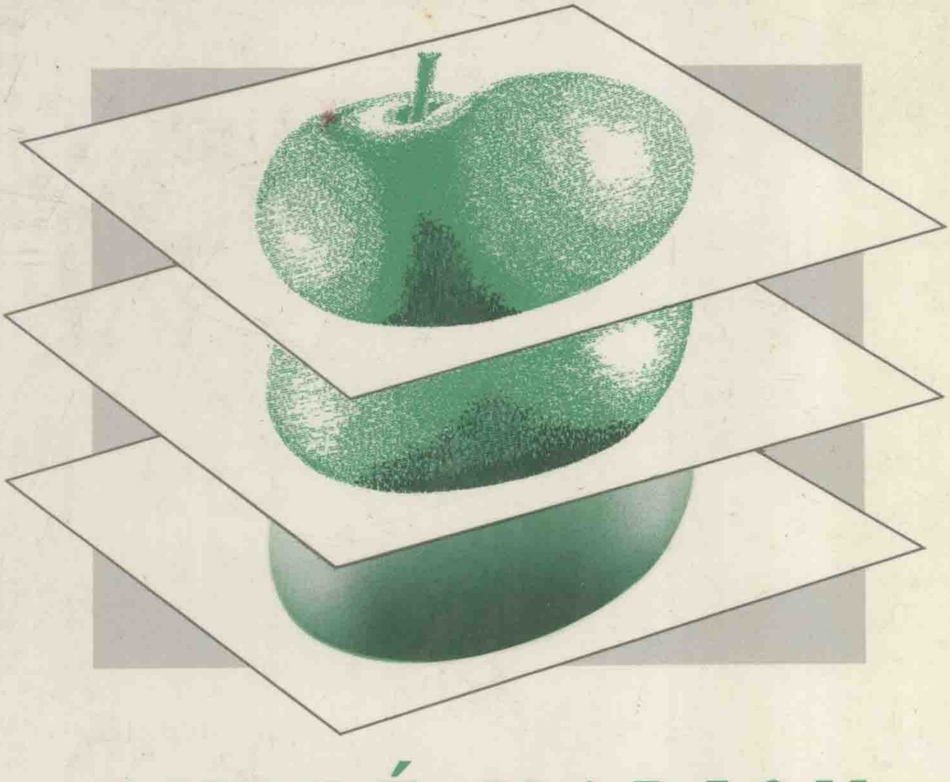
AN INTRODUCTION TO IMAGE PROCESSING



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CHAPMAN AND HALL

Introduction to Image Processing

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Introduction

I. The past, the present ... and the future

It is possible to take the view that ever since it began, the "ancient" branch of physics known as Optics has been concerned with processing images. But since the Nineteen-Thirties increasingly close ties have been forming between Optics, which until then had been largely based on instruments, and the sciences of communication and information arising out of mathematics and electronics. Such developments follow naturally, since communication systems and image-forming systems are all designed to receive or transmit information. Furthermore the same mathematical forms are used for describing the behaviour of electrical and optical systems. It is a question of systems theory, particularly linear systems, and of Fourier's analysis methods, which together constitute an important part of *Signal Theory*.

In the case of communication systems carrying signals of an electrical nature, information is time-related or temporal. Transmitted signals are one-dimensional and functions of a single variable, time t. In the case of optical systems information is spatial in nature. Signals are distributions of light intensity in space. In general they are treated as two-dimensional signals, being functions of two spatial variables written as x and y.

In the early Fifties the way forward became clearer still when some scientists at the Institut d'Optique in Paris began using *optical filtering* techniques in coherent light in order to enhance the quality of photographs. The possibilities of coherent filtering were exploited subsequently in the field of radar signal processing and later in the analysis of seismic waves. More recently, adapted filtering techniques using optical channels have been successfully applied to problems of *character identification*, which is just one aspect of the vast subject known as pattern recognition. The main attractions of optical processing are its simplicity, its moderate cost, its speed and the large amount of information which can be processed at one time.

The signals of images processed by these methods have one important characteristic: they are essentially continuous in nature. They are described as *analogue signals*, and since they are also two-dimensional it is possible to represent them mathematically as continuous functions of two variables: $f(x, y)$.

While all this research was taking place, developments in the computer field were opening up the concept of signals which were digital or *numerical* in nature. The information in such signals is represented and transmitted in the form of numbers in accordance with a selected coding convention (generally using binary code). Ever since 1920 it has been possible to transmit images digitally between New York and London by submarine cable for reconstitution on arrival. To use such techniques the continuous type of image mentioned above must first be digitized, that is transformed into an array or matrix of numbers, then processed as necessary by computer and (or) transmitted. For the purpose of retrieval and display, the digital image is then converted back to a continuous image. This process is the reverse of *digitization*, and is known as *reconstruction*.

Digital *image processing* is only a relatively recent development, starting in the Sixties when third generation computers made their appearance. In fact, as we shall see, an image of even modest size carries a large quantity of information. Due to progress in storage capacity and speed of calculation, these computers could be used to develop algorithms for processing a multitude of applications.

One of the first fields to use digital processing for the enhancement of images was space research. It was in 1964 that the Jet Propulsion Laboratory in Pasadena, California, used a computer to correct camera distortion in pictures of the lunar surface transmitted back to Earth from the Ranger 7 probe. Since that time many techniques for image enhancement and restoration have been developed in connection with the Surveyor, Mariner and Apollo missions.

At the same time the field of application for digital image processing has been gradually but decidedly growing. It now finds applications in medicine (radiography, tomography, scintigraphy), biology, geography, cartography, meteorology, astronomy, geology, archaeology, physics (spectroscopy, plasma physics, microscopy), military applications and industrial uses (materials radiography, non-destructive testing etc). The nature of the images processed is as highly varied as the subjects involved. There are aerial photographs, X-ray photographs, physical spectra, radar images, optical or electronic photomicrographs etc. Some typical applications will be mentioned in the course of this book.

Today the list is no longer limited to scientific or technical disciplines. It is true to say that no field of activity escapes or will escape the need to make use of image processing. Examples abound in live entertainment, video, fashion and every sector of artistic creation.

There are further practical applications in prospect, ranging from medical diagnostics to visual recognition by computer in the field of robotics and artificial intelligence, including automatic recognition of text, handwriting and shapes of objects by a machine for replacing inspection by the human eye.

The abundance of uses for image processing has had two important consequences:

1. There has been a growth in the number of specialised application packages as well as "standard" processing packages with virtually universal application, generally written in high-level language and easily portable to any type of large or medium-size computer.

2. Small processing workstations are now being marketed on a "turnkey" basis. These are usually organised around an expandable image memory and include a colour display console, a keyboard and visual display unit, mass storage devices such as hard disk, floppy disk, cassette and magnetic tape, as well as optional output devices such as screen dump printers, colour printers etc. Many of these systems have the double advantage of being programmable by the user for special applications and equipped with a number of standard programs which can be accessed easily by "menu" so that they can be used with ease by a non-specialist in computing.

These two differing philosophies, which may be summed up as the large computer centre and the small stand alone system, are complementary rather than competing. The choice depends above all on the type of application in question:

- For applications handling heavy and repetitious calculations, large amounts of data and algorithms which are fully-defined or needing only minor adjustment, a large computer seems most suitable.

- On the other hand, for research into new methodologies, or for the development of new algorithms, if the amount of data being processed is not prohibitive then it is very helpful to have the flexibility and *interaction* of a stand alone system, even if it is less powerful. In fact, interaction is often a selection criterion of prime importance for assessing the true effectiveness of an image processing system.

It should also be mentioned that there seems to be much promise for the future in hybrid systems which combine the advantages of computerized digital techniques with analogue optical filtering methods.

II. What is an image?

There are many definitions of the word "IMAGE". If we look in the dictionary we find that one of the definitions, relating to an image in the abstract sense, is along these lines: "An exact or analogous representation of a being or thing". An image can therefore be thought of as anything which represents something else. If we use "object" to mean anything which has a material or immaterial existence, that is any being, thing or concept, then images are obviously a form of object and we can divide objects in general into two categories: objects and the images of objects. The latter can be subdivided into three groups:

1. *Visible physical* images which are entirely real and either transitory or permanent in nature. Transitory images are either optical, composed of photons in the visible range (such as images produced by optical instruments, holograms and so on), or electro-optical (the screen of a cathode ray tube, light-emitting diode displays and things of that sort). Permanent images are reproductions of every kind, summed up in the more restrictive word "picture", including photographic negatives, drawings, paintings, engravings, sculptures, printed documents, hard-copy screen dumps and the like.

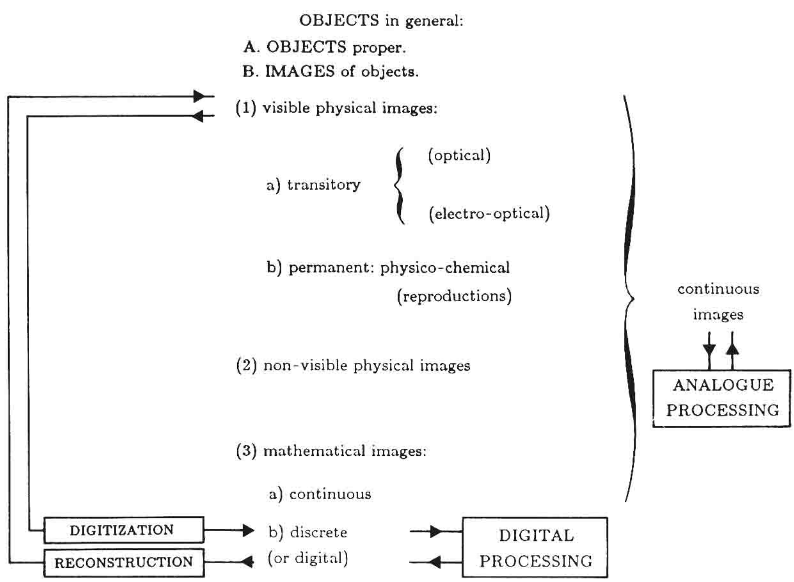
2. *Non-visible physical* images: these are optical images outside the visible range or images of an "unreal" nature. They include physical spectra, maps showing population, temperature or pressure and representations of any physical parameter in general which cannot be viewed by direct means. Thus a view in infra-red is a non-visible image, but after printing a film which is sensitive to this form of radiation it becomes a visible

physical image. The three-dimensional images produced by tomography are also in this class.

3. *Mathematical images*. These are concepts, and therefore invisible by their very nature. They may be continuous, for instance a function *f(x, y)* or they may be discrete, in which case they are arrays or matrices of numbers. Such is the situation with purely synthetic images created by computer, at least before they are restored and displayed on a suitable system. Apart from discrete mathematical images, all other images are generally continuous, at least as far as our macroscopic scale of observation is concerned.

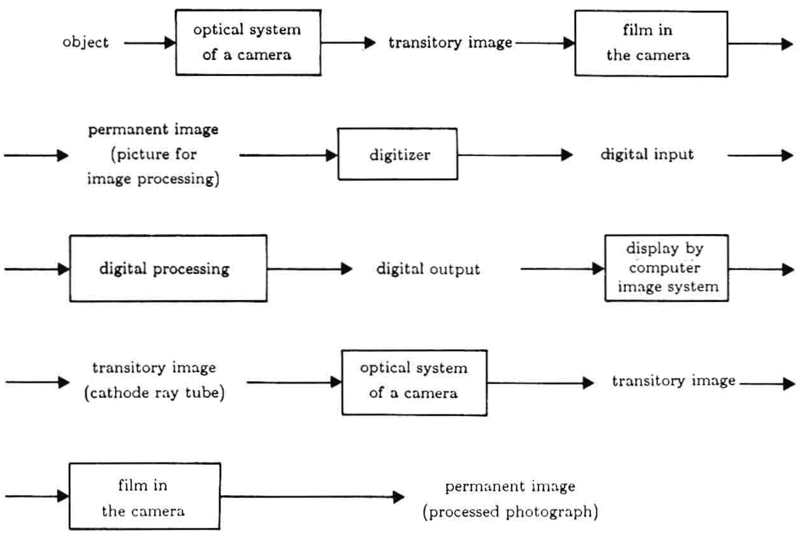
Any form of processing which converts a continuous image (the input image) into another continuous image (the output image) is known as *analogue processing*. This includes calculations carried out on analogue computers (which nowadays are used only rarely) as well as optical processing techniques. Similarly *digital processing*, which is usually carried out by computer, converts a discrete input image into a discrete output image. To make this possible, therefore, the image which requires processing has to be converted from the continuous to the discrete form. To do this requires a *digitization* system.

The table below summarizes these definitions:



Once digital processing has been carried out, a visible physical image has to be retrieved from it. This may be done by producing for instance a display on a television screen, another photograph, or a printed representation. This job is performed by *display* or *playback* systems.

An example of the classic procedure for processing, starting with the object under investigation all the way through to the production of a processed photograph, consists of the following steps:



This book examines these various stages.

Thus we shall consider in succession how optical systems form images, the process by which an image is created on a photographic medium, digitization systems, reconstruction systems and digital processing methods using computers. We shall see that each of these stages introduces defects and restrictions of various kinds, such as noise, distortion and calculation artefacts, all of which degrade perception of the object being studied. There is therefore a need for caution when interpreting a processed image.

The visible physical images which we need to digitize are often of the two-dimensional monochrome or single-colour variety such as a so-called "black-and-white" photograph. Figure 0.1 shows just such an image. This is represented by a function $f(x, y)$ expressing the light intensity of a point with coordinates x and y. Similarly it is possible to represent a three-colour image such as the classic "colour" photograph by three functions $f_R(x, y)$, $f_G(x, y)$ and $f_B(x, y)$ expressing the intensity of each of the three primary component colours red, green and blue at point (x, y) on the image.

More generally we shall make reference to a multispectral image, being an image represented by a set of n components $f_1(x, y)$, $f_2(x, y)$ ... $f_n(x, y)$. We have an instance of this when a satellite records n views of the same region of the earth in n wavelength bands.

III. Why and how images are processed

It can be said that an image is being processed as soon as information begins to be extracted from it.

This viewpoint has nothing whatever to do with using a computer to produce purely synthetic images. Artificial image creation, or image synthesis, is not a part of the field commonly described by the term "image processing", and this book will not be dealing with it.

Having made this clear, we can say that there are many ways in which images can be processed. One way of classifying the types of processing which exist is by objective, in other words the reason for wanting to process the image in the first place.

1) There may be a need to improve its quality. This may be subjective, such as making it more attractive to look at. It may be a quality which can be measured objectively, such as increasing contrast, improving the ability to make out certain details or contours,

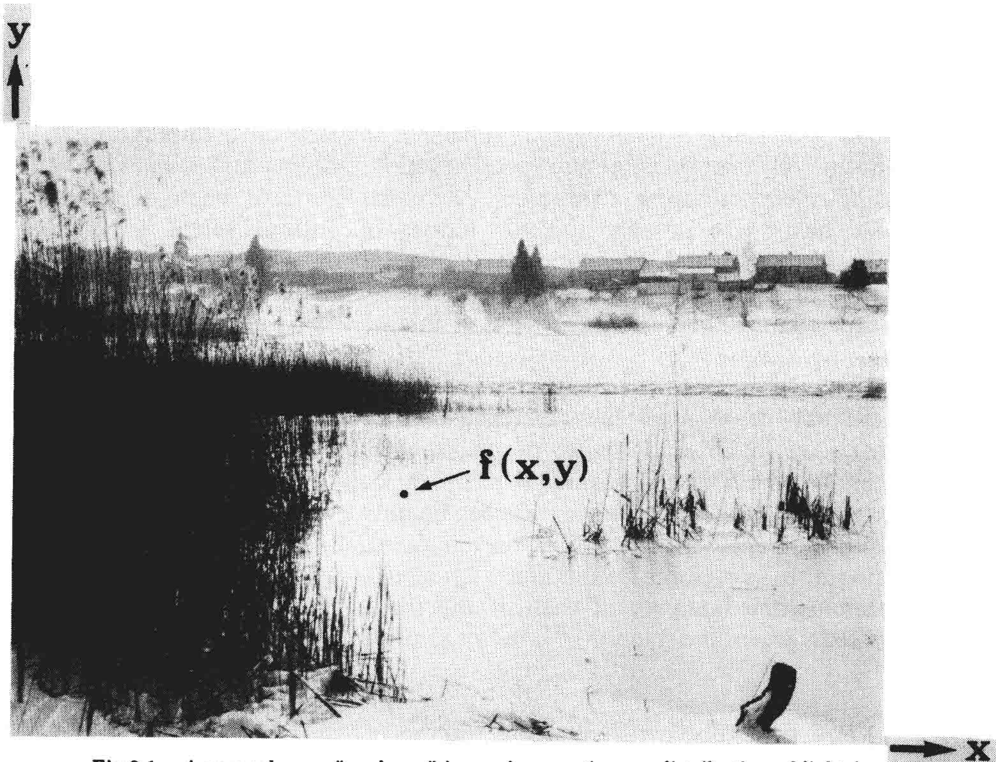


Fig.0.1 - A monochrome "analogue" image is a continuous distribution of light intensity represented as a function of the two spatial variables x and y: $f(x, y)$.

enhancing the clarity of certain zones or shapes, or reducing the noise or interference which can have a variety of causes and make the information less useful.
It is therefore a matter of *enhancement* techniques which make use of such varied procedures as histogram modification, convolution, linear filtering, non-linear filtering etc., in order to produce smoothing, contour accentuation, enhancement and so on. Most of these processes will be examined in this book.

2) Enhancing the quality of an image may also mean the search for an "ideal" image of the object if it has become degraded in a number of ways. There is a need to correct geometrical or photometric distortions introduced by a sensor, to reduce fluctuations caused by atmospheric turbulence, or to correct haze arising from camera shake etc. These are therefore *restoration* techniques. Here again, various types of linear or non-linear filters are used, including inverse

filters and Wiener's filtering. Some of these will be dealt with in the final chapter.

3) There may be a need to look for certain shapes, contours or textures of a particular kind, but no need to keep the other information in the image. We are referring here to *detection*, one of the classic problems of signal theory, concerning the need to extract a signal of a known shape when everything other than the useful signal is behaving like a sea of noise.

4) An important aspect of image processing is the enormous amount of information which has to be handled when transmitting one or more images. It is helpful to find a way of reducing the quantity of information involved. "Compressing" it to improve the transmission rate also reduces the size of the equipment and storage space required. All this needs to be achieved whilst sacrificing as little of the image quality as possible. This field concerns coding, data compression and image approximation. It is one of the more difficult aspects of information theory, and will not be given detailed treatment in this book. Readers interested in knowing more about this topic may refer to the works numbered 1, 3, 5, 8 and 12 in the bibliography.

5) Image processing also involves the analysis and comprehension of images. One of the aims of this activity is to equip machines with the ability to see. Machine vision leads us straight into the realms of robotics. *Image analysis*, also known as scene analysis, seeks to extract the information contained in the various objects in a scene without placing any interpretation on them. The basic techniques are **attribute extraction**, including the analysis of shapes, contours and textures; and **segmentation** of the image into zones exhibiting specific characteristics, by thresholding, by extracting and following contours, by erosion and enlargement, and by other methods. *Pattern recognition* techniques rely on the classification of shapes into preset categories on the basis of mathematical morphology. At a higher level, various models based on knowledge of the chosen goal are used for making the decisions and estimates needed to interpret the image. Image comprehension is the starting point of machine vision and other techniques based on artificial intelligence.

Another classification of processing operations involves dividing them according to the nature of the mathematical operations carried out. Thus within enhancement and restoration as well as detection we find both *linear* and *non-linear processing*. An operation or system is said to be linear when any linear combination of input signals gives the same linear combination of output signals. A large part of this work is devoted to examining linear systems.

A distinction is also made between operations which are *shift invariant* (or *stationary*) and those which are not. In a shift invariant operation a large-scale displacement of the input image is matched by identical displacement of the output image.

In section IV, "STRUCTURE OF THE BOOK", we shall see the meaning of the terms: *point operations, local operations* and *global operations*. We should also bear in mind the distinction between *analogue processing, digital processing* and *hybrid processing.*

IV. Structure of the book

This general introduction is followed by chapter I. Its aim is to familiarize the reader with the basic mathematical ideas behind the theory of *analogue signals*. We begin with a one-dimensional signal, such as the electrical signal representing a sound in a high-fidelity channel, which is a function of time. We use it to explain the concepts of the frequency *spectrum* and the *Fourier transform*. The same ideas are then extended to include images, considering them as continuous signals in two dimensions.

Chapter II is devoted to the fundamental concept of a linear system, regarded as both a *convolution* system and a *frequency filter*. To explain the principle of convolution we consider the scanning of a simple luminous object, in this case by a square aperture being moved across a stripe. We then define the *impulse response* and *transfer function* of a linear system, and give examples of simple square, circular and Gaussian apertures.

Chapter III discusses how *optical systems* form images. In appropriate circumstances these systems can be treated as linear. This is the case with systems which are said to be "diffraction limited". Their impulse response and transfer function, as determined by the system exit pupil, are examined first in coherent lighting and then in incoherent.

One kind of image which is commonly being processed is the photographic image. Chapter IV is devoted to how images are formed on photographic media. It studies the process from exposure to development as well as examining the properties of photographic emulsions. Having defined such concepts as density, transmittance and the basic characteristics of an emulsion, we consider resolution and the *modulation transfer function* (MTF).

The grain of the emulsion limits the perception of fine details and creates fluctuations in the observed density. This fluctuation may be thought of as a "noise" analogous to electronic hum. This means we can refer to an emulsion's signal-to-noise ratio and define the notion of equivalent quantum efficiency (EQE). We then go on to define both the autocorrelation and the power spectrum, or *Wiener's spectrum*, of this noise.

In order to be processed by computer the image in question, such as the photograph in chapter IV, must first be digitized. Once processing has been carried out the digital image so obtained is generally displayed, or restored in a form which is visible to the eye of the observer. This may be done by producing for instance a display on a television screen, a printed image or another photograph. Chapter V examines the processes of *digitization* and *reconstruction*. Particular attention is paid to the errors and limitations which these processes introduce. The distinction is drawn between the errors inherent in the operations themselves (especially errors arising during sampling and quantization of the analogue image) and the technological limitations caused by the less than perfect characteristics of the equipment, digitizers and restorers used.

In chapter VI we see the *basic techniques* used in image processing. We begin with important definitions of the *histogram* and cumulative histogram of an image. We then consider a number of procedures known as *point operations*, in which each point on the output image is simply a function of the same point on the input image, without taking account of neighbouring points. In this context we meet classic techniques such as histogram equalisation, obtaining a histogram of a given form and correcting the non-linear characteristics of sensors and restorers.

Chapter VII is devoted to the simple *algebraic operations* which can be carried out between two or more images, such as addition, subtraction or multiplication. These, too, are point operations, in which each point on the derived output image depends only on the point with the same coordinates on each of the other images involved. The chapter then examines the effect which such operations have on the histogram, and illustrates their usefulness by introducing some typical applications. So for example by averaging a series of images of the same scene it is possible to improve the signal-to-noise ratio considerably.

Coloured image displays can often be useful. If the image is naturally in colour, the primary components are used to reconstitute the original colours by an additive or subtractive process. On this basis the screen of a colour display monitor produces a coloured image by an additive process, whereas a photograph or printout from a colour printer uses a subtractive process. This mode of representation, called *"true colour" mode*, preserves the colour information in the image and analyses it as necessary into its different components.