DIGITAL IMAGE PROCESSING

SECOND EDITION

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Dedicated to
My father
Shri P. Sundaramurthy
Who taught me everything in life

Preface to the Second Edition

Images are used in almost all application domains—from magazines where images are used for better communication of ideas to the medical domain where images are used for better treatment of patients. With improved technology, it has also become very easy to acquire digital images. Hence, the popularity of image processing has increased tremendously in recent years. Digital image processing refers to the processing of digital images for specific tasks such as image enhancement, image analysis, object recognition, and image understanding. Numerous applications of image processing and its links with other related domains such as computer vision, medical image processing, digital imaging, and pattern recognition makes this field exciting and challenging for students of Computer Science, Information Technology, Electronics and Communication, and Electrical Engineering. In addition, there is an increasing need for awareness about this subject among doctors, visual media students, scientists, and the general public. This book has been developed to provide a comprehensive and practical coverage of the fundamental and advanced aspects of image processing.

ABOUT THE BOOK

This second edition of *Digital Image Processing* has been thoroughly revised and updated to incorporate faculty feedback as well as the necessary additions required to conform to the syllabi of various technical universities.

The following are the salient features of the book:

- Adopts an algorithmic approach to illustrate the concepts of image processing
- Provides simple explanation to topics such as Shannon–Fano coding, chain code, image security, digital image forensics, image segmentation, and image features
- Contains appendices that discuss the basics of MATLAB programming and ImageJ, and provides information on other public domain image processing software
- Includes a laboratory manual with examples illustrated through MATLAB

NEW TO THE SECOND EDITION

The following are the most notable additions in this edition:

- A chapter on wavelet transforms and multiresolution analysis which focuses on the wavelet transform-based image processing as well as wavelet-based image compression

- The chapter on image enhancement and restoration has been split into two separate and exclusive chapters on image enhancement and image restoration
- Topics such as image security, visual effects, Radon transform, digital image forensics, and computer vision
- Pedagogical features such as Crossword and Word search problems
- Colour plates illustrating the effect of different image processing operations and image processing applications such as visual effects
- Additional illustrations, solved examples, and MATLAB exercises

EXTENDED CHAPTER MATERIAL

Chapter 1 The section on image processing applications has been completely rewritten, with the inclusion of new applications. The applications are now classified into two categories— applications based on EM radiation and those based on application domain. In addition, new solved examples have been included. The section on digital imaging systems has been moved to Chapter 2.

Chapter 2 This chapter has been completely revised so that it now discusses all the components of digital imaging systems. The part on sampling has been updated and new solved examples have been added in this chapter.

Chapter 3 The section on image interpolation techniques has been rewritten. The portion on data structures has been removed and moved to appropriate locations in the book. Figures have been added to illustrate image processing operations.

Chapter 4 Image transforms such as DCT, DST, Slant, and SVD transforms have been completely revised. A section on comparison between transforms, along with new solved examples, has been included.

Chapters 5 and 6 Chapter 5 of the first edition has been split into two exclusive chapters, one on image enhancement and the other on image restoration. New examples have been included for image enhancement. The portion on deconvolution has been rewritten.

Chapter 7 The discussion on Huffman coding has been strengthened with more detailed explanation and solved examples. The topic of video compression has been moved to Chapter 14.

Chapter 8 This edition dedicates an independent chapter to multiresolution analysis which was covered briefly in Chapter 12 of the first edition. Additional material on wavelet-based compression techniques such as EZW and SPHIT, along with an overview of JPEG 2000, has been included.

Chapter 9 Sections on corner detection and active contour models have been rewritten for better clarity.

Chapter 10 In order to make the text more coherent, the section on colour fundamentals has been moved to Chapter 2 and the section on TV colour models has been moved to Chapter 14.

Chapter 11 Sections on morphological operators and distance transform and medial axis transform, and watershed algorithm have been elaborated.

Chapter 12 Chain code and shape features have been discussed and new examples have been included to illustrate the text. In addition, a detailed algorithm for PCA has been added.

Chapter 13 Detailed algorithms have been included for minimum-distance classifier and Bayesian classifier. Additionally, there are new examples. Biometric case studies have been moved to Chapter 14.

Chapter 14 This chapter has been completely rewritten with additional material on different types of visual effects, techniques used for implementing security of digital images such as image encryption, digital scrambling, visual cryptography, captcha, digital image forensics, and computer vision.

Appendix C Additional MATLAB exercises on image compression using SVD, corner extraction, Radon transform, K-means clustering, and visual effects have been included.

The content from the CD that accompanied the first edition has been uploaded onto the Oxford University Press India website (https://india.oup.com/orcs/9780199459353) from where they can be accessed easily.

CONTENT AND STRUCTURE

The book has been structured into 14 chapters and three appendices.

Chapter 1 provides an introduction to digital image processing. It gives an overview of the image types and the fundamental steps in digital image processing, and highlights the relationship between image processing and other domains. The chapter also surveys different applications of image processing.

Chapter 2 gives an overview of the elements of a digital imaging system, followed by a discussion on the physical and biological aspects of image acquisition. It also discusses sampling and quantization, digital halftoning, and image file formats.

Chapter 3 introduces image processing operations, including arithmetic, logical, geometrical, set, and spatial operations. This chapter also focuses on the relevance and utility of these image processing applications.

Chapter 4 deals with different image transforms which are an important tool in image processing. The chapter covers all important transforms such as Fast Fourier Transform (FFT), Discrete Cosine Transform (DCT), Hadamard, Walsh, Singular-value Decomposition (SVD), and Karhunen–Loeve (KL) transform.

Chapter 5 provides an overview of digital image enhancement. It introduces concepts related to grey-level transformations and the concept of filtering, including spatial and frequency domain filtering of images.

Chapter 6 covers the basics of digital image restoration. It discusses order-statistic filters, noise models, image degradation model, and image deconvolution algorithms.

Chapter 7 details the concept of image compression. As image sizes are often very large, images need to be compressed to facilitate storage, processing, and transmission. The chapter discusses the concepts related to image compression, such as image redundancy, and important image compression algorithms. JPEG compression is briefly discussed as part of this chapter.

Chapter 8 provides an overview of multiresolution analysis and discusses the various forms of wavelet transforms. The chapter also covers applications of wavelet transforms such as image denoising and wavelet-based image compression.

Chapter 9 describes image segmentation. Often, image analysis begins with the segmentation of regions that are necessary for image analysis. The chapter discusses segmentation algorithms and methods for evaluating their quality.

Chapter 10 deals with colour image processing. It describes the capturing of colour information from objects, devices for handling colour, colour models, and colour image processing algorithms.

Chapter 11 introduces the concept of image morphology. Image morphology deals with the study of structures of objects in an image. This chapter explains set-based morphological operations and their applications. It ends with a discussion on extending morphological operations to grey scale images.

Chapter 12 covers concepts related to image feature extraction. It discusses the need for image features, their types, and algorithms to extract and represent image features. The relevance of image features for better object recognition is also discussed.

Chapter 13 introduces the concept of pattern recognition. It first discusses image classification followed by a discussion of image clustering algorithms and evaluation techniques.

Chapter 14 discusses the emerging trends related to soft computing techniques in image processing applications (such as fuzzy logic, neural networks, and genetic algorithms) and exciting research topics (such as image security, biometrics, image encryption, digital image forensics, medical image processing, and computer vision). The chapter ends with a discussion of image mining and content-based image retrieval systems.

Appendix A briefly explains the fundamentals of MATLAB programming and the MATLAB image processing toolbox.

Appendix B provides an overview of the open-source environment ImageJ. It also lists the URLs of other useful open-source software.

Appendix C is the laboratory manual, which contains 20 simple exercises illustrating basic concepts such as image operations, image enhancement and restoration, image segmentation, and feature extraction. The aim of these exercises is to reinforce the concepts discussed in Chapters 1–14.

ACKNOWLEDGEMENTS

I acknowledge the help I received from senior professors Dr N. Kumaravel and Dr Y.V. Ramana Rao during the writing of this revised edition. I am also grateful to my colleagues from National Institute of Technology, Tiruchirapalli, and current colleagues at Anna University for their support. I am thankful to the countless students who took up a course on image processing and offered valuable advice. I also thank the reviewers for providing their valuable feedback on the manuscript.

My sincere thanks are also due to my family members, especially my wife, Dr N. Vasanthy, my mother, Mrs S. Parameswari, my mother-in-law, Mrs N. Renuga, and my children, Shobika and Shreevarshika for their constant support and encouragement during the development of the first and second editions of this book.

Last but not the least, I thank the editorial team of Oxford University Press, India, who diligently and sincerely worked towards the successful completion of this edition.

S. Sridhar

Preface to the First Edition

Images are powerful tools for effective communication. It is easier to convey messages through images than through text. Broadly speaking, image processing refers to the processing of digital images for specific tasks such as image enhancement, image analysis, object recognition, and image understanding. Thus, image processing aims to extract information from an image for a variety of applications.

The use of pictures for effective communication dates back to the stone age. Historical research shows that during this period, human beings used a variety of sketches to convey information. Language scripts were then developed by incorporating these sketches. Later, such sketches were developed into the art of drawing and painting for conveying information and emotions. With the invention of the camera, photography evolved as a tool for communication. Thus, the history of photography predates that of image processing. While the subjective aesthetics of an object might be lost in an image captured by a camera, the advantage is that it reduces the effort and skill required, compared to drawing or painting. Over the years, analog pictures have been replaced by digital ones, as processing of digital images is much easier. Image processing, as an area of study started with the requirement of transmitting an image as part of the Bartlane cable picture transmission system, between London and New York, in the 1920s. The field of image processing retained its importance because of the processing of remote sensing images as part of the Jet Propulsion Laboratory's Ranger 7 project in 1964 and subsequent work related to remote sensing. With reduction in the cost of digital cameras and digital computers, digital image processing is, slowly but steadily, becoming part and parcel of our everyday life.

Today, image processing is a subject of interest not only to computer science students, but also to medical professionals, web designers, and multimedia professionals. Images are now used in medicine, forensics, entertainment, corporate presentations, and web pages for a variety of reasons. Even non-technical people encounter images while browsing the Internet, and often come across computer jargon such as image resolution, and file formats such as JPEG and MPEG.

Many allied developments in disciplines such as biometrics, pattern recognition, machine vision, computer vision, image fusion, steganography, digital watermarking, image mining, and content-based image retrieval systems such as image-based search engines have helped in increasing the scope of image processing immensely. This has led to the development of many imaging applications that affect our daily lives, such as fingerprint-based attendance systems, medical diagnosis, weather forecasting based on remote sensing images, and object recognition systems such as fingerprint, iris, and face recognition systems. Therefore, image processing is offered as a core or elective course for students of computer science, information technology, electronics and communication, and electrical engineering.

ABOUT THE BOOK

This book has been conceived and written with the objective of providing students with a comprehensive textbook on image processing. The book follows a simple algorithmic approach, as against a theorem and proof-based approach, for explaining basic image processing concepts. This approach stems from the author's experience in teaching undergraduate and postgraduate students of Anna University, Chennai, and National Institute of Technology (NIT), Thiruchirapalli, over the years.

The book targets undergraduate engineering students who study image processing as a core or elective subject. The book will also be useful to students who opt for courses such as medical image processing, machine vision, remote sensing, computer vision, and pattern recognition.

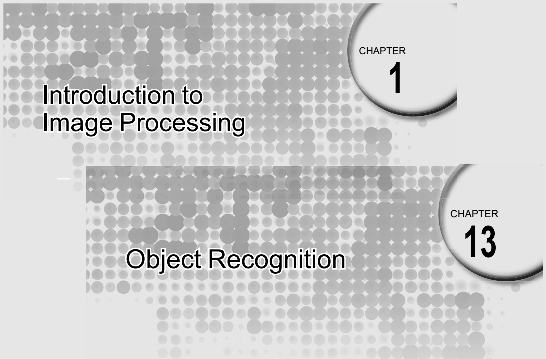
Divided into twelve chapters, the book is organized in a fashion that will enable teachers to offer image processing and analysis as a one-semester course. Chapters 1–6 take the reader through image processing concepts while Chapters 7–11 deal with image analysis concepts, ideally suited for an image analysis course. Chapter 12 provides an introductory note on relevant allied subjects, including image understanding.

ACKNOWLEDGEMENTS

A book of this kind would not have been possible without the help of many well wishers. I thank all my students who enrolled for my image processing course and at many times kindled my desire to write a book. I express my sincere thanks to Dr N. Kumaravel, Professor and Head, Department of Electronics and Communication Engineering, Anna University, Chennai, for his constant encouragement, guidance, and efforts in motivating me in my research. I am grateful to all my colleagues at the Department of Information Science and Technology and Department of Computer Science and Engineering, College of Engineering, Anna University, Chennai and my old colleagues at NIT, Thiruchirapalli, for spending countless hours reading the manuscript, providing valuable suggestions, and encouraging me throughout my work. I thank the authorities of Anna University for providing the necessary facilities to write this book. I also thank the editorial team of Oxford University Press, India for their support, and their reviewers for providing comments on the manuscript. My thanks are also due to my family members for their prayers and constant encouragement during the lengthy book-writing process.

S. Sridhar

Features of



COVERAGE

The book provides a comprehensive coverage of topics ranging from the fundamentals of image processing applications to soft computing techniques in image processing.

ILLUSTRATIONS

Text has been well supported with suitable illustrations to allow easy visualization of image processing operations.

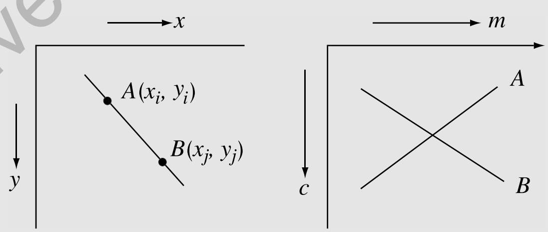
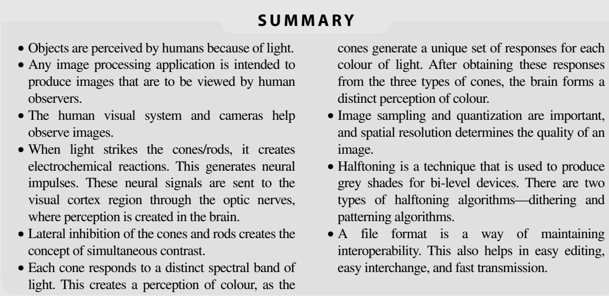


Fig. 9.18 Line in Hough transform



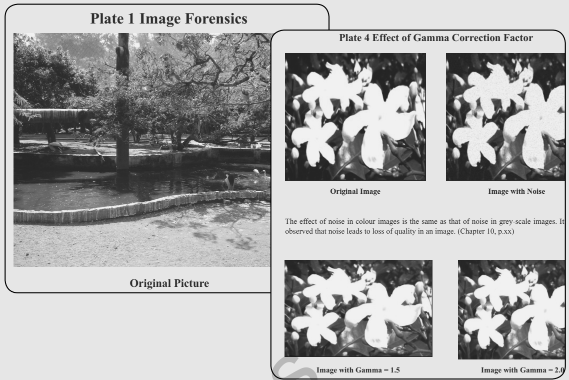
SUMMARY

- Objects are perceived by humans because of light.
- Any image processing application is intended to produce images that are to be viewed by human observers.
- The human visual system and cameras help observe images.
- When light strikes the cones/rods, it creates electrochemical reactions. This generates neural impulses. These neural signals are sent to the visual cortex region through the optic nerves, where perception is created in the brain.
- Lateral inhibition of the cones and rods creates the concept of simultaneous contrast.
- Each cone responds to a distinct spectral band of light. This creates a perception of colour, as the cones generate a unique set of responses for each colour of light. After obtaining these responses from the three types of cones, the brain forms a distinct perception of colour.
- Image sampling and quantization are important, and spatial resolution determines the quality of an image.
- Halftoning is a technique that is used to produce grey shades for bi-level devices. There are two types of halftoning algorithms—dithering and patterning algorithms.
- A file format is a way of maintaining interoperability. This also helps in easy editing, easy interchange, and fast transmission.

SUMMARY

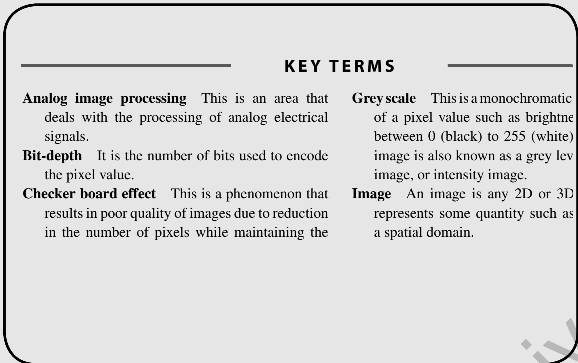
A list of key topics at the end of each chapter helps readers to revise all the important concepts explained in the chapter.

the Book



COLOUR PLATES

Coloured illustrations depicting applications such as image forensics, mosaicking, and visual effects are present.

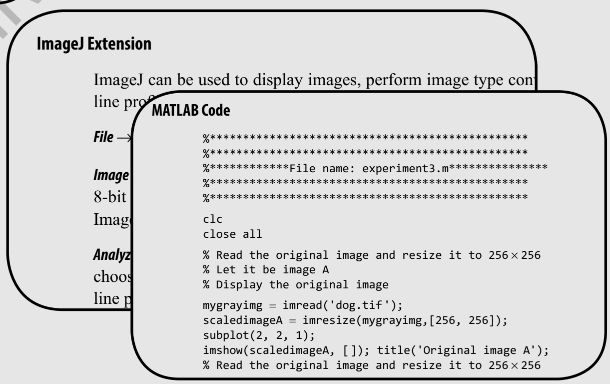


KEY TERMS

Analog image processing This is an area that deals with the processing of analog electrical signals.
Bit-depth It is the number of bits used to encode the pixel value.
Checker board effect This is a phenomenon that results in poor quality of images due to reduction in the number of pixels while maintaining the
Grey scale This is a monochromatic of a pixel value such as brightne between 0 (black) to 255 (white) image is also known as a grey lev image, or intensity image.
Image An image is any 2D or 3D represents some quantity such as a spatial domain.

KEY TERMS

All chapters provide a glossary of important terms along with their definitions for quick recapitulation of the important terms learnt.

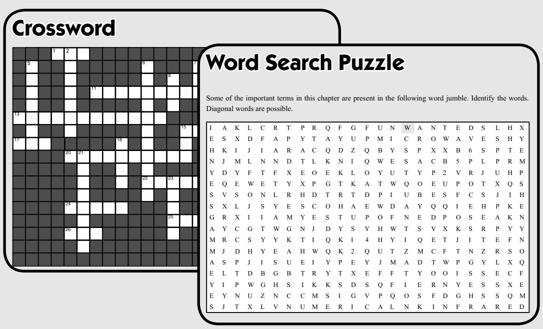



```
%**********************************************
%**********************************************
%***********File name: experiment3.m**************
%**********************************************
%**********************************************

clc
close all
% Read the original image and resize it to 256×256
% Let it be image A
% Display the original image
mygrayimg = imread('dog.tif');
scaledimageA = imresize(mygrayimg,[256, 256]);
subplot(2, 2, 1);
imshow(scaledimageA, []); title('Original image A');
% Read the original image and resize it to 256×256
```

LAB MANUAL

A separate laboratory manual is included at the end of the book which contains 20 programs in Matlab and ImageJ



CROSSWORDS AND WORD SEARCH PUZZLES

These interesting elements help in self evaluation of the concepts presented in a chapter. Answers to these questions are provided in the Online Resources Centre <https://india.oup.com/orcs/9780199459353/>

Companion Online Resources

Visit india.oup.com/orcs/9780199459353 to access teaching and learning solutions online.

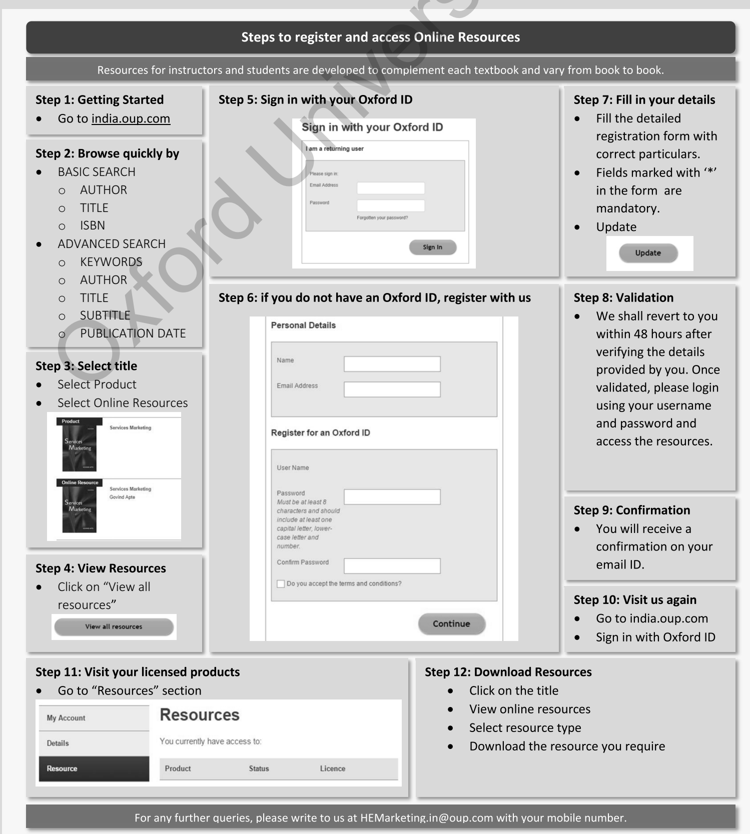
The following resources are available to support the faculty and students using this book:

For Instructors

- Chapter PowerPoint Slides
- Solutions Manual

For Students

- MATLAB Programs
- Test Images for Performing Lab Exercises
- Colour Images from Select Chapters
- Solutions to Crosswords and Word Search Problems



Brief Contents

Detailed Contents

CHAPTER

1

Introduction to Image Processing

Of all of our inventions for mass communication, pictures still speak the most universally understood language.

–Walt Disney Company

LEARNING OBJECTIVES

This chapter provides an overview of digital image processing concepts. Image processing refers to the processing of visual information sources, such as images for some specific task, as per the application requirements. The objective of this chapter is to provide basic definitions that are associated with image processing and to give an overview of image types, imaging applications, and the digital image processing environment. The reader will become familiar with the following after studying the chapter:

- Elements of a digital image
- Types of images
- Fundamental steps in digital image processing
- Fundamental classes of image processing
- Survey of image processing applications

1.1 OVERVIEW OF IMAGE PROCESSING

Computers are faster and more accurate than human beings in processing numerical data. However, human beings score over computers in recognition capability. The human brain is so sophisticated that we recognize objects in a few seconds, without much difficulty. We may see a friend after ten years, yet recognize him/her in spite of the change in his/her appearance, as the method by which humans gather knowledge for recognition is very unique. Human beings use all the five sensory organs to gather knowledge about the outside world. Among these perceptions, visual information plays a major role in understanding the surroundings. Other kinds of sensory information are obtained from hearing, taste, smell, and touch. The old Chinese proverb 'A picture speaks a thousand words' rightly points out that images are very powerful tools in communication. With the advent of cheaper digital cameras and computer systems, we are witnessing a powerful digital revolution, where images are being increasingly used to communicate ideas effectively.

We encounter images everywhere in our daily lives. We see many visual information sources such as paintings and photographs in magazines, journals, image galleries, digital libraries, newspapers, advertisement boards, television, and the Internet. Images are virtually everywhere! Many of us take digital snaps of important events in our lives and preserve them as digital albums. Then from the digital album, we print digital pictures and/or mail them to our friends to share our feelings of happiness and sorrow. However, images are not used merely for entertainment purposes. Doctors use medical images to diagnose problems for providing treatment. With modern technology, it is possible to image virtually all anatomical structures, which is of immense help to doctors in providing better treatment. Forensic imaging applications process fingerprints, faces, and irises to identify criminals. Industrial applications use imaging technology to count and analyse industrial components. Remote sensing applications use images sent by satellites to locate the minerals present in the earth. Thus, images find major applications in our everyday life.

Images are imitations of real-world objects. Often an image is a two-dimensional (2D) signal $f(x, y)$, where the values of the function $f(x, y)$ represent the amplitude or intensity of the image. For processing using digital computers, this image has to be converted into a discrete form using the process of sampling and quantization, known collectively as digitization. In image processing, the term 'image' is used to denote the image data that is sampled, quantized, and readily available in a form suitable for further processing by digital computers. Some authors use the term 'picture' to refer to analog or raw image data and the term 'image' to refer to digital data that is suitable for processing using digital computers. Broadly speaking, image processing is an area that deals with manipulation of visual information. One of the major objectives of image processing is to improve the quality of pictorial information for better human interpretation. Another objective is to facilitate the automatic machine interpretation of images.

1.2 NATURE OF IMAGE PROCESSING

There are three scenarios or ways of acquiring an image—reflective mode imaging, emissive type imaging, and transmissive imaging. These are illustrated in Fig. 1.1. The radiation source shown in Fig. 1.1 is the light source. Can you imagine a world without light? Objects are perceived by the eye because of light. The sun, lamps, and clouds are all examples of radiation or light sources. The object is the target for which the image needs to be created. The object can be people, industrial components, or the anatomical structure of a patient. The objects can be two-dimensional, three-dimensional, or multidimensional mathematical functions involving many variables. For example, a printed document is a 2D object. Most real-world objects are 3D. *Reflective mode imaging* represents the simplest form of imaging and uses a sensor to acquire the digital image. All video cameras, digital cameras, and scanners use some types of sensors for capturing the image. Image sensors are important components of imaging systems. They convert light energy to electric signals.

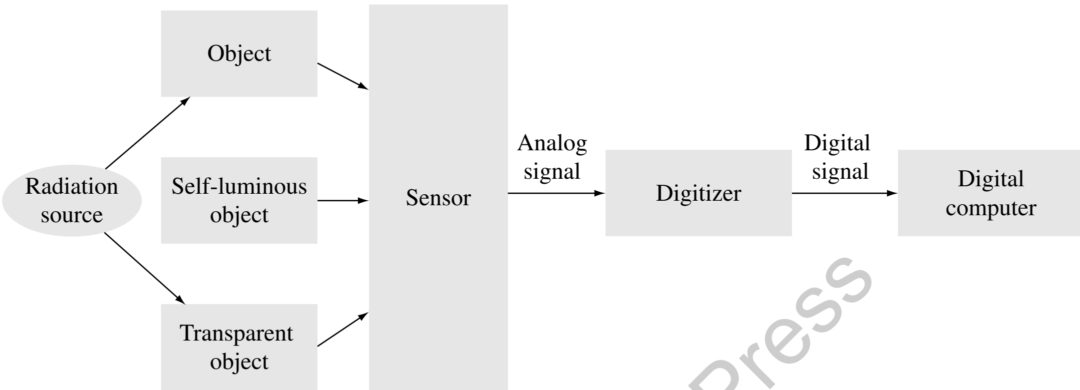


Fig. 1.1 Image processing environment

Emissive type imaging is the second type, where the images are acquired from self-luminous objects without the help of a radiation source. In emissive type imaging, the objects are self-luminous. The radiation emitted by the object is directly captured by the sensor to form an image. Thermal imaging is an example of emissive type imaging. In thermal imaging, a specialized thermal camera is used in low light situations to produce images of objects based on temperature. Other examples of emissive type imaging are magnetic resonance imaging (MRI) and positron emissive tomography (PET).

Transmissive imaging is the third type, where the radiation source illuminates the object. The absorption of radiation by the objects depends upon the nature of the material. Some of the radiation passes through the objects. The attenuated radiation is sensed into an image. This is called transmissive imaging. Examples of this kind of imaging are X-ray imaging, microscopic imaging, and ultrasound imaging.

The first major challenge in image processing is to acquire the image for further processing. Figure 1.1 shows three types of processing—optical, analog, and digital image processing. Optical image processing is the study of the radiation source, the object, and other optical processes involved. It refers to the processing of images using lenses and coherent light beams instead of computers. Human beings can see only the optical image. An optical image is the 2D projection of a 3D scene. This is a continuous distribution of light in a 2D surface and contains information about the object that is in focus. This is the kind of information that needs to be captured for the target image. *Optical image processing* is an area that deals with the object, optics, and how processes are applied to an image that is available in the form of reflected or transmitted light. The optical image is said to be available in optical form till it is converted into analog form.

An analog or continuous image is a continuous function $f(x, y)$, where x and y are two spatial coordinates. Analog signals are characterized by continuous signals varying with time. They are often referred to as pictures. The processes that are applied to the analog signal are called analog processes. *Analog image processing* is an area that deals with the processing of analog electrical signals using analog circuits. The imaging systems that use film for recording images are also known as analog imaging systems. In medical imaging, still films are used, as films provide better quality than digital systems.

The analog signal is often sampled, quantized, and converted into digital form using a digitizer. *Digitization* refers to the process of sampling and quantization. *Sampling* is the process of converting a continuous-valued image $f(x, y)$ into a discrete image, as computers cannot handle continuous data. So the main aim is to create a discretized version of the continuous data. Sampling is a reversible process, as it is possible to get the original image back. *Quantization* is the process of converting the sampled analog value of the function $f(x, y)$ into a discrete-valued integer. *Digital image processing* is an area that uses digital circuits, systems, and software algorithms to carry out the image processing operations. The image processing operations may include quality enhancement of an image, counting of objects, and image analysis.

Digital image processing has become very popular now, as digital images have many advantages over analog images. Some of the advantages are as follows:

1. It is easy to post-process the image. Small corrections can be made in the captured image using software.
2. It is easy to store the image in the digital memory.
3. It is possible to transmit the image over networks. So sharing an image is quite easy.
4. A digital image does not require any chemical process. So it is very environment friendly, as harmful film chemicals are not required or used.
5. It is easy to operate a digital camera.

The disadvantages of digital images are very few. Some of the disadvantages are the initial cost, problems associated with sensors such as high power consumption and potential equipment failure, and other security issues associated with the storage and transmission of digital images. Digital imaging is the technique practised now, as the advantages of digital image processing outweigh the disadvantages.

The final form of an image is the display image. The human eye can recognize only the optical form. So the digital image needs to be converted to optical form through the digital to analog conversion process.

1.3 IMAGE PROCESSING AND RELATED FIELDS

Image processing is an exciting interdisciplinary field that borrows ideas freely from many fields. Figure 1.2 illustrates the relationships between image processing and other related fields.

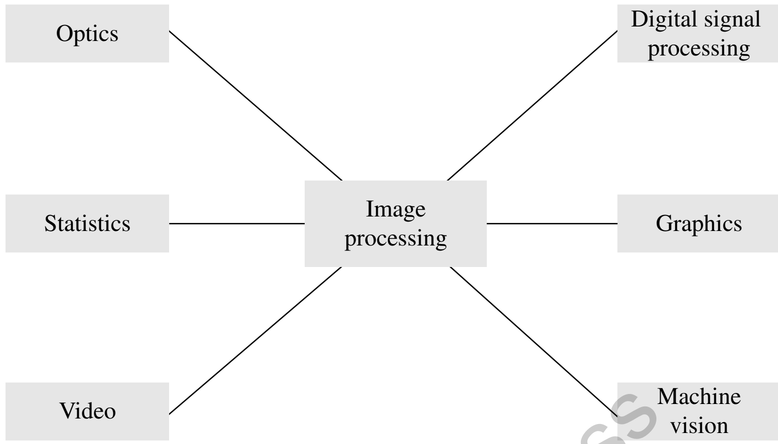


Fig. 1.2 Image processing and other closely related fields

1.3.1 Image Processing and Computer Graphics

Computer graphics and image processing are very closely related areas. Image processing deals with raster data or bitmaps, whereas computer graphics primarily deals with vector data. Raster data or bitmaps are stored in a 2D matrix form and often used to depict real images. However, vector images are composed of vectors, which represent the mathematical relationships between the objects. Vectors are lines or primitive curves that are used to describe an image. Vector graphics are often used to represent abstract, basic line drawings.

The algorithms in computer graphics often take numerical data as input and produce an image as output. However, in image processing, the input is often an image. The goal of image processing is to enhance the quality of the image to assist in interpreting it. Hence, the result of image processing is often an image or the description of an image. Thus, image processing is a logical extension of computer graphics and serves as a complementary field.

1.3.2 Image Processing and Signal Processing

Human beings interact with the environment by means of various signals. In digital signal processing, one often deals with the processing of a one-dimensional signal. In the domain of image processing, one deals with visual information that is often in two or more dimensions. Therefore, image processing is a logical extension of signal processing.

1.3.3 Image Processing and Machine Vision

The main goal of machine vision is to interpret the image and to extract its physical, geometric, or topological properties. Thus, the output of image processing operations can be subjected to more techniques, to produce additional information for interpretation.

Artificial vision is a vast field, with two main subfields—machine vision and computer vision. The domain of *machine vision* includes many aspects such as lighting and camera, as part of the implementation of industrial projects, since most of the applications associated with machine vision are automated visual inspection systems. The applications involving machine vision aim to inspect a large number of products and achieve improved quality controls. *Computer vision* is more ambitious. It tries to mimic the human visual system and is often associated with scene understanding. Most image processing algorithms produce results that can serve as the first input for machine vision algorithms.

1.3.4 Image Processing and Video Processing

Image processing is about still images. In fact, analog video cameras can be used to capture still images. A video can be considered as a collection of images indexed by time. Most image processing algorithms work with video readily. Thus, video processing is an extension of image processing. In addition, images are strongly related to multimedia, as the field of multimedia broadly includes the study of audio, video, images, graphics, and animation.

1.3.5 Image Processing and Optics

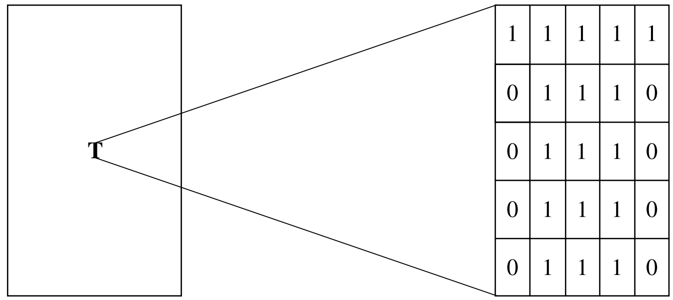
Optical image processing deals with lenses, light, lighting conditions, and associated optical circuits. The study of lenses and lighting conditions has an important role in the study of image processing.

1.3.6 Image Processing and Statistics

Image analysis is an area that concerns the extraction and analysis of object information from the image. Imaging applications involve both simple statistics such as counting and mensuration and complex statistics such as advanced statistical inference. So statistics play an important role in imaging applications. Image understanding is an area that applies statistical inferencing to extract more information from the image.

1.4 DIGITAL IMAGE REPRESENTATION

An image can be defined as a 2D signal that varies over the spatial coordinates x and y, and can be written mathematically as $f(x, y)$. Medical images such as magnetic resonance images and computerized tomography (CT) images are 3D images that can be represented as $f(x, y, z)$, where x, y, and z are spatial coordinates. A sample digital image and its matrix equivalent are shown in Figs 1.3(a) and 1.3(b).



(a) (b)

Fig. 1.3 Digital image representation (a) Small binary digital image (b) Equivalent image contents in matrix form

Figure 1.3(a) shows a displayed image. The source of the image is a matrix as shown in Fig. 1.3(b). The image has five rows and five columns. In general, the image can be written as a mathematical function $f(x, y)$ as follows:

$$f(x,y)=\begin{pmatrix} f(0,0) & f(0,1) & f(0,2) & \cdots & f(0,Y-1) \\ f(1,0) & f(1,1) & f(1,2) & \cdots & f(1,Y-1) \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ f(X-1,0) & f(X-1,1) & f(X-1,2) & \cdots & f(X-1,Y-1) \end{pmatrix}$$

In general, the image $f(x, y)$ is divided into X rows and Y columns. Thus, the coordinate ranges are $\{x=0, 1,\ldots, X-1\}$ and $\{y=0, 1, 2,\ldots, Y-1\}$. At the intersection of rows and columns, pixels are present. The word 'pixel' is an abbreviation of 'picture element'. The terms pixel, picture element, and pel are synonymous. A typical digital image consists of millions of pixels. Pixels are considered the building blocks of digital images, as they combine together to give a digital image. Pixels represent discrete data. Their meaning varies with context. A pixel can be considered as a single sensor, photosite (physical element of the sensor array of a digital camera), element of a matrix, or display element on a monitor.

The value of the function $f(x, y)$ at every point indexed by a row and a column is called *grey value* or *intensity* of the image. Generally, the value of the pixel is the intensity value of the image at that point. The intensity value is the sampled, quantized value of the light that is captured by the sensor at that point. It is a number and has no units. However, the value of the pixel is not always the intensity value. In an X-ray image, the value of the pixel indicates the attenuation of the X-ray at that point. In an MRI, the pixel value denotes the average MR signal intensity.

The number of rows in a digital image is called *vertical resolution*. The number of columns is called *horizontal resolution*. The number of rows and columns describes the dimensions of the image. The image size is often expressed in terms of the rectangular pixel dimensions of the array. Images can be of various sizes. Some examples of image size are 256×256, 512×512, etc. For a digital camera, the image size is defined as the total number of pixels (specified in megapixels).

Resolution is an important characteristic of an imaging system. It is the ability of the imaging system to produce the smallest discernable details, that is the smallest sized object clearly, and differentiate it from the neighbouring small objects that are present in the image. Image resolution depends on two factors—optical resolution of the lens and spatial resolution. Optical resolution is covered in Chapter 2.

Spatial resolution of the image is very crucial as the digital image must show the object and its separation from the other spatial objects that are present in the image clearly and precisely. Consider a chart with vertical lines of width W. Let the space between the lines also be W. Then the line and the adjacent space constitute a line pair. The width of the line pair is $2W$, that is, W for the line and W for the space. Thus there are $1/2W$ line pairs per unit distance. A useful way to define resolution is the smallest number of line pairs per unit distance. The resolution can then be quantified as 200 line pairs per mm.

Spatial resolution depends on two parameters—the number of pixels of the image and the number of bits necessary for adequate intensity resolution, referred to as the bit depth. The numbers of pixels determine the quality of the digital image. The total number of pixels that are present in the digital image is the number of rows multiplied by the number of columns.

The choice of bit depth is very crucial and often depends on the precision of the measurement system. To represent the pixel intensity value, certain bits are required. For example, in binary images, the possible pixel values are 0 or 1. To represent two values, one bit is sufficient. The number of bits necessary to encode the pixel value is called *bit depth*. Bit depth is a power of two; it can be written as 2^m. In monochrome grey scale images (e.g., medical images such as X-rays and ultrasound images), the pixel values can be between 0 and 255. Hence, eight bits are used to represent the grey shades between 0 and 255 (as $2^8 = 256$). So the bit depth of grey scale images is 8. In colour images, the pixel value is characterized by both colour value and intensity value. So colour resolution refers to the number of bits used to represent the colour of the pixel. The set of all colours that can be represented by the bit depth is called *gamut* or *palette*.

So the total number of bits necessary to represent the image is

$$\text{Number of rows} \times \text{Number of columns} \times \text{Bit depth}$$

As discussed earlier, spatial resolution depends on the number of pixels present in the image and the bit depth. Keeping the number of pixels constant but reducing the quantization levels (bit depth) leads to a phenomenon called *false contouring*. On the other hand, the decrease in the number of pixels while retaining the quantization levels leads to a phenomenon called *checkerboard effect* (or *pixelization error*). These effects are discussed in detail in Chapter 2.

The concept of 2D images can be extended to 3D images also. A 3D image is a function $f(x, y, z)$, where x, y, and z are spatial coordinates. In 3D images, the term 'voxel' is used for pixel. Voxel is an abbreviation of 'volume element'.

1.5 TYPES OF IMAGES

There is no single accepted way of classifying images. They can be classified based on many criteria. Some ways in which images can be classified are shown in Fig. 1.4.

1.5.1 Based on Nature

Images can be broadly classified as natural and synthetic images. Natural images are, as the name implies, images of the natural objects obtained using devices such as cameras or scanners. Synthetic images are images that are generated using computer programs.

1.5.2 Based on Attributes

Based on attributes, images can be classified as raster images and vector graphics. Vector graphics use basic geometric attributes such as lines and circles, to describe an image. Hence the notion of resolution is practically not present in graphics. However, raster images (discussed in Section 1.3.1) are pixel-based. The quality of the raster images is dependent on the number of pixels. So operations such as enlarging or blowing-up of a raster image often result in quality reduction.

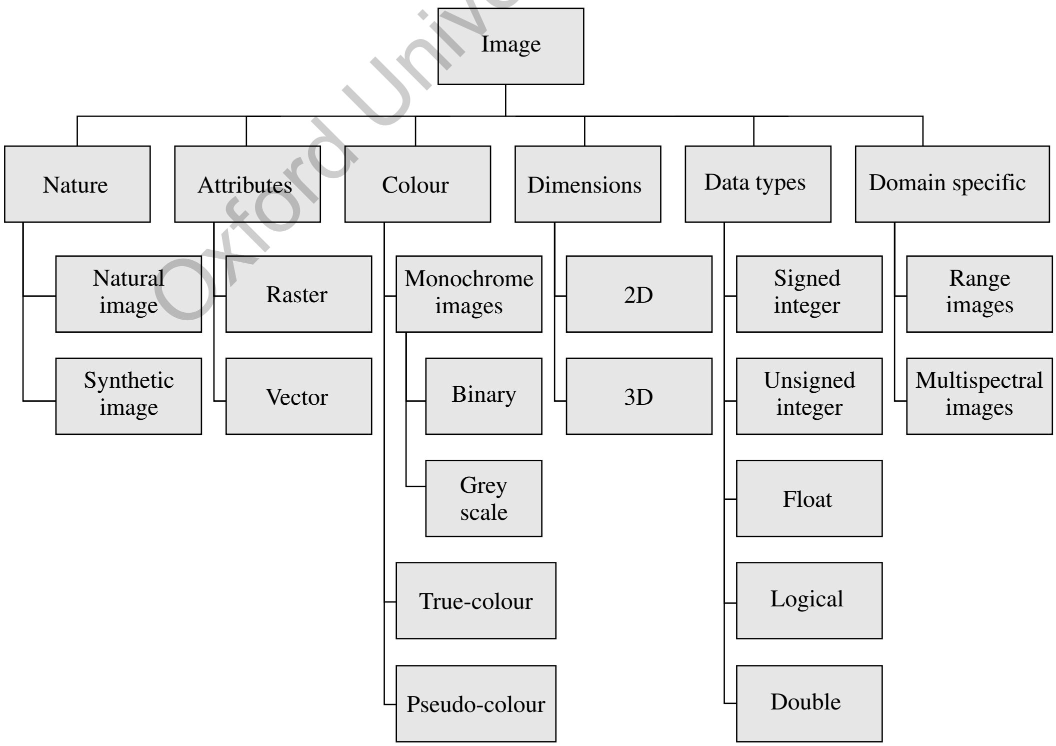


Fig. 1.4 Classification of images

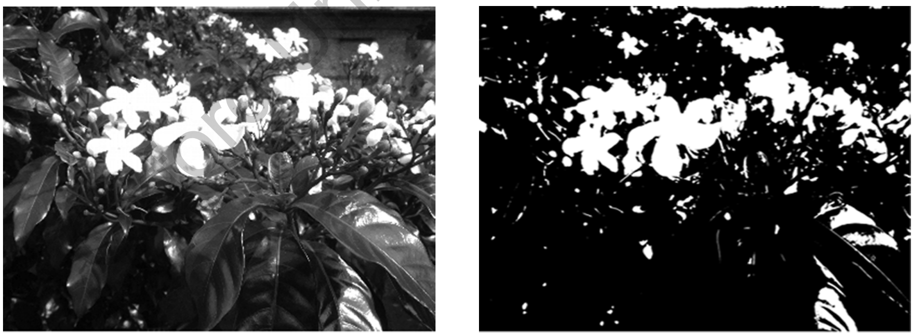
1.5.3 Based on Colour

Based on colour, images can be classified as grey scale, binary, true colour, and pseudocolour images. Grey scale and binary images are called monochrome images as there is no colour component in these images. True colour (or full colour) images represent the full range of available colours. So the images are almost similar to the actual object and hence called true colour images. In addition, true colour images do not use any lookup table but store the pixel information with full precision. On the other hand, pseudocolour images are false colour images where the colour is added artificially based on the interpretation of data.

1.5.3.1 Grey scale images

Grey scale images are different from binary images as they have many shades of grey between black and white. A sample grey scale image is shown in Fig. 1.5(a). These images are also called monochromatic as there is no colour component in the image, like in binary images. *Grey scale* is the term that refers to the range of shades between white and black or vice versa.

Eight bits ($2^8 = 256$) are enough to represent grey scale as the human visual system can distinguish only 32 different grey levels. The additional bits are necessary to cover noise margins. Most medical images such as X-rays, CT images, MRIs, and ultrasound images are grey scale images. These images may use more than eight bits. For example, CT images may require a range of 10–12 bits to accurately represent the image contrast.



(a) (b)

Fig. 1.5 Monochrome images (a) Grey scale image (b) Binary image

1.5.3.2 Binary images

In binary images, the pixels assume a value of 0 or 1. So one bit is sufficient to represent the pixel value. Binary images are also called bi-level images. In image processing, binary images are encountered in many ways.

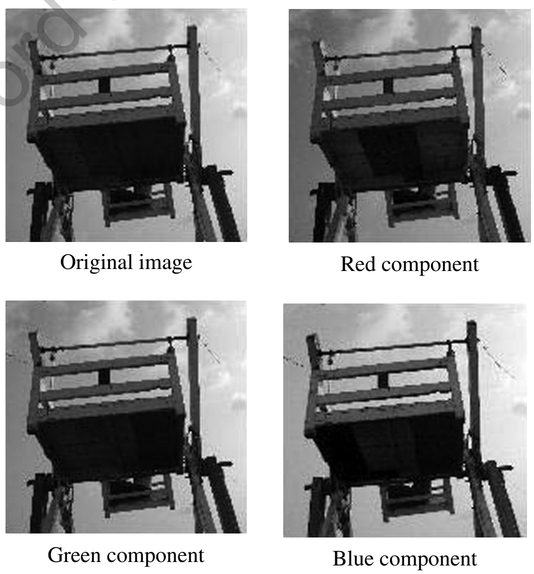
The binary image is created from a grey scale image using a threshold process. The pixel value is compared with the threshold value. If the pixel value of the grey scale image is greater than the threshold value, the pixel value in the binary image is considered as 1.

Otherwise, the pixel value is 0. The binary image created by applying the threshold process on the grey scale image in Fig. 1.5(a) is displayed in Fig. 1.5(b). It can be observed that most of the details are eliminated. However, binary images are often used in representing basic shapes and line drawings. They are also used as masks. In addition, image processing operations produce binary images at intermediate stages.

1.5.3.3 True colour images

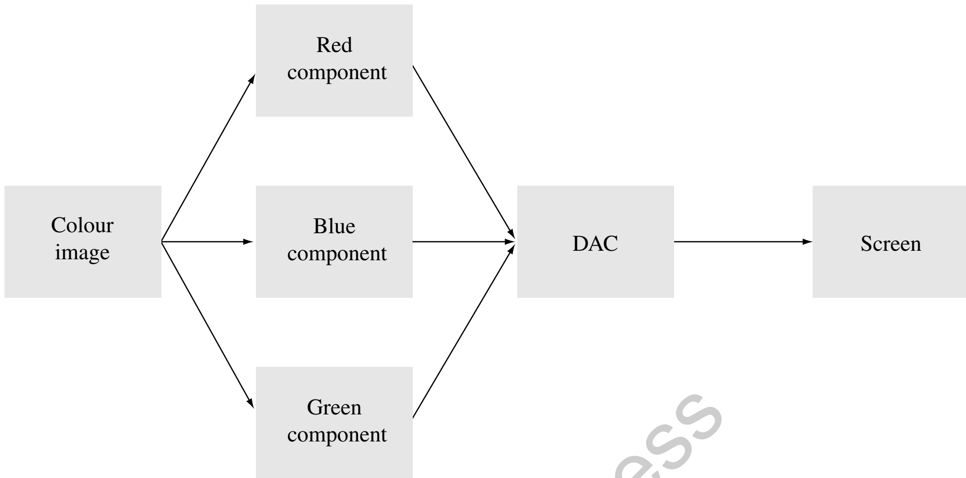
In true colour images, the pixel has a colour that is obtained by mixing the primary colours red, green, and blue. Each colour component is represented like a grey scale image using eight bits. Mostly, true colour images use 24 bits to represent all the colours. Hence true colour images can be considered as three-band images. The number of colours that is possible is 256^3 (i.e., $256 \times 256 \times 256 = 1{,}67{,}77{,}216$ colours). Figure 1.6(a) shows a colour image and its three primary colour components. Figure 1.6(b) illustrates the general storage structure of the colour image. A display controller then uses a digital-to-analog converter (DAC) to convert the colour value to the pixel intensity of the monitor.

A special category of colour images is the indexed image. In most images, the full range of colours is not used. So it is better to reduce the number of bits by maintaining a colour map, gamut, or palette with the image. Figure 1.6(c) illustrates the storage structure of an indexed image. The pixel value can be considered as a pointer to the index, which contains the address of the colour map. The colour map has RGB components. Using this indexed approach, the number of bits required to represent the colours can be drastically reduced. The display controller uses a DAC to convert the RGB value to the pixel intensity of the monitor.

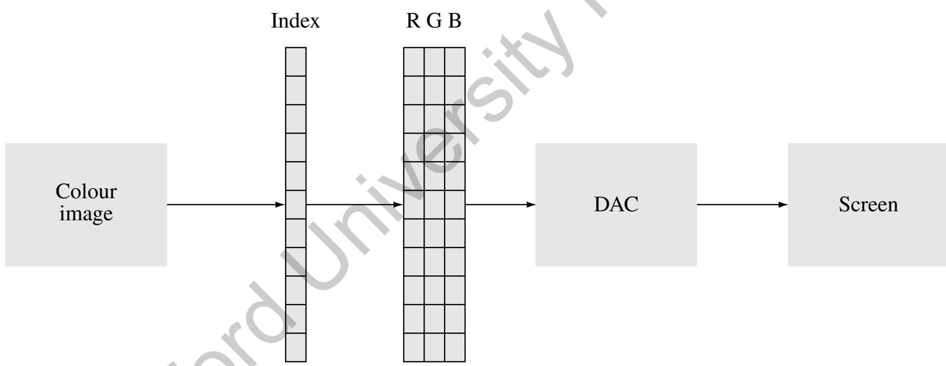


(a)

Fig. 1.6 True colour images (a) Original image and its colour components



(b)



(c)

Fig. 1.6 (b) Storage structure of colour images (c) Storage structure of an indexed image [Refer to Oxford University Press (OUPI) website for colour images]

1.5.3.4 Pseudocolour images

Like true colour images, pseudocolour images are also used widely in image processing. True colour images are called three-band images. However, in remote sensing applications, multi-band images or multi-spectral images are generally used. These images, which are captured by satellites, contain many bands. A typical remote sensing image may have 3–11 bands in an image. This information is beyond the human perceptual range. Hence it is mostly not visible to the human observer. So colour is artificially added to these bands, so as to distinguish the bands and to increase operational convenience. These are called artificial colour or pseudocolour images. Pseudocolour images are popular in the medical domain also. For example, the Doppler colour image is a pseudocolour image.

Example 1.1 What is the storage requirement for a 1024×1024 binary image?

Solution For a binary image, one bit is sufficient for representing the pixel value. So the number of bits required will be $1024 \times 1024 \times 1 = 10{,}48{,}576$ bits $= 1{,}31{,}072$ bytes = 131.072 Kb (Assume 1 Kb = 1000 bytes).

Example 1.2 What is the storage requirement for a 1024×1024 24-bit colour image?

Solution Since colour images are three-band images (red, green, and blue components), the storage requirement is $1024 \times 1024 \times 3$ bytes $= 31{,}45{,}728$ bytes. If it is assumed that 1 Kb is 1000 bytes, the storage requirement is 3,145.728 Kb.

Example 1.3 A picture of physical size 2.5 inches by 2 inches is scanned at 150 dpi. How many pixels would be there in the image?

Solution The relation between the physical dimensions and the spatial resolution is simple. The pixel dimensions are obtained by multiplying the physical width and height by the scanned resolution. Therefore, the pixel dimension is as follows.

$$(2.5 \times 150) \times (2 \times 150)$$

$$= 375 \times 300 = 112500 \text{ pixels would be present}$$

Example 1.4 If a 375×300 grey-scale image needs to be sent across the channel of capacity 28 kbps, then how much transmission time is required?

Solution If the picture is grey scale, then 8 bits are used. Therefore, transmission time would be

$$= \frac{375 \times 300 \times 8}{28 \times 1000} = \frac{112500 \times 8}{28000} = 32.143 \text{ sec}$$

Example 1.5 Given a grey-scale image of size 5 inches by 6 inches scanned at the rate of 300 dpi, answer the following:

(a) How many bits are required to represent the image?
(b) How much time is required to transmit the image if the modem is 28 kbps?
(c) Repeat the aforementioned if it were a binary image.

Solution

(a) Number of bits required to represent grey-scale image (uses 8 bits)

$$= 5 \times 300 \times 6 \times 300 \times 8 = 1500 \times 1800 \times 8 = 21600000 \text{ bits}$$

(b) Total time taken to transmit image

$$= \frac{\text{Total number of bits in image}}{\text{Transmission Speed}} = \frac{21600000}{28000} = 771.43 \text{ sec}$$

(c) If it is binary image, then the number of bits required to represent binary image

$$= 5 \times 300 \times 6 \times 300 \times 1 = 1500 \times 1800 \times 1 = 2700000 \text{ bits}$$

$$\text{The total transmission time would be} = \frac{\text{Total number of bits}}{\text{Transmission speed}} = \frac{2700000}{28000} = 96.429 \text{ sec}$$

1.5.4 Based on Dimensions

Images can be classified based on dimensions also. Normally, digital images are a 2D rectangular array of pixels. If another dimension, of depth or any other characteristic, is considered, it may be necessary to use a higher-order stack of images. A good example of a 3D image is a volume image, where pixels are called voxels. By '3D image', it is meant that the dimension of the target in the imaging system is 3D. The target of the imaging system may be a scene or an object. In medical imaging, some of the frequently encountered 3D images are CT images, MRIs, and microscopy images. Range images, which are often used in remote sensing applications, are also 3D images.

1.5.5 Based on Data Types

Images may be classified based on their data type. A binary image is a 1-bit image as one bit is sufficient to represent black and white pixels. Grey scale images are stored as one-byte (8-bit) or two-byte (16-bit) images. With one byte, it is possible to represent 2^8, that is 0–255 = 256 shades and with 16 bits, it is possible to represent 2^{16}, that is, 65,536 shades. Colour images often use 24 or 32 bits to represent the colour and intensity value.

Sometimes, image processing operations produce images with negative numbers, decimal fractions, and complex numbers. For example, Fourier transforms produce images involving complex numbers. To handle negative numbers, signed and unsigned integer types are used. In these data types, the first bit is used to encode whether the number is positive or negative. For example, the signed data type encodes the numbers from −128 to 127 where one bit is used to encode the sign. In general, an n-bit signed integer can represent integers from -2^{n-1} to $2^{n-1}-1$, a total of 2^n. Unsigned integers represent all integers from 0 to $2^n - 1$ with n bits.

Floating-point involves storing the data in scientific notation. For example, 1230 can be represented as 0.123×10^4, where 0.123 is called the significand and the power is called the exponent. There are many floating-point conventions.

The quality of such data representation is characterized by parameters such as data accuracy and precision. Data accuracy is the property of how well the pixel values of an image are able to represent the physical properties of the object that is being imaged. Data accuracy is an important parameter, as the failure to capture the actual physical properties of the image leads to the loss of vital information that can affect the quality of the application. While accuracy refers to the correctness of a measurement, precision refers to the repeatability of the measurement. In other words, repeated measurements of the physical properties of the object should give the same result. Most software use the data type ‘double’ to maintain precision as well as accuracy.

1.5.6 Domain Specific Images

Images can be classified based on the domains and applications where such images are encountered. The following are some of those images that are popular.

1.5.6.1. Range images

Range images are often encountered in computer vision. In range images, the pixel values denote the distance between the object and the camera. These images are also referred to as depth images. This is in contrast to all other images that have been discussed so far whose pixel values denote intensity and hence are often known as intensity images.

1.5.6.2. Multispectral images

Multispectral images are encountered mostly in remote sensing applications. These images are taken at different bands of visible or infrared regions of the electromagnetic wave. Just as a colour image is of three bands, multispectral images may have many bands that may include infrared and ultraviolet regions of the electromagnetic spectrum.

1.6 DIGITAL IMAGE PROCESSING OPERATIONS

The flow of an image processing operation is illustrated in Fig. 1.7. Image processing applications take an image as input and produce either an image or descriptions of the objects that are present in the image as output. Generally the output of image processing operations is another image. Brightness enhancement and contrast manipulation are examples of image processing operations.

Fig. 1.7 Image processing operation

Figure 1.8 illustrates the general framework of an image analysis operation. The input for image analysis operations is in the form of an image. Image analysis operations produce a numerical output or descriptions of either the objects that are present in the image or the image itself. Some examples of image analysis operations are histogram of an image, and counting and gauging of objects.

Fig. 1.8 Image analysis operation

Image processing and image analysis operations take the information from the image as it is. However, when the knowledge of the user is combined with image information, many intelligent applications can be designed. An image understanding operation is one such intelligent application that tries to mimic the human visual system. Image understanding applications aim to construct models using the knowledge constructs, and use the constructs to identify and analyse the spatial relations among the objects that are present in the image, just like the human visual system. Normally, image understanding applications are the primary goal of machine vision systems.

Generally, image processing operations are divided into two categories as follows:

1. Low-level operations 2. High-level operations

They are illustrated in Fig. 1.9.

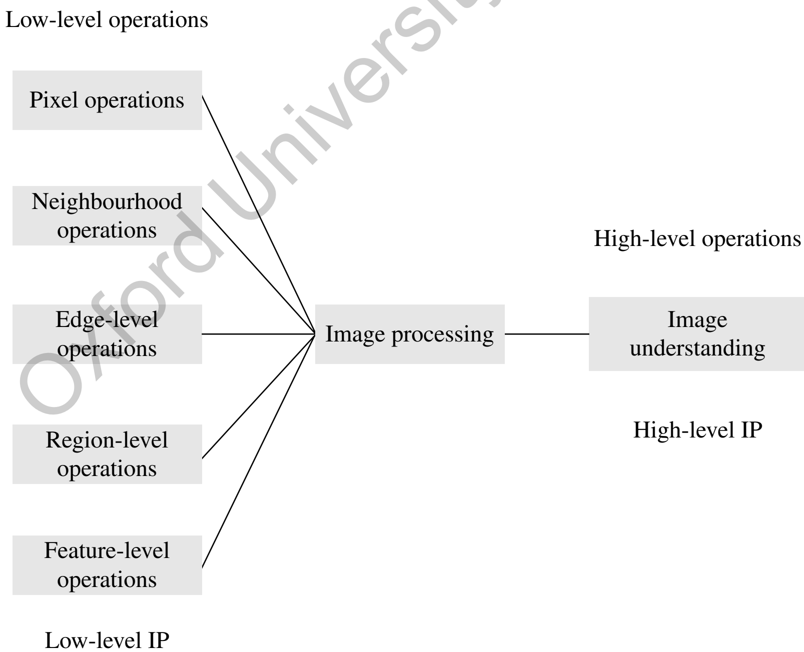


Fig. 1.9 Levels of image processing operations

Generally, low-level image processing is associated with traditional image processing, and there is a tendency to associate high-level operations with image understanding. There is no complete agreement among researchers as to what constitutes low-level processing. However, it is assumed that the knowledge requirements of low-level operations are very less. In that context, operations such as image acquisition, preprocessing, and compression are considered as low-level operations.

Image segmentation and feature extraction deal with the extraction of necessary image portions and analysis of images for image features. Image features are essential information for recognition. Hence, segmentation and feature extraction are considered to be important areas, as these stages serve as a link between low-level and high-level image processing.

High-level image processing predominantly deals with image understanding. It deals with the interpretation of the image in a more meaningful manner, like an expert human observer. To do that, high-level operations construct models of the images, with knowledge constructs. High-level processing is based on knowledge, goals, and plans. Image understanding uses the concepts of artificial intelligence heavily to imitate human cognition. The process of image understanding involves the iteration of the following steps till adequate knowledge is gained:

1. Construction of the model of the real-world object or scene
2. Construction of the model from the image
3. A matching process, initiated between the real-world model and the model created from the image, which results in partial or complete matching
4. A feedback mechanism that invokes additional routines to update the models if necessary

This process is iteratively performed to create additional knowledge and feedback mechanisms. These steps are performed till the models converge to achieve the global goal. Naturally, these tasks are complex and often computationally intensive.

1.7 FUNDAMENTAL STEPS IN IMAGE PROCESSING

Automatic image interpretation is often desirable. A comparison of computer-based and manual interpretation is given in Table 1.1.

Table 1.1 Comparison of computer-based and manual interpretation

Computer-based interpretation	Manual interpretation
Computers are very accurate in performing numerical calculations, but less skilled in recognition compared to human beings.	Human beings are highly skilled in recognition, but slow in performing numerical calculations.
Computers are very fast.	Human beings are affected by many factors such as fatigue and boredom. Human errors are inevitable.
Computers are robust.	Human analysis is subjective. Often experts themselves differ from one another in interpretation. There are intra- and inter-operator differences.
Computers are flexible. They are easily configurable and easily deployable.	Human expertise is costly and less flexible.
Computer interpretation is reliable.	Human interpretation is subjective and variable. This affects reliability.

These points prove that computers can serve as effective tools in assisting experts. For example, in medical imaging applications, computer-based diagnosis may assist a physician by providing valuable information, so that the physician may use his expertise to arrive at the final diagnosis. This way, a computer-based diagnosis may lead to a more accurate diagnostic decision by a physician. The same logic applies to other domains as well.

Figure 1.10 illustrates the steps in automatic image analysis and interpretation. These steps are crucial for implementing any imaging application.

These steps are described as follows:

Image acquisition This step aims to obtain the digital image of the object.

Image enhancement This step aims to improve the quality of the image so that the analysis of the images is reliable.

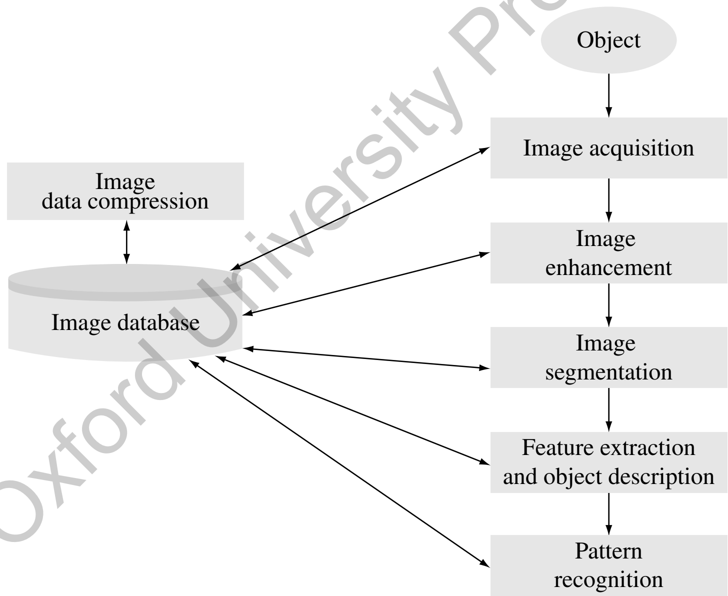


Fig. 1.10 Steps in image processing

Image segmentation This step divides the image into many sub-regions and extracts the regions that are necessary for further analysis. The portions of the image that are not necessary, such as image backgrounds (dictated by the imaging requirement), are discarded.

Feature extraction and object description Imaging applications use many routines for extraction of image features that are necessary for recognition. This is called image feature extraction step. The extracted object features are represented in meaningful data structures and the objects are described.

Pattern recognition This step is for identifying and recognizing the object that is present in the image, using the features generated in the earlier step and pattern recognition algorithms such as classification or clustering.

Image data compression and image database are the other important steps in image processing. Image databases are used to store the acquired images and the temporary images that are created during processing. The data compression step is crucial as it aims to reduce the storage requirement by removing the redundancies that are present in the image. This step is crucial as the storage requirements of images are very high.

This basic model clearly serves as the baseline design for most imaging applications, where the aim is to recognize the object. Any practical application can be fitted into this baseline model. For example, the utility of this model can be explained for fingerprint recognition. The fingerprints are acquired in the image acquisition phase. Then the acquired fingerprint quality is enhanced for brightness and contrast. Then the portions that are necessary for fingerprint recognition such as loops, whorls, and minutiae are extracted in the image segmentation phase, represented as features, and analysed. Pattern recognition tasks such as classifiers can then use these features for recognizing the given fingerprint. The end result is the recognition of the fingerprint as either valid or invalid.

Amongst these stages, the following imaging operation classes are considered very fundamental. A class is a group of image operations that share the same objectives. The fundamental classes are as follows:

1. Image enhancement
2. Image restoration
3. Image compression
4. Image analysis
5. Image synthesis

1.7.1 Image Enhancement

Image enhancement is one of the most important classes of algorithms. Often, the captured image may not be of good quality (i.e., vital information that is necessary for the imaging application may not be available) because of factors such as noise, poor brightness, contrast, blur, or artefact. *Noise* is any unwanted signal. *Blur* is a disturbance that makes the image difficult for interpretation. *Artefacts* are features of the object that are not true. These are observational errors, including dust and scratches on the image surface, which complicate the process of accurate image interpretation. Therefore, it may be necessary to reduce the noise and to sharpen the details. These algorithms form the core of image enhancement. The dark image of Fig. 1.11(a) is enhanced by an image enhancement algorithm to increase the brightness of the image. A better quality image is shown in Fig. 1.11(b). The improvement can be assessed visually.

(a) (b)

Fig. 1.11 Image enhancement (a) Dark image (b) Enhanced image

1.7.2 Image Restoration

Image restoration is the objective way of improving the quality of the image. The goal of image restoration is the same as that of image enhancement. However, image restoration is different from image enhancement, as image restoration deals with degradations of extreme nature such as distortions created by the sensor system, poor lighting conditions, and artefacts. Image restoration is more mathematical and formal. Hence, image restoration problems are stated mathematically. Image restoration includes techniques such as inverse filtering and blind deconvolution algorithms. Sometimes, complete knowledge of the source of degradation is available. In that case, the simple inverse filtering process can be used to reverse the original degradations, as inverse filtering is the negation process for removing the degradations. However, if the causes of degradations are not known, then the degradations are estimated approximately and a process known as blind deconvolution is used to restore the original image. An example of motion blur and the restored image is shown in Figs 1.12(a) and 1.12(b).

(a) (b)

Fig. 1.12 Image restoration (a) Blurred image (b) Restored image

1.7.3 Image Compression

Multimedia objects occupy a lot of storage space. Often, these images need to be transmitted across a channel to a remote imaging system in imaging applications such as telemedicine. Hence in such a case, the storage and transmission of the image becomes an important task. Image compression algorithms reduce the data that is needed to describe the object, by eliminating the redundancies that are present in the image.

There are two classes of image compression algorithms. One class is lossless compression algorithms and the other is lossy compression algorithms. Lossless compression algorithms preserve the information that is very critical, and are useful in medical domains where even a subtle feature may contain valuable information. Lossy compression algorithms are used where the loss of image data cannot be perceived by the human observer or the loss of information is acceptable. Figure 1.13(a) illustrates an original image and the application of lossy compression on it to yield the resultant images shown in Figs 1.13(b) and 1.13(c) with a quality of 95% and 5%, respectively. It can be observed that loss of quality is not perceivable by the human eye. This illustrates that the image has more redundant data. Many imaging and video applications such as video conferencing require lossy compression algorithms to manage the size of the multimedia objects.

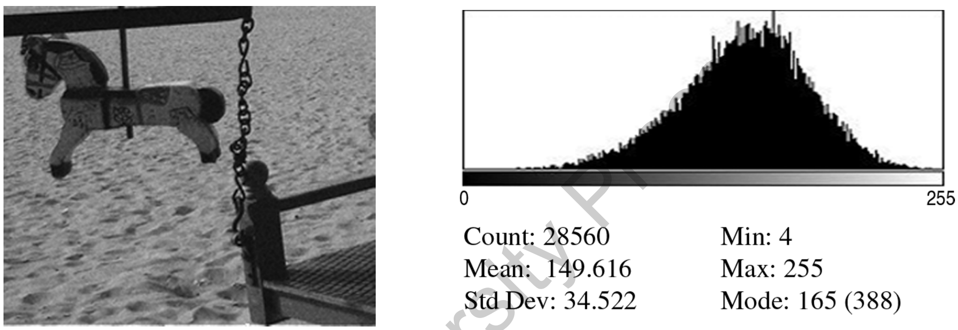
(a) (b) (c)

Fig. 1.13 Image compression (a) Original image (b) Image quality at 95% (c) Image quality at 5%

1.7.4 Image Analysis

Often, machine vision systems require image measurement. This includes measurement of shape, size, texture, and colour of the objects that are present in the image. Hence, image analysis is a very important class of algorithms that takes images as input and produces numerical and graphical information based on the characteristics of the image data. Image analysis comprises, but is not limited to, classification of the objects, performing statistical tasks, and providing extraction and description of the scene for ultimate interpretation. One example of image analysis is plotting the histogram of an image.

Figures 1.14(a) and 1.14(b) illustrate an image and its histogram. Histogram is a simple image analysis technique. It illustrates the distribution of grey levels of an image in the form of a table or graph. Based on the histogram, one can obtain information about the quality of the image. The darkness of the image is manifested in the histogram, as the dynamic ranges of the pixels are not good. Perhaps the presence of all pixels as a cluster illustrates that the image needs to be improved. In addition, image analysis involves finding measurements of the objects such as mean and variance. Some of the statistical measurements are shown in Fig. 1.14(b).



(a) (b)

Fig. 1.14 Image analysis (a) Original image (b) Histogram and its statistics

1.7.5 Image Synthesis

Image synthesis deals with the creation of images from other images or non-image data. Image synthesis is used to create images that are not available physically or cannot be acquired using any imaging procedure. The medical imaging domain uses image synthesis extensively. A CT is a reconstructed image. For example, the image shown in Fig. 1.15 is a simulated image as it is neither scanned nor captured, but created through software. These simulated images are useful for presentation and experimental purposes as benchmark and test images.

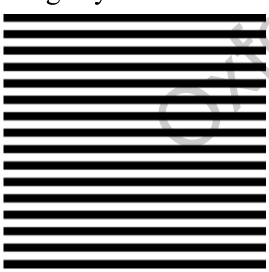


Fig. 1.15 Sample synthetic grating

1.8 IMAGE PROCESSING APPLICATIONS

This section briefly surveys image processing applications. The survey of imaging applications can be from the viewpoint of either the electromagnetic spectrum or the application domain.

1.8.1 Survey of Image Processing Applications Based on EM Radiation

The survey from the electromagnetic domain is justified as visible light is part of the electromagnetic spectrum. Electromagnetic waves are waves of energy that have both electric and magnetic characteristics and which can travel at the speed of light in vacuum. Electromagnetic waves can be classified based on the frequency or wavelength and its select parts are shown in Table 1.2.

Table 1.2 Select parts of the electromagnetic spectrum

Types of radiation	Frequency range (in Hertz)	Wave length (in cm)	Nature of imaging and its relevance for image processing
Radio waves	10^5–10^{10}	> 10^9	AM/FM radio
Microwave	10^{10}–10^{12}	10^9–10^6	Radar imaging
Infrared	10^{12}–10^{14}	10^9–7000	Thermal imaging
Visible light	4–7.5 × 10^{14}	7000–4000	Optical
Ultraviolet	10^{15}–10^{17}	4000–10	Optical
X-rays	10^{17}–10^{20}	10–0.1	Medical and industrial
Gamma rays	10^{20}–10^{24}	< 0.1	Medical

Image processing applications fully exploit the entire range of the electromagnetic spectrum and some of the applications are given here.

Radio waves Radio waves have the lowest energy level and are used in radio and video broadcast as well as by mobile phones. Radio waves are used extensively in radios, satellites, radar, and computer networks for transmission of data. In image processing domain, radio waves are useful in two areas—remote sensing and medical imaging. Hydrogen gas in space releases energy in low frequency and is collected as radio waves. In radar systems, the released energy is collected back, which helps to image the surface of the earth and is useful in predicting weather forecasts. In medical imaging, radio waves are used in the form of magnetic resonance imaging (MRI). A patient is placed on a powerful magnet, and then radio waves are passed through the patient's body in short pulses. The responding pulses of the radio waves are collected by the computer, which determines the location of these signals and their strength. MRI is capable of detecting soft tissues, and image processing applications can be used for analysing MRI images.

Microwaves Microwaves are useful in radar and medical imaging. Radar is an abbreviation of RAdio Detection And Ranging. Radar systems use microwaves in addition to radio waves at higher frequency and are used in applications such as weather forecasting, imaging planetary surfaces, and determining earth resources. Synthetic aperture radar (SAR) is a tool for detecting targets and its velocity. The concept of microwaves is used in medical imaging to probe the magnetic resonance (MR) properties of electrons. This phenomenon is called electron spin resonance (ESR) and electron paramagnetic resonance (EPR), and is used for measurement of free radicals in biological images.

Infrared waves The range of infrared (IR) radiation is about 1 mm–750 nm. The range adjacent to the visible spectrum is called 'near infrared' and the larger wavelength is called 'far infrared'. All objects at a fixed temperature can emit EM radiation and the quantity, type, and distribution of wavelength depend on temperature. The domain of thermal imaging involves the use of temperature images of the human body surfaces. Night-vision technology is another major domain of infrared waves. In night vision, one can see objects in the absence of light. The military, world over, uses infrared cameras, to detect objects at night. Another domain is thermographic imaging, where the images are called thermograms. Infrared cameras can penetrate smokes to detect locations, moving objects, and fleeing criminals. Thermograms are also used in military reconnaissance applications. In medical imaging, infrared is useful for applications such as detecting breast cancer and in locating hot and cold regions of the human body.

Visible light region Visible light is part of the EM spectrum that the human eye can perceive and it varies between 750 nm and 400 nm. Most of the traditional image processing applications such as photography, image archiving, and content-based retrieval systems are in the visible light range only. Telescopes are also examples of how imaging can be used for astronomy applications. The medical domain applications in the visible light range are endoscopy and dermoscopy. Endoscopy is used for examining the inner body parts. Microscopy images that are used to study the strain tissue patterns also fall in the visible range.

Ultraviolet rays Ultraviolet rays are used in applications such as lithography, microscopy, lasers, biomedical imaging, and astronomical observations.

Fig. 1.16 X- ray image

X-rays X-rays are high-frequency electromagnetic rays. They are used in a number of medical imaging applications. X-ray imaging helps doctors in providing vital details for effective diagnosis. Figure 1.16 illustrates a chest X-ray image. Some of the other image processing applications are analysis of electrophoresis gels, chromosome analysis, bacterial colony counting, and autoradiography analysis.

Gamma rays Gamma rays have the smallest wavelengths. They also have the highest energy in comparison with other waves in the EM spectrum. Radioactive elements emit gamma rays which are used extensively in nuclear medicine. Normally, a patient is injected with an isotope, which emits gamma rays as it decays. These emissions are collected by the gamma ray detector and an image is formed. This kind of imaging is called invasive imaging. Gamma rays are also used in industries for finding tiny cracks in metal surfaces and in astronomical observations.

Apart from EM, sound waves can be used by imaging devices. One example is ultrasound imaging.

Ultrasound imaging Sound is a longitudinal wave and it is possible to detect objects and produce images with sound.

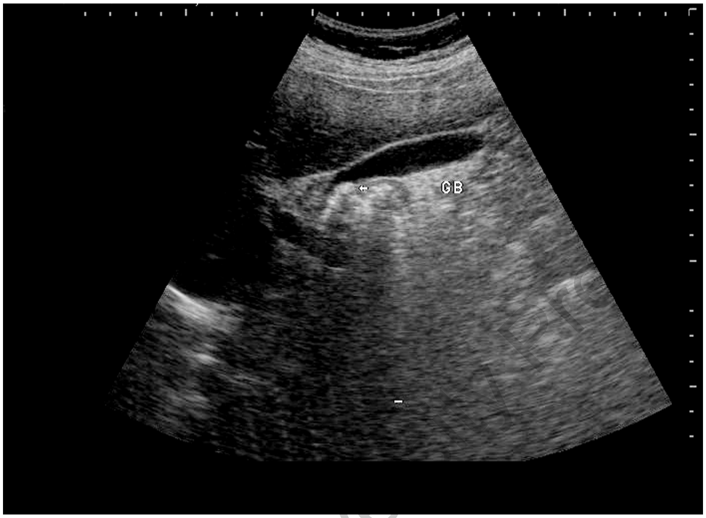


Fig. 1.17 Ultrasound image

Like radar applications, a transducer can send sound waves at shorter burst. The reflected sound waves are picked by sensors and the time interval between the sending and receiving of waves can be used to locate the objects. Figure 1.17 shows an ultrasound image of a gallstone formed in the gallbladder, a common disorder affecting the biliary system. Ultrasound images have very good temporal resolution, good tissue contrast and its low cost makes it useful for many medical imaging applications.

Another important application using sound waves is SONAR. SONAR is an abbreviation of SOund Navigation And Ranging. It can be used to find underwater objects. Synthetic aperture sonar can be used to locate the seabed and wrecks. It can be used to locate broken objects of naval vessels and submarines.

1.8.2 Survey of Image Processing Applications Based on Application Domain

Imaging applications can also be surveyed based on the domains where images are used. The survey of applications involving image processing based on the applications domains are given here.

Pattern recognition and biometrics Biometrics literally means measurement of life. This involves measuring and analysing physical attributes such as fingerprint, facial features, DNA, and iris and behavioural attributes such as gait, voice, and signatures for verification and identification purposes. With the concept of pattern recognition, many image-based applications like object recognition is possible. We will discuss the concept of pattern recognition in detail in Chapter 13. Other applications include biometrics-based attendance system, biometrics-based authentication system and biometric matching.

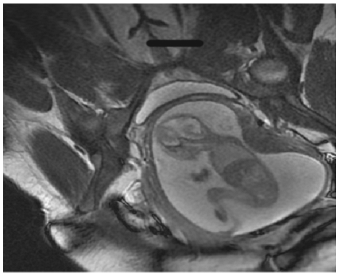


Fig. 1.18 Foetal MRI image

Medical imaging Medical imaging is one area where image processing is fully utilized. Image processing is very useful in interpreting medical images, from simple diagnosis to advanced telesurgical applications. Telesurgical applications are those where robots are used to perform surgical operations. A sample foetal MRI image is shown in Fig. 1.18.

Fig. 1.19 CT skull image

Image visualization and rendering Image visualization is a growing area in image processing. Image processing algorithms can assist in visualization of images by converting a set of 2D images to form 3D images. Image rendering algorithms on the other hand can render 3D images to form 2D images. Figure 1.19 shows a CT scan of the skull.

The figure clearly shows anatomical structures such as soft tissues and bones, which aid in diagnosis and treatment. In general, image visualization is helpful in various applications such as in educating medical students, planning of medical treatment, and in telesurgery applications.

Industrial automation Machine vision systems based on image processing guarantee increased quality using automatic inspection and process monitoring. Automated visual inspection is a vast field where image processing is used by industries such as aerospace, food, textiles, and plastic for automated surface testing. As humans are bound to make mistakes because of the repeated and routine nature of the job, many automated systems are deployed by industries for applications such as visual inspection, surface defect testing, and measurement. Applications such as measurement of belt width, surface quality inspection, fiber analysis, and elimination of surface defects in aluminum foils are some examples of factory automation.

Remote sensing The role of image processing in remote sensing applications is quite immense. Imaging applications in meteorological domain include weather forecasting and prediction of atmospheric changes; locating natural resources such as drinking water, forests, vegetation areas, land cover, and terrain rendering; and automatic event detection.

Many environmental monitoring applications have been developed to monitor large or remote tracts of land such as deserts and forests. Cartography applications also use image processing techniques to fix the boundaries of a region. Aerial archeology is another growing area where applications are being developed for imaging earth, weather forecasts and environmental science where changes that happen over time (such as agriculture, urban development, deserts) can be recorded and processed.

Image communication Image communication as a domain started with the transmission of images by newspaper industry using the submarine cable between London and New York. This led to the need and development of image enhancement and compression algorithms. The developments in the domain of image compression made possible many image-based communication applications such as television and video broadcasting and transmission of CCTV footages. The availability of low-cost cameras and the Internet led to many applications such as facsimile image transmission, video conferencing, and video phones.

Image security and copyright protection Media security, or multimedia security, is a domain involving security of images, video, audio, and graphics. Many image-based applications are developed involving the image security concepts. Digital steganography is a technique for data hiding where an image is concealed within another image such that no one can detect the presence of the image. Another domain that is of interest is digital watermarking which is similar to steganography in which one or more items of information known as watermarks are added to the image. Any attempt to tamper the images affects watermarks. Therefore digital watermarking technology can be useful for copyright identification, monitoring, and copyright protection. A related technique, called digital signatures, is used to assert the ownership. Any change in the content on the part of an unauthorized user invalidates the signature. One such example is shown in Fig. 1.20. Fingerprinting is another technique that asserts the purchaser information as the illegal copies betray the purchaser.

(a)

Fig. 1.20 Watermarking (a) Original image

(b)

Fig. 1.20 (b) Image with watermark—'Visible Watermark Demo'

Digital scrambling technique uses encryption algorithms such as substitution, transposition and modular functions to scramble the image contents, and the original image can be recovered using decryption algorithms. Digital scrambling algorithms are used effectively by television industry. Virtual cryptography is another emerging area where the user needs no knowledge of the cryptographic concepts and can be used to share secrets using the concepts of image processing.

Image processing also helps in the authentication process using the concept of artificial intelligence. CAPTCHA is an example of how image-based security applications can be developed using the assumption that slanting letters, broken, and highly noisy background can make recognition by machines very complicated. However, at the same time, most humans can solve this problem easily. This fact helps in the development of applications for protecting websites and to prevent automatic indexing of websites by search engines.

Digital image forensics Image forensics is an emerging field that aims to validate the authenticity of the given image. In many countries, court of law permits images and video as valid evidence. However, with the proliferation of applications which can be used to manipulate images, tampering can be done with the images with or without any malicious intention. If tampering is done with malicious intention, then digital forensics can help to find whether the image is authentic or not.

Video processing A video signal is a one-dimensional time-varying signal whose contents represent a sequence of images. Thus, one can visualize video processing as an extension of image processing. Video processing applications include video enhancement, video restoration, video compression, and video tracking.

Image understanding Image understanding or computer vision is useful in recovering 3D information from a scene in 2D. Stereoscopic imaging is one simple example of how human eyes observe objects of the scene and reconstruct to get the depth information.

They then use these reconstructed images to perceive the 3D world. The movie industry uses this concept to produce many 3D movies. Robotic vision aims at developing robotic applications such as hurdle detection and bypassing.

Document image processing Document image processing aims to create a paperless office by capturing the documents in the form of images. Image archival systems are used to store the document images which can be retrieved by the retrieval systems. This leads to some interesting applications such as content-based retrieval systems, image search engines, and script recognition systems.

Image processing in military applications Many military reconnaissance systems use image processing technology. Thermal imaging systems have the ability to acquire useful images at night and under adverse atmospheric conditions such as fog and smoke. This helps military personnel involved in target acquisition and reconnaissance operations.

Computational photography and photography Photography is an excellent example of how image processing is helpful to the common man. Image processing is helpful in creating special effects such as warping, blending, animation, and other visual effects. Similarly, publishers can enhance the layout of the pages by using digital images for publication. High dynamic range imaging is one of the recent areas of research where many images are combined to create images which have dynamic range such that the images look more realistic.

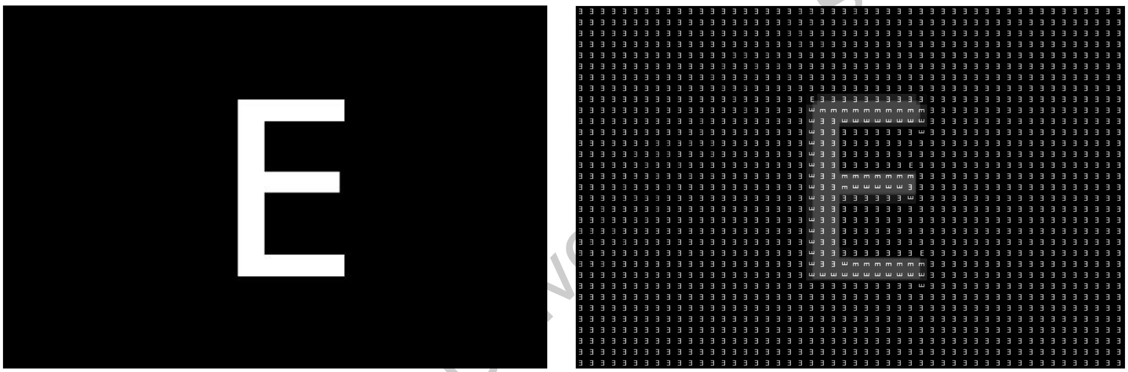
Image and video analytics Image and video data can be analysed using data mining algorithms for extracting knowledge. As images and videos have enormous amount of data, data analytics can be used to extract quality knowledge that can be used to improve the performance of the existing systems substantially. Thus, image and video analytics can enable development of knowledge-based systems and intelligent systems.

Visual effects Sometimes images can be manipulated to create a visual effect for entertainment purposes. For example, polar transformation can be performed by mapping the transformation of image from the Cartesian to polar coordinate system. One such polar transformation is shown in Fig. 1.21.

Fig. 1.21 Polar transformation (a) Original image (b) Polar transform

Such visual effects can be used for personal entertainment as well as for commercial applications. Image compositioning is an operation that takes two or more images as input and produces an integrated result of all images as output. Digital imaging makes this easier and is useful in creating photographs that can be used in web pages and imaging applications. This technique is achieved by dividing the image into many pieces. These pieces are then combined in different combinations to create a single output image called an element.

Image mosaicking is an operation where every group of pixels is approximated by a given image. A collection of small images gives an illusion of a larger image when viewed from a distance. The small images called tile images can be placed either manually or automatically. One such mosaic is shown in Fig. 1.22.



(a) (b)

Fig. 1.22 Image mosaic (a) Tile mosaic (b) Photo mosaic

Entertainment Video editing, animation, and image morphing are few of the many applications that can be used for both personal as well as commercial purposes. Cinematography is one of the popular ones where the sequence of images is shown in rapid succession to create movie effect. Both the movie and television industry use image applications such as visual effects and background for name slides.

Image-based retrieval systems In text-based retrieval systems, the input is a query involving search terms. Using search terms as key words, the systems retrieve the content. Similarly, content-based image retrieval systems (CBIR) involve text and image queries to retrieve identical or related images. Picture archival systems are used by hospitals to capture, store, and retrieve medical images that are relevant for the patients.

SUMMARY

- Images are sampled and discretized mathematical functions.
- The objective of digital image processing is to improve the quality of the pictorial information and to facilitate automatic machine interpretation.
- Image processing is a complex task because of difficulties such as illusion, loss of information, extensive knowledge requirement for interpretation, presence of noise, and artefacts.
- Images can be classified based on nature, attributes, colour, dimensions, data types, and domain of imaging applications.
- Image processing applications are present in all domains.

KEY TERMS

Analog image processing This is an area that deals with the processing of analog electrical signals.

Bit-depth It is the number of bits used to encode the pixel value.

Checker board effect This is a phenomenon that results in poor quality of images due to reduction in the number of pixels while maintaining the quantization levels constant.

Digital image processing A restricted domain of processing of digital images using digital circuits, systems, and collections of software algorithms as per the image processing applications.

Digital imaging Acquisition and storing of images is called digital imaging.

Electromagnetic waves A transverse wave that transfers energy and requires no medium for travel or propagation.

Emissive type imaging A technique of imaging where images are acquired by sensors from self-luminous images without the help of a radiation source.

False contouring A decrease in quality resulting from reducing the bit depth while maintaining the pixel numbers as constant.

False contouring This is a phenomenon that results in poor quality of images due to reduction in the quantization levels while maintaining the number of pixels constant.

Gamut or Palette This refers to the set of all colours that can be represented by the bit depth.

Grey scale This is a monochromatic representation of a pixel value such as brightness that ranges between 0 (black) to 255 (white). A grey scale image is also known as a grey level image, grey image, or intensity image.

Image An image is any 2D or 3D function that represents some quantity such as brightness in a spatial domain.

Low-level operations These refer to all the operations in the initial stages of image processing when the knowledge requirements are low. High-level operations deal with the abstract information of images and like the human visual system, deal with image understanding.

Megapixel This refers to one million pixels approximately and is used to refer to the number of image sensor elements of a digital camera.

Monochrome image An image that consists of a single colour against a natural background and often referred to black and white images.

Optical image processing Processing of an optical image where focus is on optics and objects.

Optical image processing This is an area that deals with the processing of an image using lens and coherent light instead of computers. Optical image processing includes study of objects, lenses, and light.

Pixel A picture element or 'pel' that represents the intensity value of a digital image at discrete points in a grid.

Pseudocolour image This is an image where colours are added artificially based on the interpretation of data rather than the actual object colour.

Quantization It is the process of converting the sampled analog value of the image function into a discrete-valued integer.

Reflective mode imaging A technique of imaging where sensors are used to capture images using the reflected radiation from an object.

Sampling It is the process of converting a continuous signal into discrete values.

Spatial resolution This refers to the smallest details, for example, the separation of features between objects, which can be captured or measured in an image by the sensor.

Transmissive imaging A technique of imaging where sensors capture the radiation that passes through an object as an Image

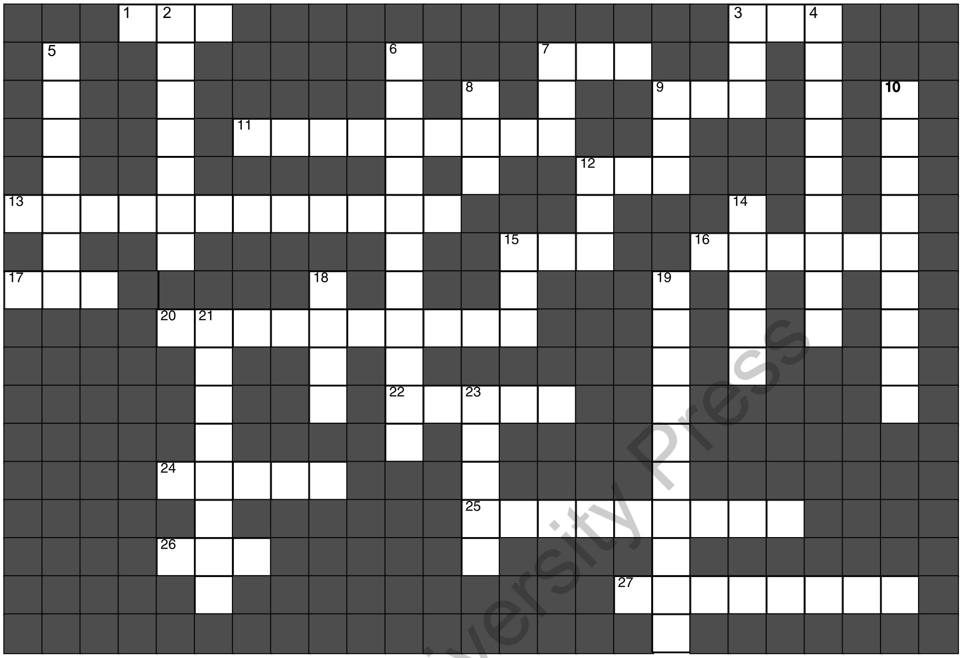
True colour image This is a 24-bit image that represents all the colours that make the image similar to the real object that is being imaged. This is also known as an RGB image or full colour image.

Video It is a collection of images indexed by time.

REVIEW QUESTIONS

1. What is an image?
2. What is the goal of digital image processing?
3. What is meant by resolution?
4. What are the ways in which images can be classified?
5. What are the classes of image processing?
6. Provide a brief survey of image processing applications.
7. Explain the steps in an image processing application.
8. Explain in detail the image processing workstation.
9. What is the storage requirement of a 1024×1024, 8-level grey scale image?
10. Consider a colour 1024×1024 image. If this image is transmitted across a channel of 2 Mbps, what will be the transmission time?

CROSSWORD



Across

1. Printers use _______ as the unit for resolution.
3. MRI is emissive type imaging. (Yes/No)
7. Machine vision applications guarantee increased quality using automatic inspection and process monitoring. (Yes/No)
9. Image processing operations produce another image as output. (Yes/No)
11. Document image processing can create _______ office.
12. Does computer vision aim to extract physical, geometric, and topological features of the scene? (Yes/No)
13. Digitization refers to the process of sampling and _______.
15. Image compression removes redundancy to compress images. (Yes/No)
16. Line drawings are examples of _______ graphics.
17. Biometric applications can be used for authentication. (Yes/No)
20. Radar imaging uses _______.
22. The unit of frequency is _______.
24. Radioactive elements emit _______ rays.
25. The value of the image function $f(x, y)$ is called grey-value or _______ of the image.
26. Visible light applications include microscopy applications. (Yes/No)
27. Noise is any _______ signal part.

Down

2. The set of colours represented by the bit depth is called gamut or _______.
3. Images and pictures are different. (Yes/No)
4. X-ray is a _______ (natural/synthetic) image.
5. Pixel is an abbreviation of _______ element.
6. _______ is the domain used to fix boundaries of regions.
7. Thermal images can capture images at night. (Yes/No)
8. X-ray is a transmissive type imaging. (Yes/No)
9. Photography uses reflective mode imaging. (Yes/No)
10. Image analysis uses images to produce _______ data.
12. Noise, blur, and artefacts reduce the quality of the image. (Yes/No)
14. The number of bits necessary to encode the pixel value is called bit _______.
15. The unit of wavelength is metres. (Yes/No)
18. DPI is an abbreviation of _______ per inch.
19. Image enhancement is image _______ (processing/analysis) operation.
21. Thermograms use _______ rays.
23. MRI uses _______ waves.

WORD SEARCH PUZZLE

Some of the important terms in this chapter are present in the following word jumble. Identify the words. Diagonal words are possible.

I	A	K	L	C	R	T	P	R	Q	F	G	F	U	N	W	A	N	T	E	D	S	L	H	X
E	S	X	D	F	A	P	Y	T	A	Y	U	P	M	I	C	R	O	W	A	V	E	S	H	Y
H	K	I	J	I	A	R	A	C	Q	D	Z	Q	B	Y	S	P	X	X	B	6	S	P	T	E
N	J	M	L	N	N	D	T	L	K	N	I	Q	W	E	S	A	C	B	5	P	L	P	R	M
Y	D	Y	F	T	F	X	E	O	E	K	L	O	Y	U	T	Y	P	2	V	R	J	U	H	P
E	Q	E	W	E	T	Y	X	P	G	T	K	A	T	W	Q	O	E	U	P	O	T	X	Q	S
S	V	S	O	N	L	R	H	D	T	R	T	D	P	I	U	B	E	S	F	C	S	J	I	H
S	X	L	J	S	Y	E	S	C	O	H	A	E	W	D	A	Y	Q	Q	I	E	H	P	K	E
G	R	X	I	I	A	M	Y	E	S	T	U	P	O	F	N	E	D	P	O	S	E	A	K	N
A	Y	C	G	T	W	G	N	J	D	Y	S	Y	H	W	T	S	V	X	K	S	R	P	Y	Y
M	R	C	S	Y	Y	K	T	I	Q	K	I	4	H	Y	I	Q	E	T	J	I	T	E	F	N
M	J	D	H	Y	E	A	H	W	Q	K	2	Q	U	T	Z	M	C	F	T	N	Z	R	S	O
A	S	P	J	I	S	U	E	I	Y	P	E	Y	J	M	A	D	T	W	P	G	Y	L	X	Q
E	L	T	D	B	G	B	T	R	Y	T	X	E	F	F	T	Y	O	O	I	S	S	E	C	F
Y	I	P	W	G	H	S	I	K	K	S	D	S	Q	F	I	E	R	N	Y	E	S	S	X	E
E	Y	N	U	Z	N	C	C	M	S	I	G	V	P	Q	O	S	F	D	G	H	S	S	Q	M
S	J	T	X	L	V	N	U	M	E	R	I	C	A	L	N	K	I	N	F	R	A	R	E	D

Hints

1. Digitization process includes sampling and _______.
2. Images can be broadly classified as raster and _______ images.
3. _______ is an analog representation while images are often used to refer to the digital representation of a scene.
4. The pixel value represents the _______ of the pixel.
5. The number of bits used to represent the image is called _______ of the image.
6. The range of colours is called a _______.
7. _______ per inch is often referred to as resolution of the screen.
8. _______ stands for dots per inch.
9. The number of bits is _______ for colour images.
10. Image analysis operations often take an image as input and produce _______ output.
11. _______ waves are used in MRI.
12. The unit of frequency is _______.
13. Radar imaging is an example of _______ in EM spectrum.
14. The range of _______ radiation is about 1mm–750 nm.
15. _______ rays have the smallest wavelengths.
16. _______ is the domain where the boundaries of a difficult terrain are fixed.
17. Document image processing aims at creating a _______ office.
18. Computer generated images are called ___________ images.