IOANNIS PITAS

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DIGITAL IMAGE PROCESSING ALGORITHMS

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Digital Image Processing Algorithms

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Preface

Digital image processing, analysis and computer vision have exhibited an impressive growth in the past decade in terms of both theoretical development and applications. They constitute a leading technology in a number of very important areas, e.g. in digital telecommunications, broadcasting, medical imaging, multimedia systems, biology, material sciences, robotics and manufacturing, intelligent sensing systems, remote sensing, graphic arts and printing. This growth is reflected in the large number of papers published in international scientific journals each year, as well as in a good number of specialized books in digital image processing, analysis and computer vision. The application tasks created the need to construct a variety of digital image processing and analysis algorithms. Most of them are scattered in the relevant scientific journals. Several of them are described in specialized books. However, most of the digital image processing and computer vision books concentrate on the theory and the applications of digital image processing rather than on its algorithmic part. No systematic effort has been made so far to gather, analyze and present digital image processing and analysis algorithms. The novelty and the aim of this monograph is to present such algorithms in a rather systematic way. The algorithms described cover many aspects of digital image processing, analysis and coding. However, these algorithms are only a small fraction of the total number of algorithms existing in the literature. They have been selected on the basis of their acceptance by the scientific community. Indications of their acceptance are their appearance in classical digital image processing textbooks as well as their reference by scientists. This book is a result of the active involvement of the author in digital image processing over the past decade. Therefore, it is strongly related to his research activities, especially in digital image transform algorithms, nonlinear digital image processing and mathematical morphology. Several algorithms and programs presented in the book are byproducts of the author's research and teaching activities.

The algorithms described in this book are presented in C code. This language has been chosen because of its wide acceptance by the digital image processing community. FORTRAN is also quite popular in digital image processing. However, we think that C has definite advantages over FORTRAN in algorithms where dynamic memory allocation, lists or trees are needed. This is the case in several digital image analysis and computer vision algorithms. Several non-essential control commands have been removed from the body of subroutines. This increases C code readability and, at the same time, reduces software robustness, especially with respect to inappropriate subroutine parameter passing at subroutine calls. The algorithms described are compatible with each other. Together they form a digital image processing library called EIKONA. MICROSOFT C has been used for the development of EIKONA, because of its widespread use in IBM PC compatible computers. The author thinks that such a personal computer equipped with a true colour graphics card (or even a super VGA with 256/32,768 colours) and the MICROSOFT WINDOWS 3.x environment can be a very efficient and cheap instrument for developing digital image processing applications. A minimum of 2 MB RAM and a 386 processor with a mathematical coprocessor or a 486 processor is recommended. The C code is ANSI compatible for most subroutines, except those that perform memory allocation, I/O operations and image display. However, even these routines can be easily transformed to be linked with C programs in UNIX workstations.

The algorithms are accompanied by a discussion of the related theory. In many cases, algorithm description and discussion uses advanced mathematical concepts. Thus, it is assumed that the reader already has a basic understanding of digital signal/image processing and computer vision. Such knowledge can be obtained from any classical book on digital image processing and/or computer vision. This book is not intended to serve as a substitute for these textbooks. It is rather a guide that can be used by the student, scientist or engineer to deepen knowledge of digital image processing algorithms and their structure and/or to solve specific problems encountered in various applications. Advanced readers can read the material in section 1.4 and go directly to the description of the algorithms of interest. Less advanced readers are recommended to study Chapter 1 first and to proceed to more complicated algorithms in subsequent chapters as a second step. The study of Chapter 2 is recommended before the study of Chapters 3, 4 and the study of Chapters 5, 6 is recommended before the study of Chapter 7. Those readers interested in digital image processing can focus their attention on Chapters 1, 2, 3. Those readers interested in digital image coding can study Chapters 1, 2, 4. Finally, those readers interested in digital image analysis and computer vision can study Chapters 1, 5, 6, 7.

As has already been mentioned, the material presented in this monograph is the result of the involvement of the author in digital image processing over the past decade in research, teaching and the development of applications. The research has been supported by various projects funded by Greek as well as European Community research programmes. The author acknowledges the help of PhD students as well as Diploma Thesis students who have been involved in these projects in the past five years and who helped in the preparation of the material for this book. The following students have been involved actively in the past academic year under close supervision by the author: G. Angelopoulos, K.

Kotropoulos, N. Nikolaidis, V. Spais, G. Samoladas, G. Georgiou, A. Kanlis, D. Tzovaras, N. Grammalidis, X. Magnisalis, K. Mourtzanos, K. Palakidis. Furthermore, the teaching of the Digital Image Processing Course at the University of Thessaloniki has given the author an excellent audience for checking the contents of this book. The author acknowledges the secretarial support of these students in preparing the manuscript of this book.

I. Pitas
Thessaloniki, October 1992

Important note. The source code presented in this book has been carefully debugged. However, the author cannot accept responsibility for any loss or damage produced by use of this code. The code cannot be used in any form (source, object, executable) in any commercial product or software package without the written permission of the author.

Contents

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Digital Image Processing Fundamentals

1.1 Introduction

Human vision is one of the most important and complex perception mechanisms. It provides information needed for relatively simple tasks (e.g. object recognition) and for very complex tasks as well (e.g. planning, decision making, scientific research, development of human intelligence). The Chinese proverb 'One picture is worth a thousand words' expresses correctly the amount of information contained in a single picture. Pictures (images) play an important role in the organization of our society as a mass communication medium. Most media (e.g. newspapers, TV, cinema) use pictures (still or moving) as *information carriers*. The tremendous volume of optical information and the need for its processing and transmission paved the way to image processing by digital computers. The relevant efforts started around 1964 at the Jet Propulsion Laboratory (Pasadena, California) and concerned the digital processing of satellite images coming from the moon. Soon, a new branch of science called *digital image processing* emerged. Since then, it has exhibited a tremendous growth and created an important technological impact in several areas, e.g. in telecommunications, TV broadcasting, the printing and graphic arts industry, medicine and scientific research.

Digital image processing concerns the transformation of an image to a digital format and its processing by digital computers. Both the input and output of a digital image processing system are digital images. *Digital image analysis* is related to the description and recognition of the digital image content. Its input is a digital image and its output is a symbolic image description. In many cases, digital image analysis techniques simulate human vision functions. Therefore, the term *computer vision* can be used as equivalent to (or the superset of) digital image analysis. Human vision is a very complex neuro-physiological process. Its characteristics are only partially known, despite the tremendous progress that has been made in this area in the past decades. Therefore, its simulation by digital image analysis and computer vision is a very difficult task. In general, the techniques used in digital image analysis and computer vision differ greatly from the human visual perception mechanisms, although both have similar goals.

Another classification of digital image processing and computer vision techniques has three distinct classes: low-level vision, intermediate-level vision and high-level vision. *Low-level vision* algorithms are essentially digital image processing algorithms: their input and output are digital images. *Intermediate-level vision* algorithms have digital images as input and low-level symbolic representations of image features as output (e.g. representations of the object contours). *High-level vision* algorithms use symbolic representations for both input and output. High-level vision is closely related to artificial intelligence and to pattern recognition. It tries to simulate the high levels of human visual perception (image understanding).

The aim of this book is to provide algorithms that are employed either in digital image processing or in digital image analysis. An overview of the topics that will be covered in this book will be given in the next section. The fundamentals of digital image representation and the description of basic image processing operations will follow in subsequent sections. Thus, this chapter will provide the algorithmic basis for more advanced techniques that will be described in subsequent chapters.

1.2 Topics of digital image processing and analysis

This section will give a short overview of the various topics of digital image processing and analysis that will be covered in this book. The description will be rather qualitative and will be treated from an algorithmic point of view. More detailed descriptions will be given in the introduction of the relevant chapters. If the interested reader needs more information or a more thorough exposure to digital image processing and analysis, he or she is referred to the excellent literature in this area [JAI89], [BAL82], [GON87], [PRA91], [SCH89], [LEV85], [ROS82].

Digital image formation is the first step in any digital image processing application. The digital image formation system consists basically of an optical system, the sensor and the digitizer. The optical signal is usually transformed to an electrical signal by using a sensing device (e.g. a CCD sensor). The analog (electrical) signal is transformed to a digital one by using a video digitizer (frame grabber). Thus, the optical image is transformed to a digital one. Each digital image formation subsystem introduces a deformation or degradation to the digital image (e.g. geometrical distortion, noise, nonlinear transformation). The mathematical modelling of the digital image formation system is very important in order to have precise knowledge of the degradations introduced.

Digital image restoration techniques concern the reduction of the deformations and degradations introduced during digital image formation. Such techniques try to reconstruct or to recover the digital image. Knowledge of the mathematical model of the degradations is essential in digital image restoration. Digital image enhancement techniques concern the improvement of the quality of the digital image. This usually involves contrast enhancement, digital image sharpening and noise reduction. In certain applications, digital image pseudocolouring and digital image halftoning are considered to belong to digital image enhancement as well. Enhancement techniques have a rather heuristic basis compared to the digital restoration techniques that have rigorous mathematical foundations.

Digital image frequency content plays an important role in digital noise filtering, digital image restoration and digital image compression. Digital image transforms are used to obtain the digital image frequency content. Thus, transform theory is an integral part of digital image processing. The transforms used are two-dimensional, because the digital image itself is a two-dimensional signal. Their computation requires a large number of numerical operations (multiplications and additions). Therefore, the construction of fast transform algorithms is a very important task.

Digital images require a large amount of memory for their storage. A colour image of size 1024×1024 pixels occupies 3 MB of disk or RAM space. Thus, the reduction of the memory requirements is of utmost importance in many applications (e.g. in image storage or transmission). Digital image coding and compression take advantage of the information redundancy existing in the image in order to reduce its information content and to compress it. Large compression ratios (e.g. 1:24) can be obtained by proper exploitation of the information redundancy. Excessive image compression results, of course, in image degradation after the decompression phase. Therefore, a good compromise between fidelity and compression ratio must be found. Image compression plays an important role in several vital applications, e.g. image data bases, digital image transmission, facsimile, digital video and high-definition TV (HDTV). Therefore, intensive research has been carried out that has led to a multitude of digital image compression techniques. Some of them are already CCITT (Consultative Committee on International Telephony and Telegraphy) standards.

The first step towards digital image analysis is often the detection of object boundaries. This is performed by using edge and line detection techniques. The lines or edges detected are followed subsequently and a list of the boundary coordinates is created. Edge-following algorithms can be constructed in such a way that they are robust to noise and can follow broken edges. Special algorithms can be written to follow lines or edges having a particular shape, e.g. straight line segments or circles.

The dual problem of edge detection is region segmentation. Segmentation algorithms identify homogeneous image regions. Hopefully each of them corresponds to image objects or to image background. Regions are disjoint sets whose union covers the entire image. Region segmentation techniques can be grouped in three classes. Local techniques employ the local properties within an image neighbourhood. Global techniques segment the image on the basis of global information (e.g. global texture properties). Split and merge techniques employ both pixel proximity and region homogeneity in order to obtain good segmentation results.

Object recognition is a very important task in digital image analysis. Shape description models are extensively used to attain this goal. Shape description and representation schemes have been thoroughly studied in the past two decades by researchers working in computer vision and in computer graphics. Both areas have overlapping interests: computer vision concerns the creation of object models from object pictures, whereas computer graphics concern creating digital pictures from symbolic models. Several two-dimensional shape description schemes will be described in this book. Such schemes can be divided into two classes: external and internal representations. External representations employ the object boundaries and their features. Internal representations use region descriptions and features related to the region occupied by an object. Such important object features are related to its illumination texture. Texture description schemes are of great importance in object recognition applications.

Digital image processing and analysis have exhibited a tremendous growth in the past three decades. A multitude of algorithms have been presented in the literature in all the above-mentioned areas. The aim of this book is to provide an algorithmic description of some of the established techniques and algorithms, rather than to give an extensive survey of all proposed algorithms. The algorithms that will be described will form the backbone of an algorithmic package covering all important tasks related to digital image processing and analysis.

1.3 Digital image formation

An image is the optical representation of an object illuminated by a radiating source. Thus, the following elements are used in an image formation process: object, radiating source and image formation system. The mathematical model underlying the image formation depends on the radiation source (e.g. visible light, X-rays, ultrasound), on the physics of the radiation–object interaction and on the acquisition system used. For simplicity, we shall restrict our description to the case of the visible light reflected on an object, as shown in Figure 1.3.1. The reflected light $f(\xi, n)$ is the optical image which is the input of the digital image formation system. Such a system usually consists of optical lenses, an optical sensor and an image digitizer. The model of such a formation system is shown in Figure 1.3.2.

The optical subsystem H can be modelled as a linear shift-invariant system

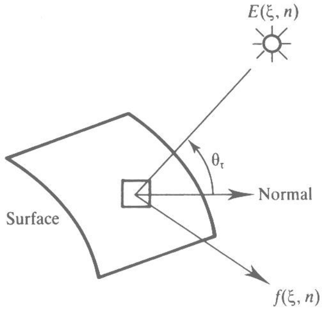

Figure 1.3.1 Reflection of light on an object surface.

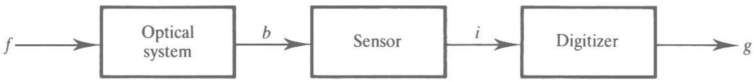

Figure 1.3.2 Model of a digital image formation system.

having a two-dimensional impulse response $h(x, y)$. H is usually a low-pass system and suppresses the high-frequency content of its input image $f(\xi, n)$. Thus, its output image $b(x, y)$ is usually a blurred or unfocused version of the original image $f(\xi, n)$. Since both signals $f(\xi, n)$, $b(x, y)$ represent optical intensities, they must take non-negative values:

$$f(\xi, n) \geq 0 \tag{1.3.1}$$

$$b(x, y) \geq 0 \tag{1.3.2}$$

The input–output relation of the optical subsystem is described by a 2-d convolution:

$$b(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\xi, n) h(x - \xi, y - n) d\xi dn \tag{1.3.3}$$

The mathematical model of the sensing device depends on the photoelectronic sensor used. Several types of sensors exist, e.g. standard vidicon tubes, charge injection devices (CIDs) and charge coupled devices (CCDs). In most cases, the relation between the input image $b(x, y)$ and the output electric current $i(x, y)$ is highly nonlinear. The characteristic curve of the vidicon camera is shown in Figure 1.3.3. It is clear that the current–illumination relation is nonlinear. At the saturation region a further increase in the illumination does not affect the output current. A dark current exists, even in the absence of illumination. Even in the 'linear' part of the characteristic curve, the input–output relation is

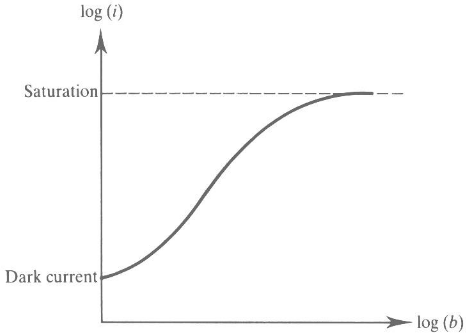

Figure 1.3.3 Current–illumination curve of a photoelectric sensor.

nonlinear:

$$\log(i(x,y)) = \gamma \log(b(x,y)) + c_1 \tag{1.3.4}$$

$$i(x,y) = c_2[b(x,y)]^\gamma \tag{1.3.5}$$

Typical values of γ are 0.65 (for vidicon tubes) and [0.95,...,1] (for silicon vidicons).

The output $i(x,y)$ of the sensing devices is still a two-dimensional analog signal. It must be sampled and digitized before it can be processed by the computer. Sampling and digitization are performed by an A/D converter. It transforms the analog image $i(x,y)$ to a digital image $i(n_1,n_2)$, $n_1 = 1,\ldots,N$, $n_2 = 1,\ldots,M$:

$$i(n_1,n_2) = i(n_1T_1, n_2T_2) \tag{1.3.6}$$

The sampling (1.3.6) is performed on a rectangular grid having sampling intervals T_1, T_2. The image size is $N \times M$ pixels. Typical digital image sizes are 256×256 and 512×512 pixels. In the case of colour images, sampling is performed on each channel (red, green, blue) independently, thus producing three digital images having equal sizes.

The A/D converter performs quantization of the sampled image as well. If q is the quantization step, the quantized image is allowed to have illumination at the levels kq, $k = 0,1,2,\ldots$, as shown in Figure 1.3.4. If an image pixel is represented by b bits, the quantization step is given by:

$$q = 1/2^b \tag{1.3.7}$$

In most applications, the *greyscale* images are quantized at 256 levels and require 1 byte (8 bits) for the representation of each pixel. In certain cases, *binary* images are produced having only two quantization levels: 0, 1. They are represented with 1 bit per pixel. A digital image quantized at 256, 64, 8 and 2 levels respectively is shown in Figure 1.3.5. Image quantization introduces an error term, $e(n_1,n_2)$,