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Excerpt
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Part I

Introduction to image processing

1 Introduction

Overview

Imaging systems construct an (output) image in response to (input) signals from diverse types of objects. They can be classified in a number of ways, e.g. according to the radiation or field used, the property being investigated, or whether the images are formed directly or indirectly. Medical imaging systems, for example, take input signals which arise from various properties of the body of a patient, such as its attenuation of x-rays or reflection of ultrasound. The resulting images can be continuous, i.e. *analog*, or discrete, i.e. *digital*; the former can be converted into the latter by *digitization*. The challenge is to obtain an output image that is an accurate representation of the input signal, and then to analyze it and extract as much diagnostic information from the image as possible.

Learning objectives

After reading this chapter you will be able to:

- appreciate the breadth and scope of digital image processing;
- classify imaging systems according to different criteria;
- distinguish between analog, sampled and digital images;
- identify the advantages of digital imaging;
- describe the components of a generic digital image processing system;
- outline the operations involved in the various fundamental classes of image processing;
- list examples of digital image processing applications within a variety of fields.

1.1 Imaging systems

Of the five senses – sight, hearing, touch, smell and taste – which humans use to perceive their environment, sight is the most powerful. Receiving and analyzing images forms a large part of the routine cerebral activity of human beings throughout their waking lives. In fact, more than 99% of the activity of the human brain is involved in processing images from the visual cortex. A visual image is rich in information. Confucius said, “A picture is worth a thousand words,” and we shall see that that is an underestimate.

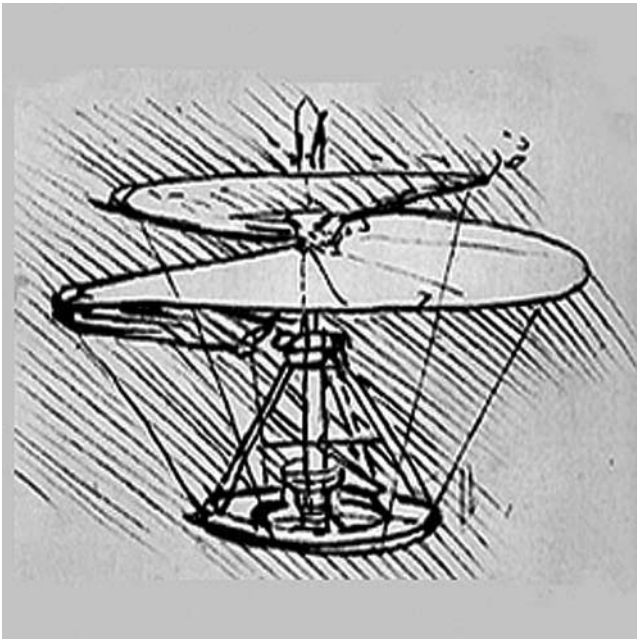


Figure 1.1 Leonardo da Vinci's concept for a helicopter.

On a more sophisticated level, humans generate, record and transmit images. Since the early days of science, researchers have tried to record their observations and even their conceptions pictorially. Leonardo da Vinci was the primary exponent of the visual image of his time: he gave absolute precedence to illustration over the written word (Fig. 1.1).

More recently, technology has tremendously extended the possibilities for visual observation. Photography makes it possible to record images objectively, preserving scenes for later, repeated, and perhaps more careful, examination. Telescopes and microscopes greatly extend the human visual range, permitting the visualization of objects of vastly differing scales. Technology can even compensate for inherent limitations of the human eye. The human eye is receptive to only a very narrow range of frequencies within the electromagnetic spectrum (Fig. 1.2). Nowadays there are sensors capable of detecting electromagnetic radiation outside this narrow range of “visible” frequencies, ranging from γ -rays and x-rays, through ultraviolet and infrared, to radio waves.

Images can be formed from many kinds of objects using differing mechanisms of formation, and, consequently, imaging systems can be classified according to several different criteria. Table 1.1 classifies systems according to the type of radiation or field used to form an image. Electromagnetic radiation is used most often in imaging systems. The radiofrequency band is used in astronomy and in magnetic resonance imaging (MRI). Microwaves are used in radar imaging, since they can penetrate clouds and other atmospheric conditions that interfere with imaging using visible light. A vast number of systems use visible light and infrared radiation, including microscopy, remote sensing and industrial inspection. Ultraviolet radiation is used in fluorescence microscopy, for example, and x-rays are used in medical diagnostic work, in industrial imaging, to detect

Table 1.1 Classification of imaging systems by type of radiation or field used.

Type of radiation or field	Examples
Electromagnetic waves	Radio, microwaves, infrared, visible light, ultraviolet, (soft) x-rays
Other waves	Water, sonar, seismic, ultrasound, gravity
Particles	Neutrons, protons, electrons, heavy ions, (hard) x-rays, γ -rays
Quasistatic fields	Geomagnetic, biomagnetic, bioelectric, electrical impedance

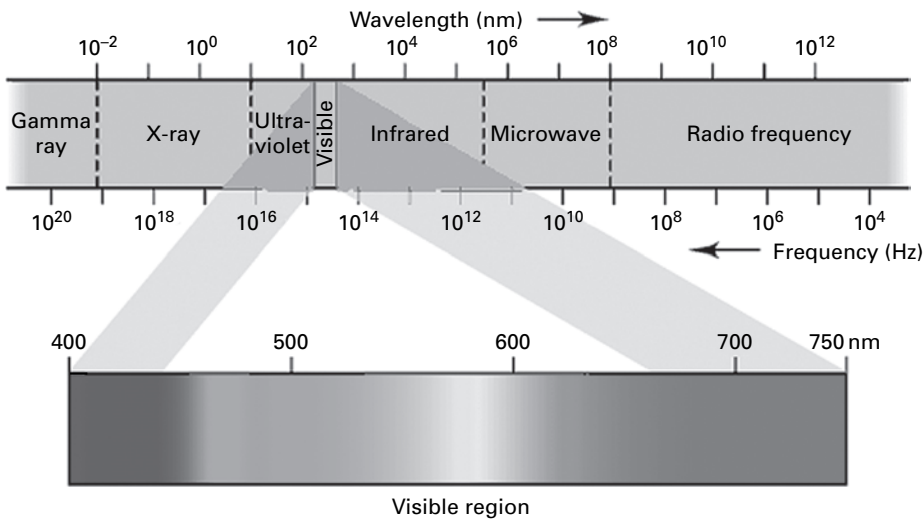


Figure 1.2 The electromagnetic spectrum arranged according to the energy of the photons, or the frequency of the waves. See also color plate.

manufacturing flaws and in astronomy. The more energetic the electromagnetic radiation, such as higher-energy (hard) x-rays and γ -rays, the shorter its wavelength and the better it can reveal small details. We often think of electrons as particles, but they have wave-like properties too. Their wavelength is very much smaller than that of visible light, enabling electron microscopes to “see” much smaller details and achieve much larger magnifications, on the order of 10000 or more, whereas light microscopes have a theoretical limit of about 1000 or so. Low frequency (~ 100 Hz) sound waves are used in seismic imaging to detect oil and gas deposits and high-frequency ($\sim$ MHz) ultrasound is used in medical imaging, especially in obstetrics to determine the health of the fetus (Fig. 1.3).

Even static or nearly static (*quasistatic*) fields can be used in imaging. In electric impedance tomographic imaging, electric fields set up within the body, as a result of applying voltages to an array of electrodes on the surface, allow imaging of the internal organs.

Another way of classifying imaging systems is according to the property of the object that is being exploited (Table 1.2). For example, light entering the human visual pathway originates either from a self-luminous object or from light reflected by, or transmitted through, an object. An astronomical image is an emission image, related to the spectral energy distribution of the light emitted by the object over different frequencies. In other



Figure 1.3 Fetal ultrasound image.

cases, the light entering the eye represents the spectral energy distribution of the light reflected from the scene, which is related to the product of the illumination and the optical reflectance of the objects in the scene. For objects that transmit light, the observed spectral energy distribution depends on the product of the illumination and the transmittance of the objects. Radiopharmaceutical substances injected into, or ingested by, the body in nuclear medicine imaging emit γ -rays that characterize the concentration of the source and its location. Radar imaging and medical ultrasound are based on reflectance properties. And x-ray imaging produces radiographs that depend on the transmittance of x-rays through an object. Other properties can also be exploited to produce images. For example, phase-contrast microscopy uses the refractive properties of an object and weather radar uses scattering properties.

Another distinction that can be made is between *direct* and *indirect* imaging systems (Table 1.3). In direct imaging the acquired data is a recognizable image, whereas in indirect imaging a data processing or reconstruction step is required before the image is available for observation.

Direct imaging can be subdivided further, depending on whether the image is acquired as a whole, parallel acquisition, or in parts, serial acquisition. Indirect imaging includes the image stored in the emulsion of a photographic film, which is rendered observable by chemical development of the film; the image consisting of valence electrons stored in the high-energy traps of a photostimulable phosphor image plate as used in computed radiography (CR), rendered observable by stimulating the image plate with laser light and digitizing the resulting image; and tomographic imaging, from the Greek *tomos*, a slice, which requires extensive processing of the raw data to produce a slice image.

Table 1.2 Classification of imaging systems by property of object.

Property	Examples
Source strength	Astronomical imaging, fluorescence microscopy
Concentration	Nuclear medicine, MRI (spin density)
Wave amplitude	Seismology
Field strength	Biomagnetic and geomagnetic imaging
Optical reflectance	Photography, remote sensing
Microwave reflectance	Radar
Acoustic reflectance	Medical ultrasound, sonar
Attenuation	Transmission x-ray, film densitometry
Refractive index	Phase-contrast microscopy
Scattering properties	Medical ultrasound, weather radar
Electric/magnetic properties	Impedance tomography, MRI (magnetization and spin relaxation)
Surface height	Laser ranging, topography

Table 1.3 Classification of imaging systems into direct or indirect systems.

		Examples
Direct imaging	Parallel acquisition	Human eye, electronic (i.e. digital) camera, optical microscope, optical telescope, scintillation camera
	Serial acquisition	Scanning microdensitometer, (confocal) scanning microscope, medical γ -camera
Indirect imaging		Film camera, x-ray CT, SPECT and PET, MRI, holography, synthetic aperture radar (SAR)

Tomographic imaging includes x-ray computed tomography (CT) (Fig. 1.4), emission tomography, such as single-photon emission computed tomography (SPECT) and positron emission tomography (PET), magnetic resonance imaging (MRI) and three-dimensional (3-D) ultrasound.

The disadvantages of indirect imaging are the time delay between capturing the data and obtaining the observable image, and the possible degradation, which may occur during this time, e.g. due to heat, humidity or light leakage affecting the photographic emulsion, or the thermal leakage of electrons out of the traps in an image plate. An advantage of indirect imaging is that the final image is often digital.

1.2

Objects and images

Real objects can be regarded as functions of one or more continuous variables. For example, the position of a star in the sky can be specified by two angles, so that the star is a two-dimensional function. In nuclear medicine the object of interest is the three-dimensional distribution of a radiopharmaceutical substance, i.e. it can be described by a three-dimensional function. If its distribution changes with time, a four-dimensional function would be needed: three spatial dimensions plus time.



Figure 1.4 Abdominal CT image at the level of the kidneys, reconstructed from several hundred individual one-dimensional projections.

An imaging system senses or responds to an *input signal*, such as reflected or transmitted electromagnetic radiation from an object, and produces an *output signal* or *image*. When this radiation is focused and then sensed by a photographic film, for example, it gives rise to an image that is recognized as *analog*, comprising continuously varying shades or colors. A grayscale photographic image is a two-dimensional function of optical density or brightness with position; if the object can move, the image is an average over the exposure time. A color image is represented by three two-dimensional functions, each corresponding to the density of one of the three color emulsions, red, green and blue, on the film. It might be argued that these images are not continuous (i.e., analog) at the level of the silver halide particles of the photographic emulsion, which are the sensors; but the scale of these is considerably below the level of perception of the human eye.

More recently, with the advent of small solid-state electronic detectors in digital still and video cameras, the option exists to capture the radiation using sensors organized in a two-dimensional array. This sensor array, placed at the focal plane, produces outputs proportional to the integral of the radiation received at each sensor during the exposure time, and these values become the terms in a two-dimensional matrix, which represents the scene; this is called a *sampled* image. It is not yet a digital image. The physical disposition of sensors facilitates the collection of data into an array, but the values themselves are still integrals and hence continuous; they need to be quantized to a discrete scale before the image is a *digital* image. Digital images can be represented by an array of discrete values, which makes them amenable to storage and manipulation within a computer.

1.2 Objects and images

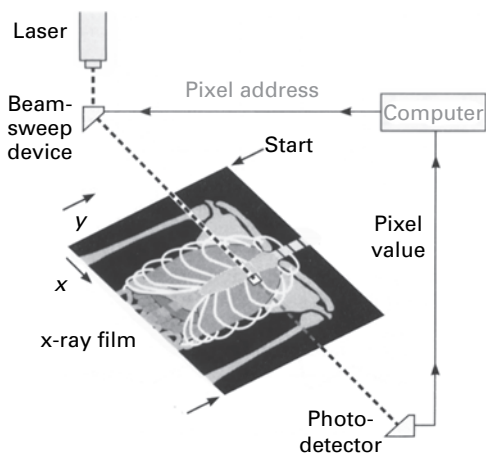


Figure 1.5 Scanning an analog image in a raster fashion. (Adapted from Wolbarst, 1993, p. 207.)

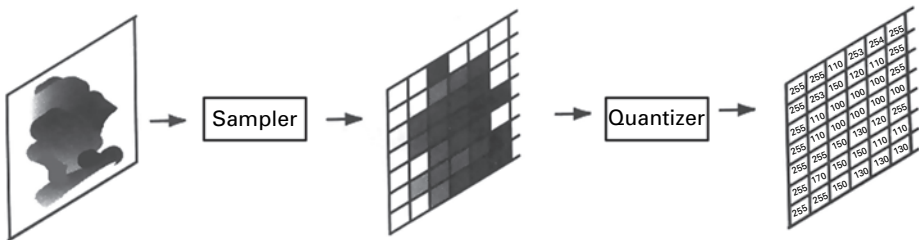


Figure 1.6 The relationship between an analog image and a digitized image.

An imaging system can either be a *continuous-to-continuous system*, responding to a continuous input signal and producing a continuous or analog output image, or it can be a *continuous-to-discrete system*, responding to the continuous input signal by producing a discrete, digital output image. Tomographic images are reconstructed from many, one-dimensional, views or projections collected over the exposure time. X-ray computed tomography (CT) imaging is an example of a continuous-to-discrete imaging system, using computer reconstruction to produce a digital image from a set of projection data collected by discrete sensors.

The advent of computers has opened up vast new possibilities for the quantitative processing and analysis of images, as long as these can be represented by arrays of discrete values, rather than continuous functions. In the case of analog images, they can be converted into digital images by a two-step process known as digitization. This involves scanning the image in a raster fashion (Fig. 1.5), i.e. from top left, in rows, to bottom right. The image is *sampled* (i.e. readings of the amount of light reflected, or transmitted, are taken at equally spaced positions, which defines the size of the resulting pixels), and these readings are *quantized*, i.e. assigned to one of a finite set of pixel values (Fig. 1.6). The image is now digital.

Many digital images contain 256 possible gray levels, running from black to white. This is the number of levels that can be labeled with 8 bits (i.e. 1 byte) in a binary

numbering system. It is convenient to allocate a byte of computer memory to store the brightness (gray) level, and to allocate 0000 0000 to black and 1111 1111 (decimal 255) to white, giving 256 gray levels in total; the resulting images are said to be *8 bits deep*.
Larger units of storage include:

- kilobyte (KB) = decimal 1024 (or 2^{10} bytes);
- megabyte (MB) = 1024 KB (or 2^{20} bytes);
- gigabyte (GB) = 1024 MB (or 2^{30} bytes);
- terabyte (TB) = 1024 GB (or 2^{40} bytes).

A standard CD ROM has about 700 MB of storage; double-sided double-layered DVDs have about 17 GB, while HD-DVDs and Blu-ray disks have about 50 GB; and computer hard disks typically have hundreds of GB of storage.

The ability to process and analyze images is a major advantage in having digital images; they can also be copied an infinite number of times, with appropriate error-checking to ensure perfect copies. Additional advantages include: the ease with which they can be displayed on computer monitors, and their appearance modified at will; the ease with which they can be stored on, for example, CD-ROM or DVD; the ability to send them between computers, via the Internet or via satellite; the option to compress them to save on storage space or reduce communication times. Many of these advantages are particularly relevant to medical imaging. The saving in physical space in not having to store bulky x-ray film is a distinct advantage, and the move towards film-less imaging has saved on chemical processing costs. Increasingly, hospitals are networking their digital imaging systems into either so-called PACS (picture and archiving systems) or RIS/HIS (radiological/ hospital information systems), which include patient diagnoses and billing details along with the images.

1.3 The digital image processing system

A complete digital image processing system (Fig. 1.7) is a collection of hardware (equipment) and software (computer programs) that can:

- (i) acquire an image, using appropriate sensors to detect the radiation or field (Table 1.1) and capture the features of interest from the object in the best possible way. If the detected image is continuous, i.e. analog, it will need to be digitized by an *analog-to-digital converter* (ADC);
- (ii) store the image, either temporarily in a *working image store* using read/write memory devices known as *random access memory* (RAM) or, more permanently, using magnetic media (e.g. floppy disks or the computer hard disk memory), optical media (e.g. CD-ROMs or DVDs) or semiconductor technology (e.g. flash memory devices);
- (iii) manipulate, i.e. process, the image; and
- (iv) display the image, ideally on a television or computer monitor, which comprises lines of continuously varying, i.e. analog, intensity. This requires the production of an analog video display signal by a *digital-to-analog converter* (DAC).

1.3 The digital image processing system

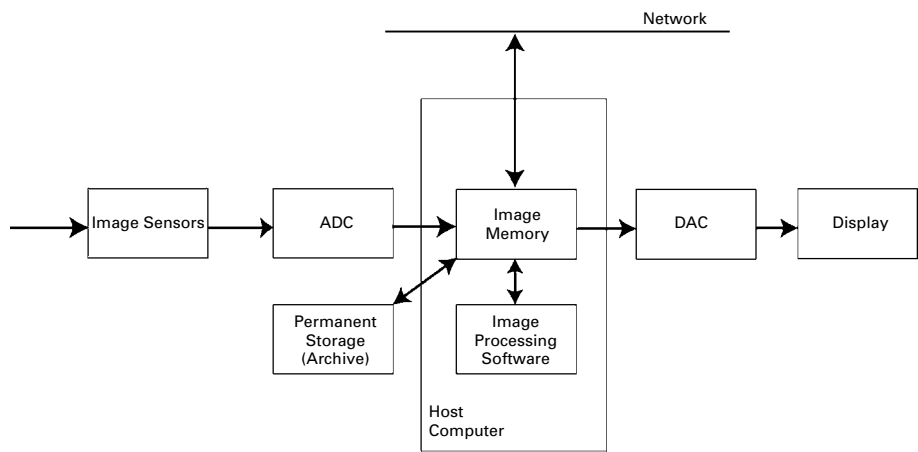


Figure 1.7 A digital image processing system.

Table 1.4 Digital image processing classes and examples of the operations within them.

Classes	Examples of operations
Image enhancement	Brightness adjustment, contrast enhancement, image averaging, convolution, frequency domain filtering, edge enhancement
Image restoration	Photometric correction, inverse filtering
Image analysis	Segmentation, feature extraction, object classification
Image compression	Lossless and lossy compression
Image synthesis	Tomographic imaging, 3-D reconstruction

In this book we shall be interested predominantly in the manipulation or processing operations. These can be grouped, broadly, into five fundamental classes: image enhancement, restoration, analysis, compression and synthesis (Table 1.4). Each class contains certain representative operations.

Image enhancement results in an image which either looks better to an observer, a subjective phenomenon, or which performs better in a subsequent processing class. Enhancement might involve adjusting the brightness of the image, if it were too dark or too bright, or its contrast, if for example it comprised only a few shades of gray, giving it a washed-out appearance. Alternatively, it might involve smoothing an image that contains a lot of *noise* or *speckle*, or sharpening an image so that edges within it are more easily seen.

Images are often significantly degraded in the imaging system, and *image restoration* is used to reverse this degradation. This would include reversing the effects of: uneven illumination, non-linear detectors which produce an output (response) that is not proportional to the input (stimulus), distortion, e.g. “pincushion” and “barrel” distortions caused by poorly focusing lenses or electron optics (Fig. 1.8), movement of the object during acquisition, and unwanted noise (Fig. 1.9). The key to image restoration is to model the degradation and then to use an inverse operation to reverse it.