Digital Image Processing

Third Edition

Rafael C. Gonzalez
University of Tennessee

Richard E. Woods
MedData Interactive

Pearson International Edition
prepared by Pearson Education

PEARSON
Prentice
Hall

Pearson Education International

To Samantha
and
To Janice, David, and Jonathan

Contents

Preface

When something can be read without effort,
great effort has gone into its writing.
Enrique Jardiel Poncela

This edition of *Digital Image Processing* is a major revision of the book. As in the 1977 and 1987 editions by Gonzalez and Wintz, and the 1992 and 2002 editions by Gonzalez and Woods, this fifth-generation edition was prepared with students and instructors in mind. The principal objectives of the book continue to be to provide an introduction to basic concepts and methodologies for digital image processing, and to develop a foundation that can be used as the basis for further study and research in this field. To achieve these objectives, we focused again on material that we believe is fundamental and whose scope of application is not limited to the solution of specialized problems. The mathematical complexity of the book remains at a level well within the grasp of college seniors and first-year graduate students who have introductory preparation in mathematical analysis, vectors, matrices, probability, statistics, linear systems, and computer programming. The book Web site provides tutorials to support readers needing a review of this background material.

One of the principal reasons this book has been the world leader in its field for more than 30 years is the level of attention we pay to the changing educational needs of our readers. The present edition is based on the most extensive survey we have ever conducted. The survey involved faculty, students, and independent readers of the book in 134 institutions from 32 countries. The major findings of the survey indicated a need for:

- A more comprehensive introduction early in the book to the mathematical tools used in image processing.
- An expanded explanation of histogram processing techniques.
- Stating complex algorithms in step-by-step summaries.
- An expanded explanation of spatial correlation and convolution.
- An introduction to fuzzy set theory and its application to image processing.
- A revision of the material dealing with the frequency domain, starting with basic principles and showing how the discrete Fourier transform follows from data sampling.
- Coverage of computed tomography (CT).
- Clarification of basic concepts in the wavelets chapter.
- A revision of the data compression chapter to include more video compression techniques, updated standards, and watermarking.
- Expansion of the chapter on morphology to include morphological reconstruction and a revision of gray-scale morphology.

- Expansion of the coverage on image segmentation to include more advanced edge detection techniques such as Canny's algorithm, and a more comprehensive treatment of image thresholding.
- An update of the chapter dealing with image representation and description.
- Streamlining the material dealing with structural object recognition.

The new and reorganized material that resulted in the present edition is our attempt at providing a reasonable degree of balance between rigor, clarity of presentation, and the findings of the market survey, while at the same time keeping the length of the book at a manageable level. The major changes in this edition of the book are as follows.

Chapter 1: A few figures were updated and part of the text was rewritten to correspond to changes in later chapters.

Chapter 2: Approximately 50% of this chapter was revised to include new images and clearer explanations. Major revisions include a new section on image interpolation and a comprehensive new section summarizing the principal mathematical tools used in the book. Instead of presenting "dry" mathematical concepts one after the other, however, we took this opportunity to bring into Chapter 2 a number of image processing applications that were scattered throughout the book. For example, image averaging and image subtraction were moved to this chapter to illustrate arithmetic operations. This follows a trend we began in the second edition of the book to move as many applications as possible early in the discussion not only as illustrations, but also as motivation for students. After finishing the newly organized Chapter 2, a reader will have a basic understanding of how digital images are manipulated and processed. This is a solid platform upon which the rest of the book is built.

Chapter 3: Major revisions of this chapter include a detailed discussion of spatial correlation and convolution, and their application to image filtering using spatial masks. We also found a consistent theme in the market survey asking for numerical examples to illustrate histogram equalization and specification, so we added several such examples to illustrate the mechanics of these processing tools. Coverage of fuzzy sets and their application to image processing was also requested frequently in the survey. We included in this chapter a new section on the foundation of fuzzy set theory, and its application to intensity transformations and spatial filtering, two of the principal uses of this theory in image processing.

Chapter 4: The topic we heard most about in comments and suggestions during the past four years dealt with the changes we made in Chapter 4 from the first to the second edition. Our objective in making those changes was to simplify the presentation of the Fourier transform and the frequency domain. Evidently, we went too far, and numerous users of the book complained that the new material was too superficial. We corrected that problem in the present edition. The material now begins with the Fourier transform of one continuous variable and proceeds to derive the discrete Fourier transform starting with basic concepts of sampling and convolution. A by-product of the flow of this material is an intuitive derivation of the sampling theorem and its implications. The 1-D material is then extended to 2-D, where we give a number of examples to illustrate the effects of sampling on digital images, including aliasing and moiré patterns. The 2-D discrete Fourier transform is then illustrated and a number of important properties are derived and summarized. These concepts are then used as the basis for filtering in the frequency domain. Finally, we discuss implementation issues such as transform decomposition and the derivation of a fast Fourier transform algorithm. At the end of this chapter, the reader will have progressed from sampling of 1-D functions through a clear derivation of the foundation of the discrete Fourier transform and some of its most important uses in digital image processing.

Chapter 5: The major revision in this chapter was the addition of a section dealing with image reconstruction from projections, with a focus on computed tomography (CT). Coverage of CT starts with an intuitive example of the underlying principles of image reconstruction from projections and the various imaging modalities used in practice. We then derive the Radon transform and the Fourier slice theorem and use them as the basis for formulating the concept of filtered backprojections. Both parallel- and fan-beam reconstruction are discussed and illustrated using several examples. Inclusion of this material was long overdue and represents an important addition to the book.

Chapter 6: Revisions to this chapter were limited to clarifications and a few corrections in notation. No new concepts were added.

Chapter 7: We received numerous comments regarding the fact that the transition from previous chapters into wavelets was proving difficult for beginners. Several of the foundation sections were rewritten in an effort to make the material clearer.

Chapter 8: This chapter was rewritten completely to bring it up to date. New coding techniques, expanded coverage of video, a revision of the section on standards, and an introduction to image watermarking are among the major changes. The new organization will make it easier for beginning students to follow the material.

Chapter 9: The major changes in this chapter are the inclusion of a new section on morphological reconstruction and a complete revision of the section on gray-scale morphology. The inclusion of morphological reconstruction for both binary and gray-scale images made it possible to develop more complex and useful morphological algorithms than before.

Chapter 10: This chapter also underwent a major revision. The organization is as before, but the new material includes greater emphasis on basic principles as well as discussion of more advanced segmentation techniques. Edge models are discussed and illustrated in more detail, as are properties of the gradient. The Marr-Hildreth and Canny edge detectors are included to illustrate more advanced edge detection techniques. The section on thresholding was rewritten also to include Otsu's method, an optimum thresholding technique whose popularity has increased significantly over the past few years. We introduced this approach in favor of optimum thresholding based on the Bayes classification rule, not only because it is easier to understand and implement, but also because it is used considerably more in practice. The Bayes approach was moved to Chapter 12, where the Bayes decision rule is discussed in more detail. We also added a discussion on how to use edge information to improve thresholding and several new adaptive thresholding examples. Except for minor clarifications, the sections on morphological watersheds and the use of motion for segmentation are as in the previous edition.

Chapter 11: The principal changes in this chapter are the inclusion of a boundary-following algorithm, a detailed derivation of an algorithm to fit a minimum-perimeter polygon to a digital boundary, and a new section on co-occurrence matrices for texture description. Numerous examples in Sections 11.2 and 11.3 are new, as are all the examples in Section 11.4.

Chapter 12: Changes in this chapter include a new section on matching by correlation and a new example on using the Bayes classifier to recognize regions of interest in multispectral images. The section on structural classification now limits discussion only to string matching.

All the revisions just mentioned resulted in over 400 new images, over 200 new line drawings and tables, and more than 80 new homework problems. Where appropriate, complex processing procedures were summarized in the form of step-by-step algorithm formats. The references at the end of all chapters were updated also.

The book Web site, established during the launch of the second edition, has been a success, attracting more than 20,000 visitors each month. The site was redesigned and upgraded to correspond to the launch of this edition. For more details on features and content, see *The Book Web Site*, following the *Acknowledgments*.

This edition of *Digital Image Processing* is a reflection of how the educational needs of our readers have changed since 2002. As is usual in a project such as this, progress in the field continues after work on the manuscript stops. One of the reasons why this book has been so well accepted since it first appeared in 1977 is its continued emphasis on fundamental concepts—an approach that, among other things, attempts to provide a measure of stability in a rapidly evolving body of knowledge. We have tried to follow the same principle in preparing this edition of the book.

R. C. G.
R. E. W.

Acknowledgments

We are indebted to a number of individuals in academic circles as well as in industry and government who have contributed to this edition of the book. Their contributions have been important in so many different ways that we find it difficult to acknowledge them in any other way but alphabetically. In particular, we wish to extend our appreciation to our colleagues Mongi A. Abidi, Steven L. Eddins, Yongmin Kim, Bryan Morse, Andrew Oldroyd, Ali M. Reza, Edgardo Felipe Riveron, Jose Ruiz Shulcloper, and Cameron H. G. Wright for their many suggestions on how to improve the presentation and/or the scope of coverage in the book.

Numerous individuals and organizations provided us with valuable assistance during the writing of this edition. Again, we list them alphabetically. We are particularly indebted to Courtney Esposito and Naomi Fernandes at The Mathworks for providing us with MATLAB software and support that were important in our ability to create or clarify many of the examples and experimental results included in this edition of the book. A significant percentage of the new images used in this edition (and in some cases their history and interpretation) were obtained through the efforts of individuals whose contributions are sincerely appreciated. In particular, we wish to acknowledge the efforts of Serge Beucher, Melissa D. Binde, James Blankenship, Uwe Boos, Ernesto Bribiesca, Michael E. Casey, Michael W. Davidson, Susan L. Forsburg, Thomas R. Gest, Lalit Gupta, Daniel A. Hammer, Zhong He, Roger Heady, Juan A. Herrera, John M. Hudak, Michael Hurwitz, Chris J. Johannsen, Rhonda Knighton, Don P. Mitchell, Ashley Mohamed, A. Morris, Curtis C. Ober, Joseph E. Pascente, David. R. Pickens, Michael Robinson, Barrett A. Schaefer, Michael Shaffer, Pete Sites, Sally Stowe, Craig Watson, David K. Wehe, and Robert A. West. We also wish to acknowledge other individuals and organizations cited in the captions of numerous figures throughout the book for their permission to use that material.

Special thanks go to Vince O'Brien, Rose Kernan, Scott Disanno, Michael McDonald, Joe Ruddick, Heather Scott, and Alice Dworkin, at Prentice Hall. Their creativity, assistance, and patience during the production of this book are truly appreciated.

R.C.G.
R.E.W.

The Book Web Site

www.prenhall.com/gonzalezwoods
or its mirror site,
www.imageprocessingplace.com

Digital Image Processing is a completely self-contained book. However, the companion Web site offers additional support in a number of important areas.

For the Student or Independent Reader the site contains

- Reviews in areas such as probability, statistics, vectors, and matrices.
- Complete solutions to selected problems.
- Computer projects.
- A Tutorials section containing dozens of tutorials on most of the topics discussed in the book.
- A database containing all the images in the book.

For the Instructor the site contains

- An *Instructor's Manual* with complete solutions to all the problems in the book, as well as course and laboratory teaching guidelines. The manual is available free of charge to instructors who have adopted the book for classroom use.
- Classroom presentation materials in PowerPoint format.
- Material removed from previous editions, downloadable in convenient PDF format.
- Numerous links to other educational resources.

For the Practitioner the site contains additional specialized topics such as

- Links to commercial sites.
- Selected new references.
- Links to commercial image databases.

The Web site is an ideal tool for keeping the book current between editions by including new topics, digital images, and other relevant material that has appeared after the book was published. Although considerable care was taken in the production of the book, the Web site is also a convenient repository for any errors that may be discovered between printings. References to the book Web site are designated in the book by the following icon:

About the Authors

Rafael C. Gonzalez

R. C. Gonzalez received the B.S.E.E. degree from the University of Miami in 1965 and the M.E. and Ph.D. degrees in electrical engineering from the University of Florida, Gainesville, in 1967 and 1970, respectively. He joined the Electrical and Computer Engineering Department at the University of Tennessee, Knoxville (UTK) in 1970, where he became Associate Professor in 1973, Professor in 1978, and Distinguished Service Professor in 1984. He served as Chairman of the department from 1994 through 1997. He is currently a Professor Emeritus at UTK.

Gonzalez is the founder of the Image & Pattern Analysis Laboratory and the Robotics & Computer Vision Laboratory at the University of Tennessee. He also founded Perceptics Corporation in 1982 and was its president until 1992. The last three years of this period were spent under a full-time employment contract with Westinghouse Corporation, who acquired the company in 1989.

Under his direction, Perceptics became highly successful in image processing, computer vision, and laser disk storage technology. In its initial ten years, Perceptics introduced a series of innovative products, including: The world's first commercially available computer vision system for automatically reading license plates on moving vehicles; a series of large-scale image processing and archiving systems used by the U.S. Navy at six different manufacturing sites throughout the country to inspect the rocket motors of missiles in the Trident II Submarine Program; the market-leading family of imaging boards for advanced Macintosh computers; and a line of trillion-byte laser disk products.

He is a frequent consultant to industry and government in the areas of pattern recognition, image processing, and machine learning. His academic honors for work in these fields include the 1977 UTK College of Engineering Faculty Achievement Award; the 1978 UTK Chancellor's Research Scholar Award; the 1980 Magnavox Engineering Professor Award; and the 1980 M.E. Brooks Distinguished Professor Award. In 1981, he became an IBM Professor at the University of Tennessee, and in 1984, he was named a Distinguished Service Professor there. He was awarded a Distinguished Alumnus Award by the University of Miami in 1985, the Phi Kappa Phi Scholar Award in 1986, and the University of Tennessee's Nathan W. Dougherty Award for Excellence in Engineering in 1992.

Honors for industrial accomplishment include the 1987 IEEE Outstanding Engineer Award for Commercial Development in Tennessee; the 1988 Albert Rose Nat'l Award for Excellence in Commercial Image Processing; the 1989 B. Otto Wheeley Award for Excellence in Technology Transfer; the 1989 Coopers and Lybrand Entrepreneur of the Year Award; the 1992 IEEE Region 3 Outstanding Engineer Award; and the 1993 Automated Imaging Association National Award for Technology Development.

Gonzalez is author or co-author of over 100 technical articles, two edited books, and four textbooks in the fields of pattern recognition, image processing, and robotics. His books are used in over 1000 universities and research institutions throughout the world. He is listed in the prestigious Marquis *Who's Who in America*, Marquis *Who's Who in Engineering*, Marquis *Who's Who in the World*, and in 10 other national and international biographical citations. He is the co-holder of two U.S. Patents, and has been an associate editor of the *IEEE Transactions on Systems, Man and Cybernetics*, and the *International Journal of Computer and Information Sciences*. He is a member of numerous professional and honorary societies, including Tau Beta Pi, Phi Kappa Phi, Eta Kappa Nu, and Sigma Xi. He is a Fellow of the IEEE.

Richard E. Woods

Richard E. Woods earned his B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Tennessee, Knoxville. His professional experiences range from entrepreneurial to the more traditional academic, consulting, governmental, and industrial pursuits. Most recently, he founded MedData Interactive, a high technology company specializing in the development of handheld computer systems for medical applications. He was also a founder and Vice President of Perceptics Corporation, where he was responsible for the development of many of the company's quantitative image analysis and autonomous decision-making products.

Prior to Perceptics and MedData, Dr. Woods was an Assistant Professor of Electrical Engineering and Computer Science at the University of Tennessee and prior to that, a computer applications engineer at Union Carbide Corporation. As a consultant, he has been involved in the development of a number of special-purpose digital processors for a variety of space and military agencies, including NASA, the Ballistic Missile Systems Command, and the Oak Ridge National Laboratory.

Dr. Woods has published numerous articles related to digital signal processing and is a member of several professional societies, including Tau Beta Pi, Phi Kappa Phi, and the IEEE. In 1986, he was recognized as a Distinguished Engineering Alumnus of the University of Tennessee.

1 Introduction

One picture is worth more than ten thousand words.

Anonymous

Preview

Interest in digital image processing methods stems from two principal application areas: improvement of pictorial information for human interpretation; and processing of image data for storage, transmission, and representation for autonomous machine perception. This chapter has several objectives: (1) to define the scope of the field that we call image processing; (2) to give a historical perspective of the origins of this field; (3) to give you an idea of the state of the art in image processing by examining some of the principal areas in which it is applied; (4) to discuss briefly the principal approaches used in digital image processing; (5) to give an overview of the components contained in a typical, general-purpose image processing system; and (6) to provide direction to the books and other literature where image processing work normally is reported.

1.1 What Is Digital Image Processing?

An image may be defined as a two-dimensional function, $f(x, y)$, where x and y are *spatial* (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the *intensity* or *gray level* of the image at that point. When x, y, and the intensity values of f are all finite, discrete quantities, we call the image a *digital image*. The field of *digital image processing* refers to processing digital images by means of a digital computer. Note that a digital image is composed of a finite number of elements, each of which has a particular location and value. These elements are called *picture elements*, *image elements*, *pels*, and *pixels*. *Pixel* is the term used most widely to denote the elements of a digital image. We consider these definitions in more formal terms in Chapter 2.

Vision is the most advanced of our senses, so it is not surprising that images play the single most important role in human perception. However, unlike humans, who are limited to the visual band of the electromagnetic (EM) spectrum, imaging machines cover almost the entire EM spectrum, ranging from gamma to radio waves. They can operate on images generated by sources that humans are not accustomed to associating with images. These include ultrasound, electron microscopy, and computer-generated images. Thus, digital image processing encompasses a wide and varied field of applications.

There is no general agreement among authors regarding where image processing stops and other related areas, such as image analysis and computer vision, start. Sometimes a distinction is made by defining image processing as a discipline in which both the input and output of a process are images. We believe this to be a limiting and somewhat artificial boundary. For example, under this definition, even the trivial task of computing the average intensity of an image (which yields a single number) would not be considered an image processing operation. On the other hand, there are fields such as computer vision whose ultimate goal is to use computers to emulate human vision, including learning and being able to make inferences and take actions based on visual inputs. This area itself is a branch of artificial intelligence (AI) whose objective is to emulate human intelligence. The field of AI is in its earliest stages of infancy in terms of development, with progress having been much slower than originally anticipated. The area of image analysis (also called image understanding) is in between image processing and computer vision.

There are no clear-cut boundaries in the continuum from image processing at one end to computer vision at the other. However, one useful paradigm is to consider three types of computerized processes in this continuum: low-, mid-, and high-level processes. Low-level processes involve primitive operations such as image preprocessing to reduce noise, contrast enhancement, and image sharpening. A low-level process is characterized by the fact that both its inputs and outputs are images. Mid-level processing on images involves tasks such as segmentation (partitioning an image into regions or objects), description of those objects to reduce them to a form suitable for computer processing, and classification (recognition) of individual objects. A mid-level process is characterized by the fact that its inputs generally are images, but its outputs are attributes extracted from those images (e.g., edges, contours, and the identity of individual objects). Finally, higher-level processing involves "making sense" of an ensemble of recognized objects, as in image analysis, and, at the far end of the continuum, performing the cognitive functions normally associated with vision.

Based on the preceding comments, we see that a logical place of overlap between image processing and image analysis is the area of recognition of individual regions or objects in an image. Thus, what we call in this book *digital image processing* encompasses processes whose inputs and outputs are images and, in addition, encompasses processes that extract attributes from images, up to and including the recognition of individual objects. As an illustration to clarify these concepts, consider the area of automated analysis of text. The processes of acquiring an image of the area containing the text, preprocessing that image, extracting (segmenting) the individual characters, describing the characters in a form suitable for computer processing, and recognizing those individual characters are in the scope of what we call digital image processing in this book. Making sense of the content of the page may be viewed as being in the domain of image analysis and even computer vision, depending on the level of complexity implied by the statement "making sense." As will become evident shortly, digital image processing, as we have defined it, is used successfully in a broad range of areas of exceptional social and economic value. The concepts developed in the following chapters are the foundation for the methods used in those application areas.

1.2 The Origins of Digital Image Processing

One of the first applications of digital images was in the newspaper industry, when pictures were first sent by submarine cable between London and New York. Introduction of the Bartlane cable picture transmission system in the early 1920s reduced the time required to transport a picture across the Atlantic from more than a week to less than three hours. Specialized printing equipment coded pictures for cable transmission and then reconstructed them at the receiving end. Figure 1.1 was transmitted in this way and reproduced on a telegraph printer fitted with typefaces simulating a halftone pattern.

Some of the initial problems in improving the visual quality of these early digital pictures were related to the selection of printing procedures and the distribution of intensity levels. The printing method used to obtain Fig. 1.1 was abandoned toward the end of 1921 in favor of a technique based on photographic reproduction made from tapes perforated at the telegraph receiving terminal. Figure 1.2 shows an image obtained using this method. The improvements over Fig. 1.1 are evident, both in tonal quality and in resolution.

FIGURE 1.1 A digital picture produced in 1921 from a coded tape by a telegraph printer with special type faces. (McFarlane.[†])

[†]References in the Bibliography at the end of the book are listed in alphabetical order by authors' last names.

FIGURE 1.2 A digital picture made in 1922 from a tape punched after the signals had crossed the Atlantic twice. (McFarlane.)

The early Bartlane systems were capable of coding images in five distinct levels of gray. This capability was increased to 15 levels in 1929. Figure 1.3 is typical of the type of images that could be obtained using the 15-tone equipment. During this period, introduction of a system for developing a film plate via light beams that were modulated by the coded picture tape improved the reproduction process considerably.

Although the examples just cited involve digital images, they are not considered digital image processing results in the context of our definition because computers were not involved in their creation. Thus, the history of digital image processing is intimately tied to the development of the digital computer. In fact, digital images require so much storage and computational power that progress in the field of digital image processing has been dependent on the development of digital computers and of supporting technologies that include data storage, display, and transmission.

The idea of a computer goes back to the invention of the abacus in Asia Minor, more than 5000 years ago. More recently, there were developments in the past two centuries that are the foundation of what we call a computer today. However, the basis for what we call a *modern* digital computer dates back to only the 1940s with the introduction by John von Neumann of two key concepts: (1) a memory to hold a stored program and data, and (2) conditional branching. These two ideas are the foundation of a central processing unit (CPU), which is at the heart of computers today. Starting with von Neumann, there were a series of key advances that led to computers powerful enough to

FIGURE 1.3 Unretouched cable picture of Generals Pershing and Foch, transmitted in 1929 from London to New York by 15-tone equipment. (McFarlane.)

be used for digital image processing. Briefly, these advances may be summarized as follows: (1) the invention of the transistor at Bell Laboratories in 1948; (2) the development in the 1950s and 1960s of the high-level programming languages COBOL (Common Business-Oriented Language) and FORTRAN (Formula Translator); (3) the invention of the integrated circuit (IC) at Texas Instruments in 1958; (4) the development of operating systems in the early 1960s; (5) the development of the microprocessor (a single chip consisting of the central processing unit, memory, and input and output controls) by Intel in the early 1970s; (6) introduction by IBM of the personal computer in 1981; and (7) progressive miniaturization of components, starting with large scale integration (LI) in the late 1970s, then very large scale integration (VLSI) in the 1980s, to the present use of ultra large scale integration (ULSI). Concurrent with these advances were developments in the areas of mass storage and display systems, both of which are fundamental requirements for digital image processing.

The first computers powerful enough to carry out meaningful image processing tasks appeared in the early 1960s. The birth of what we call digital image processing today can be traced to the availability of those machines and to the onset of the space program during that period. It took the combination of those two developments to bring into focus the potential of digital image processing concepts. Work on using computer techniques for improving images from a space probe began at the Jet Propulsion Laboratory (Pasadena, California) in 1964 when pictures of the moon transmitted by *Ranger 7* were processed by a computer to correct various types of image distortion inherent in the on-board television camera. Figure 1.4 shows the first image of the moon taken by *Ranger 7* on July 31, 1964 at 9:09 A.M. Eastern Daylight Time (EDT), about 17 minutes before impacting the lunar surface (the markers, called *reseau* marks, are used for geometric corrections, as discussed in Chapter 2). This also is the first image of the moon taken by a U.S. spacecraft. The imaging lessons learned with *Ranger 7* served as the basis for improved methods used to enhance and restore images from the Surveyor missions to the moon, the Mariner series of flyby missions to Mars, the Apollo manned flights to the moon, and others.

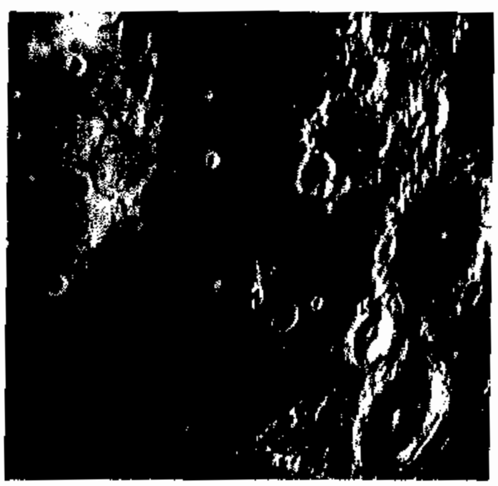


FIGURE 1.4 The first picture of the moon by a U.S. spacecraft. *Ranger 7* took this image on July 31, 1964 at 9:09 A.M. EDT, about 17 minutes before impacting the lunar surface. (Courtesy of NASA.)

In parallel with space applications, digital image processing techniques began in the late 1960s and early 1970s to be used in medical imaging, remote Earth resources observations, and astronomy. The invention in the early 1970s of computerized axial tomography (CAT), also called computerized tomography (CT) for short, is one of the most important events in the application of image processing in medical diagnosis. Computerized axial tomography is a process in which a ring of detectors encircles an object (or patient) and an X-ray source, concentric with the detector ring, rotates about the object. The X-rays pass through the object and are collected at the opposite end by the corresponding detectors in the ring. As the source rotates, this procedure is repeated. Tomography consists of algorithms that use the sensed data to construct an image that represents a "slice" through the object. Motion of the object in a direction perpendicular to the ring of detectors produces a set of such slices, which constitute a three-dimensional (3-D) rendition of the inside of the object. Tomography was invented independently by Sir Godfrey N. Hounsfield and Professor Allan M. Cormack, who shared the 1979 Nobel Prize in Medicine for their invention. It is interesting to note that X-rays were discovered in 1895 by Wilhelm Conrad Roentgen, for which he received the 1901 Nobel Prize for Physics. These two inventions, nearly 100 years apart, led to some of the most important applications of image processing today.

From the 1960s until the present, the field of image processing has grown vigorously. In addition to applications in medicine and the space program, digital image processing techniques now are used in a broad range of applications. Computer procedures are used to enhance the contrast or code the intensity levels into color for easier interpretation of X-rays and other images used in industry, medicine, and the biological sciences. Geographers use the same or similar techniques to study pollution patterns from aerial and satellite imagery. Image enhancement and restoration procedures are used to process degraded images of unrecoverable objects or experimental results too expensive to duplicate. In archeology, image processing methods have successfully restored blurred pictures that were the only available records of rare artifacts lost or damaged after being photographed. In physics and related fields, computer techniques routinely enhance images of experiments in areas such as high-energy plasmas and electron microscopy. Similarly successful applications of image processing concepts can be found in astronomy, biology, nuclear medicine, law enforcement, defense, and industry.

These examples illustrate processing results intended for human interpretation. The second major area of application of digital image processing techniques mentioned at the beginning of this chapter is in solving problems dealing with machine perception. In this case, interest is on procedures for extracting from an image information in a form suitable for computer processing. Often, this information bears little resemblance to visual features that humans use in interpreting the content of an image. Examples of the type of information used in machine perception are statistical moments, Fourier transform coefficients, and multidimensional distance measures. Typical problems in machine perception that routinely utilize image processing techniques are automatic character recognition, industrial machine vision for product assembly and inspection, military recognizance, automatic processing of fingerprints, screening of X-rays and blood samples, and machine processing of aerial and satellite imagery for weather prediction and environmental assessment. The continuing decline in the ratio of computer price to performance and the expansion of networking and communication bandwidth via the World Wide Web and the Internet have created unprecedented opportunities for continued growth of digital image processing. Some of these application areas are illustrated in the following section.

1.3 Examples of Fields that Use Digital Image Processing

Today, there is almost no area of technical endeavor that is not impacted in some way by digital image processing. We can cover only a few of these applications in the context and space of the current discussion. However, limited as it is, the material presented in this section will leave no doubt in your mind regarding the breadth and importance of digital image processing. We show in this section numerous areas of application, each of which routinely utilizes the digital image processing techniques developed in the following chapters. Many of the images shown in this section are used later in one or more of the examples given in the book. All images shown are digital.

The areas of application of digital image processing are so varied that some form of organization is desirable in attempting to capture the breadth of this field. One of the simplest ways to develop a basic understanding of the extent of image processing applications is to categorize images according to their source (e.g., visual, X-ray, and so on). The principal energy source for images in use today is the electromagnetic energy spectrum. Other important sources of energy include acoustic, ultrasonic, and electronic (in the form of electron beams used in electron microscopy). Synthetic images, used for modeling and visualization, are generated by computer. In this section we discuss briefly how images are generated in these various categories and the areas in which they are applied. Methods for converting images into digital form are discussed in the next chapter.

Images based on radiation from the EM spectrum are the most familiar, especially images in the X-ray and visual bands of the spectrum. Electromagnetic waves can be conceptualized as propagating sinusoidal waves of varying wavelengths, or they can be thought of as a stream of massless particles, each traveling in a wavelike pattern and moving at the speed of light. Each massless particle contains a certain amount (or bundle) of energy. Each bundle of energy is called a *photon*. If spectral bands are grouped according to energy per photon, we obtain the spectrum shown in Fig. 1.5, ranging from gamma rays (highest energy) at one end to radio waves (lowest energy) at the other.

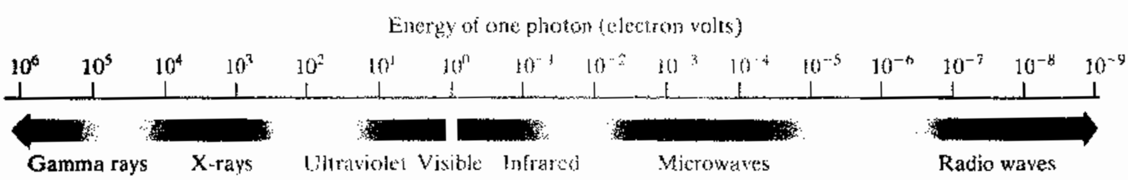
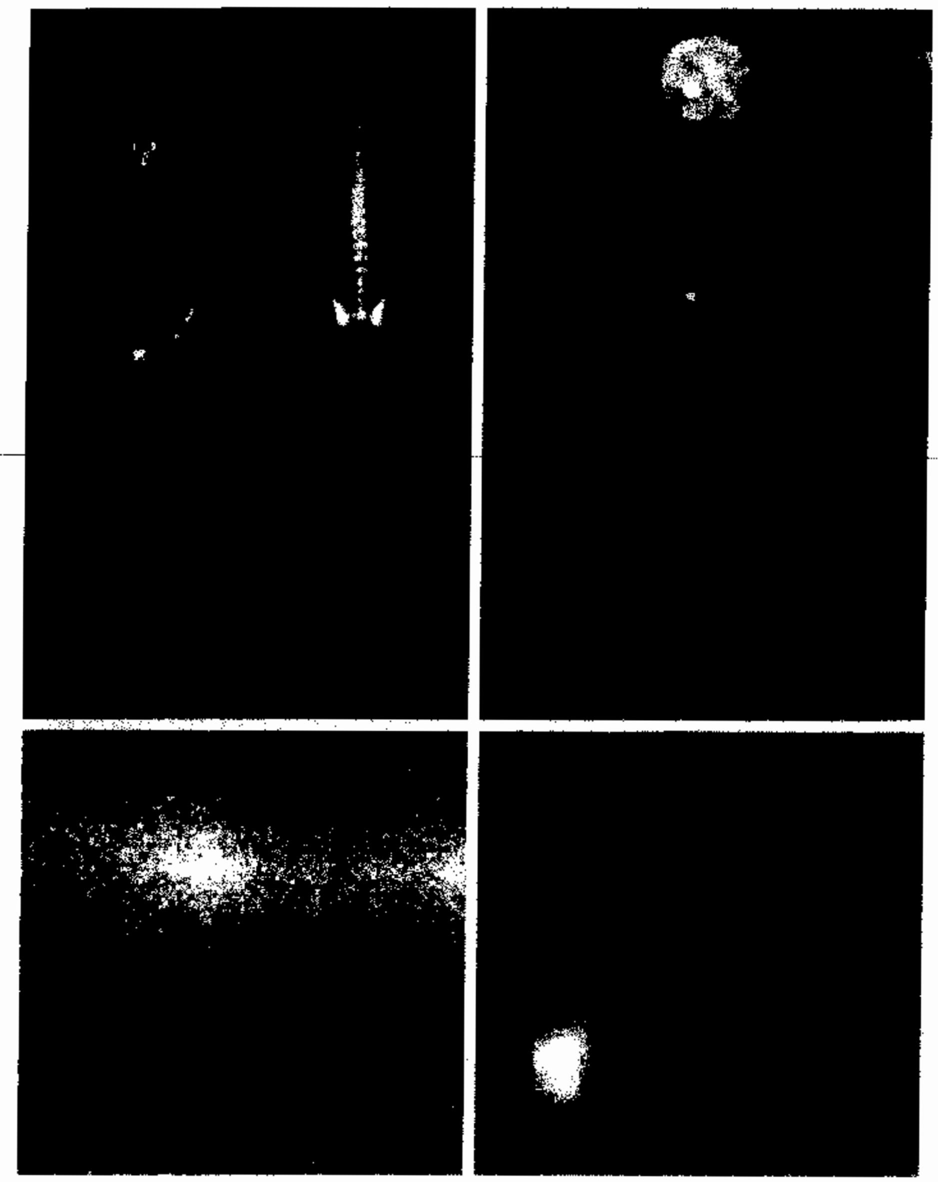


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

The bands are shown shaded to convey the fact that bands of the EM spectrum are not distinct but rather transition smoothly from one to the other.

1.3.1 Gamma-Ray Imaging

Major uses of imaging based on gamma rays include nuclear medicine and astronomical observations. In nuclear medicine, the approach is to inject a patient with a radioactive isotope that emits gamma rays as it decays. Images are produced from the emissions collected by gamma ray detectors. Figure 1.6(a) shows an image of a complete bone scan obtained by using gamma-ray imaging. Images of this sort are used to locate sites of bone pathology, such as infections



a b
c d

FIGURE 1.6 Examples of gamma-ray imaging. (a) Bone scan. (b) PET image. (c) Cygnus Loop. (d) Gamma radiation (bright spot) from a reactor valve. (Images courtesy of (a) G.E. Medical Systems, (b) Dr. Michael E. Casey, CTI PET Systems, (c) NASA, (d) Professors Zhong He and David K. Wehe, University of Michigan.)