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Modeling the Imaging Chain of Digital Cameras

Robert D. Fiete

Tutorial Texts in Optical Engineering
Volume TT92

SPIE PRESS
Bellingham, Washington USA
To Kathy, Katie, Allie, and Greg
Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to cover many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated independently by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University
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Preface

This tutorial aims to help people interested in designing digital cameras who have not had the opportunity to delve into the mathematical modeling that allows understanding of how a digital image is created. My involvement with developing models for the imaging chain began with my fascination in the fact that image processing allows us to “see” mathematics. What does a Fourier transform look like? What do derivatives look like? We can visualize the mathematical operations by applying them to images and interpreting the outcomes. It was then a short jump to investigate the mathematical operations that describe the physical process of forming an image. As my interest in camera design grew, I wanted to learn how different design elements influenced the final image. More importantly, can we see how modifications to a camera design will affect the image before any hardware is built? Through the generous help of very intelligent professors, friends, and colleagues I was able to gain a better understanding of how to model the image formation process for digital cameras.

_Modeling the Imaging Chain of Digital Cameras_ is derived from a course that I teach to share my perspectives on this topic. This book is written as a tutorial, so many details are left out and assumptions made in order to generalize some of the more difficult concepts. I urge the reader to pick up the references and other sources to gain a more in-depth understanding of modeling the different elements of the imaging chain. I hope that the reader finds many of the discussions and illustrations helpful, and I hope that others will find modeling the imaging chain as fascinating as I do.

*Robert D. Fiete*

*October 2010*
Acknowledgments

I would like to acknowledge the people who reviewed the manuscript, especially Mark Crews, Bernie Brower, Jim Mooney, Brad Paul, Frank Tantalo, and Ted Tantalo, for their wonderful comments and suggestions. I would like to thank the incredibly talented people that I have the honor of working with at ITT, Kodak, and RIT, for their insightful discussions and support. Many people have mentored me over the years, but I would like to particularly thank Harry Barrett for teaching me how to mathematically model and simulate imaging systems, and Dave Nead for teaching me the fundamentals of the imaging chain. Finally, I would like to acknowledge my furry friends Casan, Opal, Blaze, and Rory who make excellent subjects for illustrating the imaging chain.
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>A/D</td>
<td>analog-to-digital</td>
</tr>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CI</td>
<td>confidence interval</td>
</tr>
<tr>
<td>CMOS</td>
<td>complimentary metal-oxide semiconductor</td>
</tr>
<tr>
<td>CRT</td>
<td>cathode ray tube</td>
</tr>
<tr>
<td>CSF</td>
<td>contrast sensitivity function</td>
</tr>
<tr>
<td>CTE</td>
<td>charge transfer efficiency</td>
</tr>
<tr>
<td>DCT</td>
<td>discrete cosine transform</td>
</tr>
<tr>
<td>DFT</td>
<td>discrete Fourier transform</td>
</tr>
<tr>
<td>DIRSIG</td>
<td>Digital Imaging and Remote Sensing Image Generation</td>
</tr>
<tr>
<td>DRA</td>
<td>dynamic range adjustment</td>
</tr>
<tr>
<td>EO</td>
<td>electro-optic</td>
</tr>
<tr>
<td>FOV</td>
<td>field of view</td>
</tr>
<tr>
<td>FPA</td>
<td>focal plane array</td>
</tr>
<tr>
<td>GIQE</td>
<td>generalized image quality equation</td>
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<tr>
<td>GL</td>
<td>gray level</td>
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<tr>
<td>GRD</td>
<td>ground-resolvable distance</td>
</tr>
<tr>
<td>GSD</td>
<td>ground sample distance</td>
</tr>
<tr>
<td>GSS</td>
<td>ground spot size</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>HVS</td>
<td>human visual system</td>
</tr>
<tr>
<td>IFOV</td>
<td>instantaneous field of view</td>
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<tr>
<td>IQE</td>
<td>image quality equation</td>
</tr>
<tr>
<td>IRARS</td>
<td>Imagery Resolution Assessment and Reporting Standards</td>
</tr>
<tr>
<td>IRF</td>
<td>impulse response function</td>
</tr>
<tr>
<td>JND</td>
<td>just noticeable difference</td>
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<tr>
<td>LCD</td>
<td>liquid crystal display</td>
</tr>
<tr>
<td>LSI</td>
<td>linear shift invariant</td>
</tr>
<tr>
<td>MAP</td>
<td>maximum <em>a posteriori</em></td>
</tr>
<tr>
<td>MMSE</td>
<td>minimum mean-square error</td>
</tr>
<tr>
<td>MSE</td>
<td>mean-square error</td>
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<tr>
<td>MTF</td>
<td>modulation transfer function</td>
</tr>
<tr>
<td>MTFC</td>
<td>modulation transfer function compensation</td>
</tr>
<tr>
<td>NEΔρ</td>
<td>noise equivalent change in reflectance</td>
</tr>
<tr>
<td>NIIRS</td>
<td>National Imagery Interpretability Rating Scale</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>OQF</td>
<td>optical quality factor</td>
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<tr>
<td>OTF</td>
<td>optical transfer function</td>
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<tr>
<td>PSF</td>
<td>point spread function</td>
</tr>
<tr>
<td>PTF</td>
<td>phase transfer function</td>
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<tr>
<td>QSE</td>
<td>quantum step equivalence</td>
</tr>
<tr>
<td>RER</td>
<td>relative edge response</td>
</tr>
<tr>
<td>RMS</td>
<td>root-mean-square</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>TDI</td>
<td>time delay and integration</td>
</tr>
<tr>
<td>TTC</td>
<td>tonal transfer curve</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Array (radio telescope)</td>
</tr>
<tr>
<td>WNG</td>
<td>white noise gain</td>
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