America (OSA) in 1999 and a fellow member (inaugural) of ARVO in 2009. Prof. Artal received a number of national and international research awards. Prof. Artal is the founder and director of the Laboratorio de Optica at the University of Murcia with about 20 co-workers. He has published more than 120 reviewed papers, received more than 4000 citations (H-index: 36), presented more than 140 invited talks in international meetings and around 120 seminars in research institutions around the world. He has been funded by more than 5 Million €grant money since 1993 and is also a co-inventor in a number of international patents. Dr. Artal's research interests are centered in the optics of eye and the retina and the development of optical and electronic imaging techniques to be applied in Vision, Ophthalmology and Biomedicine. He has pioneered a number of highly innovative and significant advances in the methods for studying the optics of the eye and has contributed substantially to our understanding of the factors that limit human visual resolution. In addition, several of his results and ideas in the area of ophthalmic instrumentation over the last years have been introduced in instruments and devices currently in use in Vision and Ophthalmology. During the last years, he built from scratch an Optics Laboratory in Murcia University (south-est Spain), a location without any previous tradition in Optics. He was instrumental to continuously attract external financial support from government and private international companies. Dr. Artal is a pioneer in exploring the human eye with new technologies and designed new ways of optical corrections that will improve vision in patients. Several of his proposed solutions and instrument are currently in use in the clinical practice. He is dedicated to the excellence in basic research to be transferred to real life applications. He is mentor of many graduate and post-doctoral students. His blog “Optics confidential” `http://pabloartal.blogspot.com`, is followed by many readers around the world.

Abstract

The use of adaptive optics allows the simultaneous measurement and manipulation of ocular aberrations in the eye of a subject while he or she is performing any type of specific visual task. This concept, that we first called adaptive optics visual simulator, has been used in different experiments in visual science in recent years. I will revise the basic concepts of this type of systems, including several of the used corrector devices, and some of the vision science results obtained. As an example, the neural adaptation to the aberrations was first suggested using an adaptive optics visual simulator. Another practical application is the search and evaluation of phase profiles to extend depth of focus to correct presbyopia. I will also revise the current status of a binocular adaptive optics visual simulators that would allow extending the range of studies to the conditions of natural binocular vision. Some of the recent history, together with my personal views of the future developments of the field will be also covered in the presentation.

The slides of the presentation are included in the Appendix on page 37 of this proceedings.

Nicholas Devaney — Adaptive Optics in Astronomy, Vision Science and other Applications

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Received B.Sc (1985) and Ph.D. (1989) in Experimental Physics from the National University of Ireland, Galway. Worked as a post-doctoral researcher at the Royal Greenwich Observtory, then based in Cambridge, and the Observatoire de Meudon, Paris, specialising in high-resolution imaging in Astronomy. Moved to the Canary Islands in 1993 to take up position as support astronomer at the Instituto de Astrofísica de Canarias. From 1995-2005 formed part of the team designing and building the 10m Gran Telescopio de Canarias, with particular responsibility for the telescope’s Adaptive Optics system. Moved back to Ireland in 2005 to take up a lecturing post in the Applied Optics group in Galway. Research interests include exoplanet detection techniques, retinal imaging and wide-field adaptive optics.

Abstract

Adaptive optics (AO) was first proposed in 1953 by an astronomer, Horace Babcock, but it took about 30 years before the idea was first implemented by the US military (on the 1.6m satellite tracking telescope at Maui) and 40 years before the first astronomical systems were operational. Nowadays all large Earth-based telescopes are equipped with AO, and other applications are emerging, particularly in vision science. Research at NUI Galway is focusing on the following areas:

Astronomy Two of the areas of the most active research in astronomical AO are the development of techniques for exoplanet detection by direct imaging, and wide-field AO systems, in particular

for the next generation of Extremely Large Telescopes (ELTs). We have developed novel techniques to discriminate the exoplanet signal from residual speckle due to incomplete wavefront correction; this noise source is recognized as the main factor limiting the detection of exoplanets, which are at least 106 times as faint as their parent stars. The other area of astronomical AO research is wide-field AO, which seeks to extend correction beyond the isoplanatic patch. We developed a test-bench for multi-conjugate adaptive optics, and plan to investigate other approaches to wide-field AO. Another problem we are tackling is the mitigation of perspective elongation in laser guide stars; this effect is due to the non-negligible thickness of the sodium layer (10km at an altitude of 90km) as viewed from wavefront sensor subapertures distant from the laser launch position. Solutions proposed include tailoring the wavefront sensor detector to the elongation, and correct modeling of the effect in the wavefront reconstruction algorithm. We are also interested in possible optical solutions.

Vision Science The two main applications of adaptive optics in vision are (i) retinal imaging and (ii) vision enhancement and simulation. In the former area, we have built a pyramid wave front sensor system, which has the advantage of flexibility over the usual Shack-Hartmann sensor. Our main effort is in the area of vision simulation: the idea is to use adaptive optics to simulate the effect of new designs for vision-correction devices (intraocular lenses, contact lenses). Adaptive optics allows one to simulate now just normal operation of the device but also the visual effects of decentration and tilt.

Free Space Optical Communication Adaptive optics has a role in free space optical communication, correcting phase and intensity fluctuations and therefore lowering the bit-error-rate. We have built a high speed PC-based AO system for correcting atmospheric turbulence. Current work is focusing on wave front sensing in the present of phase singularities (vortices), and we are applying the branch point potential method to the detection of the singularities. We are also investigating methods for eliminating vortices in optical fields.

Other Potential Applications Confocal microscopy is another application that could benefit from adaptive optics. For this and all other applications, low cost solutions need to be developed. We have built a low cost, high speed platform for AO based on a membrane mirror and also a very high speed (up to 4000 fps) wavefront sensor, as well as a flexible software package for AO.

The slides of the presentation are included in the Appendix on page 55 of this proceedings.

Invited guests

Martin Booth

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Martin's interests lie in the application of advanced optical techniques to sub-micron scale imaging and engineering. His work includes analysis of aberrations and the application of adaptive optics to microscopy, data storage, optical manipulation and fabrication technologies. Martin is Associate Editor of both Optics Express and Biomedical Optics Express. He is also a Fellow of Jesus College, Oxford and a Lecturer at Lincoln College, Oxford.

Jean-Marc Conan

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Dr Jean-Marc Conan is a senior research scientist at Onera. He has a 20 year experience in adaptive optics. During this period he supervised 8 PhDs and was a leader for adaptive optics developments in the field of astronomy and defence. He has in particular developed innovative approaches in signal processing and inverse problems applied to wave-front sensing, adaptive optics control and image post-processing. More recently he started investigating adaptive optics for ophthalmology.

Alan H. Greenaway

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Alan has worked in the UK, the Netherlands and France on a range of research topics including electron microscopy, remote sensing, optical systems and astronomy. Joint winner of the John Benjamin Memorial Prize (1999) for his invention of the IMP®-based 3-D imaging technique, he has undertaken advisory work for industrial and public bodies in the UK, the US and France. Honorary Professor of Physics at Cardiff University and Honorary Senior DERA Fellow, he took a full time Chair at Heriot-Watt in 2000. His research interests include adaptive optics, optical metrology; optical aperture synthesis; optical propagation; studying dynamic processes in 4-dimensions (space and time) in fluid flow and bio-medical applications; ultra-high dynamic range imaging and femtosecond lasers. His principal research interests at present are in applying astronomy-derived techniques in life-science applications.

Austin Roorda

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Austin Roorda received his Ph.D. in Vision Science/Physics from the University of Waterloo, Canada in 1996. In a following postdoctoral appointment at the University of Rochester, he used the world's first adaptive optics ophthalmoscope to measure the properties of human photoreceptors, which included generating the first-ever maps of the trichromatic cone mosaic. From 1998 to 2004, he was at the University of Houston College of Optometry, where he designed and built the Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO), a system that has since been replicated in many labs. His current research efforts focus on both clinical and basic science applications of adaptive optics technology. He served on the executive committee of the NSF Center for Adaptive Optics and his research is supported by NIH, Foundation Fighting Blindness, and other foundation and industrial support. In 2009, he was elected as a Fellow of the Optical Society of America and received the Glenn A. Fry award from the American Academy of Optometry, which is their highest research honor. Since January 2005, he's been at the UC Berkeley School of Optometry where he is the current chair of the Vision Science Graduate Group. His research involves clinical applications for microscopic retinal imaging as well as basic investigations of structure and function of the visual system.

Ulrich Wittrock

Prof. Ulrich Wittrock
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Ulrich Wittrock was born in 1962. He studied physics at the Technische Hochschule Darmstadt, Germany, and at the State University of New York at Buffalo, USA, where he received the Master's degree in physics in 1988.

In 1988 he began employment at the Festkoerper-Laser-Institut Berlin GmbH and also began graduate study at the Technical University of Berlin in the research group of Prof. Weber. Since 1995 he is professor at Muenster University of Applied Sciences in the Department of Applied Physics. In 2002 he spent a sabbatical at Stanford University.

His current research activities include adaptive optics for solid state lasers and advanced diode-pumped solid state lasers.

Anton van Dijsseldonk

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Anton van Dijsseldonk is manager of the System Engineering-Imaging group at ASML Netherlands BV. He has extensive experience in EUV, optical systems, and in the management of large national and international projects. Already in 1998 he was a member of the EU funded research project EUCLIDES. He was project manager of the EXTATIC project on the development of the EUV alpha tool and was an active member of the EUV cluster of MEDEA+ projects comprising projects on source -, mask -, and process research and development. He was work package manager of the EU-funded More Moore project, and he initiated the EAGLE project (under the MEDEA+ umbrella) on the development of the technology for a EUV pre-production tool and platform. He was work package manager in the EAGLE project and is currently work package manager of the EXEPT project on the development of the 22nm lithographic platform. Prior to being engaged at ASML, Anton van Dijsseldonk has worked: i) 19 years as system engineer at the European Southern Observatory in Garching, Germany on the development of instrumentation for astronomical research, and ii) 10 years at the Philips Research Laboratories, Eindhoven on the development of optical measurement equipment.

Gleb Vdovin

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Dr. Gleb Vdovin received his masters degree in Optical Engineering in 1986 from the Leningrad Institute of Fine Mechanics and Optics (USSR), and his PhD in 1996 from Delft University of Technology in the Netherlands, with thesis "Adaptive mirror micromachined in silicon".

He is a founder of OKO Technologies, a company that develops and produces adaptive optical components and systems since 1997.

In 1997 he received Rudolph Kingslake Medal and Prize form SPIE. Some work published by Dr. G. Vdovin received citation index of higher than 100.

Klaus Boller

Prof. Klaus Boller (leader SOS project WECSL)
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Prof. Klaus Boller obtained his Ph.D. degree from the University of Hamburg with contributions on multimode laser intra-cavity spectroscopy, nonlinear optical conversion in alkali vapours, and with work on two-photon lasers. He spent two years at Stanford University where he contributed significantly to a major break-through, now known as electromagnetically induced transparency (EIT). As a research group leader in the University of Kaiserslautern, Germany, he focused on modern solid state laser systems, high-power diode laser systems, and on efficient conversion into various spectral ranges, particularly the IR and mid-IR with diode pumped optical parametric oscillators. In 2000, he was appointed full professor and chair of the Laser Physics and Nonlinear Optics research group in the University of Twente. Here, among research topics in the field of nonlinear optics at elevated powers, such as laser-based particle acceleration with TW lasers and high harmonic generation into the EUV range, other activities are aiming towards infrared generation with improved power levels, and with advanced spatial, temporal and spectral control for applications. Examples are fiber and diode pumped optical parametric oscillators, research towards compact free-electron laser for the THz range, and the implementation of spectral and temporal control in miniaturized lasers via integrated optical waveguide circuits. He has contributed to some 200 journal and conference papers and also serves as referee for many physical and optical journals.

Gert van Cappellen

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Gert van Cappellen obtained in 1980 HTS chemistry degree. In 1983 he joined the Erasmus University (later Erasmus MC). After a period as an analyst in the Department of Anatomy, where he researched gender development in the rat, he came in 1990 at the Department of Reproduction and Development (Reproductive Endocrinology and Procreation). In May 1998 he was promoted to his research on ovarian follicle development in the rat.

In addition to computer support and research into apoptosis, Gert made since 1996 on the development of confocal microscopy and other forms of art within the Erasmus MC, in collaboration with fellow researchers. Today he gives training and support to users, it provides maintenance and expansion of the equipment, set new techniques and applied them to current research. In this way he guides a number of researchers.

Gert van Cappellen is initiator and president of the Erasmus MC - Optical Imaging Centre (OIC). Co-founders were: Adriaan Houtsmuller, Timo ten Hagen, Niels Galjart and Wim Vermeulen. In 2006, the OIC slimmed down to three people: Adriaan Houtsmuller, Alex Nigg and Gert van Cappellen. The OIC is one of the largest optical imaging research centers in the Netherlands:

- 4 confocal microscopes
- 1 multi-photon confocal microscope scan head with FCS
- 1 TIRF microscope
- 1 4Pi microscope (global only 8 pieces)
- 1 wide-field microscope

In 2006, approximately 10h/day used confocal microscopes (365h/year) by 150 users. Every year, dozens of scholarly articles published has been used by OIC supported microscopes. Nationally and internationally the OIC has a good reputation.

Gert van Cappellen provides monthly classes in Laser Scanning Microscopy. Each year he comes from the OIC international PhD course 'In Vivo Imaging.

Hans Gerritsen

Prof.dr. Hans C. Gerritsen (leader SOS project Smart Microscopy Biol. Tissues)
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Prof.Dr. Hans Gerritsen, 1955, studied experimental physics and graduated in 1985 on work carried out at the AMOLF institute in Amsterdam. After a 2 year postdoctoral position at the Daresbury Synchrotron Radiation Source in the UK with Prof. J.Bordas, he started at Utrecht University at the Molecular Biophysics group of Prof. Levine. In 1995 he received a ’Pionier’ grant from the Dutch Science Foundation (NWO) to set up his own group. At present he is specialised in the development and use of fluorescence spectroscopy and microscopy techniques including Multi-photon excitation techniques, spectral imaging, fluorescence lifetime imaging and FRET.

Christoph Keller

Prof. Dr. Christoph Keller (leader SOS project IntHiResT)
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Christoph Keller is a full professor at the Astronomical Institute of Utrecht University and hold the Chair in Experimental Astrophysics. My research centers around polarized light. While our eyes and electronic detectors are not sensitive to the polarization aspect of electromagnetic waves, we can build instruments that measure the polarization. The polarization of light tells us about anisotropies in the area where the light is generated or where it passes through before we detect it. Measuring the polarization of light can thereby tell us about properties such as geometries, temperature gradients, magnetic and electric fields in astronomical objects.

My current research interests can be grouped into three areas: solar physics, exoplanetary systems, and instrumentation in general. In solar physics, I use observations of the Sun in polarized light to learn more about its magnetic field. Polarized light is also used to characterize exoplanets around other stars as well as solar system bodies that orbit around our Sun. The polarimetry technology developed for astronomical purposes is then also used to develop advanced instruments to remotely measure aerosols in the Earth’s atmosphere and biomedical analyses.

I teach students from the BSci to the PhD levels on a variety of subjects. Regular courses include ’Solar Physics’ and ’Observational Astrophysics 2’ and soon also ’Project Management for Scientists’. Student projects range from purely theoretical physics on the nature of polarized light in anisotropic media to experimental polarization measurements. My goal is to have students not only be able to reproduce what they have been tought, but to achieve a level of understanding and thinking such that they can create new knowledge.

Erik Meijering

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Erik Meijering received a MSc degree (cum laude) in Electrical Engineering from Delft University of Technology, the Netherlands, in 1996, and a PhD degree in Medical Imaging from Utrecht University, the Netherlands, in 2000. During 2000-2002, he was a Postdoc at the Biomedical Imaging Group of the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. In October 2002, he joined the Biomedical Imaging Group Rotterdam of the Erasmus MC - University Medical Center Rotterdam, as an Assistant Professor. Since June 2008, he is an Associate Professor at the Erasmus MC, and leads a research group on cellular and molecular image analysis. He is a Senior Member of the IEEE, the IEEE Engineering in Medicine and Biology Society (EMBS), and the IEEE Signal Processing Society (SPS). He was Special Sessions Chair for the 2002 and the 2004 IEEE International Symposium on Biomedical Imaging (ISBI), and Technical Program Chair for that meeting in 2006 and 2010. He was/is an Associate Editor for the IEEE Transactions on Medical Imaging (since 2004), the IEEE Transactions on Image Processing (term 2008-2011), and the International Journal on Biomedical Imaging (2006-2009), and was a Guest Editor for the IEEE Transactions on Image Processing for its September 2005 Special Issue on Molecular and Cellular Bioimaging. He also served/serves on a great variety of conference, advisory, and review boards."

Rob Munnig Schmidt

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Prof.ir. Robert H. Munnig Schmidt received the MSc degree in Mechanical Engineering at the Delft University of Technology, the Netherlands in 1977. From 1977 to 1983 he worked at Philips Research on the development of motion systems for the first wafersteppers and control of direct driven refrigerator compressors. In 1983 he became technical manager at Philips Domestic Appliances in various roles In 1997 he joined ASML where he fulfilled different management roles in the fields ranging from mechanical and mechatronic development to systems engineering. He was appointed full Professor in Mechanical Engineering at the Delft University of Technology, faculty 3mE in 2007 and became the head of the Mechatronic System Design Laboratory. Since beginning of 2010 he is also acting as departmental chairman of the Precision and Microsystems Engineering department within 3mE. He is member of the technical program committee for the Euspen International conference and the local organization of Euspen 2010 where he will deliver a keynote speech on recent developments in Adaptive Optics. Besides his contributions to several journal and conference papers he is inventor and co-inventor of about 30 patents.

Niek Doelman

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Niek Doelman was born in The Netherlands in 1964. He received the MSc degree (cum laude) in Applied Physics and the PhD degree from the Delft University of Technology, The Netherlands in 1987 and 1993 respectively. Currently, he is a Senior Scientist with the Department of Mechatronic Equipment of TNO Science and Industry. His main activities focus on the design and implementation of advanced motion control systems for high precision application in space and astronomy, lithography, nuclear fusion and robotics. His research interests include: adaptive filtering and control, mechatronics, adaptive optics and vibration control.

Rufus Fraanje

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Rufus Fraanje was born in The Netherlands in 1976. He received the M.Sc. degree in electrical engineering from Delft University of Technology, Delft, The Netherlands, in 1999, and the Ph.D. degree from the University of Twente, Enschede, The Netherlands, in 2004. Since 2004, he has been a Postdoctoral Researcher with the Delft Center for Systems and Control from the Delft University of Technology. From 2007 he combines his research at the TU Delft with a position at TNO Science and Industry. He was a visiting researcher with INRIA, Rennes, France, the Adaptive Systems Lab, University of California, Los Angeles, and the Institute of Sound and Vibration Research (ISVR), Southampton, U.K. His current research interests are in data-driven modelling of turbulent flows and computationally efficient control for large scale adaptive optics systems. Rufus has published on adaptive filtering, (distributed) model identification and adaptive optics.

Michel Verhaegen

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Michel Verhaegen received an engineering degree in aeronautics from the Delft University of Technology, Delft, The Netherlands, in 1982 and the doctoral degree in applied sciences from the Catholic University Leuven, Belgium, in 1985.

During his graduate study, he held a research assistantship sponsored by the Flemish Institute for scientific research (IWT). From 1985 to 1994, he was a Research Fellow of the U.S. National Research Council (NRC), affiliated with the NASA Ames Research Center in California, and of the Dutch Academy of Arts and Sciences, affiliated with the Network Theory Group of the Delft University of Technology. From 1994 to 1999, he was an Associate Professor of the Control Laboratory, Delft University of Technology and was appointed as Full Professor with the Faculty of Applied Physics, University of Twente, The Netherlands, in 1999. In 2001, he moved back to the University of Delft and is now a member of the Delft Center for Systems and Control. He has held short sabbatical leaves at the University of Uppsala, McGill, Lund, and the German Aerospace Research Center (DLR) in Munich and is participating in several European Research Networks. His main research interest is the interdisciplinary domain of numerical algebra and system theory. In this field he has published over 100 referreed journal publications. Current activities focus on the transfer of knowledge about new identification, fault tolerant control and data-driven controller design methodologies to industry. Application areas include smart structures, adaptive optics, and vehicle mechatronics.

Integrated High-Resolution Observing through Turbulence

Applicants:	Prof. Christoph Keller (Utrecht University) (project leader) Prof. Michel Verhaegen (TU Delft)
Researchers:	Dr. Visa Korkiakoski Federico Pinchetti
Budget:	671k€

Project outline

Dynamic optical aberrations induced by atmospheric turbulence form a major limitation in the achievable resolution of high-end optical imaging instruments, like ground-based telescopes and longrange surveillance cameras. Several techniques have been developed to reduce the effect of these distortions on the imaging quality, including adaptive optics (AO) and post-facto reconstruction algorithms. Although, the two approaches have been combined in the past, they have not been studied as constituents of an overall system, such as to optimize the total system performance. This research proposal aims at an integrated approach of optimization of overall image quality, in which the actions of the AO deformable mirror and the post-facto reconstruction algorithm are geared to one another.

Major improvements in resolution are expected with the joint optimization approach, in particular with the aspects of (i) the use of AO wavefront sensor signal data and deformable mirror signal data as input to post-facto reconstruction and (ii) introducing known phase aberrations during the real-time correction with the AO system to improve the performance of post-facto reconstruction, in particular of phase-diversity algorithms. Moving towards an overall real-time system, (iii) the feedback of wavefront aberration information deduced by post-facto reconstruction into the adaptive optics system is also a very promising aspect. Furthermore, important issues like adaptivity with respect to the timevariant turbulence statistics and the use of robust estimation tools taking into account the uncertainty in the point spread function will be addressed in this research.

The developed techniques will be tested and validated on a laboratory set-up first and later on by performing real-life turbulence experiments on a telescope and with a long-range surveillance camera.

Jointly optimizing adaptive optics control and post-facto image reconstruction techniques

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Introduction

At the 1970s it became possible to apply digital image post-processing methods for short-exposure images obtained through the turbulent atmosphere. With sufficiently short exposure times, the images contain high resolution information of the imaged object (and the instantaneous state of the atmospheric turbulence) that would be lost in the long-exposure images.

The first methods to utilize the post-processing techniques was the speckle-imaging, invented by [1] and further developed by [2]. These methods have been successfully applied, and are still routinely used, in both stellar and solar astronomy. However, the disadvantage of the speckle-imaging is the necessity of large amount of samples and reliance on statistical turbulence models. These can be overcome by another popular branch of post-processing methods, called phase-diversity, where a set of simultaneous short-exposure image are made such that some are distorted by a known phase difference – typically a defocus.

A groundwork of phase-diversity methods is the introduction of a Fourier space based error metrics that can be minimized using non-linear optimization tools to estimate the unknown wavefront [3]. The idea has been developed further, for instance in a framework of multi-frame multi-object blind deconvolution (MFBD), to include information also from multiple frames and multiple objects (in practice the solar surface at different wavelengths) [4].

Another major technique to improve the quality of astronomical observations is the real-time correction by adaptive optics (AO), where the distorted wavefront is measured by a sensor, and the aberrations are corrected by a deformable mirror. However, very few attempts have been made to combine the combined potential of AO and the post-facto techniques like phase-diversity. In this work, we will jointly-optimize the performance of a conventional AO system and post-facto techniques, for instance, using the potential of the DM in phase-diversity.

Project status

The first stage of the project has been characterizing the overall potential of the phase-diversity techniques. We have utilized the publicly available codes of [4], and run simulations to test their performance in cases we expect when combined with adaptive optics.

We simulate an observation of a small (anisoplanatic) piece of solar surface (illustrated in Fig. 1). The performance of the phase-diversity, in the sense of rms error compared to the original object, is evaluated with and without adaptive optics. We test the performance depending on, for instance, the amount of applied diversity, used diversity mode and the number of diversity-frames.

The results show a lot of potential for the joint-optimization: reconstruction error can be reduced by phase-diversity in all cases, but in particular without AO the improvement is significant.

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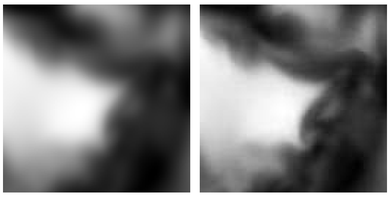

Figure 1: Simulated observed and reconstructed image.

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Integrated High Resolution Observing through Turbulence

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Introduction

While observing distant objects or night sky, the imaging resolution is deteriorated by the atmosferic turbulence. It induces wavefront aberrations that leads to a poor image quality. Both active (adaptive optics) and passive (post-facto reconstruction) methods are currently used to retrieve a better image, but this is seldomly done in a collaborative optimal way.
Objective of this research is to determine which are the optimal techniques to be used in a joint solution to achieve the best image quality.

Existing solutions

Active techniques are based on measurements of the wavefront (WF) distortion taken with dedicated sensors. Many types of sensors are in use [1,2], with different advantages and disadvantages, but the main aim for all of them is to determine the local shape of the WF. This shape is then used as an input by the controller, that, in order to improve the image quality, will command to the deformable mirror (DM) to act accordingly.
Passive techniques, instead, do not rely on real time measurements, but on differences between two or more images. In phase diversity [3] applications these differences can be used to determine the point spread function (PSF) of the optical system at the time the image has been taken and then deconvolution is applied in order to restore it. In super resolution [4] application, instead, a weighted average of the images is taken as a final result.

Research objectives

This research is focused on finding a suitable method to realize an hybrid tecnique that can work in real-time, in order to achieve optimal results through a collaboration of both active and passive strategies within a single instrument.

Efforts will be made in understanding how these processes interact and how to optimize the final result making the two strategies to collaborate.

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Smart Microscopy of Biological Tissues

Applicants:	Prof. Hans Gerritsen (Utrecht University) (project leader) Prof. Christoph Keller (Utrecht University) Prof. Michel Verhaegen (TU Delft)
Researchers:	Tim van Werkhoven Jacopo Antonello vacancy
Budget:	916k€

Project outline

Microscopy has become increasingly more important in biological and biomedical work. This is to a great extent due to the development of advanced imaging methods such as confocal microscopy and multi-photon excitation microscopy that provide 3-D imaging in (optically thick) specimens. At present, multi-photon excitation microscopy is the technique of choice for high-resolution in-vivo imaging. Unfortunately, the use of these techniques is seriously hampered by specimen-induced aberrations that result in reduced depth penetration, loss of spatial resolution, and increased phototoxicity.

Current implementations of adaptive optics (AO) provide evidence that AO can significantly improve image quality, depth penetration, and spatial resolution while reducing phototoxicity in scanning microscopy. However, severe speed limitations render them impractical for real-life applications. Here, we will focus on the development of fast, active compensation methods for specimen-induced wavefront aberrations. High compensation speeds will be realized by using adaptive optics in combination with smart predictive algorithms that take into account all system properties including the scanning nature of the acquisition, the dynamic properties of the deformable mirror based AO and the nature of the optical optimization. To realize the above, academic experts in the area of advanced microscopy (Molecular Biophysics group), adaptive optics (Experimental Astrophysics group) and advanced control systems (Delft Center for Systems and Control) will closely collaborate. The team is further strengthened by the involvement of relevant industrial partners.

The method will be validated in tissue imaging experiments including in-vivo imaging of skin, in-vivo tumour mouse models and isolated arteries. The latter part of the project will be carried out in collaboration with (bio)medical groups.

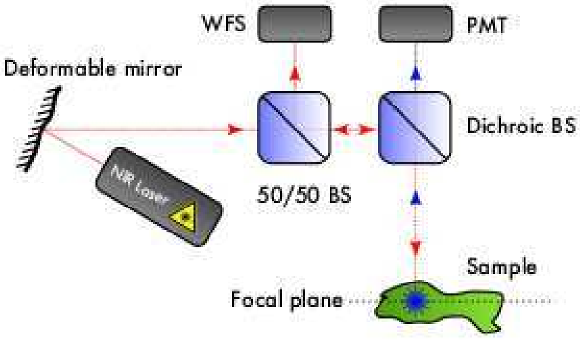

Figure 2: Schematic representation of a two-photon excitation microscope including a proposed method for implementation of wavefront sensing (WFS) and -correction.

Smart microscopy — Implementing adaptive optics in advanced scanning microscopes

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Introduction

Microscopy has become increasingly more important in biological and biomedical work. To a great extent this is due to the development of advanced imaging methods such as confocal microscopy and multi-photon excitation microscopy that provide 3-D imaging in specimens. Unfortunately, the use of these techniques is seriously hampered by specimen-induced aberrations that result in reduced depth penetration, loss of spatial resolution, and increased phototoxicity.

Current implementations of adaptive optics (AO) provide evidence that AO can significantly improve image quality, depth penetration, and spatial resolution while reducing phototoxicity in scanning microscopy. However, severe speed limitations render them impractical for real-life applications.

Method

We are developing a method to apply a fast, active compensation to the specimen-induced wavefront aberrations. We will combine adaptive optics with smart predictive algorithms to take into account all system properties such as the scanning behaviour and dynamic properties of the deformable mirror.

To measure the aberrations of the wavefront we will use a conventional Shack-Hartmann wavefront sensor on the backscattered laser-light from the tissue. Using this light for wavefront sensing has the advantage that it leaves the science beam (i.e. the fluorescent light) untouched (see Figure 2). Furthermore, by applying the phase correction on the monochromatic excitation beam, we need not worry about the chromaticity of the specimen-induced aberrations. Currently, we are investigating the optimum way to implement such a scheme.

Alternatively, we will use the more conventional intensity-optimisation as ‘wavefront-sensing’ mechanism, although this has drawbacks both with regards to speed and robustness.

Discussion

Because in our approach the beam passes through the sample twice, we will investigate whether our method is sensitive to first-order aberrations such as (de-)focus, tip and tilt of the laser spot. We may have to lock the mirror with respect to these aberration modes.

Furthermore, intensity-optimisation has the additional problem that there is a combination between the intrinsic specimen intensity (i.e. the image) and the intensity attenuation due to optical aberrations. An intensity optimisation scheme might thus not converge to a wavefront correction, but instead divert the beam to a intrinsically more bright spot in the sample.

Intensity maximisation for Sensorless Adaptive Optics

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Introduction

Adaptive Optics implementations traditionally entail the deployment of a wavefront sensor. However the development of such sensors is not trivial in some contexts such as Microscopy. Hence a viable alternative is to look into Sensorless Adaptive Optics where no direct measurement of the wavefront is performed [1,2,3].

System description

A simple optical system is considered, comprising a laser light source, a deformable mirror and a photodetector placed after a pinhole. A disturbance source induces optical aberrations resulting in a decreased light intensity measured by the photodetector. The intensity is to be maximised by actuating the deformable mirror in order to compensate for the optical aberrations.

System modelling

Consider the expansion of the aberration function Φ into an unspecified basis. We have that $\Phi = \Phi_{\text{abb}} + \Phi_{\text{off}} + \Phi_{\text{dm}}$, where Φ_{abb} is due to the disturbance source, Φ_{off} accounts for uncertainty in the initial shape of the deformable mirror and Φ_{dm} represents the influence of the deformable mirror.

Let I be the light intensity with maximum I_{max}, $\mathbf{a}$ be the modal coefficients of Φ_{abb}, $\mathbf{d}$ be the modal coefficients of Φ_{off} and $\mathbf{b}$ be the modal coefficients of Φ_{dm}. For small aberrations, I is assumed to be

$$I = I_{\text{max}} - (\mathbf{a} + \mathbf{d} - \mathbf{b})^T Q (\mathbf{a} + \mathbf{d} - \mathbf{b}) \tag{1}$$

where Q is a positive semidefinite matrix.

The variables of the model are classified into parameters Q, I_{max} and $\mathbf{d}$, unknowns values $\mathbf{a}$ and known values $\mathbf{b}$. Parameters are assumed to be invariant with respect to $\mathbf{a}$. Henceforth, the problem of maximising the intensity is reduced to the problem of computing the unknowns $\mathbf{a}$.

Calibration experiment

This experiment is performed only once with the purpose of identifying the parameters for the model. A number of intensity measurements are taken with the constraint that $\Phi_{abb} = 0$. Henceforth, the solution of a Semidefinite Programme allows for the computation of the parameters of the model.

Aberration correction

Intensity measurements $I(\mathbf{b}_i)$ where $i = 1 \ldots N + 1$ are taken. Consequently, a linear system in the unknowns $\mathbf{a}$ may be formulated. Following the computation of $\mathbf{a}$, the intensity is maximised by setting $\mathbf{b} = \mathbf{a} + \mathbf{d}$.

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Integrated Smart Microscopy

Applicants:	Prof. Paddy French (TU Delft) (project leader) Dr. Gleb Vdovin (TU Delft / Flexible Optical BV) Prof. Michel Verhaegen (TU Delft) Prof. Lina Sarro (TU Delft) Dr. Georg Schitter (TU Delft) Prof. Wiro Niessen (TU Delft / Erasmus MC, Rotterdam) Dr. Erik Meijering (Erasmus MC, Rotterdam) Dr. Adriaan Houtsmuller (Erasmus MC, Rotterdam) Dr. Gert van Cappellen (Erasmus MC, Rotterdam)
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Budget:	1000k€

Project outline

Optical microscopy and fluorescent labeling technologies have gone through impressive progress in the past decades and have provided powerful instruments for biomedical research. Especially the availability of a large variety of fluorescent proteins, including photoactivatable and -switchable mutants, has revolutionized live cell imaging. Quantitative investigation of the molecular mechanisms responsible for normal biological function of living cells and organisms, but also aberrant processes in diseases such as cancer, Alzheimer's, and Parkinson's, requires very precise localization of active factors inside subcellular organelles, as well as the structure and dynamics of active chromatin sites inside the cell nucleus. For such studies, the resolution of commercially available optical (confocal) microscopy systems is a very limiting factor. In a practical setting, the loss of performance compared to theoretical values is largely due to the mismatch between the refractive index of the specimen. Especially in a confocal setup, this mismatch increases with increasing depth of penetration into the specimen. Microscope systems available today are generally based on fixed optical setups, and are unable to correct for dynamic, higher-order wavefront aberrations due to distortions in the optical path, or manufacturing inaccuracies. Smart optics and control systems have a high potential to serve as enabling technologies to address this problem. Therefore, the aim of this multidisciplinary project is to develop and evaluate an integrated smart confocal microscoppe for live cell imaging, which combines adaptive optics in the imaging path with adaptive postprocessing of the resulting 3D image data. This requires optical systems research (design and integration of adaptive optics components), control systems research (real-time control for improved scanning, active compensation, and adaptive optics), image processing research (adaptive filtering, deconvolution, detection, and tracking), and biomedical research (evaluation of the new system by application to biomedically relevant problems).

Waveguide-based External-Cavity Semi-conductor Laser arrays

Applicants:	Prof. Klaus Boller (University of Twente) Prof. J.L. Herek (University of Twente) Prof. Michel Verhaegen (TU Delft)
Researchers:	Ruud Oldenbeuving (University of Twente) Hong Song (TU Delft)
Budget:	855k€

Project outline

The need to intensify the exchange of information with higher-speed (internet), the wish to display received information in most brilliant (Laser TV) colors, and most advanced techniques in bio-medical diagnostics, surprisingly, have their common grounds. When looking at their technological heart, one finds that it is the excellence in laser light generation that fosters their potential and growth. As a result there is a strong need to realize highly miniaturized lasers with greatly improved wavelength control, and at most affordable cost. In this project we investigate a novel approach that promises to fulfil many of these demands. For the first time, we use special (vertical cavity) diode lasers (VCSELs) and control their emission with a network of adjustable photonic wires (waveguides) made in a glass-chip. The design of these planar glass-based waveguide ring resonator circuits is that they can tune or lock the laser wavelength at will, via chip-integrated thermo-optical actuators, while at the same time allowing on-chip measurement of the wavelength.

Stable operation, at any desired wavelength, is then done via a so-called smart controller. This is eventually a miniaturized electronic control chip, in which the most advanced control theory is applied for proper functioning of the laser and low cost. The described design allows further unprecedented possibilities; To scale-up the output power, entire arrays of diode lasers can be operated on the same waveguide chip. Mutual coupling combines their output into a single beam, e.g., as highly repetitive light pulses, enabling an easy and efficient conversion into powerful visible light for display purposes.

Waveguide-based External Cavity Semiconductor Lasers

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Introduction

The need to increase the rate of information exchange with higher-speed fiber-to-the-home networks, the wish to have displays with higher contrast and greater brightness (Laser TV), and many advanced techniques in bio-medical diagnostics, surprisingly, have common ground: lasers. As a result, the realization of miniaturized lasers with greatly improved wavelength control, and affordable cost is highly desirable. In this project, we investigate a novel approach to hybrid integrated optical lasers that promises to fulfill many of these demands.

Design

To achieve a laser that operates operates at a high accuracy user-chosen wavelength, we designed a tunable external cavity mirror, based on integrated micro-ring resonators (MRR) [1,2], using TriPleX technology. A MRR is an optical cavity that provides filtering based on the free spectral range (FSR) of the cavity resonances. Fig. 3 shows a standard add-drop MRR structure, with two straight waveguides, coupled to a ring. Frequencies for which the MRR is resonant couple into the ring via the IN- and couple out to the DROP-port. A frequency selective mirror is created by combining the IN and DROP so that light now exits the IN-port instead of the DROP. The frequencies reflected by the mirror are given by the FSR of the MRR, hence, tuning is accomplished by varying the optical length of the MRR through heating and cooling of the integrated optical circuit. A Smart Optical tuning will be devised at DCSC in Delft.

However, the frequency selectivity and tunability ($\sim$4 nm) of a single MRR-mirror is not sufficient to ensure that a laser diode will oscillate at the desired wavelength. Selectivity of the mirror is increased by combining two MRRs with different radii, as shown in Fig. 4*a*, since light must now be resonant in both MRRs. The reflectivity of the mirror is the convolution of the two MRR responses, resulting in greater frequency selectivity.

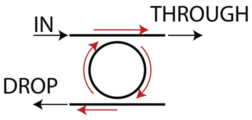

Figure 3: *A schematic overview of a single MRR. The in- and output ports are labeled IN, DROP and THROUGH. The red arrows indicate the direction of the light.*

We have calculated the reflectivity and tuning range of a two-ring MRR-mirror, designed for operation in the telecoms band (see Fig. **??***b*. Our design shows that continuous tunability over a 40 nm range is possible and that the selectivity ($\sim$40 nm) is sufficient to ensure that laser oscillation will be restricted to the desired wavelength.

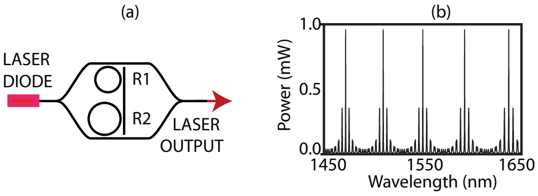

Figure 4: *(a) Schematic overview of a two-ring MRR-mirror.* R_1 *and* R_2 *are radii for the MRRs (*$R_1 \neq R_2$*). The transmitted light exits from the equivalent of the THROUGH-port, while the reflected light exits the IN-port. (b) The calculated reflection response of the mirror for* R_1*=50* μ*m and* R_2*=55* μ*m and an optical input of 1 mW.*

Acknowledgement

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Controller Design for a Waveguide-based External Cavity Semiconductor Laser

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Introduction

In recent years, tunable miniaturized lasers have received increasing attention in applications like telecommunications, spectroscopy, display and imaging systems [1]. In the joint project with University of Twente, a waveguide-based external cavity semiconductor laser (WECSL, see Figure 1) is being developed with tunable wavelength and power at reduced cost and small size.

The microring resonator mirror (MRM) has a bandpass characteristic with its peak response at λ_o. Due to the interaction between the laser diode (LD) and MRM, the laser output has a wavelength of λ_o. λ_o can be tuned by the temperature of the MRM, via the heaters in the MRM. The power P_o of the laser output can be tuned by the current I to LD. λ_o and P_o are obtained via a pair of photodiodes with complementary spectrum responses.

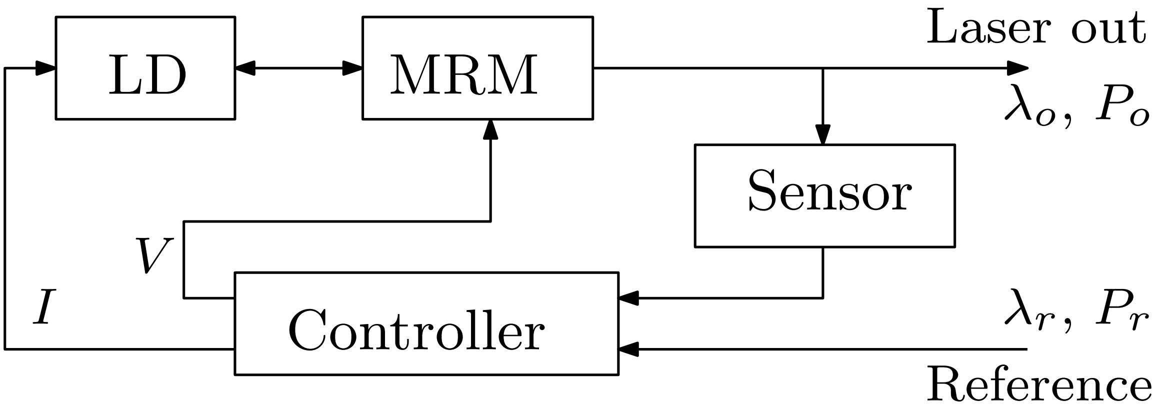

Figure 5: *Block diagram of the WECSL.*

Problem formulation

The control objective is to set the heating voltage V and the current I such that the wavelength λ_o and power P_o follow the reference values λ_r and P_r. Three issues should be concerned in the controller design: (1) dynamics and nonlinearity in the heating and cooling of the MRM; (2) intrinsic heating of the MRM by the laser; (3) reconstruction of λ_o and P_o from the photodiode measurements.

Strategy

Corresponding to the issues raised previously, controller design will consist of three successive stages as follows. Stage 1 focuses on the dynamics and the nonlinearity in the heating and cooling of the MRM, while keeping the laser power constant and obtaining λ_o and P_o directly from an optical spectrum analyzer (OSA). In Stage 2, laser heating is studied by varying the power via I and investigating the effect on λ_o and P_o. Stage 3 replaces the OSA by the photodiodes, allowing implementation of the laser at low cost and small size. In each stage, the controller will be designed based on the valid model of the system, which is identified from the input-output data of the system using the black-box identification [2].

Conclusion

Problems are formulated for controller design for the WECSL, and strategy has been proposed. Future work will focus on experimental validation of the strategy.

Acknowledgement

This work is supported by the STW Program "Smart Optics Systems". Authors would like to thank Ruud Oldenbeuving, Chris Lee, Herman Offerhaus and Klaus Boller from University of Twente for their warm discussions and valuable comments.

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Smart Multilayer Interactive optics for Lithography at Extreme UV wavelengths (SMILE)

Applicants:	Prof. Fred Bijkerk (University of Twente) Dr. R. Sobierajski (FOM Rijnhuizen and Polish Academy of Science) Dr. F. van Goor (University of Twente) Dr. C.J. Lee (University of Twente) Prof. D.H.A. Blank (University of Twente) Prof. A.J.H.M. Rijnders (University of Twente)
Researchers:	
Budget:	1069k€

Project outline

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Introduction

The aim of this project is to achieve an integrated system, where adaptive optics specifically suitable to the EUV with inherent reflectivity and wavefront sensing are individually manipulated to obtain optimized EUVL system performance. To achieve this, two scientific challenges must be met: the development of suitable active materials, and the development of precision wavefront sensing technology for the EUV.

Materials development

Multilayer mirrors (MLMs), which provide high reflectivity for a specific wavelength range, are constructed by depositing alternating layers of different materials–typically molybdenum and silicon–

with a spacing that satisfies Bragg's Law. Currently, at normal incidence and a wavelength of 13.5 nm, reflectivities of 68% are regularly achieved [1]. However, changes to the layer spacing modify the reflectivity of the optic, and distort the wavefront of the reflected radiation. Therefore, a complete smart optical system must correct the wavefront distortion and maximize reflectivity.

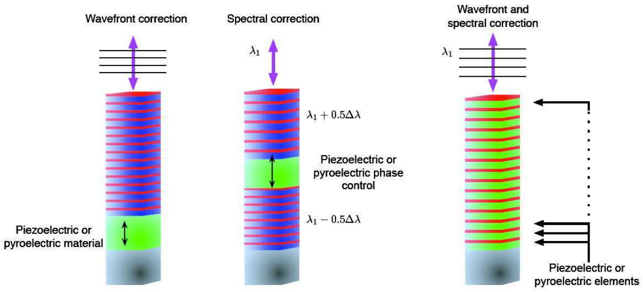

Figure 6: Spectral and wavefront control will be achieved in three ways: growing the MLM on an active substrate (left); growing two different MLMs, separated by a phase section (center); and replacing the spacer layer with an active material (right).

We are planning three different approaches (see Fig. 6): growing the MLM on an active, segmented substrate; separating two MLMs with a phase section; and replacing the spacing layer with an active material. These offer different degrees of control over the spectral reflectivity and wavefront distortion, while also placing different demands on the transparency and total displacement of the active material.

Wavefront sensing

To determine the accuracy of the wavefront correction, a wavefront sensor for the EUV must be developed. Researchers at the FLASH facility are currently developing the required optical elements, such as beam splitters and interferometers.

Acknowledgements

STW "Smart Optical Systems" program, 10448.

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Image Manipulation for Wafer Plane Conformity in Optical Lithography Systems

Applicants:	Prof. Rob Munnig Schmidt (TU Delft / ASML) (projectleader) Prof. Michel Verhaegen (TU Delft) Prof. Maarten Stijnbuch (Eindhoven Univ. of Technology Dr. Nick Rosielle (Eindhoven Univ. of Technology
Researchers:	Walter Loch (TU Delft) Geert-Jan Naaijkens (Eindhoven Univ. of Technology) vacancy (TU Delft)
Budget:	1000k€

Project outline

The goal of this research is to come to an integral mechatronic design methodology which is generally applicable to opto-mechatronic systems but specifically supports the development of key technologies that increase resolution in high speed imaging systems. The project objective is motivated by the fact that the semiconductor industry is constantly trying to reduce the minimum size, also known as Critical Dimensions (CD), of features that are used to fabricate Integrated Circuits (ICs). A reduction in feature size will result in higher information density and speed as well as reduced power consumption and cost of the IC. These effects improve performance of consumer electronics such as laptops, cellular phones and MP3 players which subsequently lead to increased mobility and economic productivity of society.

In the production process of ICs, photolithography is seen as the crucial and limiting step in realizing smaller feature size. In order to facilitate the decrease in CD and improve cost effectiveness of the production process, lithography equipment manufacturers are continuously developing imaging machines with ever increasing resolution and wafer throughput. Up to now, these specifications are achieved by increasing the numerical aperture of the lens and using laser sources with lower wavelengths. Furthermore, the mechatronic system architecture around the lens is optimized to reduce optical aberrations.

Considering the ITRS roadmap for lithography, it is clear that ever stringent demands with respect to overlay and CD control are pushing lithography equipment manufacturers to their technological limits. In order to improve conformity of the projected mask image - also known as aerial image - with the wafer surface topology, a number of performance limiting factors need to be tackled. Specifically, static optical path distortions due to lens imperfections and wafer unflatness as well as dynamic distortions due to dynamic deformations and hysteresis of optical path components must be reduced. However, overcoming these effects is becoming increasingly difficult due to the limitations of lens and wafer polishing techniques, use of friction-based (optical) component interfaces and higher component acceleration levels inside lithography equipment to achieve the desired wafer throughput.

The push into these extreme machine operating regimes has made it evident that the conventionally applied mechatronic design concepts and technologies have difficulties in tackling the above described problems. In order to be able to develop next generation lithography systems, the current mechatronic approach for imaging systems needs to be enriched with novel opto-mechatronic design rules using Adaptive Optics (AO). Considering its correction potential, the required bandwidth and its proven track record in astronomy [5], AO is seen as the key technology to reduce rapidly changing optical path distortions inside lithography systems whilst keeping complexity and cost to a minimum.

To research novel opto-mechatonic design methodologies and investigate the applicability of AO inside high speed lithography systems, the project will utilize a multi-disciplinary approach to simultaneously and iteratively tackle a number of research challenges.

Firstly, the use of opto-thermo-mechanical models for adaptive optic actuator and controller design is researched. Specifically, the trade-off between model accuracy and complexity will be investigated.

Secondly, the research will focus on the development of an adaptive optic actuation concept for lithography systems at photomask level. Moreover, emphasis is placed on the identification of the actuator number and location that enables an optimized system performance. During this study, additional challenges such as energy dissipation, cost at a minimum of complexity will require dedicated attention.

Thirdly, research is required on efficient algorithms to facilitate the multivariable control of, as well as real-time multivariable system and disturbance identification techniques for, high bandwidth AO systems inside lithography equipment. Finally, a metrology system through high speed real-time surface measurement must be developed. It is expected that the above approach will lead to a unique trend change in opto-mechatronic system design methodology and novel technologies for high end optical equipment to meet future requirements of nanometer (nm) level overlay and sub-50 nanometer focus deviations.

Real time deformation metrology for adaptive optics in lithography

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Introduction

In the market of Integrated Circuit (IC) manufacturing, photolithography is seen as the crucial and enabling step in achieving smaller feature size. In lithography scanners for the sub-45 nm regime previously less dominant performance limiting factors are influencing the conformity of the projected (photo)mask image - also known as aerial image - with the wafer surface topology (see figure 7). Major (quasi)-static contributors are lens imperfections, non-correctable substrate unflatness as well as mask deformations due to thermal and gravitational influences. The increase in acceleration levels and the reduction of settling time to boost machine productivity also lead to additional dynamic optical path distortions. [1]

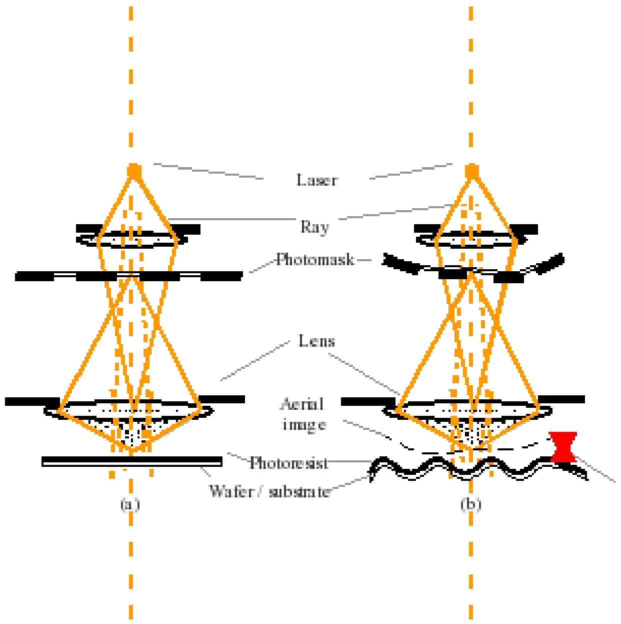

Figure 7: *A schematic overview of lithography projection system, with (a) the ideal projection configuration and (b) the situation with optical path distortions such as photomask and wafer deformation. [1]*

Inside next generation lithography systems, Adaptive Optics (AO) is seen as the key enabler to meet future requirements. For example, in [2] a method is proposed to reduce focus budget dependency on wafer unflatness. The dependency is reduced actively controlling the curvature of an optical element in the optical path with a piezoelectric actuation system.

In order to characterize the deformations on the optical element a measurement system is required. The measurement could be performed by measuring the surface of the optical element or by measuring the wavefront of the projected image. Additionally the measurement information could serve as control input for AO actuators or used for increasing accuracy of predictive feed-forward models.

Objective

This research will focus on a metrology system architecture which is able to perform in-situ and real-time measurement of deformation on an optical element. These deformations are introduced by active deformation, thermal effects or dynamic effects.

Outlook

In the first phase of the project a general study was started on measurement systems and principles.[3] Additionally, a more specific study into examples of optical measurement systems and their applications was conducted, based on [4], [5]. The goal of the coming months is to work towards a detailed problem definition and identify the specifications and boundary conditions for the metrology system. This also requires an investigation of the possible improvement potential of an in-situ real-time deformation metrology system. Eventually the goal is to develop a demonstrator in the form of soft- and hardware which consists of the measurement system and required electronics for signal conditioning and processing with possible algorithms to transfer metrology data into input for a control system.

Bibliography

[1] TU Delft, TU Eindhoven, ASML, SOS project proposal IMWACOL, 2008
[2] C.L. Valentin et al. Mechatronic System Design of an Optical Element Curvature Actuation System, Proc. of EUSPEN, 2010
[3] J.P. Bentley, Principles of measurement systems, 4th ed. 2005
[4] T. Yoshizawa, Handbook of optical metrology, 2009
[5] E. Hecht, Optics, 4th ed. 2002

Deterministic Reticle Clamping

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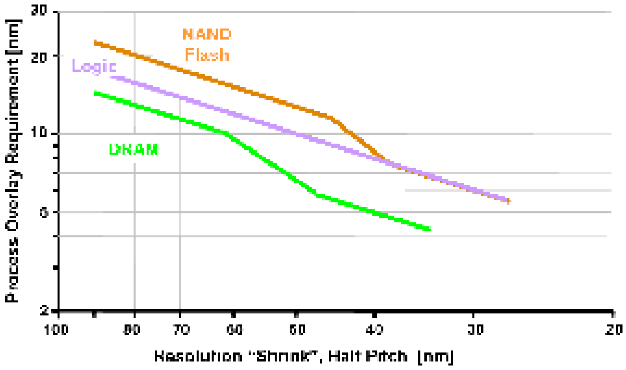
Critical Dimension

In semiconductor industry, the critical dimension of Integrated Circuit (IC) patterns etched onto wafers is moving towards the sub-45 nm regime [1].

Overlay

Each IC requires multiple lithography exposures resulting in multiple layers. Each layer has to be exposed on top of the previous layer with a high alignment accuracy (= overlay). Overlay requirements are becoming ever more stringent [2].



Accelerations of reticle stages

In the reticle stage of ASML, extremely high accelerations occur. These accelerations need to increase for increasing throughput requirements. [3]

Research subject: deterministic reticle clamping

Deviations in the optical path are, among others, caused by non-correctable reticle deformations and drift. These previously less critical influences become a dominant limiting factor for overlay performance. Reticle interfacing for high acceleration stages and concepts to minimize the above mentioned overlay performance limiters are introduced and explained. Moreover, the influence of such reticle interfacing concepts on the reticle stage is investigated.

Bibliography

[1] International Technology Roadmap for Semiconductors, http://www.itrs.net.
[2] De Jong, van de Pasch, Enabling the lithography roadmap: an immersion tool based on a Novel Stage Positioning System(2009)
[3] H. Borggreve, public session at Hightech Mechatronica 2007, Koningshof, Veldhoven, NL

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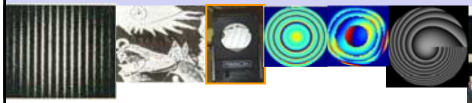
44	Wittrock	Ulrich	Prof.	wittrock@fh-muenster.de
45	Zandvoort van	Marc	Dr.	mamj.vanzandvoort@bf.unimaas.nl

Slides

Slides Keynote Artal

History and future of adaptive optics for vision

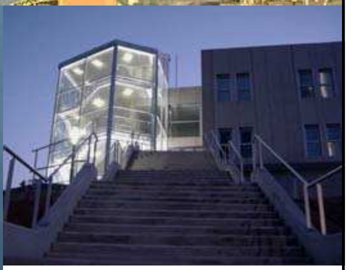



Pablo Artal

LABORATORIO DE OPTICA
UNIVERSIDAD DE MURCIA, SPAIN

SOS workshop, Holland, June 2010



LABORATORIO DE OPTICA
UNIVERSIDAD DE MURCIA

lo·um

lo·um

What is Adaptive Optics?

Technology to obtain "better" images by correcting optical aberrations!

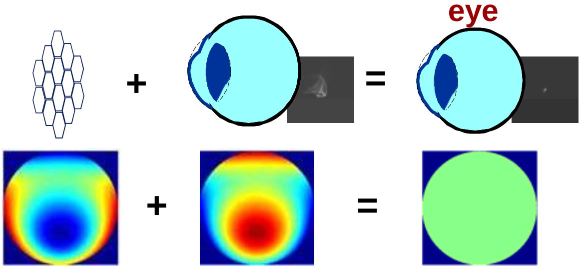
lo·um

Correcting or by-passing the eye's aberrations: towards Adaptive Optics (AO)

lo·um

Adaptive optics for the eye

corrector **Aberrated eye** **Aberration-free eye**



+ =

+ =

Correction of the eye's aberrations (some history...)

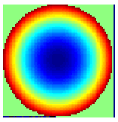
sXIII defocus

1800

1960

1990

2000



Correction of the eye's aberrations (some history...)

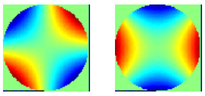
sXIII defocus

1800 astigmatism (T.Young)

1960

1990

2000



Correction of the eye's aberrations (some history...)

sXIII defocus

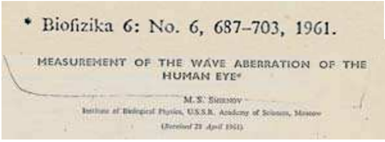
1800 astigmatism (T.Young)

high order aberrations (proposed by Smirn

1960

1990

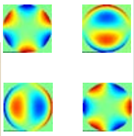
2000

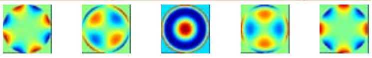


• Biofizika 6: No. 6, 687–703, 1961.

MEASUREMENT OF THE WAVE ABERRATION OF THE HUMAN EYE*

M. S. SMIRNOV





Correction of the eye's aberrations (some history...)

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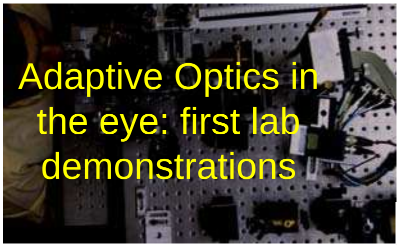
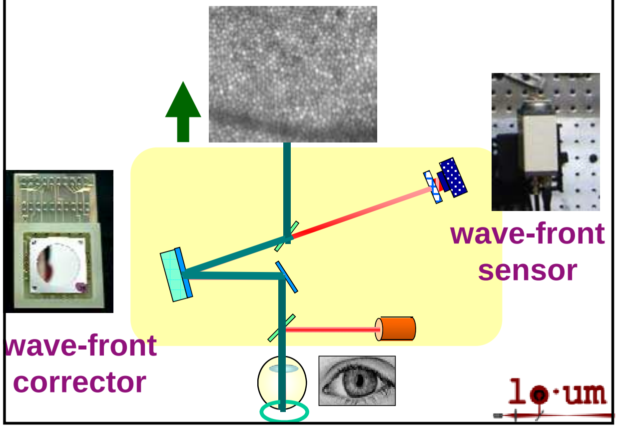


Adaptive Optics in the eye: first lab demonstrations



wave-front sensor

wave-front corrector

Adaptive Optics for the eye: some antecedents!

1980's

- Correction of astigmatism with a segmented deformable mirror
(University of Heidelberg, Appl.Opt, 1989)

Active optical depth resolution improvement of the laser tomographic scanner

Andreas W. Dreher, Josef F. Bille, and Robert N. Weinreb

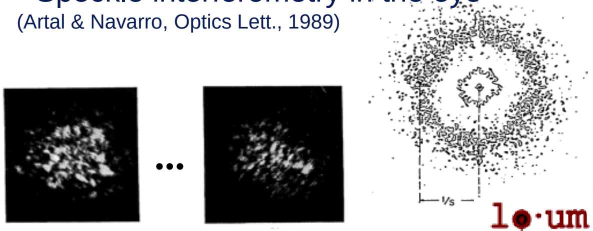
Laser scanning tomography can be used to assess retinal nerve fiber layer thickness and optic disc topography of the human eye. A pinhole is located at a plane conjugate to the focal plane of the scanning laser beam. This so-called confocal configuration assures that only the light originating from the illuminated focal plane on the retina passes through the pinhole and is detected by the photomultiplier. Consequently, images with high spatial resolution in all directions are obtained. An active optical system (active mirror) further improves the lateral/depth resolution of the laser tomographic scanner. By partially compensating for the optical aberrations introduced by the cornea and lens, the active optical system allows the illuminating beam to be enlarged to 6 mm, thus improving depth resolution twofold.

lo·um

Adaptive Optics for the eye: some antecedents!

1980's

- Speckle interferometry in the eye
(Artal & Navarro, Optics Lett., 1989)



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Adaptive Optics for the eye: some antecedents!

1990's

Static corrections

- Deformable mirror
(University of Rochester, JOSA A, 1997)

- Liquid crystal SLM
(University of Murcia, JOSA A, 1998)

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Adaptive Optics for the eye: some antecedents!

2000's (closing the loop!)

Real-time adaptive optics correction

- **University of Rochester, Opt.Express, 2001**
- **University of Murcia, Opt.Lett., 2001**

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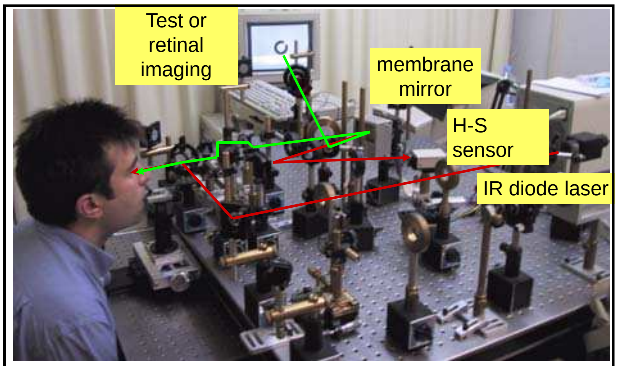
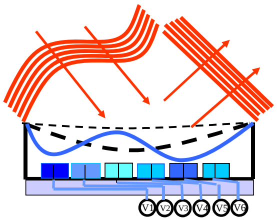
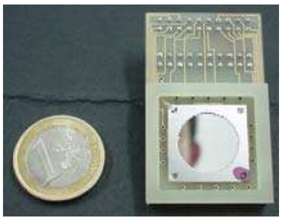


LO·UM closed-loop real-time (25 Hz) AO
(Fernández, Iglesias & Artal, Optics Letters, 2001)

lo·um

Corrector device: 37 channels membrane deformable mirror (MDM) from OKO





Static correction in an artificial eye (Zhu et al., App. Opt.,1999)
Closed-loop AO in artificial turbulence (Patterson et al., Opt.Exp.,2000)
Closed-loop astronomical AO (Dayton et al. Opt.Comm,2000)

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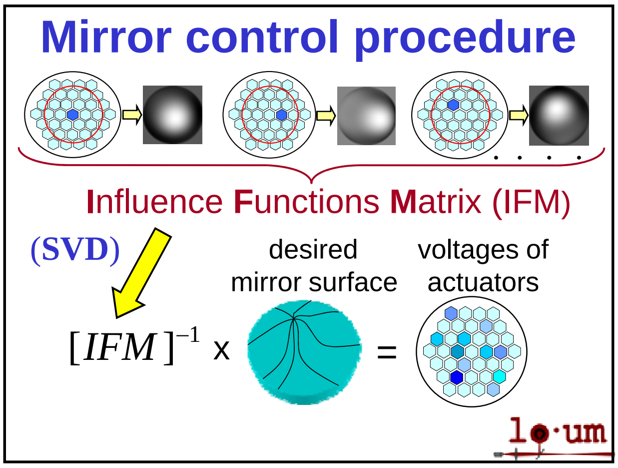
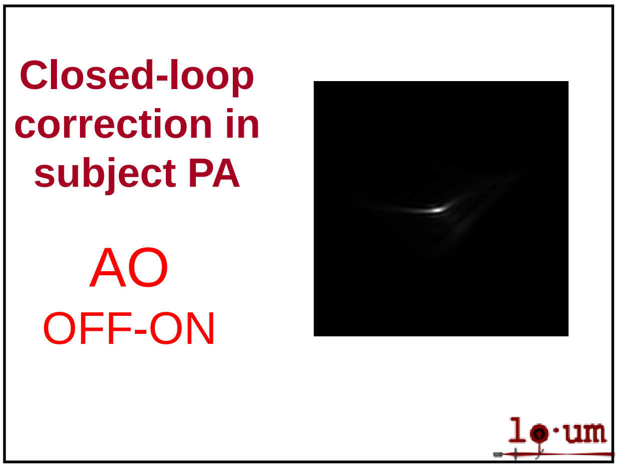


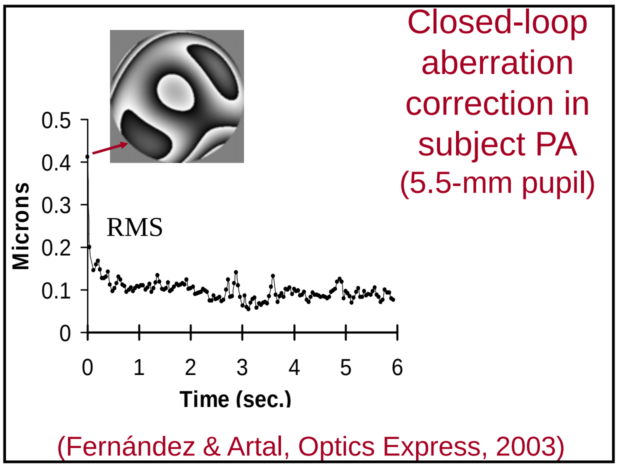
Mirror control procedure

$[IFM]^{-1}$ x desired mirror surface = voltages of actuators



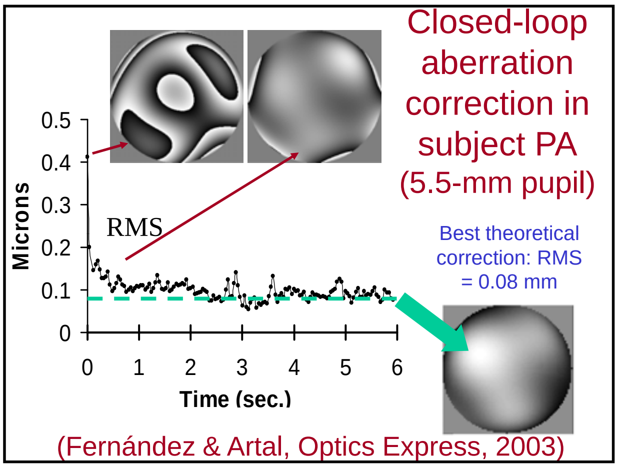
Closed-loop correction in subject PA

AO
OFF-ON



Closed-loop aberration correction in subject PA (5.5-mm pupil)

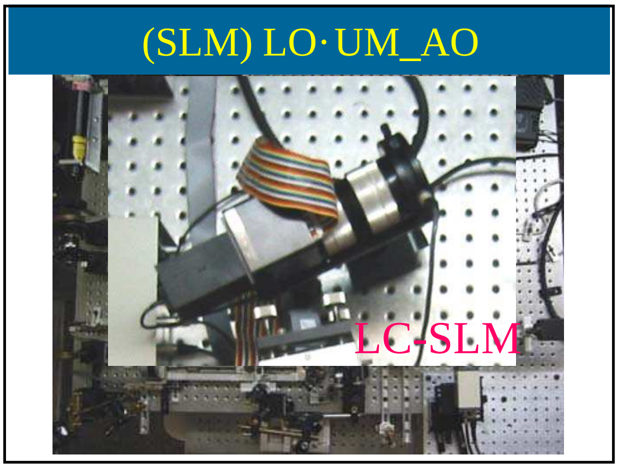
(Fernández & Artal, Optics Express, 2003)



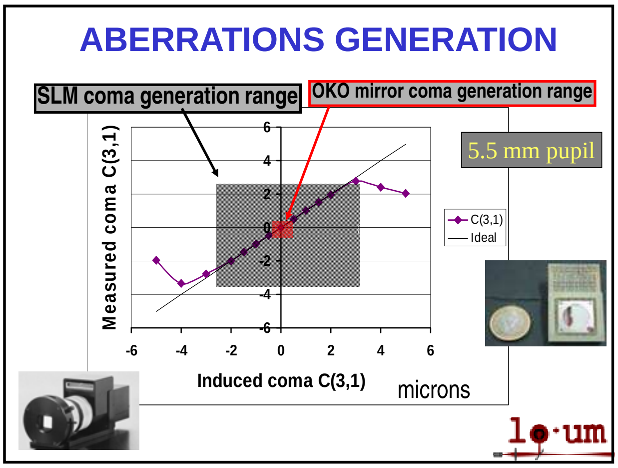
Closed-loop aberration correction in subject PA (5.5-mm pupil)

Best theoretical correction: RMS = 0.08 mm

(Fernández & Artal, Optics Express, 2003)

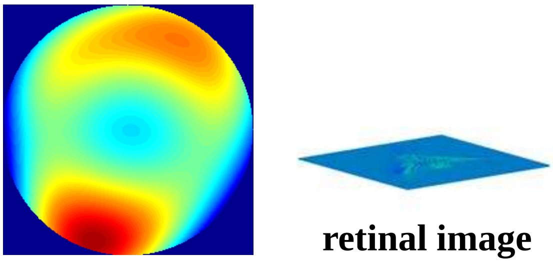


(SLM) LO· UM_AO



ABERRATIONS GENERATION

AO OFF-ON

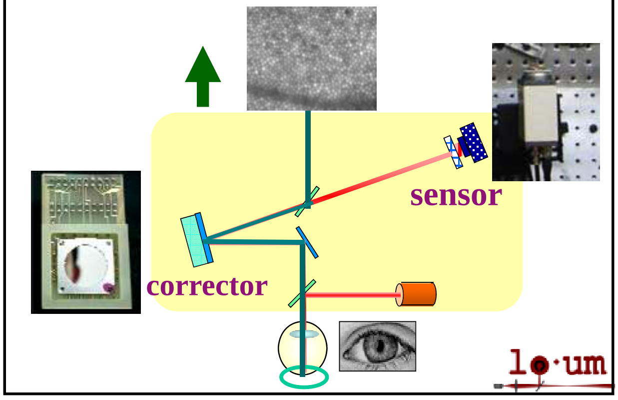


P. M. Prieto, E. J. Fernández, S. Manzanera, P. Artal,
Opt. Express, 12, 4059-4071 (2004)

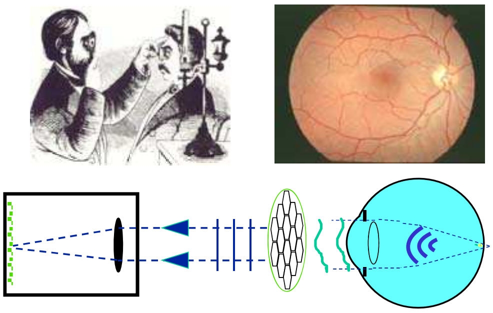
Applications of adaptive optics in the eye…

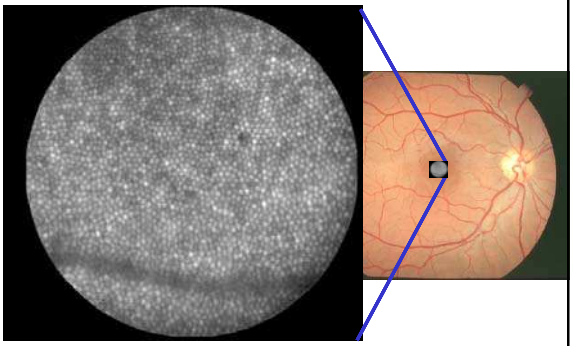
- retinal imaging
- improved vision
- simulating vision

Retinal imaging: correcting eye & instrument aberrations!



Retinal imaging: correcting eye & instrument aberrations!





(Courtesy David Williams)

Examples of AO in different retinal imaging modalities

- High resolution (conventional) ophthalmoscope
- Scanning laser ophthalmoscope
- Optical Coherence Tomography

Examples of AO in different retinal imaging modalities

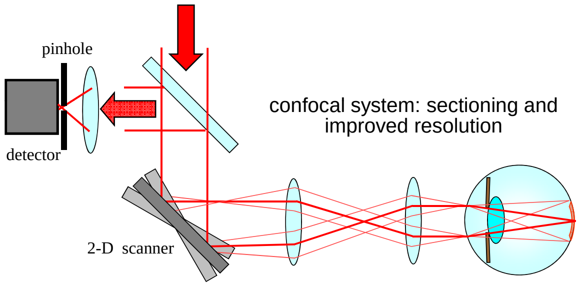
- High resolution (conventional) ophthalmoscope
- Scanning laser ophthalmoscope
- Optical Coherence Tomography

Examples of AO in different retinal imaging modalities

- High resolution (conventional) ophthalmoscope
- Scanning laser ophthalmoscope
- Optical Coherence Tomography

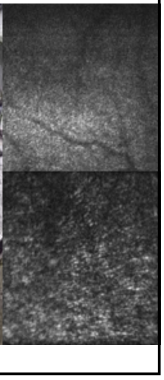
Scanning Laser Ophthalmoscope (SLO)

Scanning optical microscope with the eye as objective and the retina as sample



confocal system: sectioning and improved resolution

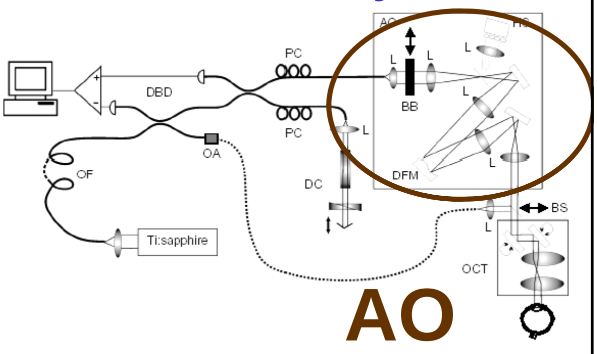
LO·UM AO-SLO



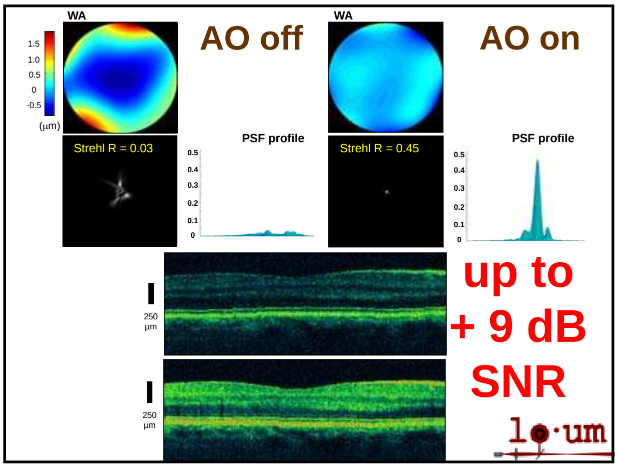
Examples of AO in different retinal imaging modalities

- High resolution (conventional) ophthalmoscope
- Scanning laser ophthalmoscope
- Optical Coherence Tomography

AO-UH OCT system



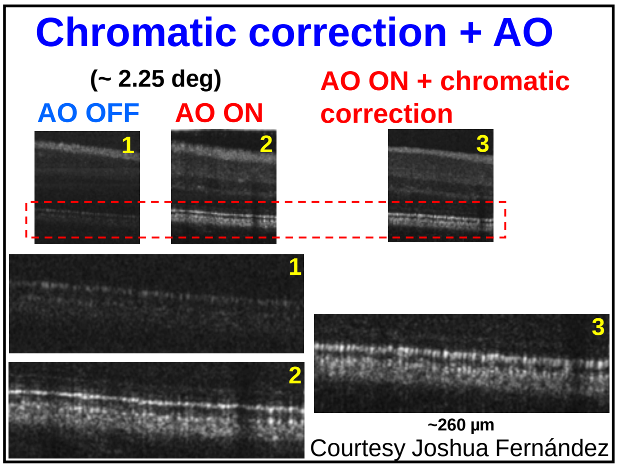
University of Vienna-LO·UM (2004)



AO off

AO on

up to + 9 dB SNR



Chromatic correction + AO

(~ 2.25 deg)

AO OFF

AO ON

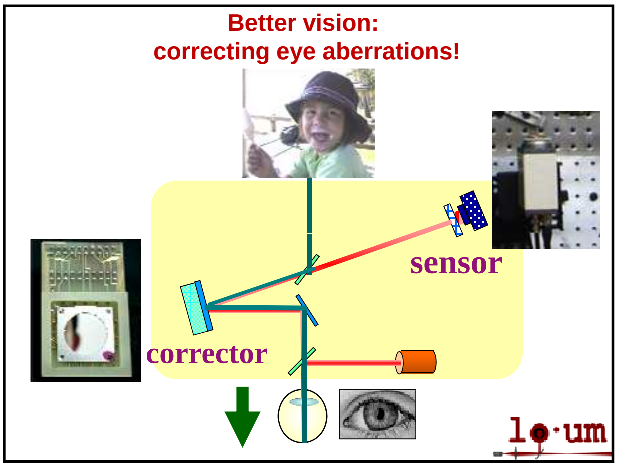
AO ON + chromatic correction

~260 µm

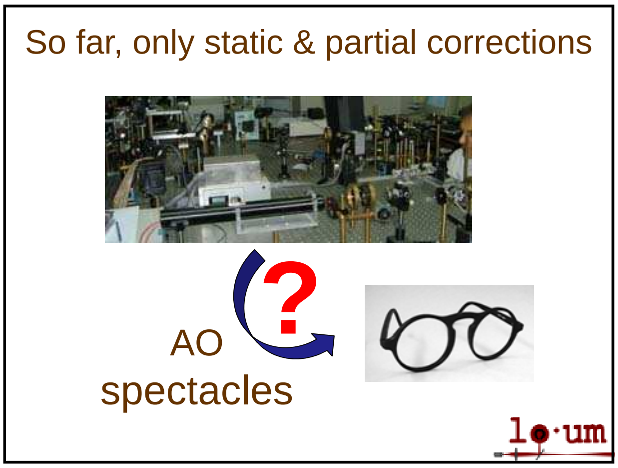
Courtesy Joshua Fernández

Applications of adaptive optics in the eye…

- retinal imaging
- improved vision
- simulating vision



Better vision: correcting eye aberrations!



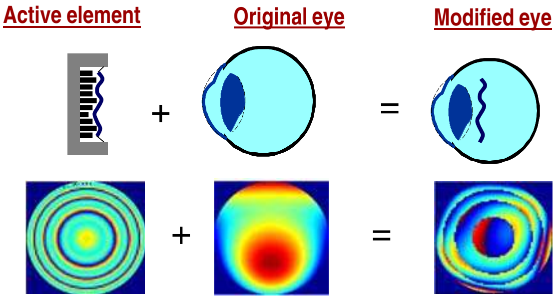
So far, only static & partial corrections

Applications of adaptive optics in the eye…

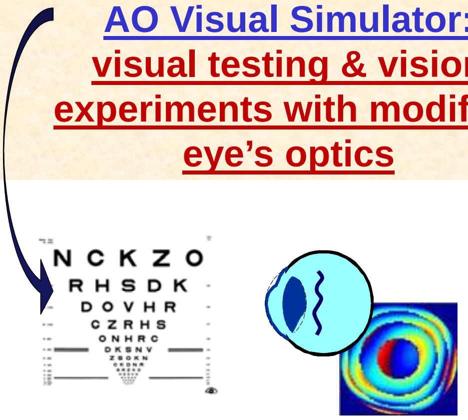
- retinal imaging
- improved vision
- simulating vision*

* EJ Fernández, S Manzanera, P Piers & P Artal; Adaptive optics visual simulator"; **J Refract Surg.** 18(5):S634-8 (2002)

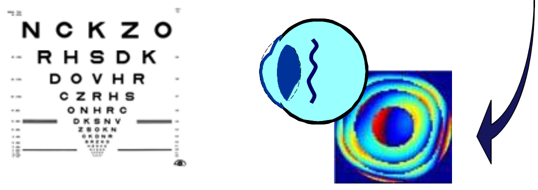
AO Visual Simulator



AO Visual Simulator: visual testing & vision experiments with modified eye's optics

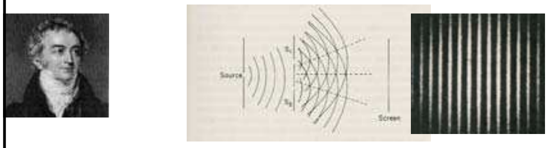


AOptics Simulator (for Visual testing)



Visual testing with modified (improved) optics before the AO era!

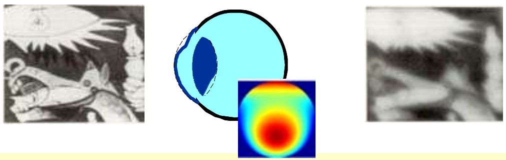
Projecting interference fringes into the retina (by-passing the eye's optics)*



* D. R. Williams, "Visibility of interference fringes near the resolution limit," J. Opt. Soc. Am. A 2, 1087-1093 (1985).

Visual testing with modified (improved) optics before the AO era!

Pre-filtered images to compensate for the eye's aberrations*



* P. Artal, "Calculations of two-dimensional foveal retinal images in real eyes"; **J.Opt.Soc.Am. A**, 7, 1374 (1990)

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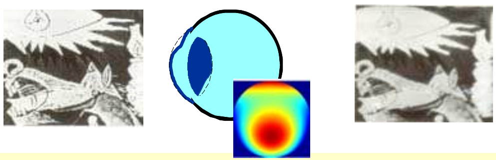
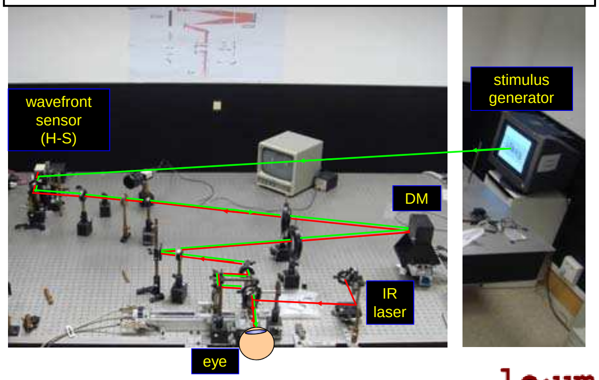
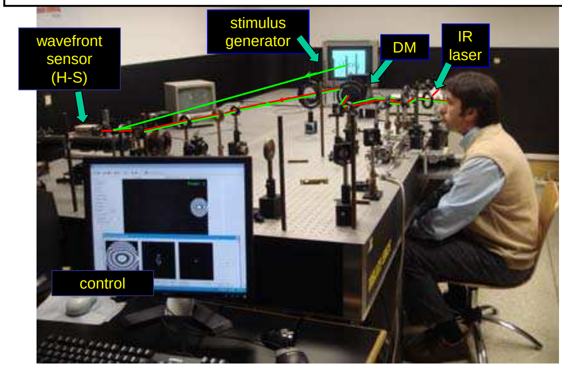


* P. Artal, "Calculations of two-dimensional foveal retinal images in real eyes"; **J.Opt.Soc.Am. A**, 7, 1374 (1990)

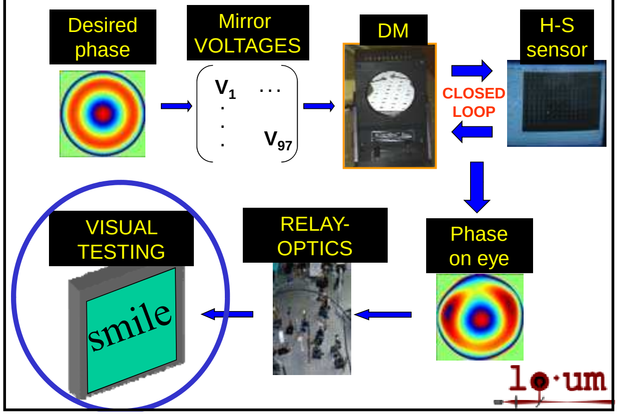
Visual testing with modified optics in the AO era!



Visual testing with modified optics in the AO era!



LO·UM AO_visual simulator

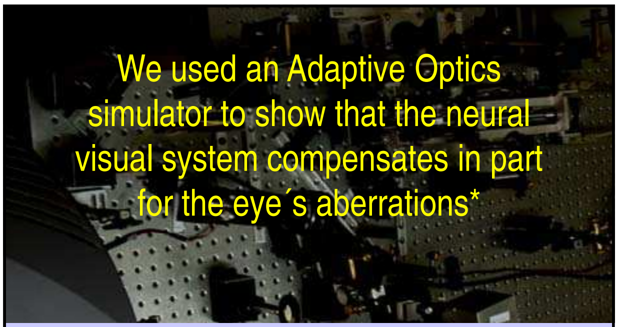


$$\begin{pmatrix} V_1 & \cdots \\ \vdots & \\ & V_{97} \end{pmatrix}$$

Applications of AO simulators

i) New (or revisited) experiments in Vision research

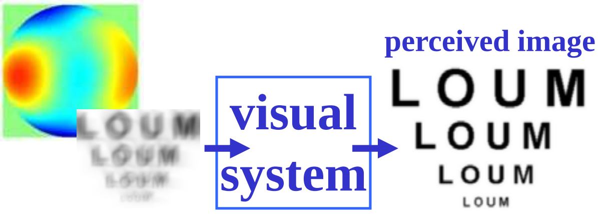
ii) Interactive design/testing of new ophthalmic solutions

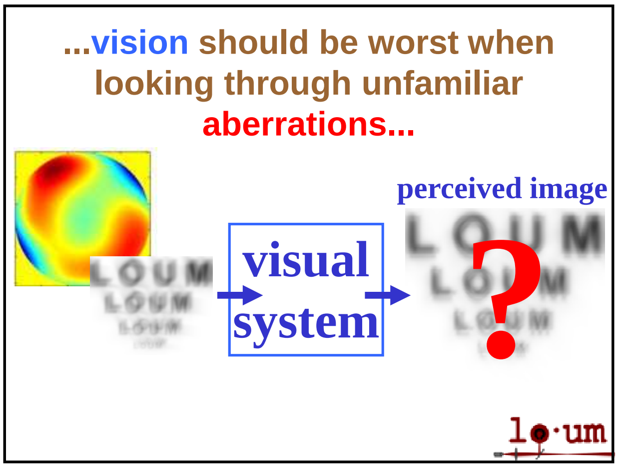


We used an Adaptive Optics simulator to show that the neural visual system compensates in part for the eye´s aberrations*

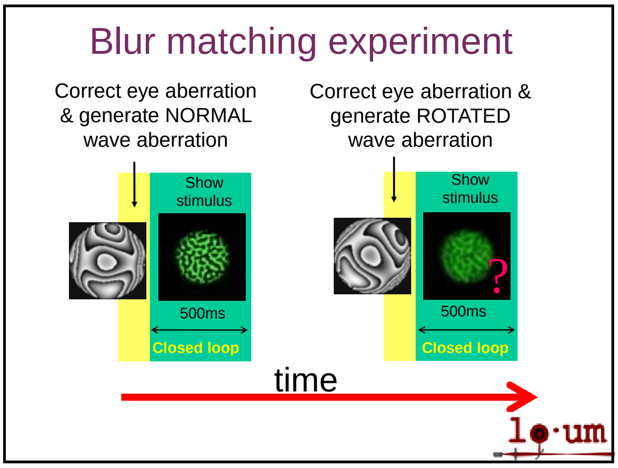
* Artal, Chen, Fernández, Singer, Manzanera & Williams, **Journal of Vision**, 4, 281-287 (2004)

If the visual system adjusts for the particular eye's aberrations...





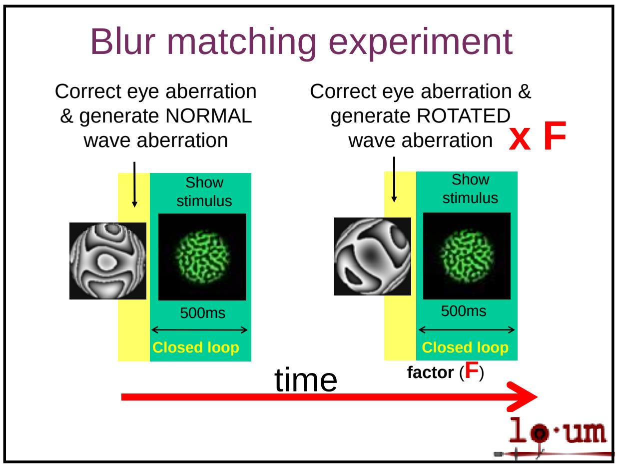
...vision should be worst when looking through unfamiliar aberrations...



Blur matching experiment

Correct eye aberration & generate NORMAL wave aberration

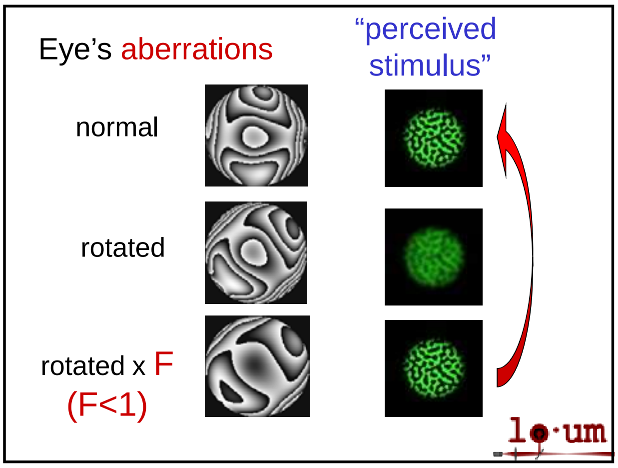
Correct eye aberration & generate ROTATED wave aberration

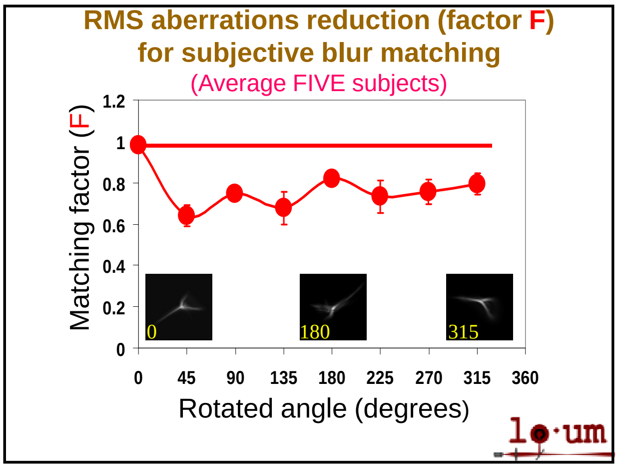


Blur matching experiment

Correct eye aberration & generate NORMAL wave aberration

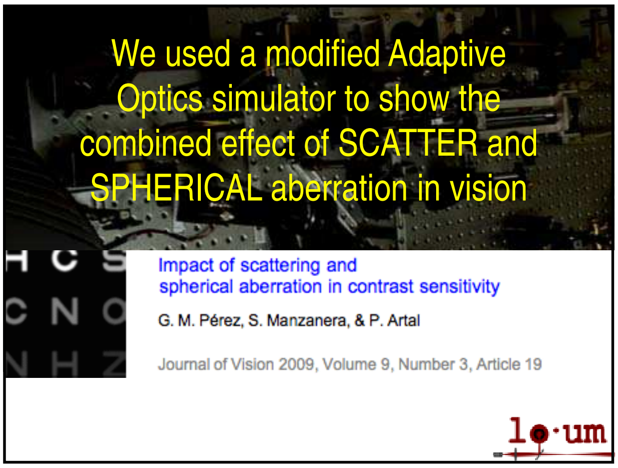
Correct eye aberration & generate ROTATED wave aberration x F





RMS aberrations reduction (factor F) for subjective blur matching

(Average FIVE subjects)



We used a modified Adaptive Optics simulator to show the combined effect of SCATTER and SPHERICAL aberration in vision

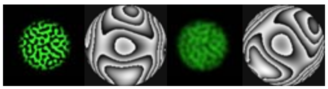
Impact of scattering and spherical aberration in contrast sensitivity

G. M. Pérez, S. Manzanera, & P. Artal

Journal of Vision 2009, Volume 9, Number 3, Article 19

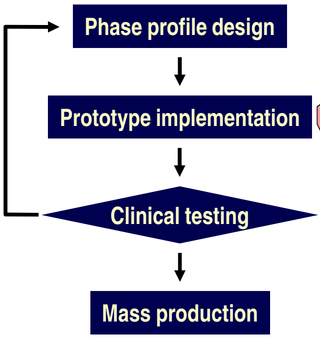
Applications of AO simulators

i) New (or revisited) experiments in Vision research



ii) Interactive design/testing of new ophthalmic solutions

Ophthalmic product development BEFORE the AO era



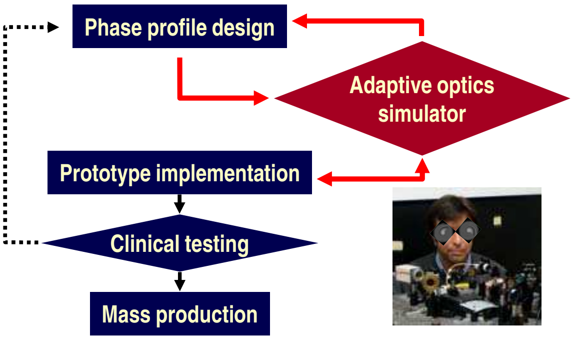
Phase profile design

Prototype implementation

Clinical testing

Mass production

Ophthalmic product development IN the AO era



Phase profile design

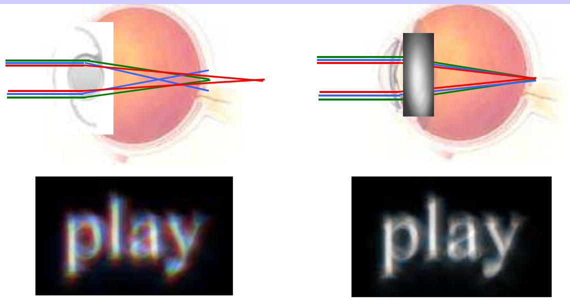
Adaptive optics simulator

Prototype implementation

Clinical testing

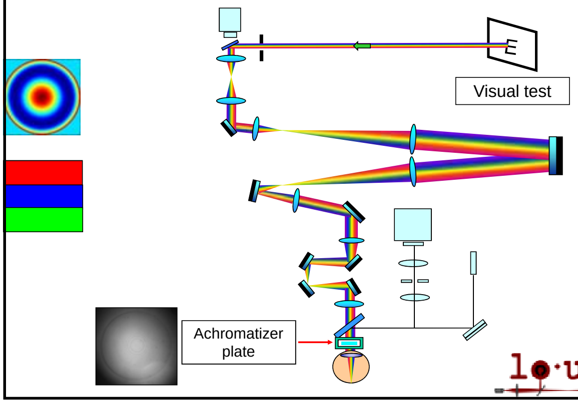
Mass production

Visual benefit of IOLs correcting chromatic aberration (achromatic IOLs)

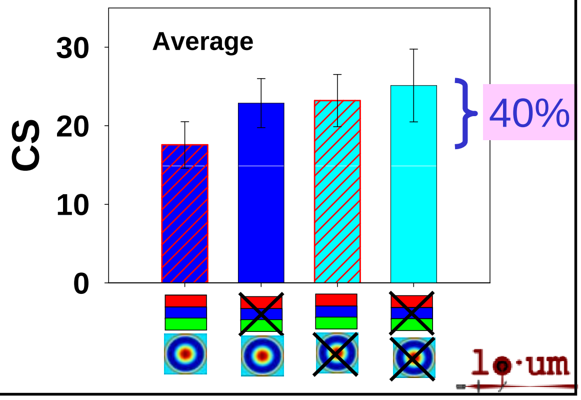


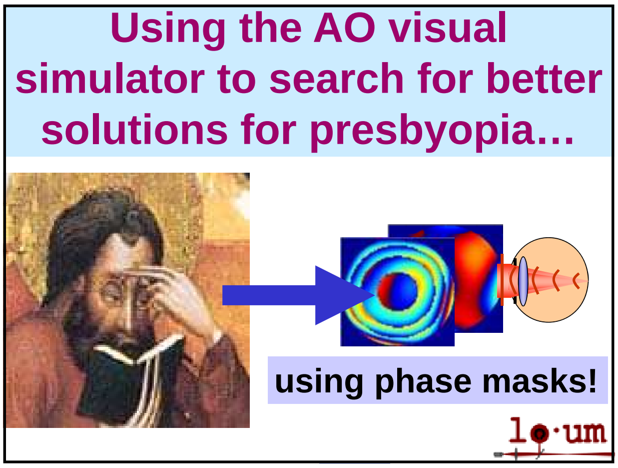
4.8 mm pupil

Visual testing after LCA & SA correction



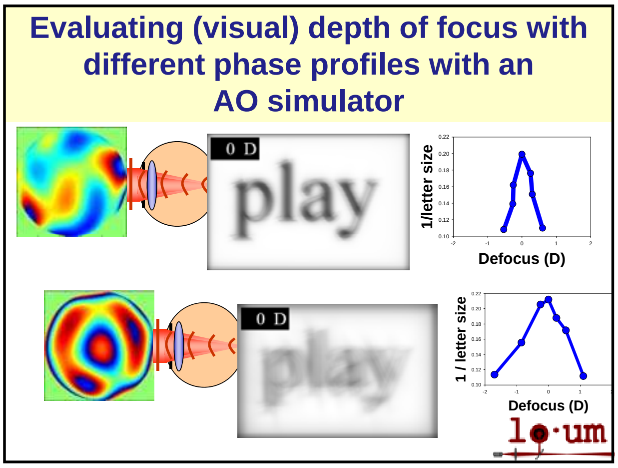
CS (at 6 c/deg) after SA & LCA correction



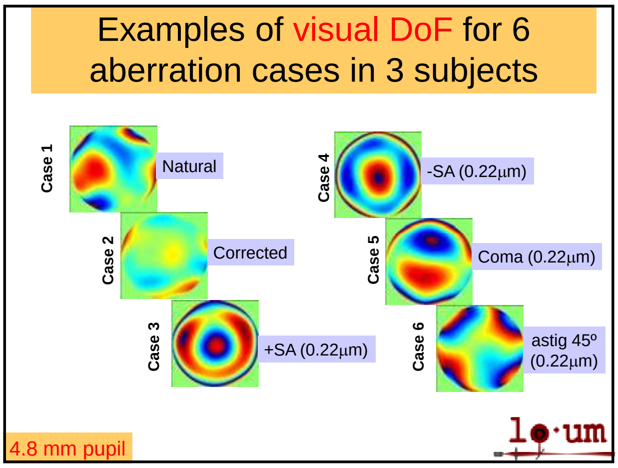


Using the AO visual simulator to search for better solutions for presbyopia…

using phase masks!



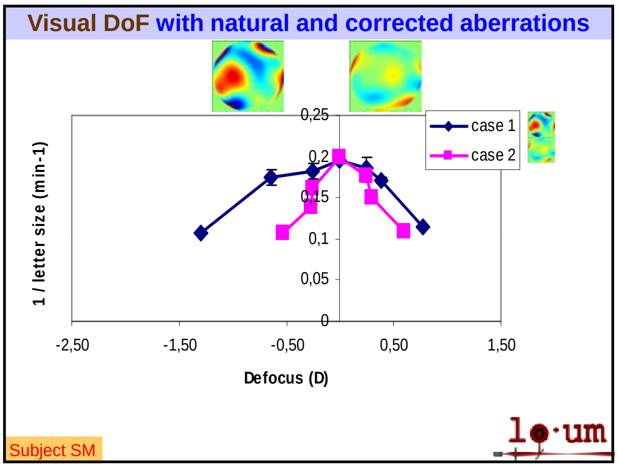
Evaluating (visual) depth of focus with different phase profiles with an AO simulator



Examples of visual DoF for 6 aberration cases in 3 subjects

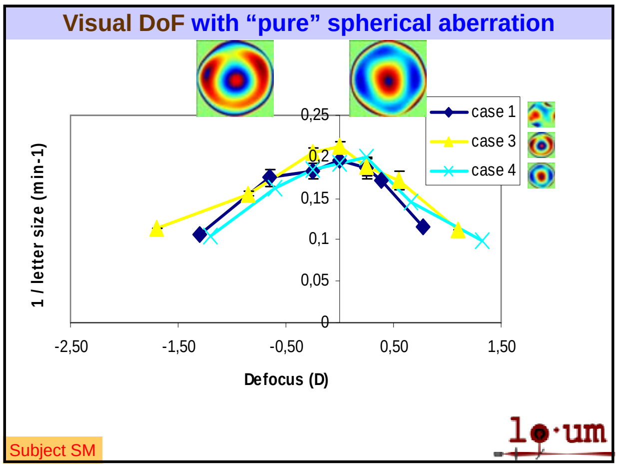
Case 1	Natural
Case 2	Corrected
Case 3	+SA (0.22μm)
Case 4	-SA (0.22μm)
Case 5	Coma (0.22μm)
Case 6	astig 45º (0.22μm)

4.8 mm pupil



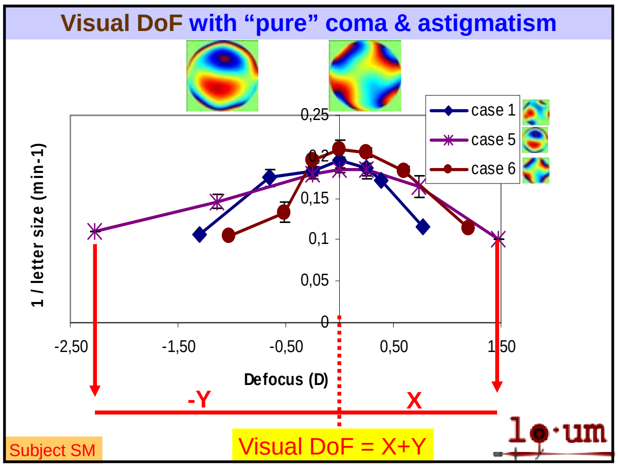
Visual DoF with natural and corrected aberrations

Subject SM



Visual DoF with “pure” spherical aberration

Subject SM



Visual DoF with “pure” coma & astigmatism

Visual DoF = X+Y

Subject SM

And what for the future… Present!

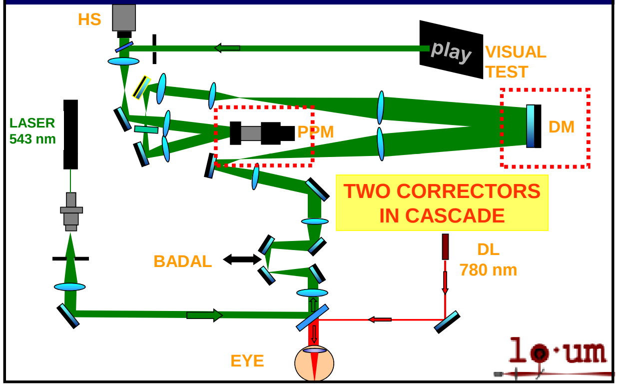
- Any phase profile…

- Binocular AO simulator

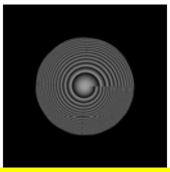
Non-continuous phase profiles (diffractive elements) are important in the search of increased depth of focus…

but cannot be produced with continuous deformable mirrors!

DUAL-Adaptive Optics Simulator
Liquid crystal SLM + Deformable mirror



DUAL-Adaptive Optics Simulator
Liquid crystal SLM + Deformable mirror



Discontinuous profile

LC-SLM

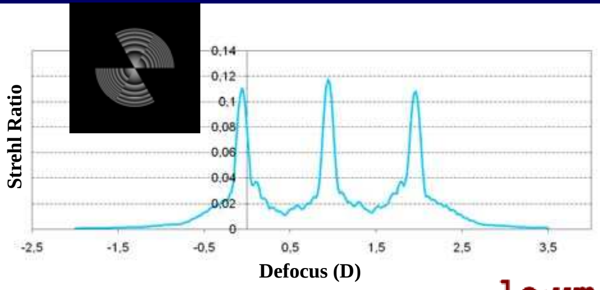
DUAL-Adaptive Optics Simulator
Liquid crystal SLM + Deformable mirror

Continuous profile

CLOSED-LOOP
real time corrections

DUAL-Adaptive Optics Simulator
Liquid crystal SLM + Deformable mirror

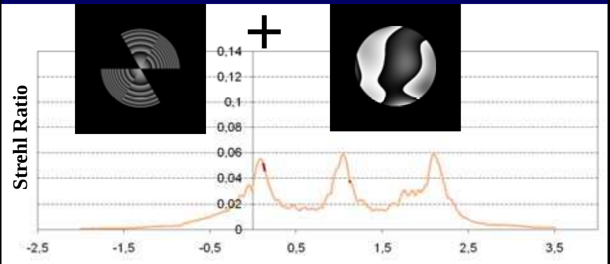
(Example: DoF of a diffractive profile)



DUAL-Adaptive Optics Simulator

Liquid crystal SLM + Deformable mirror

(Example: DoF of a diffractive profile)



And what for the future… Present!

- Any phase profile…

- **Binocular AO simulator**

TWO eyes better than ONE

BINOCULAR ADAPTIVE OPTICS SIMULATOR

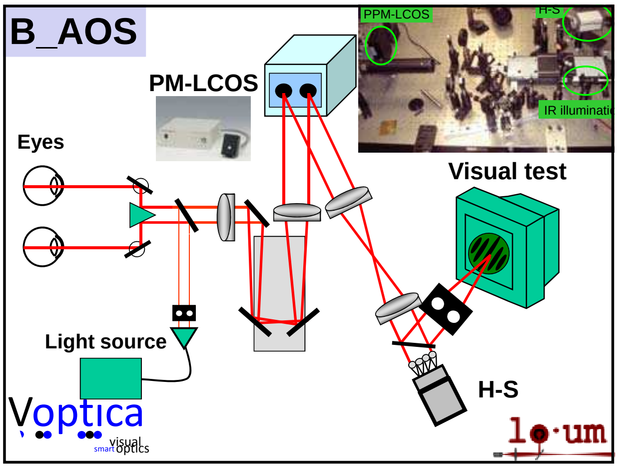
Simulating real VISION

BINOCULAR ADAPTIVE OPTICS SIMULATOR

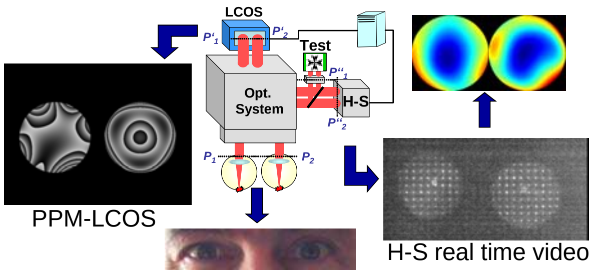
Crucial for realistic evaluations of depth of focus under actual binocular vision

Optics Letters, In the press, 2009

B_AOS

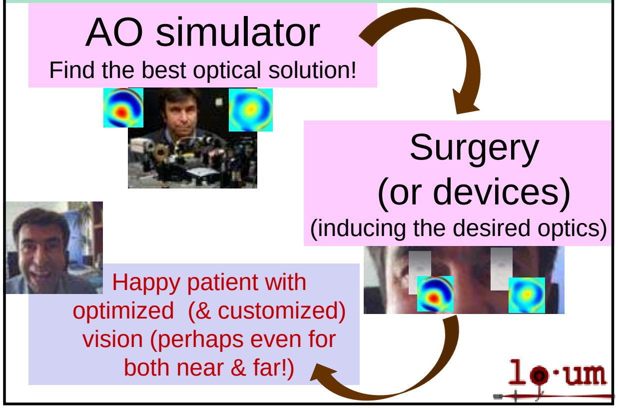


B_AOS



Binocular viewing

My personal "vision" of the future



AO simulator

Find the best optical solution!

Surgery
(or devices)
(inducing the desired optics)

Happy patient with optimized (& customized) vision (perhaps even for both near & far!)

In summary

PAST:

Current advances well based in a long time interest to understand how optics affects and limits vision (and in how to manipulate the eye's optics to improve vision!)

In summary

PRESENT

AO simulators used widely in the laboratory to perform different studies. Current systems are reasonably good in lab controlled setting. Binocular AO instruments have been already demonstrated.

In summary

FUTURE:

AO simulators based in new and cheaper technology will move from the lab to the real world.

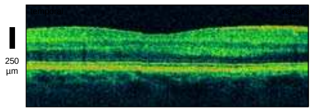
Improved visual and customized solutions will be common. Old ways to test vision will be history…

…and the future?

binocular opto-electronic googles?

…and the future?

new instruments
for early diagnosis
and treatment ?



Thank you for
your attention,

Pablo Artal

* You are welcome to visit my blog:

Optics Confidential

http://pabloartal.blogspot.com/

Slides Keynote Devaney

The Applied Optics group

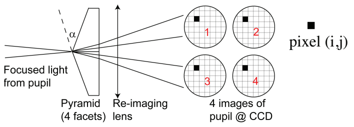
- The Applied Optics group was founded by Prof Chris Dainty in October 2002 with funding from Science Foundation Ireland
- The group has
  - 3 academic staff
  - 16 postgraduate students
  - 14 postdoctoral researchers/engineers
  - 2 admin/industry coordination
- Most of the research involves hands-on laboratory work
- Increasing number of projects funded by Industry, either directly by companies or through Enterprise Ireland (Government innovation agency)

Activities in the Applied Optics group, NUI, Galway

- Far Field Vectorial Polarimetry
- Deep UV Photolithography
- Optical vortices
- Intraocular lenses
- Measurement of aberrations in the human eye
- Vision optics modelling
- Retinal image processing
- Retinal AO using Pyramid wavefront sensor
- Development of low-cost AO
  - AO control using FPGAs
- Visual simulation using AO
  - Investigation of “super vision”
- Smart optics (wavefront sensorless AO)
- AO for free space communication
- Exoplanet imaging techniques
- Wide-field AO

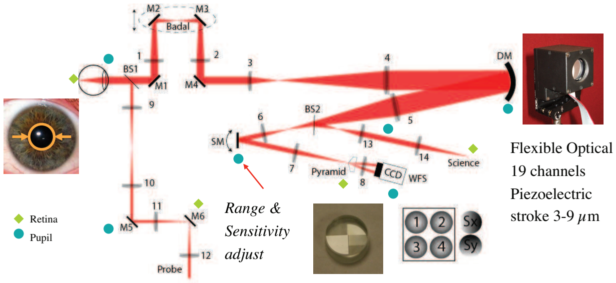
Retinal AO using a pyramid wavefront sensor

- Senses wavefront slope.
- Adv. over Shack-Hartmann sensor – easy to adjust range, sensitivity & sampling.



$$\left.\frac{\partial W}{\partial x}\right|_{i,j} \propto \left.\frac{(I_1+I_3)-(I_2+I_4)}{(I_1+I_2+I_3+I_4)}\right|_{i,j} \begin{array}{ll} =0 & \text{(no aberrations)} \\ =[-1,1] & \text{(with aberrations)} \end{array}$$

Retinal AO using a pyramid wavefront sensor



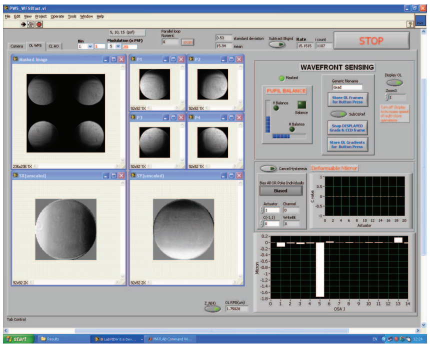
Range & Sensitivity adjust

Flexible Optical
19 channels
Piezoelectric
stroke 3-9 μm

Software control - LabVIEW

Open loop tasks:
1. display slopes
2. subtract reference
3. check pupil balance
4. manually control DM
5. acquire IFM for AO
6. store data

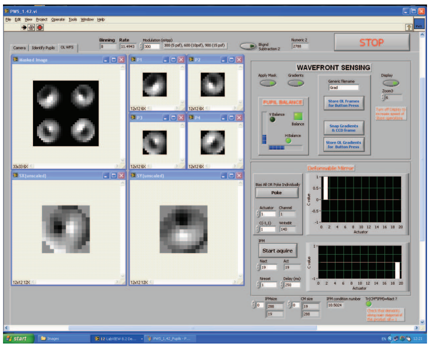
Example aberration shown is astigmatism.



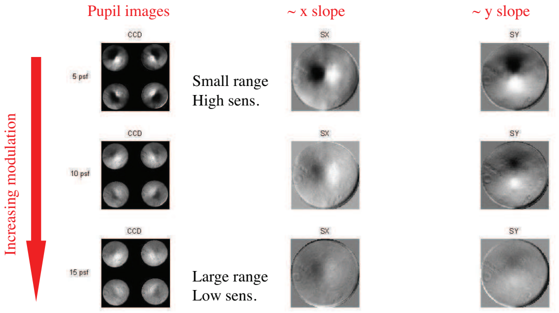
Software control - LabVIEW

Earlier iteration of s/w showing:

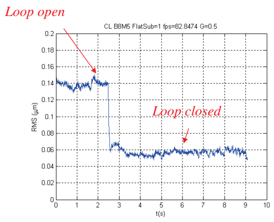
-DM poke
-B8 sampling
-balance check
-acquire sensor response to DM for AO control
-matrix checks

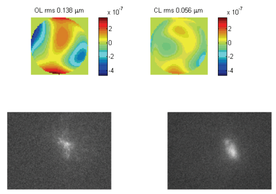


Testing – Sensitivity / Range



Eye measurements: Subject #4

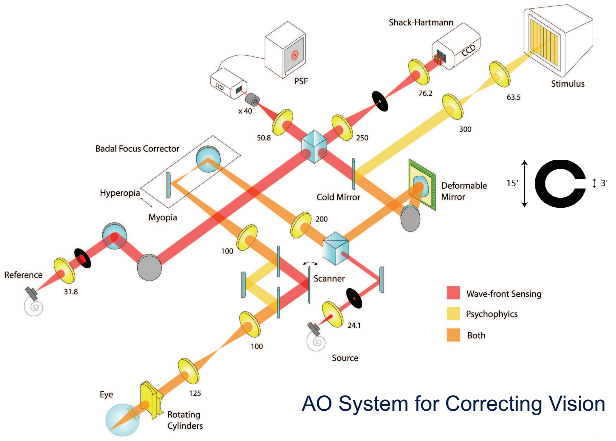




Before correction

After correction

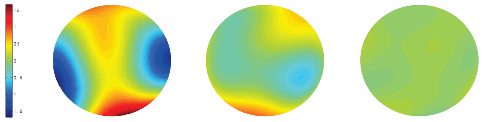
50 µm at retina: —



AO System for Correcting Vision

Low-order and higher-order correction steps

- Low-order correction (static):
  Astigmatism corrected with cylindrical lenses within 0.1 D
  Defocus adjusted subjectively with Badal optometer within 0.1 D
- Higher-order correction (dynamic):
  with 35 element bimorph mirror (AOptix),
  typically **0.07 µm rms** wavefront error residual over 6 mm pupil

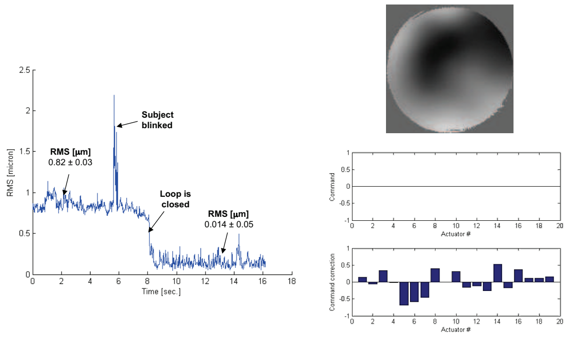


Initial wavefront **rms = 0.71 µm**

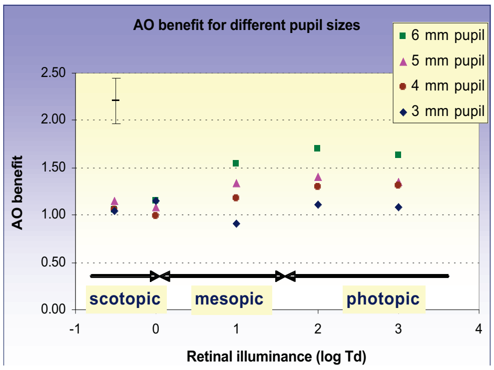
sphero-cylindrical correction **rms = 0.32 µm**

full correction **rms = 0.065 µm**

Closed-Loop on Human Eye



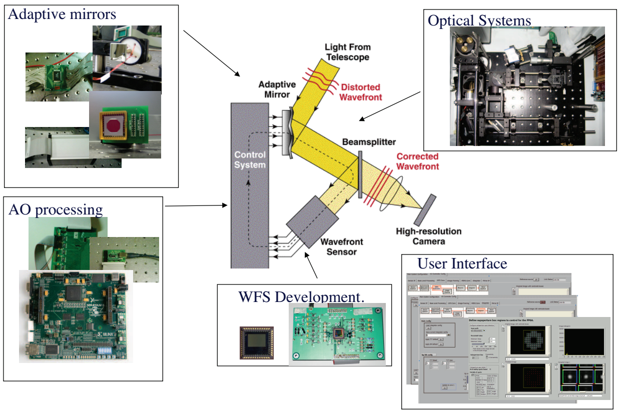
Is “Supervision” a Practical Reality?



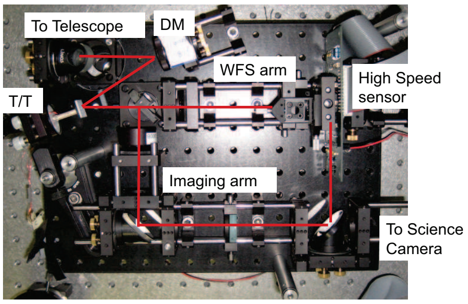
Application of AO to Simulation (IOLs)

- "Normal" AO is designed to compensate for the aberrations of the eye, resulting in "zero" overall aberration of the eye plus the AO system.
- However, once this is done, we could use AO to "dial-in" any aberration (or combination of aberrations), to simulate the optical performance of a new corrective device on a patient.
- Using this simulation procedure, we could test the optical performance aspects of a new IOL (/LASIK etc) on many subjects, without any surgical procedure.

AOPROTO- LO cost AO System development



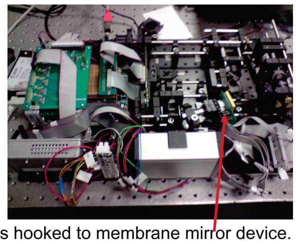
AOPROTO Main System Boards - Rev1



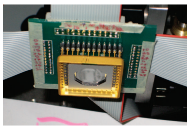
System optics - optimised to image the 600 – 950nm range.

AOPROTO

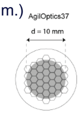
AO Controller
and System Optics



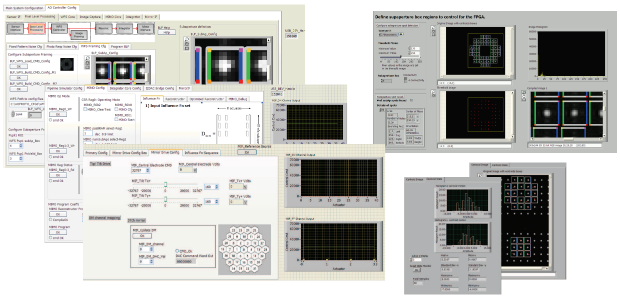
AO controller + support electronics hooked to membrane mirror device.



Membrane mirror - stroke (@ 200V) = 7.89um
(useable aperture stroke = 4.46um.)



GUI for AOPROTO

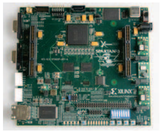


Configuration of kHz AO on non RTOS system.

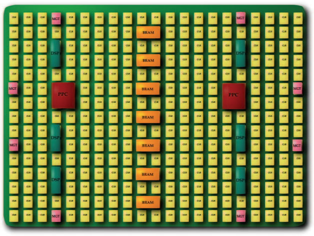
In operation labview uses very little system resources (< 5% cpu)

AO Control with FPGAs

- FPGA – Sea of LUT / registers / Multipliers / block RAM / Distributed RAM / IO blocks

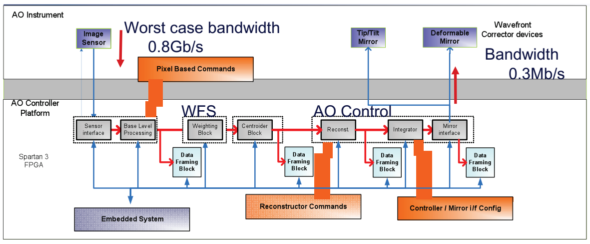


System based on Xilinx 3A-DSP FPGA



3A-DSP = 20 billion multiply-accumulates per second for under €30

Processing Pipeline Overview



Max sub-aperture – 64 x 64 pixels.

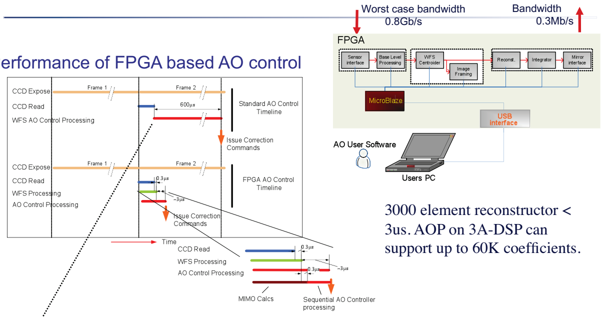
Range of WFS algorithms.

Scalable MIMO reconstructor block

AO controller - Hot-swappable reconstructor / controller gain and bleed coefficients.

AO Control Timeline

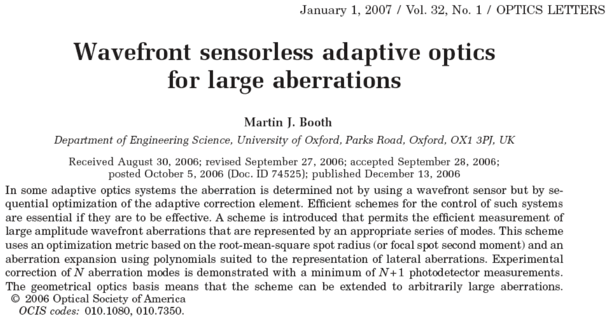
Performance of FPGA based AO control



3000 element reconstructor < 3us. AOP on 3A-DSP can support up to 60K coefficients.

AO control scales with ~ n_{ctrl}^{2} (n = number of control channels)

Do we need a wavefront sensor?



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Wavefront sensorless adaptive optics for large aberrations

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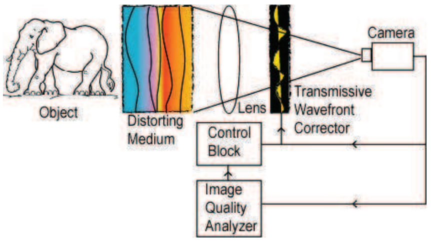
In some adaptive optics systems the aberration is determined not by using a wavefront sensor but by sequential optimization of the adaptive correction element. Efficient schemes for the control of such systems are essential if they are to be effective. A scheme is introduced that permits the efficient measurement of large amplitude wavefront aberrations that are represented by an appropriate series of modes. This scheme uses an optimization metric based on the root-mean-square spot radius (or focal spot second moment) and the aberration expansion using polynomials suited to the representation of lateral aberrations. Experimental correction of N aberration modes is demonstrated with a minimum of $N+1$ photodetector measurements. The geometrical optics basis means that the scheme can be extended to arbitrarily large aberrations.

OCIS codes: 010.1080, 010.7350.

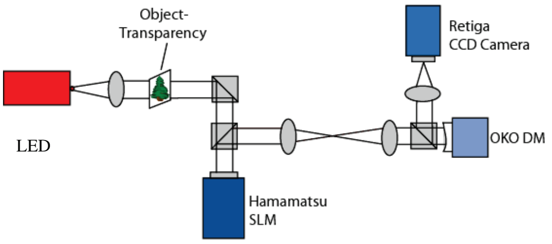
Wavefront Sensor-less AO

- Image sharpening Method first proposed by Muller & Buffington in 1974.
- Uses a definition of sharpness of image to minimize aberrations in conjunction with a wavefront correcting medium.

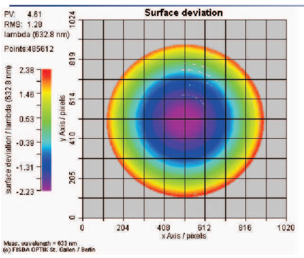


After Vorontsov et al, *J.Opt. Soc. Am. A.* **13**, 1456 (1974)

Imaging System for Extended Objects

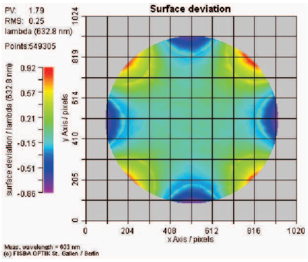


Aberrations Generated on SLM

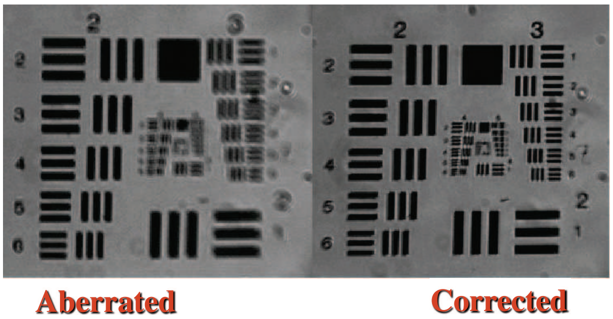


•Can input any Zernike aberration onto SLM via a Matlab Program

•Can vary magnitude of aberration to test limit of correction



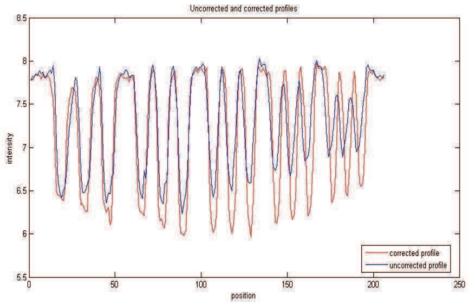
Stochastic gradient descent algorithm



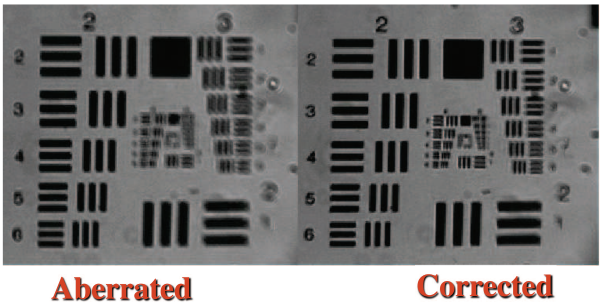
–After 100 iterations (~ 10 minutes)

–With a defocus wavefront aberration

Profile for corrected and Uncorrected SGD

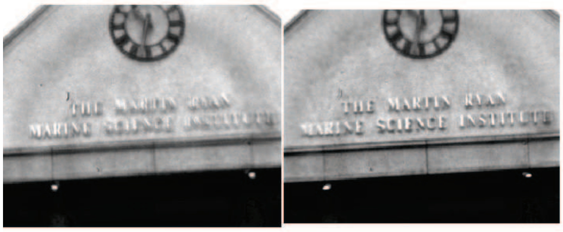


Stochastic parallel gradient descent algorithm - SPGD



- 1 iteration takes 280ms to run – approx 20 times faster than SPD

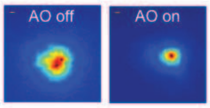
Correction in real images

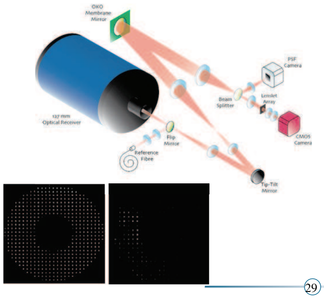


- Sharpness correction as applied to real world image
- Correction is limited by stroke of DM

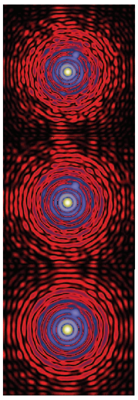
AO for free-space optical communication

Laser beacon in Galway city, 3km from reciever.





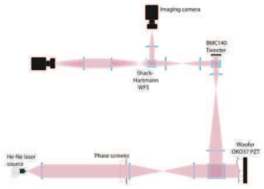
Astronomical Adaptive Optics: exoplanet detection



Exoplanet detection in AO corrected images is severely limited by residual quasi-static speckles.

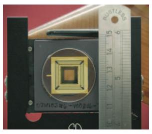
Differential techniques have been developed, including the use of multi-wavelength data (simulated here). We are developing an inverse problem approach which will optimize the detection of exoplanets for this and other direct-imaging modalities.

Woofer-tweeter AO

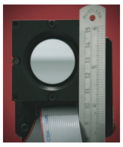


Combination of low-order-high-stroke and high-order-low-stroke DMs

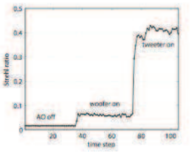
Investigation of optimal control techniques.



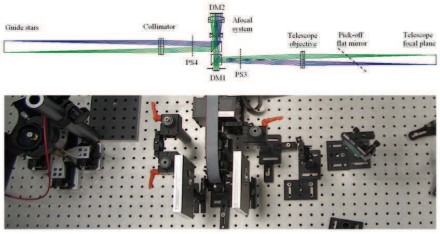
BMC140



OKO37

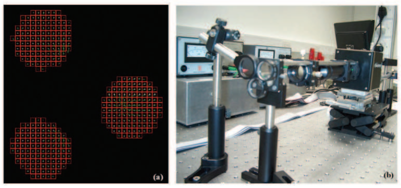


Wide-field AO



Laboratory set-up to test approaches to Multi-Conjugate AO.

Wide-field AO



Multi-object wavefront sensor developed for the MCAO test-bench

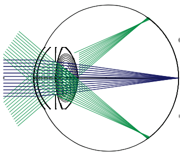
Ocular Tomography

Ophthalmic instruments measure the optical structure of the human eye, e.g. the shape of the corneal surface and the crystalline lens, axial length, and ocular aberrations

Problem: Current techniques provide only fragmental characterization of the eye; one needs to combine data from several instruments to obtain realistic eye models

Solution: Optical Device for Complete Characterization of the Eye

The ultimate goal is to use only one ophthalmic device



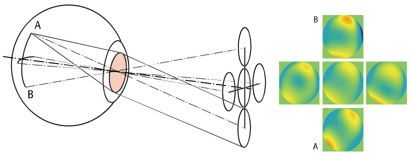
Direct Benefit for:

- Personalized Eye Modelling
- Refractive and Cataract Surgery (IOL design)
- High Resolution Retinal Imaging

Tomographic Wavefront Sensor

Device: Wide Field Tomographic Wavefront Sensor

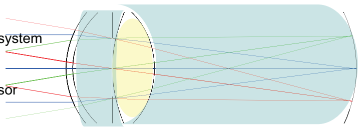
- Measuring ocular aberrations simultaneously across the visual field



Method: Inverse Optical Design of the Human Eye

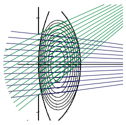
- Reconstruction of the Eye is achieved by inverse ray-tracing

Future Work on Ocular Tomography



Instrumentation Development

- Retinal beacon illumination system
- Wide-field retinal imager
- Tomographic wavefront sensor



Eye Reconstruction Methods

- Gradient-index Lens Models
- Ray-tracing with prior knowledge

Where Next for Adaptive Optics?

- Astronomy
  - eXtreme AO, planet detection
  - Increasing FoV, laser guide stars
  - AO for next generation 30-40m telescopes

- Vision Science
  - AO enhanced imagery: normal, SLO, OCT, polarisation …..
  - Wide field imaging and tomographic wavefront sensing.
  - Simulation of new corrective procedures (e.g LASIK etc) or devices (IOLs)

- Other Areas
  - AO in strong turbulence: phase singularities, FSO communication
  - Confocal microscopy (biology, metrology…)
  - Lasers (intra- and extra-cavity)
  - Digital cameras, computational imaging
  - Amateur astronomy, College/educational astronomy
  - Optical Storage