PART I

FUNDAMENTALS

CHAPTER 1

INTRODUCTION

An image is a subset of a signal. A *signal* is a function that conveys information generally about the behavior of a physical system or attributes of some phenomenon. A simple example is the traffic signal that uses three universal color codes (red, yellow, and green) signaling the moment to stop, drive, or walk. Although signals can be represented in many ways, in all cases the information is contained in a pattern of variations of some form, and with that information is typically transmitted and received over a medium. Electrical quantities such as current and voltage are called *electrical signals*, which are often used in radio, radar, sonar, telephone, television, and many other areas. An acoustic wave signal can convey speech or music information, in which people often speak of a strong or weak signal when the sound is referred to its clarity and audibility. A thermocouple can convey temperature, and a pH meter can convey the acidity of a solution.

A signal may take a form of time variations or a spatially varying pattern. Mathematically speaking, signals are represented as functions of one or more independent variables that can be either continuous or discrete. *Continuous-time* signals are defined at a continuum of the time variable. *Discrete-time* signals are defined at discrete instants of time. *Digital* signals are those for which both time and amplitude are discrete. The continuous-time and continuous-amplitude signals are called *analog* signals. Analog signals that have been converted to digital forms can be processed by a computer or other digital devices.

Signal processing is the process of extracting information from the signal. *Digital signal processing* (DSP) is concerned with the representation of signals by sequences of numbers or symbols and processing of these sequences. It was initiated in the seventeenth century and has become an important modern tool in the tremendously diverse fields of science and technology. The purpose of such processing is to estimate characteristic parameters of a signal or to transform a signal into a form that is more sensible to human beings. DSP includes subfields such as digital image processing, video processing, statistical signal processing, signal processing for communications, biomedical signal processing, audio and speech signal processing, sonar and radar signal processing, sensor array processing, spectral estimation, and so on.

Human beings possess a natural signal processing system. "Seeing" takes place in the visual system and "hearing" takes place in the auditory system. Human visual system (HVS) plays an important role in navigation, identification, verification, gait, gesture, posture, communication, psychological interpretation, and so on. Human

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auditory system converts sound waves into nerve impulses, to analyze auditory events, remember and recognize sound sources, and perceive acoustic sequences. As the speed, capability, and economic advantages of modern signal processing devices continue to increase, there is simultaneously an increase in efforts aimed at developing sophisticated, real-time automatic systems capable of emulating human abilities. Because of digital revolution, digital signals have been increasingly used. Most household electronic devices are based entirely or almost entirely upon digital signals. The entire Internet is a network of digital signals, as is modern mobile phone communication.

1.1 THE WORLD OF SIGNALS

The world is filled with many kinds of signals; each has its own physical meaning. Sometimes the human body is incapable of receiving a special signal or interpreting (decoding) a signal, so the information that the signal intends to convey cannot be captured. Those signals are not to be said nonsense or insignificant, but conversely they are exactly what people are working very hard to understand. The more we learn from the world's signals, the better living environment we can provide. Furthermore, some disaster or damage can be avoided if a warning signal can be sensed in advance. For example, it was recorded historically that animals, including rats, snakes, and weasels, deserted the Greek city of Helice in droves just days before a quake devastated the city in 373 B.C. Numerous claims have been made that dogs and cats usually behave strangely before earthquake by barking, whining, or showing signs of nervousness and restlessness.

The characteristics of a signal may be one of a broad range of shapes, amplitudes, time durations, and perhaps other physical properties. Based on the sampling of time axis, signals can be divided into continuous-time and discrete-time signals. Based on the sampling of time and amplitude axes, signals can be divided into analog and digital signals. If signals repeat in some period, they are called periodic signals; otherwise, aperiodic or nonperiodic signals. If each value of a signal is fixed by a mathematical function, it is called a deterministic signal; otherwise, a random signal that has uncertainty about its behavior. In the category of dimensionality, signals are divided into one-dimensional (1D), two-dimensional (2D), three-dimensional (3D), and multidimensional signals, which are further explained below.

1.1.1 One-Dimensional Signals

A 1D signal is usually modeled as an ensemble of time waveforms, for example, $x(t)$ or $f(t)$. One-dimensional signal processing has a rich history, and its importance is evident in such diverse fields as biomedical engineering, acoustics (Beranek, 2007), sonar (Sun et al., 2004), radar (Gini et al., 2001), seismology (Al-Alaoui, 2001), speech communication, and many others. When we use a telephone, our voice is converted to an electrical signal and through telecommunication systems circulates around the Earth. The radio signals, which are propagated through free space and by radio receivers, are converted into sound. In speech transmission and recognition, one may wish to extract some characteristic parameters of the linguistic messages, representing the temporal and spectral behavior of acoustical speech input. Alternatively, one may wish to remove interference, such as noise, from the signal or to modify the signal to present it in a form more easily interpreted by an expert.

1.1.2 Two-Dimensional Signals

Signal processing problems are not confined to 1D signals. A 2D signal is a function of two independent variables, for example, $f(x, y)$. In particular, one is concerned with the functional behavior in the form of an intensity variation over the (x, y)-plane. Everyday scenes viewed by a human observer can be considered to be composed of illuminated objects. The light energy reflected from these objects can be considered to form a 2D intensity function, which is commonly referred to as an *image*.

As a result of numerous applications, not least as a consequence of cheap computer technology, image processing now influences almost all areas of our daily life: automated acquisition, processing and production of documents, industrial process automation, acquisition and automated analysis of medical images, enhancement and analysis of aerial photographs for detection of forest fires or crop damage, analysis of satellite weather photos, and enhancement of television transmission from lunar and deep-space probes.

1.1.3 Three-Dimensional Signals

Photographs of a still scene are the images that are functions of the (x, y)-plane. By adding a time variable, the 3D signals represent image sequences of a dynamic scene that are called *video signals*. Computer analysis of image sequences requires the development of internal representations for the entities in a depicted scene as well as for discernible changes in appearance and configuration of such entities. More fundamental approaches result from efforts to improve application-oriented solutions. Some illustrative examples are given as follows.

Image sequences obtained from satellite sensors are routinely analyzed to detect and monitor changes. Evaluation of image series recorded throughout the growth and harvest periods can result in more reliable cover type mapping as well as improved estimates of crop field. Very important is the determination of cloud displacement vector fields. These are used to estimate wind velocity distributions that in turn are employed for weather prediction and meteorological modeling (Desportes et al., 2007).

Biomedical applications are concerned with the study of growth, transformation, and transport phenomena. Angiocardiography, blood circulation, and studies of metabolism are the primary areas of medical interest for the evaluation of temporal image sequences (Charalampidis et al., 2006). Architects who have to design pedestrian circulation areas would appreciate quantitative data about how pedestrians walk in halls and corridors. Efforts to extract such data from TV-frame sequences could be considered as behavioral studies. They might as well be assigned to a separate topic such as object tracking (Qu and Schonfeld, 2007), which is of special concern in cases of traffic monitoring (Zhou et al., 2007), target tracking, and visual feedback for automated navigation (Negahdaripour and Xun, 2002; Xu and Tso, 1999).

1.1.4 Multidimensional Signals

When a signal is represented in more than one dimension, it is often called a multidimensional signal. As discussed in previous sections, an image is a two-dimensional signal, and a video is a three-dimensional signal. A multidimensional signal is vector valued and may be a function of multiple relevant independent variables. One chooses the variable domain in which to process a signal by making an informed guess as to which domain best represents the essential characteristics of the signal. Multidimensional signal processing is an innovative field interested in developing technology that can capture and analyze information in more than one dimension. Some of its applications include 3D face modeling (Roy-Chowdhury et al., 2004), 3D object tracking (Wiles et al., 2001), and multidimensional signal filtering.

The need for a generally applicable artificial intelligence approach for optimal dimensionality selection in high-dimensional signal spaces is evident in problems involving vision since the dimensionality of the input data often exceeds 10^6. It is likely to fail if vision problems are handled by reducing the dimensionality by means of throwing away almost certain available information in a basically ad hoc manner. Therefore, designing a system capable of learning the relevant information extraction mechanisms is critical.

1.2 DIGITAL IMAGE PROCESSING

Images are produced by a variety of physical devices, including still and video cameras, scanners, X-ray devices, electron microscopes, radar, and ultrasound, and are used for a variety of purposes, including entertainment, medical, business, industrial, military, civil, security, and scientific. The interests in digital image processing stem from the improvement of pictorial information for human interpretation and the processing of scene data for autonomous machine perception.

Webster's Dictionary defines an image as: "An image is a representation, likeness, or imitation of an object or thing, a vivid or graphic description, something introduced to represent something else." The word "picture" is a restricted type of image. Webster's Dictionary defines a picture as: "A representation made by painting, drawing, or photography; a vivid, graphic, accurate description of an object or thing so as to suggest a mental image or give an accurate idea of the thing itself." In image processing, the word "picture" is sometimes equivalent to "image."

Digital image processing starts with one image and produces a modified version of that image. Webster's Dictionary defines digital as: "The calculation by numerical methods or discrete units," defines a digital image as: "A numerical representation of an object," defines processing as: "The act of subjecting something to a process," and

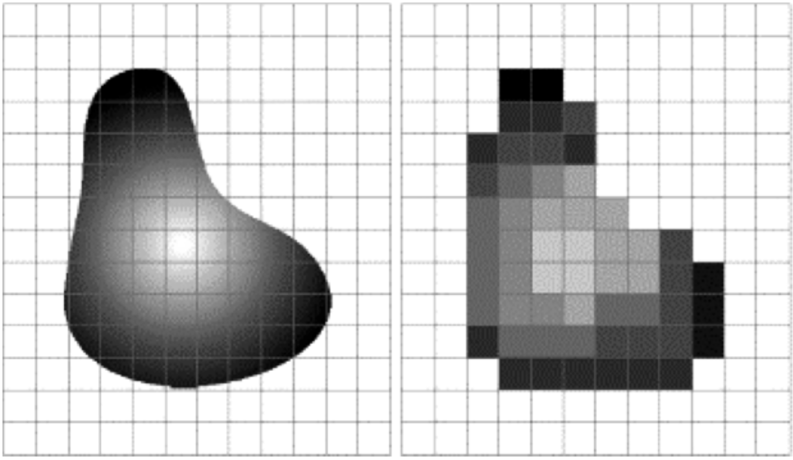
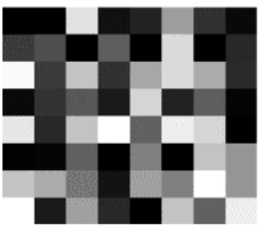


Figure 1.1 Image digitization. (Courtesy of Gonzalez and Woods, 2008)

defines a process as: "A series of actions or operations leading to a desired result." An example of a process is car wash that changes an automobile from dirty to clean.

Digital image analysis is a process that converts a digital image into something other than a digital image, such as a set of measurement data or a decision. Image digitization is a process that converts a pictorial form to numerical data. A digital image is an image $f(x, y)$ that has been discretized in both spatial coordinates and brightness (intensity). The image is divided into small regions called *picture elements* or *pixels* (see Fig. 1.1).

Image digitization includes image sampling (i.e., digitization of spatial coordinates (x, y)) and gray-level quantization (i.e., brightness amplitude digitization). An image is represented by a rectangular array of integers. The image sizes and the number of gray levels are usually integer powers of 2. The number at each pixel represents the brightness or darkness (generally called the intensity) of the image at that point. For example, Figure 1.2 shows a digital image of size 8×8 with 1 byte (i.e., 8 bits = 256 gray levels) per pixel.



1	8	219	51	69	171	81	41
94	108	20	121	17	214	15	74
233	93	197	83	177	215	183	78
41	84	118	62	210	71	122	38
222	73	197	248	125	226	210	5
35	36	127	5	151	2	197	165
196	180	142	52	173	151	243	164
254	62	172	75	21	196	126	224

Figure 1.2 A digital image and its numerical representation.

The quality of an image strongly depends upon the number of samples and gray levels; the more are these two, the better would be the quality of an image. But, this will result in a large amount of storage space as well because the storage space for an image is the product of dimensions of an image and the number of bits required to store gray levels. At lower resolution, an image can result in checkerboard effect or graininess. When an image of size 1024×1024 is reduced to 512×512, it may not show much deterioration, but when reduced to 256×256 and then rescaled back to 1024×1024 by duplication, it might show discernible graininess.

The visual quality of an image required depends upon its applications. To achieve the highest visual quality and at the same time the lowest memory requirement, we can perform fine sampling of an image in the neighborhood of sharp gray-level transitions and coarse sampling in the smooth areas of an image. This is known as sampling based on the characteristics of an image (Damera-Venkata et al., 2000). Another method, known as tapered quantization, can be used for the distribution of gray levels by computing the occurrence frequency of all allowed levels. Quantization level is finely spaced in the regions where gray levels occur frequently, but when gray levels occur rarely in other regions, the quantization level can be coarsely spaced. Images with large amounts of details can sometimes still enjoy a satisfactory appearance despite possessing a relatively small number of gray levels. This can be seen by examining isopreference curves using a set of subjective tests for images in the Nk-plane, where N is the number of samples and k is the number of gray levels (Huang, 1965).

In general, image processing operations can be categorized into four types:

1. *Pixel operations:* The output at a pixel depends only on the input at that pixel, independent of all other pixels in that image. Thresholding, a process of making the corresponding input pixels above a certain threshold level white and others black, is simply a pixel operation. Other examples include brightness addition/subtraction, contrast stretching, image inverting, log, and power law.
2. *Local (neighborhood) operations:* The output at a pixel depends on the input values in a neighborhood of that pixel. Some examples are edge detection, smoothing filters (e.g., the averaging filter and the median filter), and sharpening filters (e.g., the Laplacian filter and the gradient filter). This operation can be adaptive because results depend on the particular pixel values encountered in each image region.
3. *Geometric operations:* The output at a pixel depends only on the input levels at some other pixels defined by geometric transformations. Geometric operations are different from global operations, such that the input is only from some specific pixels based on geometric transformation. They do not require the input from all the pixels to make its transformation.
4. *Global operations:* The output at a pixel depends on all the pixels in an image. It may be independent of the pixel values in an image, or it may reflect statistics calculated for all the pixels, but not a local subset of pixels. A popular distance transformation of an image, which assigns to each object pixel the minimum distance from it to all the background pixels, belongs to a global operation.

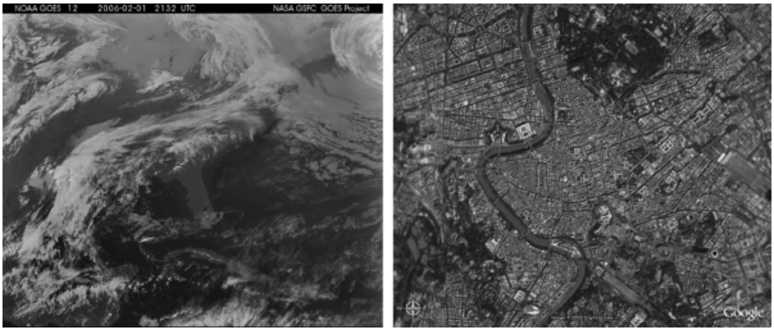


Figure 1.3 Remote sensing images for tracking Earth's climate and resources.

Other examples include histogram equalization/specification, image warping, Hough transform, and connected components.

Nowadays, there is almost no area that is not impacted in some way by digital image processing. Its applications include

1. *Remote sensing:* Images acquired by satellites and other spacecrafts are useful in tracking Earth's resources, solar features, geographical mapping (Fig. 1.3), and space image applications (Fig. 1.4).
2. *Image transmission and storage for business:* Its applications include broadcast television, teleconferencing, transmission of facsimile images for office automation, communication over computer networks, security monitoring systems, and military communications.
3. *Medical processing:* Its applications include X-ray, cineangiogram, transaxial tomography, and nuclear magnetic resonance (Fig. 1.5). These images may be

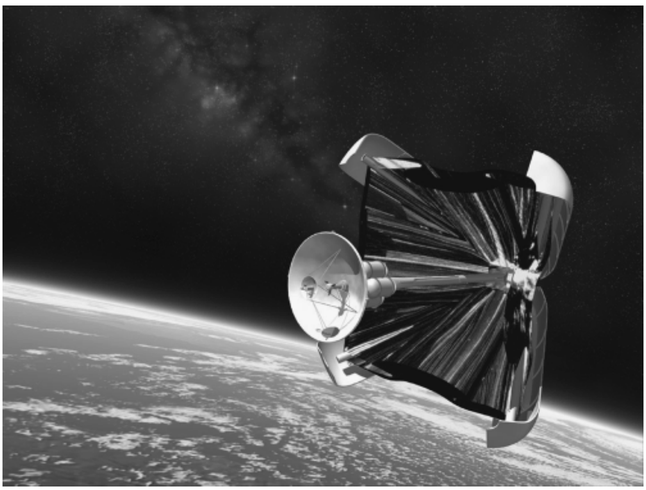


Figure 1.4 Space image applications.

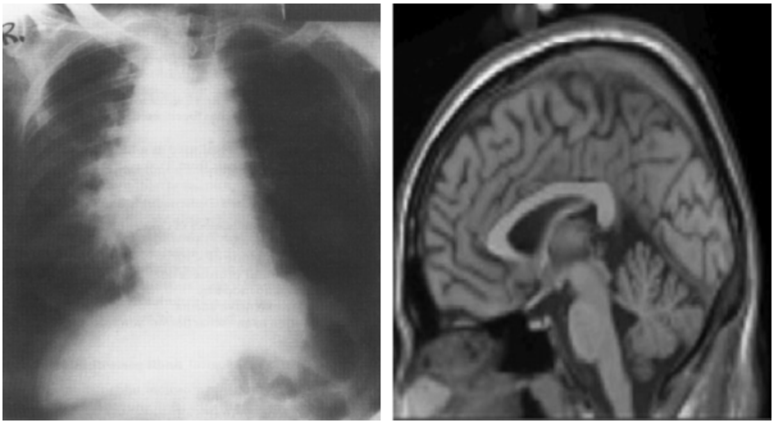


Figure 1.5 Medical imaging applications.

used for patient screening and monitoring or for detection of tumors or other diseases in patients.

4. *Radar, sonar, and acoustic image processing:* For example, the detection and recognition of various types of targets and the maneuvering of aircraft (Fig. 1.6).
5. *Robot/machine vision:* Its applications include the identification or description of objects or industrial parts in 3D scenes (Fig. 1.7).

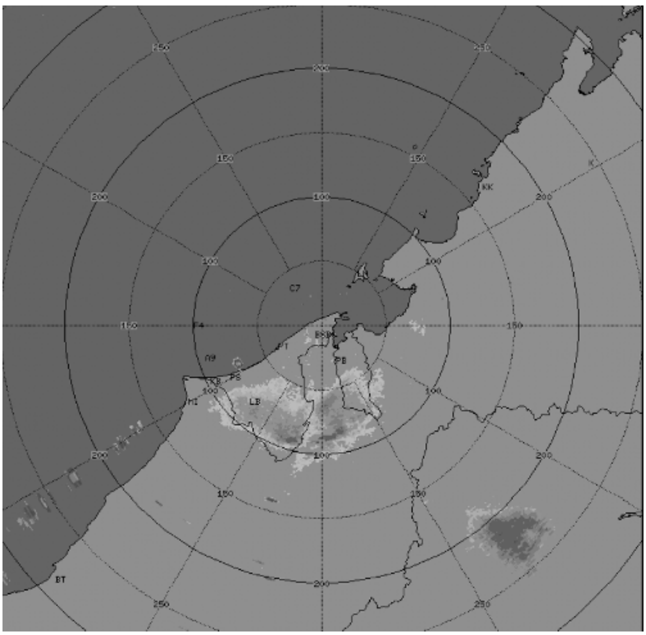


Figure 1.6 Radar imaging.

Figure 1.7 Robot and machine vision applications.

1.3 ELEMENTS OF AN IMAGE PROCESSING SYSTEM

Elements of an image processing system include

1. *Image acquisition:* A physical device that is sensitive to a band in the electromagnetic energy spectrum can produce an electrical signal output. A digitizer is used for converting the electrical signal output into a digital form. Digital images can be obtained by conversion of the analog images (such as 35 mm prints, slides, transparencies, or reflective art) into digital images with a scanner, or else by directly capturing the object or scene into digital forms by means of a digital camera or video-capturing device.
2. *Storage:*
   (**a**) Short-term storage for use during processes. One of the means of providing short-term storage is computer memory. Another is a specialized board, called a *frame buffer*.
   (**b**) Online storage for relatively fast recall.
   (**c**) Archival storage characterized by infrequent access. The term "archival quality" is used to designate materials that are permanent and durable, and therefore can be safely used for preservation purposes. The objective of archival storage is the protection against tampering, deletion, viruses, and disaster.
3. *Processing:* Most image processing functions can be implemented in software, running on a host computer.
4. *Communication:* Cable modem Internet services on average promise higher levels of bandwidth than DSL Internet services, and this bandwidth roughly translates to communication speed. Cable Internet theoretically runs faster than DSL. Cable technology can support approximately 30 Mbps (megabits per second) of bandwidth, whereas most forms of DSL cannot reach 10 Mbps.
5. *Display:* An image display device may take the form of an illuminating picture lamp providing means by which images may be illuminated by a light source on a selectable and removably attachable basis. Monochrome and color monitors are the principal display devices used. Other display media include random access cathode ray tubes (CRTs) and printing devices.

To illustrate the systematic procedures of an image processing system, we give an example of human face identification (Adler and Schuckers, 2007). The problem domain is the faces of people. The objective is to associate the face with the identity of the person. The output is a person's unique identifier (e.g., social security number). The necessary procedures to achieve the goal of face identification could include

1. *Image acquisition:* The face image could be acquired through a high-resolution still digital camera and compressed to an image file.
2. *Preprocessing:* The acquired image may be enhanced by improving contrast, sharpness, color, and so on.
3. *Segmentation*: The image may first be cropped to only the facial area. Then, the face may be segmented into eyes, mouth, nose, chin, and so on.
4. *Representation and description:* In this step, each of the segmented areas may be characterized by statistical data, for example, principal components analysis, texture, aspect ratios of eyes and nose, or the color of eyes.
5. *Matching recognition and interpretation:* This step may involve using the characteristics derived in the previous step to match each individually segmented area based on specific recognition algorithms. For example, eyes may be processed to determine, based on its features, what class of eye it is. Then, all of these interpretations are used to create a composite description of the "ensemble," perhaps in the form of a feature vector for the subject.
6. *Knowledge base:* Finally, the feature vector above may be fed to a knowledge base of all known subjects to associate it with one of the subjects in the database, thus returning perhaps the individual's social security number or perhaps a confidence score of the match.

APPENDIX 1.A SELECTED LIST OF BOOKS ON IMAGE PROCESSING AND COMPUTER VISION FROM YEAR 2000

Acharya, T. and Ray, A. K., *Image Processing: Principles and Applications*, Wiley, Sept. 2005.

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