Digital Image Processing

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SERIES EDITOR'S FOREWORD

Execution times of modern digital computers are measured in nanoseconds. They can solve hundreds of simultaneous ordinary differential equations with speed and accuracy. But what does this immense capability imply with regard to solving the scientific, engineering, economic, and social problems confronting mankind? Clearly, much effort has to be expended in finding answers to that question.

In some fields, it is not yet possible to write mathematical equations which accurately describe processes of interest. Here, the computer may be used simply to simulate a process and, perhaps, to observe the efficacy of different control processes. In others, a mathematical description may be available, but the equations are frequently difficult to solve numerically. In such cases, the difficulties may be faced squarely and possibly overcome; alternatively, formulations may be sought which are more compatible with the inherent capabilities of computers. Mathematics itself nourishes and is nourished by such developments.

Each order of magnitude increase in speed and memory size of computers requires a reexamination of computational techniques and an assessment of the new problems which may be brought within the realm of solution. Volumes in this series will provide indications of current thinking regarding problem formulations, mathematical analysis, and computational treatment.

Digital image processing cuts across many areas – medical diagnosis, planetary physics, robotics, and industrial inspection, to name a few. But as useful as these applications are, the concepts that give rise to them are even more fascinating. In this upper-division and graduate-level volume, the authors demonstrate great skill in developing a thorough treatment of digital image processing concepts at an introductory level. The volume is particularly welcome in this series for the exemplary way in which it combines mathematical analysis and computation to obtain socially useful results.

Robert Kalaba

PREFACE

Interest in digital image processing techniques dates back to the early 1920's when digitized pictures of world news events were first transmitted by submarine cable between New York and London. Application of digital image processing concepts, however, did not become widespread until the middle 1960's, when third-generation digital computers began to offer the speed and storage capabilities required for practical implementation of image processing algorithms. Since then, this area has experienced vigorous growth, having been a subject of interdisciplinary study and research in such fields as engineering, computer science, information science, statistics, physics, chemistry, biology, and medicine. The results of these efforts have established the value of image processing techniques in a variety of problems ranging from restoration and enhancement of space-probe pictures to processing of fingerprints for commercial transactions.

The principal objectives of this book are to provide an introduction to basic concepts and techniques for digital image processing and to lay a foundation which can be used as the basis for further study and research in this field. To achieve these objectives, we have focused attention on material which we feel is fundamental and where the scope of application is not limited to specialized problems. Most of the topics covered in the text have been taught by the authors in senior and first-year graduate courses at the University of Tennessee and at Purdue University. This book also contains revised material presented in short courses and seminars. The mathematical level is well within the grasp of seniors in a technical discipline such as engineering and computer science, which require introductory preparation in computer programming, matrix theory, probability, and mathematical analysis.

It has been our experience that one of the principal features which attracts students to a course in image processing is the opportunity to implement and to test with real data the concepts and algorithms developed in the classroom. The ideal environment for this is provided by an image processing system that includes an image digitizer, a general-purpose computer, and image display equipment. The appendices to this book provide an alternative route for instruction when such a system is not available. Appendix A contains a FORTRAN subroutine for displaying gray-tone images on an ordinary lineprinter, and Appendix B contains a set of coded images suitable for experimenting with the methods discussed in the text. This material can be utilized in conjunction with almost any general-purpose computer, thus allowing the reader to gain experience with image processing techniques through algorithm implementation and visual display of the results.

Digital Image Processing is one of three related books published by Addison-Wesley, Advanced Book Program. The first of these, *Pattern Recognition Principles* (Tou and Gonzalez, 1974) describes deterministic, statistical, and syntactic pattern recognition concepts. This latter topic is treated in greater depth in *Syntactic Pattern Recognition: An Introduction* (Gonzalez and Thomason, in preparation) which can be used by itself or as a supplement to *Pattern Recognition Principles*. The objective of these books is to provide a unified, introductory treatment of pattern recognition and image processing concepts with emphasis on fundamentals and consistency of notation.

Rafael C. Gonzalez
Paul Wintz

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CONTENTS

1
INTRODUCTION

One picture is worth more
than ten thousand words.
Anonymous

1.1 BACKGROUND

Interest in digital image processing methods stems from two principal application areas: improvement of pictorial information for human interpretation, and processing of scene data for autonomous machine perception. One of the first applications of image processing techniques in the first category was in improving digitized newspaper pictures sent by submarine cable between London and New York. Introduction of the Bartlane cable picture transmission system in the early 1920's reduced the time required to transport a picture across the Atlantic from more than a week to less than three hours. Pictures were coded for cable transmission and then reconstructed at the receiving end by specialized printing equipment. Figure 1.1 was transmitted in this way and reproduced on a telegraph printer fitted with type faces 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 brightness 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.

The early Bartlane systems were capable of coding images in five distinct brightness levels. This capability was increased to fifteen levels in 1929. Figure 1.3 is indicative of the type of image that could be obtained using the fifteen-tone equipment. During this period, the reproduction process was also improved considerably by the introduction of a system for

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developing a film plate via light beams which were modulated by the coded picture tape.

Figure 1.1. A digital picture produced in 1921 from a coded tape by a telegraph printer with special type faces. (From McFarlane [1972].)

Although improvements on processing methods for transmitted digital pictures continued to be made over the next thirty-five years, it took the combined advents of large-scale digital computers and the space program to bring into focus the potentials of 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. These techniques served as the basis for improved methods used in the enhancement and restoration of images from such familiar programs as the Surveyor missions to the Moon, the Mariner series of flyby missions to Mars, and the Apollo manned flights to the Moon.

From 1964 until this writing, the field of image processing has experienced vigorous growth. In addition to applications in the space program, digital image processing techniques are used today in a variety of

Figure 1.2. A digital picture made from a tape punched after the signals had crossed the Atlantic twice. Some errors are visible. (From McFarlane [1972].)

Figure 1.3. Unretouched cable picture of Generals Pershing and Foch, transmitted by 15-tone equipment from London to New York. (From McFarlane [1972].)

problems which, although often unrelated, share a common need for methods capable of enhancing pictorial information for human interpretation and analysis. In medicine, for instance, physicians are assisted by computer procedures that enhance the contrast or code the intensity levels into color for easier interpretation of x-rays and other biomedical images. The same or similar techniques are used by geographers in studying pollution patterns from aerial and satellite imagery. Image enhancement and restoration procedures have been used to process degraded images depicting unrecoverable objects or experimental results too expensive to duplicate. There have been instances in archeology, for example, where blurred pictures which were the only available records of rare artifacts lost or damaged after being photographed, have been successfully restored by image processing methods. In physics and related fields, images of experiments in such areas as high-energy plasmas and electron microscopy are routinely enhanced by computer techniques. Similar successful applications of image processing concepts can be found in astronomy, biology, nuclear medicine, law enforcement, defense, and industrial applications.

Some typical examples of the results obtainable with digital image processing techniques are shown in Fig. 1.4. The original images are shown on the left and the corresponding computer-processed images on the right. Figure 1.4(a) is a picture of the Martian surface which was corrupted by interference during transmission to Earth by a space probe. The interference, which in this case appears as a set of vertical, structured lines, can be almost completely removed by computer processing, as shown in Fig. 1.4(b). Figures 1.4(c) and (d) illustrate the considerable improvement that can be

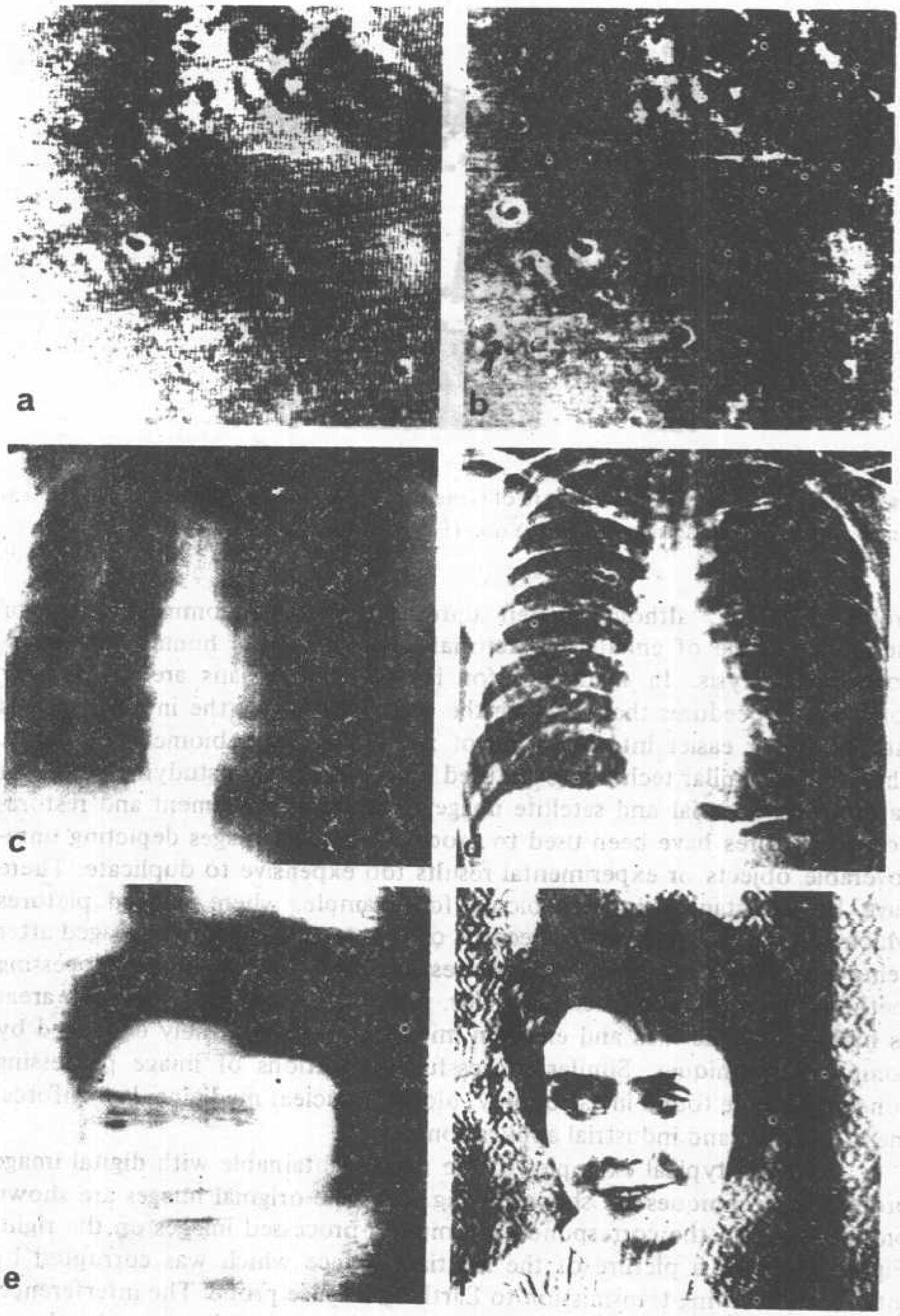

Figure 1.4. Examples of computer-processed images.

made on an x-ray image by contrast and edge enhancement. The image shown in Fig. 1.4(e) was blurred by uniform motion during exposure, and the image shown in Fig. 1.4(f) resulted after application of a deblurring algorithm. These illustrations are typical of those discussed in detail in Chapters 4 and 5.

The foregoing examples have in common the fact that processing results are intended for human interpretation. The second major application area of digital image processing techniques mentioned at the beginning of this section is in problems dealing with machine perception. In this case, interest is focused on procedures for extracting from an image information in a form suitable for computer processing. Often, this information bears little resemblance to visual features used by humans 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 which routinely employ image processing techniques are automatic character recognition, industrial robots 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 crop assessment.

1.2 DIGITAL IMAGE REPRESENTATION

As used in this book, the term *monochrome image* or simply *image*, refers to a two-dimensional light intensity function $f(x, y)$, where x and y denote spatial coordinates and the value of f at any point (x, y) is proportional to the brightness (or *gray level*) of the image at that point. An example illustrating the axis convention used throughout the following chapters is shown in Fig. 1.5. It is sometimes useful to view an image function in perspective with the third axis being brightness. If Fig. 1.5 were viewed in this way it would appear as a series of active peaks in regions with numerous changes in brightness levels and smoother regions or plateaus where the brightness levels varied little or were constant. If we follow the convention of assigning proportionately higher values to brighter areas, the height of the components in the plot would be proportional to the corresponding brightness in the image.

A *digital image* is an image $f(x, y)$ which has been discretized both in spatial coordinates and in brightness. We may consider a digital image as a matrix whose row and column indices identify a point in the image and the corresponding matrix element value identifies the gray level at that point. The elements of such a digital array are called *image elements*, *picture elements*, *pixels*, or *pels*, with the last two names being commonly used

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