OPTICAL IMAGING AND SPECTROSCOPY

DAVID J. BRADY
Duke University, Durham, North Carolina

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Co-published by John Wiley & Sons, Inc., and The Optical Society of America

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Library of Congress Cataloging-in-Publication Data:

Brady, David Jones, 1961-
Optical imaging and spectroscopy / David Jones Brady.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-04823-8 (cloth)
1. Optical spectroscopy. 2. Imaging systems. 3. Image processing. 4. Optical instruments
I. Title.
QC454.O66B73 2008
621.36—dc22

2008036200

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To the Taxpayers of the
United States of America

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PREFACE

In an age of ubiquitous information; where any question can instantly be answered at the click of a mouse, it is important to remember that some questions require book-length answers. This book answers the question, “What are the design principles of computational optical sensors?” This book is not a homage to old ideas, in fact it celebrates the death of the photochemically recorded image. But it does honor the ancient concept of the book.

A book-length idea requires a narrative, with protagonists (such as the intrepid photon, speeding information from object to data), antagonists (such as the fickle photon, arriving when it pleases with no consideration to resulting signal fluctuations), and a satisfying denouement. Careful contemplative research is necessary to develop such a narrative. For nearly a century, the Optical Society of America has fostered the research that provides the basis for this book’s story. Books and professional societies are as alive and essential to advanced science and engineering in this century as in the last.

With this in mind, it is particularly satisfying that this book is produced under the joint Wiley-OSA imprint. I knew from the moment the series was announced that this would be the perfect venue for “Optical Imaging and Spectroscopy.” While there have been many twists and turns in the text’s plot over the intervening years, including numerous delays as I struggled to resolve the narrative, these have been the natural struggles of an author. OSA’s reviewers provided essential early feedback to the structure and thrust of the text and Wiley has been a consistent and solid supporter of its editorial development.

I know that there are excellent books coming in this series and I look forward to reading those stories. For my part, given a year or two to recover I may have yet another story to tell. Try googling “What are the design methods for optical components?”

David J. Brady

Durham, North Carolina

ACKNOWLEDGMENTS

I began serious work on this text on the Fourth of July, 2004. I thank Rachael, Katherine, and Alexander for letting me write on the 4th (and occasionally on other holidays) and for their patience, love, and support over the 4 years absorbed by this project.

Draft forms of this text were used to teach courses at Duke University, the University of Illinois, and the University of Arizona. I thank the students enrolled in those courses for their patience with the text and problems and for helping to improve the material. I am also grateful to colleagues and students at the University of Minnesota, where I developed this text as a visitor to the Institute for Mathematics and Its Applications in Fall 2005.

The students and staff of the Duke Imaging and Spectroscopy Program (DISP) and its previous incarnation as the Illinois Interferometric Imaging Initiative were essential to the development of this text. Thanks to Alan Chen, Kent Hill, Scott Basinger, Ken Purchase, Junpeng Guo, Daniel Marks, Ron Stack, Remy Tumbar, Prasant Potluri, Yunhui Zheng, Evan Cull, John Burchette, Mohan Shankar, Bob Hao, Scott McCain, Scott Witt, Rick Tarka, Rick Morrison, George Barbastathis, Michal Balberg, Jose Jimenez, Matt Fetterman, Unnikrishnan Gopinathan, Santosh Narayankhedkar, Zhaochun Xu, Shawn Kraut, Ben Hamza, Michael Gehm, Yanquia Wang, Arnab Sinha, Michael Sullivan, Renu John, Nikos Pitsianis, Paul Vosburgh, Leah Goldsmith, and Bob Guenther. Current DISPers Andrew Portnoy, Christina Fernandez, Nan Zheng, Se Hoon Lim, Ashwin Wagadarikar, Yongan Tang and Nathan Hagen were particularly helpful in reviewing sections and exercises and tolerating their advisor's book obsession. I also remember that on January 1, 2001, DISP was just Steve Feller and I.

Demetri Psaltis introduced me to this subject, and Professor Psaltis and his students have been my closest friends and colleagues for many years. Mark Neifeld is central to this story and has starred in every role, including lab mate, colleague, competitor, collaborator, and friend. Ali Adibi, Ken Hsu, Mike Haney, and Kelvin Wagner have also been influential in the development of this text. Faculty colleagues at Illinois and Duke—particularly George Papen, Margery Osborne, Eric Michielssen, David Munson, Jim Coleman, Richard Blahut, Yoram Bresler, Pankaj Agrawal, Xiaobai

Sun, Jungsang Kim, Rebecca Willett, Larry Carin, Daniel Gauthier, Joseph Izatt, Adam Wax, Curtis Taylor, Robert Clark, and Jeff Glass—have been an essential means of leading me from error and pointing me to opportunity. I also thank Kristina Johnson for luring me from my comfortable home in the Midwest to my more comfortable home in the Southeast.

Professor Dennis Healy of the University of Maryland and DARPA provided enormous inspiration and guidance for the concepts described in this text. I am also deeply grateful to Ravi Athale for philosophical guidance and for creating the DARPA MONTAGE program. Historically, imaging and spectroscopy are pursued by almost distinct communities. The link between these fields developed herein is due to Karen Petersen and her extraordinary initiative in starting the Advanced Biosensors Program at the National Institute on Alcoholism and Alcohol Abuse. The vison of Alan Craig at AFOSR and Jiri Jonas of the Beckman Institute in initially seeding my work on computational imaging and of Kent Miller of AFOSR in sustaining the vision over the years is also deeply appreciated.

Timothy Schulz has been generous and incredibly insightful in the development and execution of the Compressive Optical MONTAGE Photography Initiative. The fantastic COMPI team is too large to list comprehensively, but Alan Silver, Bob Gibbons, Mike Feldman, Bob Te Kolste, Joseph Mait, Dennis Prather, Michael Fiddy, Caihua Chen, Nicholas George, and Tom Suleski have been essential collaborators. Thanks also to the members of the computational imaging community who have given me hints, including W. Thomas Cathey, Rafael Piestun, Mark Christensen, Jim Leger, Alexander Sawchuck, Joseph Goodman, Jim Fienup, Richard Baraniuk, Kevin Kelly, Emmanuel Candes, Ronald Coifman, Jun Tanida, Joseph van der Gracht, Chuck Matson, Bob Plemmons, Sudhakar Prasad, and Shaya Fainman.

I am also grateful to the editorial staff of John Wiley & Sons for their efficient and professional assistance in the preparation of this text.

Of course, none of these individuals or institutions are reponsible for error, silliness, or other weaknessness in the text. I have written this book in the “editorial we,” partly so that I need not personally discover each equation and partly to remind myself that you and I are in this together, dear reader. I hope that in these pages we discover a common passion for optical sensing.

D. J. Brady

Course materials, code used to generate figures, supplementary exercises, and other resources related to this text are available online at `www.opticalimaging.org`.

ACRONYMS

ACS	astigmatic coherence sensor
AOTF	acoustooptic tunable filter
APS	active pixel sensor
CASSI	coded aperture snapshot spectral imager
c.c.	complex conjugate
CGH	computer-generated hologram
CS	compressed sensing
CTE	charge transfer efficiency
DFT	discrete Fourier transform
DMD	digital mirror device
DOF	depth of field
EDOF	extended depth of field
EM	expectation–maximization (algorithm)
FFT	fast Fourier transform
FOV	field of view (IFOV = instantaneous FOV)
FPA	focal plane array
FSR	free spectral range
FWHM	full width at half maximum
ICA	independent component analysis
LCTF	liquid crystal tunable filter
LG	least gradient
LSI	linear shift-invariant
LSQI	least squares with quadratic inequality
LWIR	longwave infrared
MP	magnifying power
MRTD	minimum resolvable temperature difference
MSE	mean-square error
MTF	modulation transfer function
MURA	modified URA (q.v. URA, below)
NA	numerical aperture
NEP	noise equivalent power

NETD	noise equivalent temperature difference
NIR	near infrared
OCT	optical coherence tomography
OLS	ordinary least squares
OTF	optical transfer function
PCA	principal component(s) analysis
PSF	point spread function
PTF	pixel transfer function
RGB	red-green-blue
RIP	restricted isometry property
ROIC	readout integrated circuit
RSI	rotational shear interferometer/interferometry
RST	reference structure tomography
SLM	spatial light modulator
STED	stimulated emission depletion
STF	system transfer function
SVD	singular value decomposition
TCR	thermal coefficient of resistance
TOMBO	thin observation module by bound optics
TTI	total transmitted information
TV	total variation
TWIST	two-step iterative shrinkage/thresholding (algorithm)
URA	uniformly redundant array

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PAST, PRESENT, AND FUTURE

> I believe that if more effort is directed into the No-Man's land between raw sensory data and the distinguishable signals which are the starting point of statistical theory, the second decade of information theory will be as rich in practical improvements in communications techniques as the first was in intellectual clarifications.
>
> —D. Gabor [84]

1.1 THREE REVOLUTIONS

Sensing is the interface between the physical and digital worlds. This text focuses on *computational optical sensing*, by which we mean the creation of digital information from electromagnetic radiation with wavelengths ranging from 200 to 20,000 nanometers (nm). Optical sensors are incorporated in imagers, spectrometers, communication transceivers, and optical information processing devices. This text focuses on imaging and spectroscopy. Imagers include microscopes, telescopes, video- and still cameras, and machine vision systems. *Spectrometers* are sensor engines for molecular detection and imaging, chemical analysis, environmental monitoring, and manufacturing process control.

Computational sensing is revolutionizing the design and utility of optical imagers and spectrometers. In emerging applications, optical sensors are the backbone of robotics; transit control systems; security systems; medical diagnostics and genomics; and physical, chemical, and biological research. This text does not specifically consider these applications, but it does provide the reader with a solid foundation to design systems for any of them. The text focuses on

- The relationship between continuous object and optical field parameters and digital image data
- The use of coherence functions, most commonly the cross-spectral density and the power spectral density, to analyze optical systems

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- Coding strategies in the design of computational sensors
- The limits of specific spectrometer and imager design strategies

Readers active in physical, chemical, or biological research or nonoptical sensor design should find these topics helpful in understanding the limits of modern sensors. Readers seeking to become expert in optical imaging system design and development will need to supplement this text with courses in digital image processing, lens system design, and optoelectronics. Optical systems is a field of stunning complexity and beauty, and we hope that the basics of system analysis presented here will draw the reader into continuing research and study.

The optical sensing problem is illustrated in Fig. 1.1. The goal is to sense a remote object using signals communicated through the optical field. The sensor consists of optical elements, optoelectronic detectors, and digital processing. In some cases, we consider the remote object to be ambiently illuminated or to be self-luminous. In other cases we may consider temporally or spatially structured illumination as part of the sensor system. The system forms an image of the object consisting of a spatial map of the object radiance or density or of spatially resolved object features such as spectral density, polarization, or even chemical composition.

Figure 1.1 illustrates the culmination of several milliennia of optical sensor system development. The history of optical sensors is punctuated by three revolutions:

1. *Optical Elements.* Optical instruments capable of extending natural vision emerged approximately 700 years ago. Early instruments included spectacles to correct natural vision and the camera obscura for convenient image tracing. Over several hundred years these instruments evolved into microscopes and telescopes. These systems used human vision to transduce light into images. Image storage and communication occurred through handmade copies or traces or through written descriptions.
2. *Automatic Image Recording.* Photochemical recording began to replace handmade images approximately 200 years ago. The first true photographic processes emerged in 1839 from Daguerre's work in France and Talbot's work in England. Each inventor worked over a decade to perfect his process. At first, long exposure times limited photographs to static scenes. Early portraits

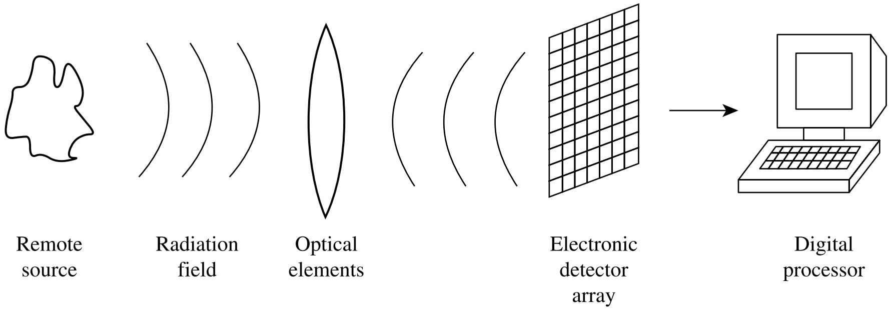

Figure 1.1 Computational optical sensor system.

required the subject to remain stationary for several minutes. Daguerre's famous image shot in 1838 from his laboratory overlooking the Boulevard du Temple in Paris is generally considered the first photograph of a human subject, a man standing still to have his shoes shined. Photographs of dynamic scenes emerged over succeeding decades with the development of flash photography, faster optical elements, and faster photochemistry. Consider, however, the revolutionary impact of the introduction of photography. Images recorded prior to 1839 have been "retouched" by the human hand. Kings are taller and cleaner-looking than they really were. Commoners are not recorded at all. Only since 1839 can one observe true snapshots of history.

3. *Computational Imaging.* Electronic imaging began about 80 years ago with the development of video capture systems for television. As with early optics, the first systems enabled people to see the previously unseen, in this case images of remote places, but did not record images for prosperity. True computational imaging requires three twentieth-century inventions: (a) optoelectronic signal transduction; (b) signal recording, communication, and digitization; and (c) digital signal processing. Signal transduction began with television, but the first electronic recording system, the Ampex VR-1000 magnetic tape deck, was not introduced until 1956. Digital signal processing emerged during World War II. Initial computational imaging applications emerged from *ra*dio *d*etecting *a*nd *r*anging (radar) applications. Electronic systems continued to emerge through the 1970s with the development of deep-space imaging and facsimile transmission. The period from 1950 through 1980 was also rich in the development of medical imaging based on x-ray and magnetic resonance tomography. The most important inventions for optical imaging during this period included semiconductor focal planes, microprocessors, and memories. These developments resulted in the first digital optical imaging systems by the mid-1980s. These systems have continued to evolve as computational hardware has gone from 1970s-style building-scale data centers, to 1980s-style desktop personal computers, to 1990s-style microprocessors in embedded microcameras.

At the moment of this writing the displacement of photochemical recording by optoelectronics is nearly complete, but the true implications of the third revolution are only just emerging. Just as the transition from an image that one could see through a telescope to an image that one could hold in one's hand was profound, the transition from analog photography to digital imaging is not about making old technology better, but about creating new technology. One hopes that this text will advance the continuing process of invention and discovery.

1.2 COMPUTATIONAL IMAGING

The transition from imaging by photochemistry to imaging by computer is comparable to the transition from accounting by abacus to accounting by computer. Just as computational accounting enables finance on a scale unimaginable in the paper era, computational imaging has drastically expanded the number of imaging systems, the number of images captured, and the utility of images—and yet, what has really changed? Isn't a picture recorded on film or on an electronic focal plane basically the same thing? The electronic version can be stored and recalled automatically, but the film version generally has comparable or better resolution, dynamic range, and sensitivity. How is being digital different or better?

In contrast to a physical object consisting of patterns on paper or film, a digital object is a mathematical entity. The digital object is independent of its physical instantiation in silicon, magnetic dipoles, or dimples on a disk. With proper care in coding and transmission, the digital object may be copied infinitely many times without loss of fidelity. A physical image, in contrast, looses resolution when copied and degrades with time. The primary difference between an analog image and a computational image is that the former is a tangible thing while the latter is an algebraic object.

Early applications exploited the mathematical nature of electronic images by enabling nearly instantaneous image transmission and storage, by creating images of multidimensional objects or invisible fields and by creating automated image analysis and enhancement systems. New disciplines of *computer vision* and *digital image processing* emerged to computationally analyze and enhance image data.

Excellent texts and a strong literature exist in support of computer vision and digital image processing. This text focuses on the tools and methods of an emerging community at the interface between digital and physical imaging and sensing system design. Computational sensing does not replace computer vision or digital image processing. Rather, by providing a more powerful and efficient physical layer, computational sensing provides new tools and options to the digital image processing and interpretation communities.

The basic issue addressed by this text is that the revolutionary opportunity represented by electronic detection and digital signal processing has yet to be fully exploited in sensor system design. The only difference between analog and digital cameras in many cases is that an electronic focal plane as replaced film. The differences between conventional design and computational sensor design are delineated as follows:

- The goal of conventional optical systems, even current electronic cameras and spectrometers, is to create an isomorphism. These systems rely on analog processing by lenses or gratings to form the image. The image is digitized after analog processing. Only modest improvements are made to the digitized image.
- The goal of computational sensor design, in contrast, is to jointly design analog preprocessing, analog-to-digital conversion, and digital postprocessing to optimize image quality or utility metrics.

Computational imaging systems may not have a "focal plane" or may deliberately distort focal plane data to enhance postprocessing capacity.

The central question, of course, is: *How might computational optical sensing improve the performance and utility of optical systems?* The short answer to this question is *in every way!* Computational design improves conventional image metrics, the utility of images for machine vision and the amenity of images for digital processing. Specific opportunities include the following:

1. *Image Metrics.* Computational sensing can improve depth of field, field of view, spatial resolution, spectral resolution, signal fidelity, sensitivity, and dynamic range. Digital systems to the time of this writing often compromised image quality to obtain the utility of digital signals, but over time digital images will increasingly exceed analog performance on all metrics.
2. *Multidimensional Imaging.* The goal of a multidimensional imaging system is to reconstruct a digital model of objects in their native embedding spaces. Conventional two-dimensional (2D) images of three-dimensional (3D) objects originate in the capacity of lens and mirror systems to form physical isomorphisms between the fields on two planes. With the development of digital processing, tomographic algorithms have been developed to transform arrays of 2D images into digital 3D object models. Integrated physical and digital design can improve on these methods by eliminating dimensional tradeoffs (such as the need to scan in time for tomographic data acquisition) and by enabling reconstruction of increasingly abstract object dimensions (space–time, space–spectrum, space–polarization, etc.).
3. *Object Analysis and Feature Detection.* The goal of object analysis is to abstract nonimage data from a scene. In emerging applications, sensors enable completely automated tasks, such as robotic positioning and control, biometric recognition, and human–computer interface management. Current systems emphasize heuristic analysis of images. Integrated design allows direct measurement of low-level physical primitives, such as basic object size, shape, position, polarization, and spectral radiance. Direct measurement of significant primitives can dramatically reduce the computational cost of object analysis. On a deeper level, one can consider object abstraction as measurement on generalized object basis states.
4. *Image Compression and Analysis.* The goal of image compression is to represent the digital model of an object as compactly as possible. One can regard the possibility of digital compression as a failure of sensor design. If it is possible to compress measured data, one might argue that too many measurements were taken. As with multidimensional imaging and object analysis, current compression algorithms assume a 2D focal model for objects. Current technology seeks a compressed linear basis or a nonlinear feature map capable of efficiently representing a picture. Integrated physical and digital design implements generalized bases and adaptive maps directly in the optical layer. One has less freedom to implement algorithms in the physical layer than in the digital system, but early data reduction enables both simpler and lower-power acquisition platforms and more efficient data processing.
5. *Sensor Array Data Fusion and Analysis.* Multiaperture imaging is common in biological systems but was alien to artificial imaging prior to the computational age. Modern computational systems will dramatically surpass the multiaperture capabilities of biology by fusing data from many subapertures spanning broad spectral ranges.

1.3 OVERVIEW

An optical sensor estimates the state of a physical object by measuring the optical field. The state of the object may be encoded in a variety of optical parameters, including both spatial and spectral features or functions of these features.

Referring again to Fig. 1.1, note that an optical sensing system includes

1. An *embedding space* populated by target objects
2. *A radiation model* mapping object properties onto the optical signal
3. *A propagation model* describing the transmission of optical signals across the embedding space
4. *A modulation model* describing the coding of optical signals by optical elements
5. *A detection model* describing transduction of optical signals at electronic interfaces
6. *An image model* describing the relationship of transduced and processed digital data to object parameters

Considerable analytical and physical complexity is possible in each of these system components. The radiation model may range from simple scattering or fluorescence up to sophisticated quantum mechanical field–matter interactions. As this is an optics text, we generally ignore the potential complexity of the object–field relationship and simply assume that we wish to image the field itself.

This text considers three propagation models:

- *Geometric fields* propagate along rays. A *ray* is a line between a point on a radiating object and a measurement sensor. In geometric analysis, light propagates in straight lines until it is reflected, refracted, or detected. Geometric fields are discussed in Chapter 2.
- *Wave fields* propagate according to physical wave equations. Wave fields add diffractive effects to the geometric description and enable physical description of the state of the field at any point in space. After review of basic mathematical tools in Chapter 3, we analyze wave fields in Chapter 4.
- *Correlation fields* propagate according to models derived from wave fields, but focus on transformations of optical observables rather than the generally unobservable electric fields. Correlation field analysis combines wave analysis with a simple model of the quantum process of optical detection. After reviewing detection processes in Chapter 5, we develop correlation field analysis in Chapter 6.

The progression from geometric to wave to correlation descriptions involves increasing attention to the physical details of the object-measurement mapping system. The geometric description shows how one might form isomorphic and encoded image capture devices, but cannot account for diffractive, spectral, or interferometric artifacts in these systems. The wave model describes diffraction, but cannot explain interferometry, noise, or spectroscopy. The correlation model accounts for these effects, but would need augmentation in analysis of quantum coherence and nonlinear optical effects. We develop optical modulation and detection models for optical sensors consistent with each propagation model in the corresponding chapters.

After establishing basic physical models for field propagation, modulation, and detection, we turn to the object model in Chapter 7, which focuses on the transformation from continuous fields to digital data, and Chapter 8, which focuses on object data coding and estimation. Discrete representation is the hallmark of digital optical sensors. In discrete analysis, the object state is represented by a vector of coefficients $\mathbf{f}$ and the measurement state is represented by a vector of coefficients $\mathbf{g}$. We consider three different relationships between $\mathbf{f}$ and $\mathbf{g}$.

- *Isomorphic mappings* form a one-to-one correspondence between components of $\mathbf{g}$ and components of $\mathbf{f}$. Examples include focal imaging systems and dispersive spectrometers. As discussed in Chapter 7, computational design and analysis is helpful even for isomorphic systems.
- *Dimension preserving mappings* capture measurements $\mathbf{g}$ embedded in a space of similar dimension with the object embedding space. One normally considers objects distributed over a 2D or 3D embedding space. Sensors based on convolutions, radon transformations, or Fourier transformations do not capture isomorphic data, but simple inversions are available to restore isomorphism.
- *Discrete mappings* assume no underlying embedding space for the measurements $\mathbf{g}$. Measurements under discrete mappings consist of linear or nonlinear projections of the object state.

The inversion algorithm applied in any specific context is determined by both the nature of the object parameters of interest and the physical mapping implemented by the sensor system.

Having completed a survey of the tools needed to analyze and design computational optical sensors in Chapters 2–8, we put the tools to use in Chapters 9 and 10 in describing specific design strategies and opportunities.

In offering the text as a one-semester course, a quick survey of Chapter 2 introduces the basic concepts of optical imaging (using ray tracing) and of computational imaging (using coded aperture imaging). Coded aperture imaging is not of great practical importance, but it provides an instructive and accessible introduction to issues that recur throughout the text. Chapters 3 and 4 present a straightforward course in Fourier optics augmented by wavelet analysis and linear spaces. While we make relatively modest direct use of wavelets in the rest of the book, the student will find wavelets of high utility for system modeling in Chapters 7–10 and will find the general concepts of vector spaces and multiscale analysis essential. Students with prior experience in signal processing may find Chapter 3 unnecessary, I hope that optics students will find the presentation of wavelets more accessible here than in the signal processing literature. Similarly, optics students with previous Fourier optics experience may find Chapter 4 unnecessary. Chapter 5 is a brief overview of optical detectors sufficient for a discussion of system design. This chapter is left for self-study in the one-semester course. Overall, the author hopes that upper-level engineering, physics, mathematics, and computer science undergraduates will find Chapters 2–5 an accessible introduction to basic optical systems. While familiarity with the material in Chapters 2–5 is essential to understanding what comes later, the reader leaving the course after Chapter 5 would be missing the most critical concepts in optical sensing.

The core of the course begins in Chapter 6, where the text considers statistical fields created by natural sources. A course that hurries through the early chapters should arrive with time to spend on this chapter and the remainder of the text. Optical coherence theory is wonderfully developed by Wolf [252], Mandel and Wolf [165], and Goodman [99], but I hope that the reader will find the focus on imaging system analysis and coherence measurement presented in Chapter 6 unique and useful. Similarly, the discussion on sampling in Chapter 7 covers issues that are also covered elsewhere, but I hope that the simple and direct treatment of isomorphic sampling is clearer than other treatments. The discussion of generalized sampling in Section 7.5 covers emerging concepts.

Chapter 8 covers algorithms and coding issues covered elsewhere, although coding strategies are uniquely colored by the understanding of optical fields and generalized sampling developed to this point. If nothing else, the reader should leave Chapter 8 with reduced faith in least-square estimators and mean-square error metrics.

Many texts conclude with an optional chapter or two on advanced topics. That is not the case here. I cannot imagine that a reader would learn the tools in Chapters 2–8 without experiencing the joy of applying them in Chapters 9 and 10.

1.4 THE FOURTH REVOLUTION

The first revolution in optical sensing, the development of optical elements, was based on glass, skilled artisans, and markets for consumer goods. This required a civilized society with advanced materials and manufacturing capabilities. The transition from spectacles to telescopes and microscopes required the existence of a sophisticated scientific community. These developments took many generations of human activity. Could early optical scientists foresee the next revolution? I expect that they could, and how often they must have wished for an automated mechanism for recording images observed by the unaided eye.

The next revolution, photochemistry, emerged nearly simultaneously with the birth of electronic communications. The inventor of electronic communications, Samuel Morse, visited Daguerre's laboratory shortly after the Boulevard du Temple was recorded and described the image in an April 20, 1839 article in the *New York Observer*. Both inventors knew well the tortured process of invention and the faith of the inventor in the previously impossible. The idea of automated image transmission was not far behind the idea of automated recording. In the grand scheme of history, the 75 years between the first photochemical images to television were brief.

The revolutionary transition from photochemistry to computational imaging is nearing completion. The necessary devices first emerged about 25 years ago (i.e., in the early 1980s); one expects that another quarter century will complete this revolution. Optical scientists and engineers now wonder, is there a fourth revolution? As an author one may hope for stasis, such that the words and analysis herein may live forever. Being more scientist and engineer than author, however, I am happy to report that a fourth revolution has already begun.

The fourth revolution will be the age of optical circuits and antennas. As discussed in Chapter 5, the bedrock assumption of modern optics is that electronic detectors measure the time-averaged irradiance of the optical field. The fourth revolution will discard this assumption. Optical design is currently profoundly influenced by the incoherent interface between optical signals and digital data. Within the next decade (i.e., by 2018), coherent coupling between optical and electronic states in nanostructured and plasmonic devices will be combined with quantum interference in electronic states to produce optical coherence sensors. These systems will be combined with complex 3D optics to produce integrated transducers. 3D optics is represented in nascent form by photonic crystal materials, but advanced modeling, 3D fabrication techniques and materials will produce imaging systems and spectrometers with very different noise characteristics and form factors.

A new revolution sometimes kills the old, as digital imaging has killed photochemical imaging, and sometimes feeds the old, as digital imaging has increased demand for optical elements. Happily, I believe that the fourth revolution will only increase the need to understand the content of this book. The basic approaches to sampling, field analysis, and signal analysis outlined herein are necessary to both the present and the future. Most significantly, limits on the bandwidth of the optical system, the significance of these limits for image metrics, and strategies to surpass the naive limits will remain the same even as the physical nature of the optical analog-to-digital interface evolves. With an eye on both the present and the future, therefore, read on, dear reader.

PROBLEMS

1.1 *Imaging and Processing*. Estimate the number of calculations performed per person worldwide in 50-year increments from 1800 to the present. Estimate the number of images photochemically and electronically recorded per person over the same time period.

1.2 *Digital Data*. Estimate the worldwide fraction of stored digital data that is image data.

1.3 *Digital Images*. Estimate the ratio of the number of images stored photochemically to the number of images stored electronically in 1960, 1980, 2000, and 2020. Explain your reasoning. What if only still or only moving pictures are considered?

1.4 *Persistence*. Estimate the lifetime of a film image and of a digital image. Discuss factors that might, over time, lead to the degradation of such images.

1.5 *Weighing Design*. Suppose that you are given 12 gold coins. Exactly one of the coins is counterfeit and weighs more or less than the rest. You have a sensitive two-pan balance, which reports only which pan is heavier. How many measurements do you need on the balance to find the counterfeit coin and determine whether it is lighter or heavier? Describe your measurement strategy. How might this problem be relevant to optical sensor design?

1.6 *Boulevard du Temple*. Consider Nicholas Jenkins' analysis of the number of people in Daguerre's Boulevard du Temple presented online at `http://www.stanford.edu/~njenkins/archives/2007/08/traces.html`. How many people do you observe in the image? What is your estimate of the exposure time?