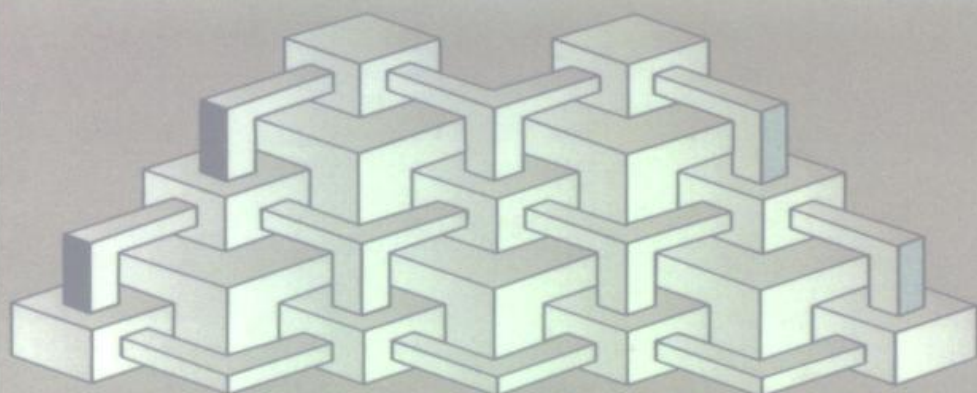


大学计算机教育丛书（影印版）

DIGITAL IMAGE PROCESSING



数字图象处理

KENNETH R. CASTLEMAN



清华大学出版社 · PRENTICE HALL

**DIGITAL IMAGE
PROCESSING**

数字图象处理

Kenneth R. Castleman

清华大学出版社

Prentice-Hall International, Inc.

(京)新登字 158 号

Digital Image Processing/Kenneth R. Castleman

© 1996 by Prentice Hall, Inc.

Original edition published by Prentice Hall, Inc., a Simon & Schuster Company.

Prentice Hall 公司授权清华大学出版社在中国境内(不包括中国香港特别行政区、澳门和台湾地区)独家出版发行本书影印本。

本书任何部分内容,未经出版者书面同意,不得用任何方式抄袭、节录或翻印。

本书封面贴有 Prentice Hall 激光防伪标签,无标签者不得销售。

北京市版权局著作权合同登记号: 01-98-0264

图书在版编目(CIP)数据

数字图象处理: 英文/卡斯尔曼(Castleman, K. R.)著. —影印版. —北京: 清华大学出版社, 1998. 3 (大学计算机教育丛书)

ISBN 7-302-02828-1

I. 数… II. 卡… III. 数字图象处理-英文 IV. TN919.8

中国版本图书馆 CIP 数据核字(98)第 01673 号

出版者: 清华大学出版社(北京清华大学校内, 邮编 100084)

<http://www.tup.tsinghua.edu.cn>

印刷者: 清华大学印刷厂

发行者: 新华书店总店北京科技发行所

开本: 850×1168 1/32 印张: 21.625

版次: 1998年4月第1版 1998年10月第2次印刷

书号: ISBN 7-302-02828-1/TN·88

印数: 5001~10000

定价: 32.00 元

出版前言

我们的大学生、研究生毕业后,面临的将是一个国际化的信息时代。他们将需要随时查阅大量的外文资料;会有更多的机会参加国际性学术交流活动;接待外国学者;走上国际会议的讲坛。作为科技工作者,他们不仅应有与国外同行进行口头和书面交流的能力,更为重要的是,他们必须具备极强的查阅外文资料获取信息的能力。有鉴于此,在国家教委所颁布的“大学英语教学大纲”中有一条规定:专业阅读应作为必修课程开设。同时,在大纲中还规定了这门课程的学时和教学要求。有些高校除开设“专业阅读”课之外,还在某些专业课拟进行英语授课。但教、学双方都苦于没有一定数量的合适的英文原版教材作为教学参考书。为满足这方面的需要,我们挑选了7本计算机科学方面最新版本的教材,进行影印出版。首批影印出版的6本书受到广大读者的热情欢迎,我们深受鼓舞,今后还将陆续推出新书。希望读者继续给予大力支持。Prentice Hall公司和清华大学出版社这次合作将国际先进水平的教材引入我国高等学校,为师生们提供了教学用书,相信会对高校教材改革产生积极的影响。

清华大学出版社
Prentice Hall 公司

1997. 11



Preface

In the 16 years since the publication of my first book on this topic, there has been a major expansion in the utilization of digital image processing. Algorithms that could run only on mainframe computers in the 1960s and minicomputers in the 1970s migrated to the desktop in the 1980s. Personal computers transformed from something a few dedicated hobbyists built in the mid-1970s into a common home office component. The jargon of personal computers became a universal language that bridged the oceans between the United States, Europe, and Asia.

Public awareness of digital image processing has been greatly increased by video games, digital video special effects used in the entertainment industry, and articles in the popular press. Present trends indicate a continuation of the explosive growth of digital image-processing applications well into the next century.

Perhaps the most significant impact of digital image processing in the 1990s will be in the area of applications to real-world problems. This book is aimed at the reader who intends to use the technology for research or commercial purposes. It also provides a foundation for those who seek to advance the state of the art.

While the scope and scale of digital image-processing applications have changed dramatically, other aspects of the field have not. For example, many of the basic techniques that perform reliably in practice today are those that were first applied in the early days of digital imaging. While several exciting new theoretical areas have opened up, generally they build upon, rather than replace, what has served well in the past.

With the recent advances in computer technology, some of the issues treated in the earlier work are no longer of major concern. These are deemphasized in this book, while several

relevant new topics have been included. New examples serve to illustrate further how the theory can be applied to the type of problems that commonly occur in industry and research.

Perhaps most significantly, a set of exercises and suggestions for projects completes each chapter. These have been selected to build the insight and understanding that are most useful to one endeavoring to apply the technology to problems of the real world. The majority of the exercises and projects emulate actual situations a professional faces working in the field of digital image processing. They are intended to give the reader a head start in gaining the insight that supplements a theoretical knowledge and can come only from the experience of solving real problems. In my own estimation, one who not only knows how to solve the problems and carry out the projects, but has actually done most of them, will be ready to take his or her place on the most productive image-processing applications team.

For about 25 years, I have had the opportunity to observe the efforts of many individuals applying digital image-processing techniques to problems offered by the real world. A few of these individuals have established an enduring track record of solid success on almost every attempt. They have consistently contributed innovative and effective solutions that creatively employ the tools of the discipline.

These highly productive individuals demonstrably hold several characteristics in common. One can venture to assume that these characteristics constitute a formula for success, to whatever extent such a thing can exist in this field.

Uniformly, these successful persons have (1) a genuine interest in—even a fascination with—the technology involved, (2) a thorough understanding of the fundamentals of this highly multidisciplinary technology, (3) a conceptual type of understanding (as opposed to rote memorization of totally abstract theory), and (4) a knack for seeing problems visually, graphically, and from more than one viewpoint. In line with this last point, they often find themselves hard pressed to explain their ideas without the aid of a graph or drawing.

This book is designed to help the reader develop the last three of these traits and perhaps enhance the first as well. The selection of materials for inclusion (and, equally important, for omission), the examples used, the references cited, and the exercises and suggestions for projects are all directed toward this goal.

In the field of digital image processing, mathematical analysis forms the stable basis upon which one can make definite predictions regarding the performance of a digital imaging system. In this treatment, however, mathematics is employed more as a faithful servant than as a ruthless master. The emphasis is on developing a conceptual understanding, and the analysis is used to support this goal.

The organization of this book generally follows that of the earlier text, simply because that particular flow of development proved to serve its purpose well. The level of mathematical complexity increases gradually through the first two parts of the book. While many readers have the background in mathematics required to begin the discussion with sampling theory and the Fourier transform, others do not.

More importantly, though, many of the most important concepts can be presented without the aid of advanced mathematics. Thus, we are able to avoid an additional element of complexity in the interest of making the learning process less burdensome and more appealing to all readers. As a general rule, topics receive attention in relation to their importance, rather than their complexity.

The field of digital image processing has now become so rich with technology that it is impossible to cover all aspects of it in a single volume of reasonable size. Hence, we concentrate upon those techniques that prove most useful in practice and leave most of the mathematical proofs to the references. Constraints of paper and ink further make it impossible to include nearly as many examples of images as would be desirable. (See [1] for an excellent source of these.)

Part 1 presents several important concepts that do not require detailed mathematical analysis for a basic understanding of them. Part 2 addresses techniques that rely more heavily upon their mathematical underpinning and elaborates analytically upon certain concepts introduced in Part 1. Part 3 addresses applications more specifically than they are addressed in earlier chapters.

A Note to Instructors. The development of this text has been accompanied by an accumulation of example digital images and problem solutions worked out in MathCAD™ [2]. Instructors interested in obtaining these as teaching aids can contact the author via the publisher, or on the Internet (castleman@psii.persci.com or <http://www.phoenix.net/~castlman/> or sci.image.processing).

A Note to Students. There are three situations that can arise during the course of study that can interfere with the learning process [3]. It is a wise reader who remains alert to their symptoms and handles them when they first occur.

The first situation is due to the nomenclature in this very multidisciplinary field. Often, ordinary words are pressed into special new usage without warning. If the concept presented in a paragraph seems unclear or leaves a blank feeling, look for the sentence that doesn't make sense. Then spot the word that doesn't fit. Look in the glossary or a dictionary for the definition that fits the context. Usually, this will resolve the entire matter. Sometimes, however, the offending word may appear one or more sentences earlier in the material. Frequent reference to the glossary and a dictionary is good insurance against any inability to fully understand and use the ideas presented.

The second situation occurs when one moves too quickly through the material. When one becomes confused, the remedy is not to restudy the confusing part, but to go back to the last part that seemed clear and restudy there. Often one will find a previously undetected confusion in the earlier area that, when resolved, will pave the way for further progress.

The third situation results when one studies theory exclusively, without any application, for too long. This can make the reader bored or even exasperated. When it occurs, the remedy is to *apply* the theory, working with actual images and image-processing equipment if possible. A balance between theory and application keeps the subject interesting. The problems and projects are included for this purpose.

REFERENCES

1. G. A. Baxes, *Digital Image Processing: Principles and Applications*, Wiley, New York, 1994.
2. MathSoft, Inc., 201 Broadway, Cambridge, MA 02139.
3. L. Ron Hubbard, *Basic Study Manual*, Bridge Publications, Los Angeles, CA, 1990.

Acknowledgments

The author wishes to thank the following people who have contributed significantly to the publication of this book: Dr. Henry Fuchs, Dr. Michael Shantz and Dr. Meir Weinstein collaborated in the work on three-dimensional reconstruction from optical sections in Chapter 22. Terry Riopka of Perceptive Scientific Instruments, Inc. (PSII) contributed to the discussion of neural networks in Chapter 20. Robert Selzer and Nancy Cornelius of the Jet Propulsion Laboratory (NASA/JPL) contributed to the discussion of curve and surface fitting in Chapter 19. Dr. Qiang Wu (PSII) contributed to the chapter on wavelet transforms.

Figures were generously supplied by Prof I. T. Young of the Delft Institute of Technology, The Netherlands; Henry Hui Li of HNC Software, Inc., in San Diego; Dr. Jian Lu of the University of California, Davis; Mr. Shishir Shah and Dr. J. K. Aggarwal of The University of Texas at Austin; Marcus Gross and Lars Lippert of the Swiss Federal Institute of Technology, Zurich; Dr. James Blinn of NASA/JPL; Luc Nocente of Noesis Vision; Dr. Bruce Cameron and Dr. Qiang Wu of PSII; and NASA/JPL.

Several reviewers made valuable comments and suggestions that improved the presentation considerably. These include Dr. Stuart Taylor (Mayo Foundation) and Dr. David Shotton (Oxford University). Also among them are Dr. Bruce F. Cameron, Steve Clarner, Chuck Johnson, Robert McGill, Robert S. Rossner, and Dr. Qiang Wu, all of PSII. Special thanks go to the four publishers' reviewers whose thoughtful comments on an early manuscript resulted in considerable improvement thereto, and to Mr. Brian Baker, publisher's copy editor, whose thoughtful comments significantly improved the clarity of the text.

Preparation of the manuscript and figures was transformed from a burdensome task to an enjoyable journey by the competent and tireless assistance of Deborah K. Cate, Sheri D.

Breaux, and Donna Call of PSII. I would also like to thank Mr. Robin Downes, Director of University Libraries, the University of Houston, and his staff at the M. D. Anderson Library for making available their excellent research facilities.

Luc Nocente of Noesis Vision made available Visilog 4.3, which was used in the preparation of several of the figures. The manuscript was prepared in Word 6.0 (Microsoft). The numerical examples were computed in MathCAD+ 5.0 (MathSoft, Inc.), and many of the drawings were done in Visio 3.0 (Shapeware Corporation).

The author has benefited significantly over the years from discussions with gifted colleagues. These include Dr. Robert Nathan, Dr. Ray Wall, and Robert Selzer (all of NASA/JPL), Dr. Benjamin S. White (Exxon Research Laboratory), Dr. Kenneth Price (Stephen F. Austin State University), and Donald Winkler (PSII), as well as many of the authors whose work is cited herein. Also of note in this regard are Prof. I. T. Young (Delft Institute of Technology), Dr. M. Don Graham (Coulter Corp.), Dr. David Zahniser (Cytoc Corp.), Dr. Jeff Brenner (Tufts New England Medical Center), Dr. James Baccus (Cell Analysis Systems) Dr. Mortimer Mendelsohn (Lawrence Livermore Laboratory) and Dr. Brian Mayall (University of California, San Francisco).



Contents

PREFACE

xiii

Part One

1	IMAGES AND DIGITAL PROCESSING	1
1.1	Introduction	1
1.2	The Elements of Digital Image Processing	2
1.3	Philosophical Considerations	7
1.4	Digital Image Processing in Practice	10
	Problems	11
	References	11
2	DIGITIZING IMAGES	13
2.1	Introduction	13
2.2	Characteristics of an Image Digitizer	14
2.3	Types of Image Digitizers	15
2.4	Image-Digitizing Components	16
2.5	Electronic Image Tube Cameras	21
2.6	Solid-State Cameras	24
2.7	Film Scanning	28
2.8	Summary of Important Points	33

v

	Problems	34	
	Projects	35	
	References	35	
3	DIGITAL IMAGE DISPLAY		37
	3.1 Introduction	37	
	3.2 Display Characteristics	39	
	3.3 Volatile Displays	49	
	3.4 Permanent Displays	49	
	3.5 Summary of Important Points	52	
	Problems	53	
	Projects	53	
	References	53	
4	IMAGE-PROCESSING SOFTWARE		55
	4.1 Introduction	55	
	4.2 Image-Processing Systems	56	
	4.3 The User Interface	57	
	4.4 The Software Development Process	61	
	4.5 Summary of Important Points	68	
	Problems	68	
	Projects	69	
	References	69	
5	THE GRAY-LEVEL HISTOGRAM		71
	5.1 Introduction	71	
	5.2 Uses of the Histogram	75	
	5.3 Relationship Between Histogram and Image	77	
	5.4 Summary of Important Points	80	
	Problems	80	
	Projects	80	
	References	81	
6	POINT OPERATIONS		83
	6.1 Introduction	83	
	6.2 Point Operations and the Histogram	86	
	6.3 Applications of Point Operations	91	
	6.4 Summary of Important Points	96	
	Problems	97	
	Projects	99	
7	ALGEBRAIC OPERATIONS		101
	7.1 Introduction	101	
	7.2 Algebraic Operations and the Histogram	102	

7.3	Applications of Algebraic Operations	106
7.4	Summary of Important Points	112
	Problems	112
	Projects	113
8	GEOMETRIC OPERATIONS	115
8.1	Introduction	115
8.2	Gray-Level Interpolation	117
8.3	The Spatial Transformation	120
8.4	Applications of Geometric Operations	125
8.5	Summary of Important Points	137
	Problems	137
	Projects	139
	References	140
Part Two		
9	LINEAR SYSTEM THEORY	143
9.1	Introduction	143
9.2	Harmonic Signals and Complex Signal Analysis	145
9.3	The Convolution Operation	148
9.4	Some Useful Functions	158
9.5	Convolution Filtering	163
9.6	Conclusion	166
9.7	Summary of Important Points	167
	Problems	167
	Projects	168
	References	169
10	THE FOURIER TRANSFORM	171
10.1	Introduction	171
10.2	Properties of the Fourier Transform	178
10.3	Linear Systems and the Fourier Transform	186
10.4	The Fourier Transform in Two Dimensions	193
10.5	Correlation and the Power Spectrum	201
10.6	Summary of Fourier Transform Properties	203
10.7	Summary of Important Points	203
	Problems	205
	Projects	206
	References	206
11	FILTER DESIGN	207
11.1	Introduction	207
11.2	Lowpass Filters	207

11.3	Bandpass and Bandstop Filters	209
11.4	High-Frequency Enhancement Filters	212
11.5	Optimal Linear Filter Design	216
11.6	Order Statistic Filters	247
11.7	Summary of Important Points	250
	Problems	250
	Projects	251
	References	251
12	PROCESSING SAMPLED DATA	253
12.1	Introduction	253
12.2	Sampling and Interpolation	253
12.3	Computing Spectra	262
12.4	Aliasing	264
12.5	Truncation	266
12.6	Digital Processing	269
12.7	Controlling Aliasing Error	273
12.8	Digitally Implemented Linear Filtering	275
12.9	Summary of Important Points	277
	Problems	277
	Projects	278
	References	279
13	DISCRETE IMAGE TRANSFORMS	281
13.1	Introduction	281
13.2	Linear Transformations	282
13.3	Basis Functions and Basis Images	285
13.4	Sinusoidal Transforms	286
13.5	Rectangular Wave Transforms	290
13.6	Eigenvector-Based Transforms	294
13.7	Transform Domain Filtering	299
13.8	Summary of Important Points	300
	Problems	301
	Projects	301
	References	301
14	WAVELET TRANSFORMS	303
14.1	Introduction	303
14.2	The Continuous Wavelet Transform	308
14.3	The Wavelet Series Expansion	312
14.4	The Discrete Wavelet Transform	314
14.5	Wavelet Selection	343
14.6	Applications	345
14.7	Summary of Important Points	346

- Problems 347
- Projects 348
- References 348

15 OPTICS AND SYSTEM ANALYSIS 351

- 15.1 Introduction 351
- 15.2 Optics and Imaging Systems 353
- 15.3 Diffraction-Limited Optical Systems 357
- 15.4 Imaging System Aberrations 366
- 15.5 Imaging System Resolution 368
- 15.6 The Analysis of Complete Systems 371
- 15.7 Examples 377
- 15.8 Summary of Important Points 381
 - Problems 383
 - Projects 385
 - References 385

Part Three

16 IMAGE RESTORATION 387

- 16.1 Introduction 387
- 16.2 Classical Restoration Filters 388
- 16.3 Linear Algebraic Restoration 393
- 16.4 Restoration of Less Restricted Degradations 397
- 16.5 Superresolution 403
- 16.6 System Identification 408
- 16.7 Noise Modeling 414
- 16.8 Implementation 416
- 16.9 Summary of Important Points 425
 - Problems 426
 - Projects 428
 - References 428

17 IMAGE COMPRESSION 431

- 17.1 Introduction 431
- 17.2 Lossless Compression Techniques 432
- 17.3 Lossy Image Coding 435
- 17.4 Transform Image Coding 438
- 17.5 Image Compression Standards 441
- 17.6 Summary of Important Points 442
 - Problems 443
 - Projects 443
 - References 444

18	PATTERN RECOGNITION: IMAGE SEGMENTATION	447
18.1	Introduction	447
18.2	The Image Segmentation Process	450
18.3	Image Segmentation by Thresholding	452
18.4	Gradient-Based Segmentation Methods	460
18.5	Edge Detection and Linking	464
18.6	Region Growing	468
18.7	Binary Image Processing	470
18.8	Segmented Image Structure	478
18.9	Summary of Important Points	482
	Problems	482
	Projects	483
	References	483
19	PATTERN RECOGNITION: OBJECT MEASUREMENT	487
19.1	Introduction	487
19.2	Size Measurements	487
19.3	Shape Analysis	492
19.4	Texture Analysis	499
19.5	Curve and Surface Fitting	501
19.6	Summary of Important Points	507
	Problems	507
	Projects	509
	References	509
20	PATTERN RECOGNITION: CLASSIFICATION AND ESTIMATION	513
20.1	Introduction	513
20.2	Classification	513
20.3	Feature Selection	515
20.4	Statistical Classification	518
20.5	Neural Networks	527
20.6	Proportion Estimation	538
20.7	Summary of Important Points	542
	Problems	543
	Projects	544
	References	544
21	COLOR AND MULTISPECTRAL IMAGE PROCESSING	547
21.1	Introduction	547
21.2	Multispectral Image Analysis	548
21.3	Color Image Processing	548
21.4	Summary of Important Points	561
	Problems	561

Projects	562	
References	562	
22 THREE-DIMENSIONAL IMAGE PROCESSING		563
22.1 Introduction	563	
22.2 Three-Dimensional Imaging	566	
22.3 Computerized Axial Tomography	582	
22.4 Stereometry	585	
22.5 Stereoscopic Image Display	590	
22.6 Shaded Surface Display	593	
22.7 Summary of Important Points	599	
Problems	599	
Projects	600	
References	601	
A1 GLOSSARY OF IMAGE PROCESSING TERMS		603
A2 BIBLIOGRAPHY		611
A2.1 Books	611	
A2.2 Research Papers	621	
A3 MATHEMATICAL BACKGROUND		637
A3.1 Linear Algebra	637	
A3.2 Set Theory	649	
INDEX		651

Part One

CHAPTER 1

Images and Digital Processing

1.1 INTRODUCTION

Digital image processing—the manipulation of images by computer—is a relatively recent development in terms of humans' ancient fascination with visual stimuli. In its short history, it has been applied to practically every type of imagery, with varying degrees of success. The inherent subjective appeal of pictorial displays attracts perhaps a disproportionate amount of attention from scientist and lay person alike.

Like other multidisciplinary fields, digital image processing suffers from myths, misunderstandings, misconceptions, and misinformation. It is a broad umbrella under which fall diverse aspects of optics, electronics, mathematics, photography, and computer technology. It is plagued with imprecise and often contradictory jargon taken from many different fields. This book attempts to collect the fundamental concepts of digital image processing into a self-consistent package for a relatively easily digested introduction to the field.

Several factors indicate continued growth for the field. A major one is the perpetually declining cost of the computer equipment required. Both processing units and bulk storage devices continue to become less expensive year by year. A second factor is the increasing availability of equipment for digitizing and displaying images. There are indications that the cost of computer equipment will continue to decline.

Several new technological trends promise to further stimulate the growth of the field. Among these are parallel processing, made practical by low-cost microprocessors; inexpensive charge-coupled devices (CCDs) for digitizing; new memory technologies for large, low-cost image storage arrays; and inexpensive, high-resolution color display systems.