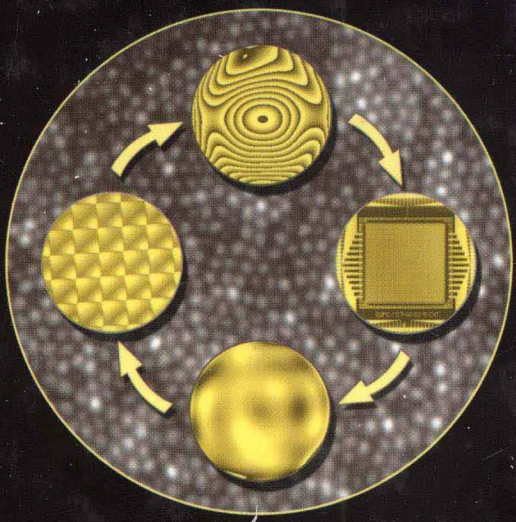
WILEY

Adaptive Optics for Vision Science



EDITED BY

JASON PORTER,
HOPE QUEENER, JULIANNA LIN,
KAREN THORN, and ABDUL AWWAL

Wiley Series in Microwave and Optical Engineering • Kai Chang, Series Editor

Leading experts present the latest technology and applications in adaptive optics for vision science

Featuring contributions from the foremost researchers in the field, *Adaptive Optics for Vision Science* is the first book devoted entirely to providing the fundamentals of adaptive optics along with its practical applications in vision science. The material for this book stems from collaborations fostered by the Center for Adaptive Optics, a consortium of more than thirty universities, government laboratories, and corporations.

Although the book is written primarily for researchers in vision science and ophthalmology, the field of adaptive optics has strong roots in astronomy. Researchers in both fields share this technology and, for this reason, the book includes chapters by both astronomers and vision scientists.

Following the introduction, chapters are divided into the following sections:

- Wavefront Measurement and Correction
- Retinal Imaging Applications
- Vision Correction Applications
- Design Examples

Readers will discover the remarkable proliferation of new applications of wavefront-related technologies developed for the human eye. For example, the book explores how wavefront sensors offer the promise of a new generation of vision correction methods that can deal with higher order aberrations beyond defocus and astigmatism, and how adaptive optics can produce images of the living retina with unprecedented resolution.

An appendix includes the Optical Society of America's Standards for Reporting Optical Aberrations. A glossary of terms and a symbol table are also included.

Adaptive Optics for Vision Science arms engineers, scientists, clinicians, and students with the basic concepts, engineering tools, and techniques needed to master adaptive optics applications in vision science and ophthalmology. Moreover, readers will discover the latest thinking and findings from the leading innovators in the field.

JASON PORTER, PHD, is a Postdoctoral Research Fellow at the Center for Visual Science, University of Rochester. **HOPE QUEENER, MSC,** is an Application Developer at the University of Houston College of Optometry. **JULIANNA LIN, MENG,** is a member of the research and technology staff for the Xerox Innovation Group at the Wilson Center for Research and Technology.

Cover Illustration: Sara Peterson (University of Rochester)

Subscribe to our free Engineering eNewsletter at www.wiley.com/enewsletters

Visit www.wiley.com/engineering

Adaptive Optics for Vision Science

Principles, Practices, Design, and Applications

Edited by

JASON PORTER, HOPE M. QUEENER, JULIANNA E. LIN, KAREN THORN, AND ABDUL AWWAL

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

Front cover art: In an adaptive optics system, a lenslet array (left circle) is used to measure an aberrated wavefront (top circle) that is then corrected by a deformable mirror (right circle) to produce a flattened wavefront (bottom circle). Lenslet array and deformable mirror images are courtesy of Adaptive Optics Associates, Inc. and Boston Micromachines Corporation, respectively.

Copyright © 2006 by John Wiley & Sons, Inc., Hoboken, NJ. All rights reserved.

Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Adaptive optics for vision science : principles, practices, design and applications / edited by Jason Porter . . . [et al.].
p. cm.
"A Wiley-Interscience publication."
Includes bibliographical references and index.
ISBN-10: *978-0-471-67941-7
ISBN-10: 0-471-67941-0
1. Optics, Adaptive. I. Porter, Jason.
TA1520.A34 2006
621.36'9–dc22

2005056953

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Adaptive Optics for Vision Science

此为试读,需要完整PDF请访问: www.ertongbook.com

Foreword

The rationale for this handbook is to make adaptive optics technology for vision science and ophthalmology as broadly accessible as possible. While the scientific literature chronicles the dramatic recent achievements enabled by adaptive optics in vision correction and retinal imaging, it does less well at conveying the practical information required to apply wavefront technology to the eye. This handbook is intended to equip engineers, scientists, and clinicians with the basic concepts, engineering tools, and tricks of the trade required to master adaptive optics-related applications in vision science and ophthalmology.

During the past decade, there has been a remarkable expansion of the application of wavefront-related technologies to the human eye, as illustrated by the rapidly growing number of publications in this area (shown in Fig. F.1).

The catalysts for this expansion have been the development of new wavefront sensors that can rapidly provide accurate and complete descriptions of the eye's aberrations, and the demonstration that adaptive optics can provide better correction of the eye's aberrations than has previously been possible. These new tools have generated an intensive effort to revise methods to correct vision, with the wavefront sensor providing a much needed yardstick for measuring the optical performance of spectacles, contact lenses, intraocular lenses, and refractive surgical procedures. Wavefront sensors offer the promise of a new generation of vision correction methods that can correct higher order aberrations beyond defocus and astigmatism in cases where these aberrations significantly blur the retinal image.

The ability of adaptive optics to correct the monochromatic aberrations of the eye has also created exciting new opportunities to image the normal and diseased retina at unprecedented spatial resolution. Adaptive optics has strong roots in astronomy, where it is used to overcome the blurring effects of atmospheric turbulence, the fundamental limitation on the resolution of

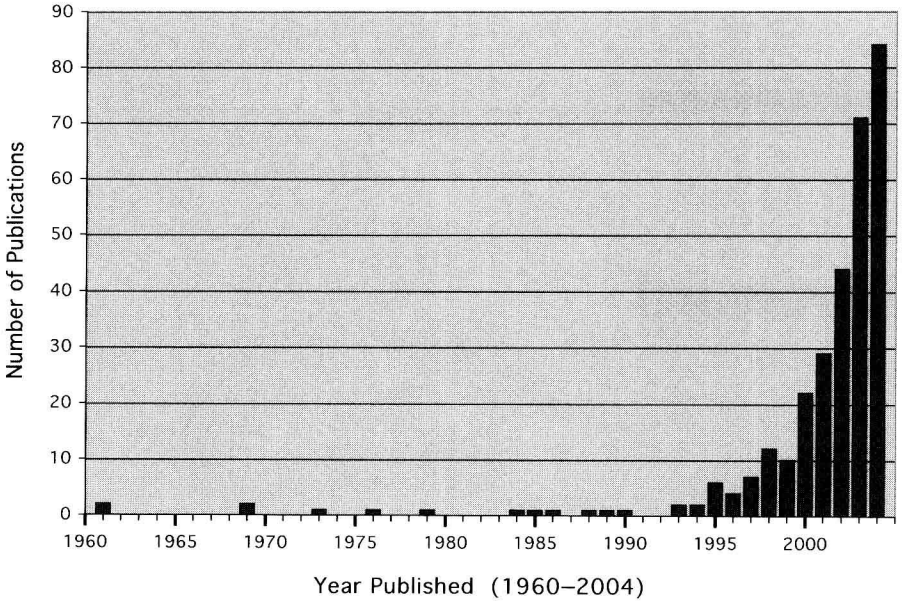


FIGURE F.1 Number of publications listed in PubMed (National Library of Medicine) that describe work where wavefront sensors were used to measure the full wave aberration of the human eye. Types of wavefront sensors included in this graph: Shack–Hartmann, spatially resolved refractometer, crossed-cylinder aberroscope, laser ray tracing, scanning slit refractometer, video keratography, corneal topography, phase retrieval, curvature sensing, and grating-based techniques.

ground-based telescopes. More recently, adaptive optics has found application in other areas, most notably vision science, where it is used to correct the eye's wave aberration. Despite the obvious difference in the scientific objectives of the astronomy and vision science communities, we share a technology that is remarkably similar across the two applications.

Recognizing this, together with Jerry Nelson and other colleagues, we created a center focused on developing adaptive optics technology for both astronomy and vision science. The Center for Adaptive Optics, with headquarters at the University of California, Santa Cruz, was founded in 1999 as a National Science Foundation Science and Technology Center. Initially under the leadership of Jerry Nelson and more recently of Claire Max, the Center for Adaptive Optics is a consortium involving more than 30 affiliated universities, government laboratories, and corporations. The Center has fostered extensive new collaborations between vision scientists and astronomers (who very soon discovered they were interested in each others' science as well as their technology!). This handbook is a direct result of the Center's collaborative energy, with chapters contributed by astronomers and vision scientists alike.

We wish to thank all of the contributors for generously sharing their expertise, and even their secrets, within the pages of this book. Especially, we congratulate Jason Porter, lead editor, and Hope Queener, Julianna Lin, Karen Thorn, and Abdul Awwal, coeditors, for their tireless dedication to this significant project.

DAVID R. WILLIAMS

University of Rochester, Rochester, New York
Center for Adaptive Optics

CLAIRE MAX

University of California, Santa Cruz
Center for Adaptive Optics

Acknowledgments

I have been extremely privileged to have worked on this book and would like to thank everyone who contributed to its development, technical and scientific content, character, and completion. I am indebted to all of the authors and reviewers from the vision science, astronomical, and engineering communities who took the time and energy to write outstanding chapters in the midst of their busy research and personal lives. Thank you to George Telecki and Rachel Witmer at John Wiley & Sons, Inc. for sticking with us over the past two years, for believing in the importance of publishing a book on this topic, and for their patience and willingness to answer any and all questions that came their way. In addition, I could not have completed the project without the energy and efforts of my fellow co-editors, Hope Queener, Julianna Lin, Karen Thorn, and Abdul Awwal. I would particularly like to thank Hope and Julianna for their tremendous dedication to compiling a book with such a high level of scientific and technical competence and integrity (and for all of the many hours and late nights required to do so!).

I am also grateful for the support, ideas, and encouragement I received from David Williams and the members of his lab (including Joe, Jess, Dan, Li, Sapna, and Alexis), and the Center for Visual Science and StrongVision administrative staff (including Michele, Debbie, Teresa, Sara, and Amy). A very special thanks goes to my family (Jen, Kevin, Debbie, Sarah, and Kyle) and friends (Mike, Lana, Frank, and others who are too numerous to mention) for their support, love, belief, encouragement, and prayers, and for helping to keep me refreshed and alive.

Scientifically, I will always be grateful to Claire Max, who first opened my eyes to the exciting field of adaptive optics during an internship at Lawrence Livermore National Lab that subsequently led me to find a path to David Williams' lab. In addition, I will always be indebted to my mentor, David Williams, for his guidance, instruction, support, encouragement, and confidence in me on so many levels in and outside of the office—it has been a

pleasure to work for one of the pioneers in the fields of vision science and adaptive optics. Finally, I would like to thank the National Science Foundation and the Center for Adaptive Optics for not only supporting this project but for also supporting and continuing the long tradition of vision scientists and astronomers working together to better science, health, and technology.

JASON PORTER

This editorial work was made possible by the support of the National Science Foundation's Center for Adaptive Optics and the associated scientific community. The University of Houston College of Optometry provided time and computing resources. The University of Rochester's Center for Visual Science provided time, space, and computing resources. I wish to particularly acknowledge the tremendous efforts of co-editors Jason Porter and Julianna Lin. As the project neared completion, the helpful responses from Larry Thibos, Marcos Van Dam, Jack Werner, and Joe Hardy were greatly appreciated.

HOPE M. QUEENER

I would like to extend a very heart-felt thank you to all of the authors, reviewers, collaborators, and supporters who dedicated so much of their time to making this book a reality. In particular, I would like to thank Jason Porter and Hope Queener for their staunch determination and perseverance, particularly toward the end of this project. I would also like to thank my husband, Gregory Brady, and my family (Y. S. Lin, G. Y. C. Lin, I. Lin, K. Su, S. Su, and little Stephen) for their love and support, even in the midst of the editing cycle. Financial and logistical support for this project was provided by the Center for Adaptive Optics. Additional support was provided by David Williams, the University of Rochester, and the Center for Visual Science.

JULIANNA E. LIN

Contributors

AUTHORS

Pablo Artal, Laboratorio de Optica (Departamento de Fisica), Universidad de Murcia, Murcia, Spain

Abdul Awwal, Lawrence Livermore National Laboratory, Livermore, California

Brian J. Bauman, Lawrence Livermore National Laboratory, Livermore, California

Juan M. Bueno, Laboratorio de Optica, Universidad de Murcia, Murcia, Spain

Li Chen, Center for Visual Science, University of Rochester, Rochester, New York

Julian Christou, Center for Adaptive Optics, University of California, Santa Cruz, Santa Cruz, California

Ian Cox, Bausch & Lomb, Rochester, New York

Peter B. Delahunt, Posit Science Corporation, San Francisco, California

Nathan Doble, Iris AO, Inc., Berkeley, California

Stephen K. Eisenbies, Sandia National Laboratories, Livermore, California

Ann E. Elsner, School of Optometry, Indiana University, Bloomington, Indiana

Antonio Guirao, Laboratorio de Optica, Universidad de Murcia, Murcia, Spain

Joseph L. Hardy, Posit Science Corporation, San Francisco, California

Heidi Hofer, College of Optometry, University of Houston, Houston, Texas

Ravi S. Jonnal, School of Optometry, Indiana University, Bloomington, Indiana

此为试读,需要完整PDF请访问: www.ertongbook.com

Scott M. MacRae, Department of Ophthalmology, University of Rochester, Rochester, New York

Donald T. Miller, School of Optometry, Indiana University, Bloomington, Indiana

Scot Olivier, Lawrence Livermore National Laboratory, Livermore, California

Jason Porter, Center for Visual Science, University of Rochester, Rochester, New York

Pedro M. Prieto, Laboratorio de Optica, Universidad de Murcia, Murcia, Spain

Jungtae Rha, School of Optometry, Indiana University, Bloomington, Indiana

Fernando Romero-Borja, Houston Community College Central, Houston, Texas

Austin Roorda, School of Optometry, University of California, Berkeley, Berkeley, California

Ben Singer, Center for the Study of Brain, Mind and Behavior, Princeton University, Princeton, New Jersey

Larry N. Thibos, School of Optometry, Indiana University, Bloomington, Indiana

Marcos A. van Dam, W. M. Keck Observatory, Kamuela, Hawaii

Krishna Venkateswaran, Alcon Research Ltd, Orlando, Florida

John S. Werner, Department of Ophthalmology, Section of Neurobiology, Physiology and Behavior, University of California, Davis Medical Center, Sacramento, California

David R. Williams, Center for Visual Science, University of Rochester, Rochester, New York

Geunyoung Yoon, Department of Ophthalmology, University of Rochester, Rochester, New York

Yan Zhang, School of Optometry, Indiana University, Bloomington, Indiana

EDITOR-IN-CHIEF

Jason Porter, Center for Visual Science, University of Rochester, Rochester, New York

CO-EDITORS

Abdul Awwal, Lawrence Livermore National Laboratory, Livermore, California

Julianna E. Lin, Center for Visual Science, University of Rochester, Rochester, New York

Hope M. Queener, College of Optometry, University of Houston, Houston, Texas

Karen Thorn, 20 Todman Street, Brookyn, Wellington, New Zealand

Contents

FOREWORD xvii

ACKNOWLEDGMENTS xxi

CONTRIBUTORS xxiii

PART ONE INTRODUCTION 1

1 **Development of Adaptive Optics in Vision Science and Ophthalmology** 3
David R. Williams and Jason Porter

1.1 Brief History of Aberration Correction in the Human Eye 3
1.1.1 Vision Correction 3
1.1.2 Retinal Imaging 5
1.2 Applications of Ocular Adaptive Optics 9
1.2.1 Vision Correction 9
1.2.2 Retinal Imaging 11

PART TWO WAVEFRONT MEASUREMENT AND CORRECTION 31

2 **Aberration Structure of the Human Eye** 33
Pablo Artal, Juan M. Bueno, Antonio Guirao, and Pedro M. Prieto

2.1 Introduction 33
2.2 Location of Monochromatic Aberrations Within the Eye 34

2.3 Temporal Properties of Aberrations: Accommodation and Aging 40
2.3.1 Effect of Accommodation on Aberrations and Their Correction 40
2.3.2 Aging and Aberrations 42
2.4 Chromatic Aberrations 43
2.4.1 Longitudinal Chromatic Aberration 44
2.4.2 Transverse Chromatic Aberration 45
2.4.3 Interaction Between Monochromatic and Chromatic Aberrations 45
2.5 Off-Axis Aberrations 46
2.5.1 Peripheral Refraction 47
2.5.2 Monochromatic and Chromatic Off-Axis Aberrations 48
2.5.3 Monochromatic Image Quality and Correction of Off-Axis Aberrations 51
2.6 Statistics of Aberrations in Normal Populations 52
2.7 Effects of Polarization and Scatter 53
2.7.1 Impact of Polarization on the Ocular Aberrations 53
2.7.2 Intraocular Scatter 55

3 Wavefront Sensing and Diagnostic Uses 63
Geunyoung Yoon

3.1 Wavefront Sensors for the Eye 63
3.1.1 Spatially Resolved Refractometer 65
3.1.2 Laser Ray Tracing 65
3.1.3 Shack–Hartmann Wavefront Sensor 66
3.2 Optimizing a Shack–Hartmann Wavefront Sensor 68
3.2.1 Number of Lenslets Versus Number of Zernike Coefficients 68
3.2.2 Trade-off Between Dynamic Range and Measurement Sensitivity 71
3.2.3 Focal Length of the Lenslet Array 73
3.2.4 Increasing the Dynamic Range of a Wavefront Sensor Without Losing Measurement Sensitivity 74
3.3 Calibration of a Wavefront Sensor 75
3.3.1 Reconstruction Algorithm 76
3.3.2 System Aberrations 77
3.4 Summary 79

4 Wavefront Correctors for Vision Science **83**
Nathan Doble and Donald T. Miller

4.1 Introduction 83
4.2 Principal Components of an AO System 84
4.3 Wavefront Correctors 86
4.4 Wavefront Correctors Used in Vision Science 88
4.4.1 Macroscopic Discrete Actuator Deformable Mirrors 89
4.4.2 Liquid Crystal Spatial Light Modulators 90
4.4.3 Bimorph Mirrors 91
4.4.4 Microelectromechanical Systems 92
4.5 Performance Predictions for Various Types of Wavefront Correctors 95
4.5.1 Description of Two Large Populations 98
4.5.2 Required Corrector Stroke 99
4.5.3 Discrete Actuator Deformable Mirrors 101
4.5.4 Piston-Only Segmented Mirrors 106
4.5.5 Piston/Tip/Tilt Segmented Mirrors 107
4.5.6 Membrane and Bimorph Mirrors 109
4.6 Summary and Conclusion 111

5 Control Algorithms **119**
Li Chen

5.1 Introduction 119
5.2 Configuration of Lenslets and Actuators 119
5.3 Influence Function Measurement 122
5.4 Spatial Control Command of the Wavefront Corrector 124
5.4.1 Control Matrix for the Direct Slope Algorithm 124
5.4.2 Modal Wavefront Correction 127
5.4.3 Wave Aberration Generator 127
5.5 Temporal Control Command of the Wavefront Corrector 128
5.5.1 Open-Loop Control 128
5.5.2 Closed-Loop Control 129
5.5.3 Transfer Function of an Adaptive Optics System 130

6 Adaptive Optics Software for Vision Research **139**
Ben Singer

6.1 Introduction 139
6.2 Image Acquisition 140
6.2.1 Frame Rate 140
6.2.2 Synchronization 140
6.2.3 Pupil Imaging 141

6.3 Measuring Wavefront Slope 142
6.3.1 Setting Regions of Interest 142
6.3.2 Issues Related to Image Coordinates 143
6.3.3 Adjusting for Image Quality 143
6.3.4 Measurement Pupils 143
6.3.5 Preparing the Image 143
6.3.6 Centroiding 144
6.4 Aberration Recovery 144
6.4.1 Principles 144
6.4.2 Implementation 145
6.4.3 Recording Aberration 147
6.4.4 Displaying a Running History of RMS 147
6.4.5 Displaying an Image of the Reconstructed Wavefront 148
6.5 Correcting Aberrations 149
6.5.1 Recording Influence Functions 149
6.5.2 Applying Actuator Voltages 150
6.6 Application-Dependent Considerations 150
6.6.1 One-Shot Retinal Imaging 150
6.6.2 Synchronizing to Display Stimuli 150
6.6.3 Selective Correction 151
6.7 Conclusion 151
6.7.1 Making Programmers Happy 151
6.7.2 Making Operators Happy 151
6.7.3 Making Researchers Happy 152
6.7.4 Making Subjects Happy 152
6.7.5 Flexibility in the Middle 153

7 Adaptive Optics System Assembly and Integration 155
Brian J. Bauman and Stephen K. Eisenbies

7.1 Introduction 155
7.2 First-Order Optics of the AO System 156
7.3 Optical Alignment 157
7.3.1 Understanding Penalties for Misalignments 158
7.3.2 Optomechanics 159
7.3.3 Common Alignment Practices 163
7.3.4 Sample Procedure for Offline Alignment 170
7.4 AO System Integration 174
7.4.1 Overview 174
7.4.2 Measure the Wavefront Error of Optical Components 175
7.4.3 Qualify the DM 175

此为试读,需要完整PDF请访问: www.ertongbook.com