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Preface

This book is the Volume I of “Image Engineering,” which is focused on “Image Processing,” the low layer of image engineering.

This book has grown out of the author’s research experience and teaching practices for full-time undergraduate and graduate students at various universities, as well as for students and engineers taking summer courses, in more than 20 years. It is prepared keeping in mind the students and instructors with the principal objective of introducing basic concepts, theories, methodologies, and techniques of image engineering in a vivid and pragmatic manner.

Image engineering is a broad subject encompassing other subjects such as computer science, electrical and electronic engineering, mathematics, physics, physiology, and psychology. Readers of this book should have some preliminary background in one of these areas. Knowledge of linear system theory, vector algebra, probability, and random process would be beneficial but may not be necessary.

This book consists of eight chapters covering the main branches of image processing. It has totally 55 sections, 99 subsections, with 164 figures, 25 tables, and 473 numbered equations, in addition to 60 examples and 96 problems (the solutions for 16 of them are provided in this book). Moreover, over 200 key references are given at the end of book for further study.

This book can be used for the first course “Image Processing” in the course series of image engineering, for undergraduate students of various disciplines such as computer science, electrical and electronic engineering, image pattern recognition, information processing, and intelligent information systems. It can also be of great help to scientists and engineers doing research and development in connection within related areas.

Special thanks go to De Gruyter and Tsinghua University Press, and their staff members. Their kind and professional assistance are truly appreciated.

Last but not least, I am deeply indebted to my wife and my daughter for their encouragement, patience, support, tolerance, and understanding during the writing of this book.

Yu-Jin ZHANG

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1 Introduction to Image Processing

This book is the first volume of the book set “Image Engineering” and is focused on image processing.

Image processing has been developed for many years. In its broad sense, image processing comprises a number of techniques for treating images to obtain information from image. With the research and application of image technology, a more suitable term used is image engineering. Image engineering refers to a new discipline comprising all subjects relating to images, in which image processing (in its narrow sense) is an important part. This chapter provides an introduction to image processing, an overview of image engineering, and an outline of this book.

The sections of this chapter are arranged as follows:

Section 1.1 introduces the basic concepts and terms of image and its expression (including image representation and display form). A general representation of image is also discussed.

Section 1.2 provides a complete introduction to the field of image engineering. Image engineering currently includes three levels (image processing described in this book is the first level). It has a number of closely related disciplines, and has a wide range of applications. For a comprehensive understanding of the development and current situation of image engineering, some statistical data of image engineering literature, such as the number of papers published each year in a number of journals for the past more than 20 years, the categorization of there papers in 5 classes and further in 23 sub-classes, and the distribution of there papers in these classes and sub-classes, etc. are also presented and analyzed.

Section 1.3 describes the principal modules in the framework and system for image processing. This book mainly focuses on the principles, approaches, and algorithms of image processing. This section summarizes some peripheral knowledge and equipment of image processing, laying the foundation for later chapters to focus purely on image processing techniques.

Section 1.4 overviews the main contents of each chapter in the book and indicates the characteristics of the preparation and some prerequisite knowledge for this book.

1.1 Basic Concepts of Images

Images are an important medium by which human beings observe the majority of the information they receive from the real world.

1.1.1 Images and Digital Images

Images can be obtained by using different observing and capturing systems from the real world in various forms and manners. They can act, directly and/or indirectly, on

human eyes and produce visual perception. The **human visual system** is a typical example of an observation system, from which humans perceive and recognize objects and scenes by observing and remembering their images.

The real world is three-dimensional (3-D) in space. However, the images obtained from the real world are generally two-dimensional (2-D). Such a **2-D image**, in most cases, is a 2-D light intensity function (2-D light pattern). An image can be represented by a 2-D array $f(x, y)$, where x and y are spatial coordinates and f is the amplitude at any pair of coordinates (x, y) representing certain properties of the scene projected on the image at that particular point. For example, in an image recording the brightness of scene, the amplitude f is proportional to the intensity of the image. In general, the amplitude f is proportional to one or several attributes of the image. For a real image, the values of x and y as well as f are real values, which are limited to a certain range.

Mathematically, an image can be explained as a function $f(x, y)$ with two variables. For the purpose of processing by computers, an **analog image** $f(x, y)$ should be digitalized to a **digital image** $I(r, c)$, in which r (row) and c (column) refer to the discrete position of any point in the digital image and the amplitude I refers to the discrete magnitude of the image at point (r, c) . Since this book mainly discusses digital images, $f(x, y)$ is used to represent a digital image at any point (x, y) and f takes integer values only. A digital image can be considered a matrix whose rows and columns refer to the position of any point in the image and the corresponding matrix value refers to the intensity at that point.

In the early days, an image was called a “picture.” When a picture is digitized, a sampling process is used to extract from the picture a discrete set of real numbers. The picture samples are usually quantized to a set of discrete gray-level values, which are often considered to be equally spaced. The result of sampling and quantizing is a digital picture. It is assumed that a digital picture is a rectangular array of integer values. An element of a digital picture is called a picture element (often abbreviated as “**pixel**” or “**pel**”). Although nowadays the term “image” rather than picture is used, because computers store numerical images of a picture or scene, the element of an image is still called a pixel. The element of a 3-D image is called a **voxel** (volume element). When combined, it is called an **imel** (2-D/3-D image element).

In its general sense, the word “image” refers to all entities that can be visualized, such as a still picture, a video, an animation, a graphic, a chart, a drawing, and text. These entities can be 2-D, 3-D, or even higher dimensions.

1.1.2 Matrix and Vector Representation

A 2-D image of $M \times N$ (where M and N are the total number of rows and the total number of columns of the image) can be represented either by a 2-D array $f(x, y)$ or by a 2-D matrix F :

$$\mathbf{F} = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1N} \\ f_{21} & f_{22} & \cdots & f_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ f_{M1} & f_{M2} & \cdots & f_{MN} \end{bmatrix} \quad (1.1)$$

The above matrix representation can also be converted to a vector representation. For example, the above equation can be rewritten as

$$\mathbf{F} = [\mathbf{f}_1 \mathbf{f}_2 \cdots \mathbf{f}_N] \quad (1.2)$$

where

$$\mathbf{f}_i = [f_{1i} \ f_{2i} \ \cdots \ f_{Mi}]^T \quad i = 1, 2, \dots, N \quad (1.3)$$

Note that the array operation and matrix operations are different. Considering two 2×2 images $f(x, y)$ and $g(x, y)$ as an example, the array product is

$$f(x, y)g(x, y) = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} f_{11}g_{11} & f_{12}g_{12} \\ f_{21}g_{21} & f_{22}g_{22} \end{bmatrix} \quad (1.4)$$

And their matrix product is

$$\mathbf{FG} = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{bmatrix} \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} f_{11}g_{11} + f_{12}g_{21} & f_{12}g_{12} + f_{12}g_{22} \\ f_{21}g_{11} + f_{22}g_{21} & f_{21}g_{12} + f_{22}g_{22} \end{bmatrix} \quad (1.5)$$

1.1.3 Image Display

Image display means to put the image in a visible form that is shown on display equipment. In normal display equipment, an image is displayed as a 2-D pattern with different shades or colors.

Example 1.1 Digital image display

Figure 1.1 shows two examples of digital images. Two axis conventions are adopted in Figure 1.1 for image display. Figure 1.1(a) takes the top-left corner as the origin of the coordinate system, the row axis goes left-right, and the column axis goes top-down. Such a display is often used, for example, in screen displays. Figure 1.1(b) takes the

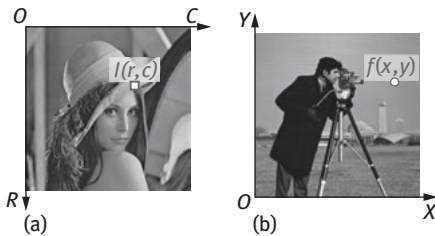


Figure 1.1: Examples of digital image display.

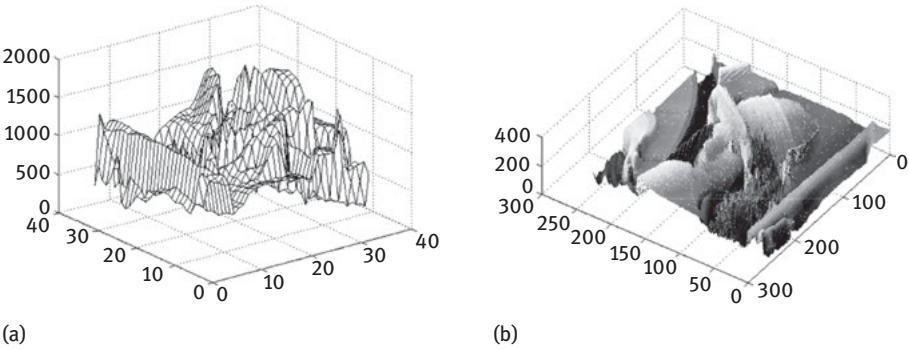


Figure 1.2: Other examples of digital image display.

down-left corner as the origin of the coordinate system, the X -axis goes left-right, and the Y -axis goes down-up. Such a display is used frequently, for example, in image manipulation.

In Figure 1.1, the gray levels of images represent the brightness of the image. Higher levels represent brighter pixels, while lower levels represent darker pixels. The gray levels of images can also be represented by a perspective plot in which the elevation corresponds to the brightness of pixel. One example of such a plot for Figure 1.1(a) is shown in Figure 1.2(a). A combination of the above two kinds of representations for Figure 1.1(a) is shown in Figure 1.2(b), in which the gray levels of images are represented by both elevation and brightness. □

Example 1.2 Binary image representation and display

A binary image can be represented by a 2-D matrix, and there are different ways to show this matrix. Figure 1.3 gives three modes of showing a 4×4 binary image. In the mathematical model for image representation, the pixel area is represented by its center. The image thus obtained forms a discrete set of points on the plane, corresponding to Figure 1.3(a). If the pixel area is represented by its covered region, the Figure 1.3(b) is obtained. When the amplitude values corresponding to the pixel areas are marked in the image, the matrix representation results are shown as in Figure 1.3(c). The mode of Figure 1.3(b) may also be used for representing multiple grayscale images, where different shades of gray are required. The mode of Figure 1.3(b) may also be used for representing multiple grayscale images, in which case different gray values are represented by different number values. □

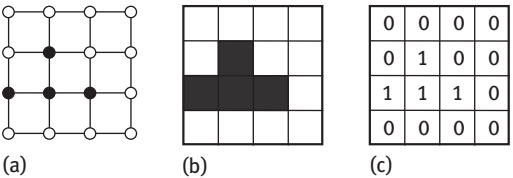


Figure 1.3: Three modes of representation for a 4×4 binary image.

1.1.4 High Dimensional Images

A basic representation of images is in the form of 2-D still gray-level images, which is represented by $f(x, y)$. A **general image representation function** is a vector function $\mathbf{f}(x, y, z, t, \lambda)$ with five variables, where \mathbf{f} stands for the properties of the world represented by the image, x, y, z are spatial variables, t is a time variable, and λ is a frequency variable (corresponding to wavelength). Some typical examples of the extension from $f(x, y)$ to $\mathbf{f}(x, y, z, t, \lambda)$ are listed below.

- (1) Consider that $f(x, y)$ is an image formed by the irradiance from object surfaces. If the object is cut along the capture direction into a number of sections and capture the image for each section, the integrated 3-D spatial information of the object (including its inside) can be obtained. In other words, a **3-D image** $f(x, y, z)$ is obtained. Imaging modalities, such as CT and MRI, are typical examples.
- (2) Consider that $f(x, y)$ is a still image captured at a certain moment. If multiple images are captured consecutively along the time axis, the integrated 3-D temporal information (including dynamic information) of the object can be obtained. Video and other sequence images are examples of a 3-D image $f(x, y, t)$.
- (3) Consider that $f(x, y)$ is an image which captured the irradiance of only one wavelength. If multiple wavelengths are captured, images with different properties (corresponding to reflection and absorption of different wavelengths λ) can be obtained. These images are either 3-D images $f(x, y, \lambda)$ or **4-D images** $\mathbf{f}(x, y, t, \lambda)$. **Multi-spectrum images** are typical examples, in which each image corresponds to a certain wavelength, while all of them correspond to the same space and time.
- (4) Consider that $f(x, y)$ is an image with only one property in the space location. In fact, the scene at one space location can have multiple properties. Therefore, an image can have several values at point (x, y) and it can be represented by a vector \mathbf{f} . For example, a color image is an image having three RGB values at a pixel, $\mathbf{f}(x, y) = [f_r(x, y), f_g(x, y), f_b(x, y)]$.
- (5) Consider that $f(x, y)$ is an image obtained when projecting a 3-D scene onto 2-D plane. In this process, the depth or distance (from camera to object in scene) information in scene would be lost. If multiple images can be obtained from different viewpoints but for the same scene and if they can be combined, an image with all the information in the scene (including the depth information) can be obtained. The image with property as depth is called a **depth map**: $z = f(x, y)$. From the depth map, the 3-D image $f(x, y, z)$ can be derived.

1.2 Image Engineering

This book is focused on image processing that is part of image engineering. Several fundamental aspects of image engineering are given below.

1.2.1 Image Techniques and Image Engineering

Image techniques, which are expanding over wider and wider application areas, have attracted much attention in recent years. Because of the accumulation of solid research results and the improvement of electronic technology, many new theories have been proposed, many new techniques have been exploited, and many new applications have been created. It has become evident that a systematic study of the different branches of image techniques is of great importance.

In the following, a well-regulated explanation of the definition of image engineering, as well as its intention and extension, together with a classification of the theories of image engineering and the applications of image technology is provided.

Image engineering is a broad subject encompassing and based on subjects such as mathematics, physics, biology, physiology, psychology, electrical engineering, computer science, and automation. Its advances are also closely related to the development of telecommunications, biomedical engineering, remote sensing, document processing, industrial applications, and so on (Zhang, 1996c).

Some historical events related to image engineering made their effects a long time ago. Image techniques came into reality after the building of the first electronic computer ENIAC in 1946. The first image analysis started from grayscale data and ended with the derivation of a complete drawing in 1970. One of the earliest papers on understanding (line) drawings in a block world, such as making conclusions on what kinds of objects are presented, what relation exists between them, and what group they form, appeared in 1975. Note that this paper is included in a collected volume, *The Psychology of Computer Vision* (which introduces the first appearance of the word “Computer Vision (CV)” in literature).

The scope of image engineering has changed enormously since then. “Part of the reason for [this] change is that solid research results have been accumulated” (Kak, 1995). Many techniques have been developed, exploited, or applied only in the last decade. It can be seen that techniques for image engineering are implemented and used on a scale that few would have predicted a decade ago. It is also likely that these techniques will find more applications in the future (Zhang, 2008b; 2015c).

1.2.2 Three Levels of Image Engineering

What is the current “picture” of image engineering? Image engineering, from a perspective more oriented to techniques, should be referred to as a collection of the three related and partially overlapped image technique categories: image processing (IP), image analysis (IA), and image understanding (IU). In a structural sense, IP, IA, and IU build up three closely related and interconnected layers of IE as shown in Figure 1.4. Each layer operates on different elements and works with altered semantic levels. These layers follow a progression of increasing abstractness up and of decreasing compactness down.

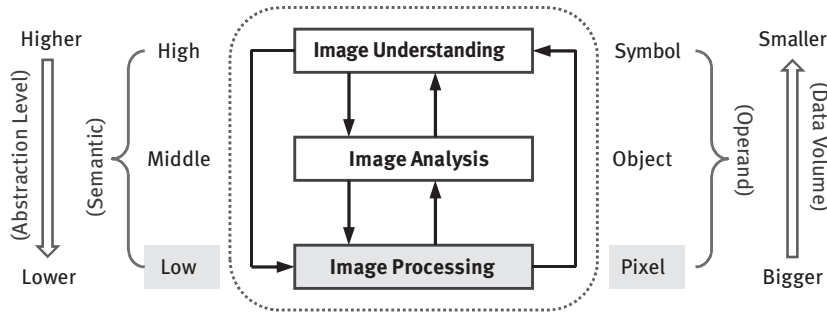


Figure 1.4: Three layers of image engineering.

Image processing primarily includes the acquisition, representation, compression, enhancement, restoration, and reconstruction of images. Although image processing concerns the manipulation of an image to produce another (improved) image, **image analysis** concerns the extraction of information from an image. In a general sense, it can be said that an image yields an image out for the former and an image yields data out for the latter. Here, the extracted data can be the measurement results associated with specific image properties or the representative symbols of certain object attributes. Based on image analysis, **image understanding** refers to a body of knowledge used in transforming these extracted data into certain commonly understood descriptions, and making subsequent decisions and actions according to this interpretation of the images.

One useful paradigm is to consider the three types of computerized operations in this continuum: low-level, mid-level, and high-level processes. Low-level processes involve primitive operations, such as image preprocessing to reduce noise, contrast enhancement, and image sharpening. A low-level process is characterized by the fact that both its inputs and outputs are images. Mid-level processing involves tasks such as segmentation, description of objects to reduce them to a suitable form for computer processing, and classification of individual objects. A mid-level process is characterized by the fact that its inputs are generally images, but its outputs are attributes extracted from those images. Finally, higher-level processing involves “making sense” of an ensemble of recognized objects, as in image analysis, and at the far end of the continuum, performing the cognitive functions normally associated with human visual system.

Example 1.3 Illustrative examples for IP, IA, and IU

One simple illustrative example, which pertains to image processing, image analysis, and image understanding, respectively, is given below.

- (1) **Image processing:** Suppose an image is taken with insufficient light (as shown in Figure 1.5(a)), with suitable image processing techniques, a possible result would be Figure 1.5(b) with better clarity and contrast.

- (2) Image analysis: Continuing the above example, starting from Figure 1.6(a) (the result of image processing in Figure 1.5(b)), with suitable image analysis techniques, information can be extracted, as listed in Figure 1.6(b).
- (3) Image understanding: Continuing with the above example and starting from Figure 1.7(a) (the result of image analysis in Figure 1.6(b)), with suitable image understanding techniques, a few inferences and/or interpretations can be made, as listed in Figure 1.7(b).

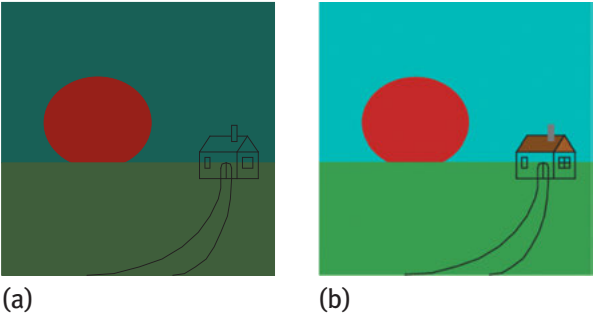


Figure 1.5: Input and output of image processing.

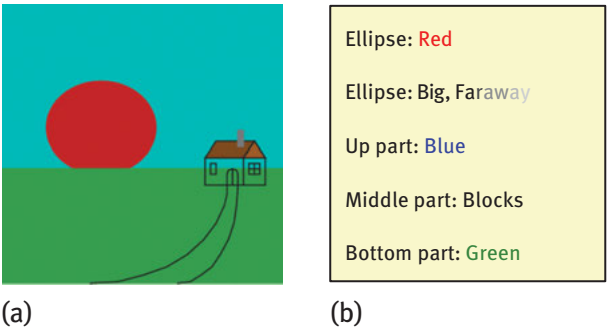


Figure 1.6: Input and output of image analysis.



Figure 1.7: Input and output of image understanding.

1.2.3 Related Disciplines and Fields

According to different science politics/perspectives, various terms such as **computer graphics** (CG), **pattern recognition** (PR), and **computer vision** (CV) are currently employed and (partially) overlapped with IP, IA, and/or IU. All of these subjects obtain help from a number of new techniques/tools, such as artificial intelligence (AI), fuzzy logic (FL), genetic algorithms (GA), neural networks (NN), soft science (SS), and wavelet transforms (WT). A diagram describing the relationship among the abovementioned subjects is given in Figure 1.8. Images are captured from the real world and processed to provide the basis for image analysis or pattern recognition. The former produces data that can be visualized by computer graphics techniques, while the latter continually classifies them into one of several categories that could be abstractly represented by symbols. Results produced by both can be converted to each other and can be further interpreted to help human beings understand the real world. This whole process aims to make computers capable of understanding environments from visual information, which is also the purpose of computer vision.

1.2.4 A Survey on Image Engineering

Image engineering is progressing very quickly. To capture the current status and the development trends of image engineering, a yearly survey series on image engineering has been on progress since 1996 and has lasted for more than 20 years (Zhang, 2015c; 2017).

In this survey series, the papers published in 15 important journals (covering electronic engineering, computer science, automation, and information technology) are considered. Those papers related to the image engineering are selected for classification. The papers are first classified into different categories, such as image processing, image analysis, and image understanding, then are further classified into different subcategories (see below), and finally, a number of statistics are gathered.

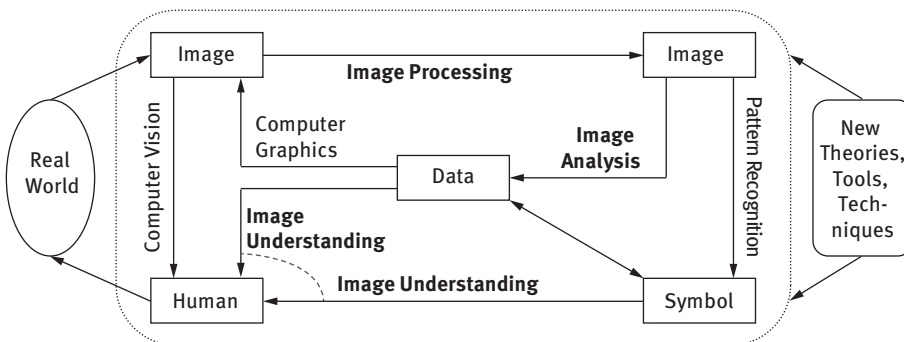


Figure 1.8: Image engineering and related subjects.

Table 1.1: Summary of image engineering over 22 years.

| Year | #T | #S | SR | #IP |
|---------|--------|--------|-------|---------------|
| 1995 | 997 | 147 | 14.7% | 35 (23.8%) |
| 1996 | 1,205 | 212 | 17.6% | 52 (24.5%) |
| 1997 | 1,438 | 280 | 19.5% | 104 (37.1%) |
| 1998 | 1,477 | 306 | 20.7% | 108 (35.3%) |
| 1999 | 2,048 | 388 | 19.0% | 132 (34.0%) |
| 2000 | 2,117 | 464 | 21.9% | 165 (35.6%) |
| 2001 | 2,297 | 481 | 20.9% | 161 (33.5%) |
| 2002 | 2,426 | 545 | 22.5% | 178 (32.7%) |
| 2003 | 2,341 | 577 | 24.7% | 194 (33.6%) |
| 2004 | 2,473 | 632 | 25.6% | 235 (37.2%) |
| 2005 | 2,734 | 656 | 24.0% | 221 (33.7%) |
| 2006 | 3,013 | 711 | 23.60 | 239 (33.6%) |
| 2007 | 3,312 | 895 | 27.02 | 315 (35.2%) |
| 2008 | 3,359 | 915 | 27.24 | 269 (29.4%) |
| 2009 | 3,604 | 1,008 | 27.97 | 312 (31.0%) |
| 2010 | 3,251 | 782 | 24.05 | 239 (30.6%) |
| 2011 | 3,214 | 797 | 24.80 | 245 (30.7%) |
| 2012 | 3,083 | 792 | 25.69 | 249 (31.4%) |
| 2013 | 2,986 | 716 | 23.98 | 209 (29.2%) |
| 2014 | 3,103 | 822 | 26.49 | 260 (31.6%) |
| 2015 | 2,975 | 723 | 24.30 | 199 (27.5%) |
| 2016 | 2,938 | 728 | 24.78 | 174 (23.9%) |
| Total | 56,391 | 13,577 | | 4,296 (31.64) |
| Average | 2,563 | 617 | 24.08 | 195 |

A summary of the number of publications concerning image engineering from 1995 to 2016 is shown in Table 1.1. In Table 1.1, the total number of papers published in these journals (#T), the number of papers selected for survey as they are related to image engineering (#S), and the selection ratio (SR) for each year, as well as the numbers of papers belonging to image processing (#IP) are provided (the ratios of #IP/#S are also listed in parenthesis).

It is seen that image engineering is (more and more) becoming an important topic for electronic engineering, computer science, automation, and information technology. The SR reflects the relative importance of image engineering in the specialties covered by each publication. In 1995, the SR was only about 1/7. In 1996, the SR was about 1/6, then until 2002 it has been around 1/5 or so. The SR in 2003 was about one-fourth, and in 2004 the SR first exceeded one-fourth. In terms of the number of selected images, the number of selected image engineering documents in 2009 is nearly seven times that of 1995 (the total number of documents is only 3.6 times), which is remarkable considering the wide coverage of these journals. This results from the increase in the number of image engineering researches and contributors over the years; it is also the evidence of the vigorous development of image engineering disciplines.

Table 1.2: The classification of image processing category

| Subcategory | # / Year |
|--|----------|
| P1: Image capturing (including camera models and calibration) and storage | 33 |
| P2: Image reconstruction from projections or indirect sensing | 18 |
| P3: Filtering, transformation, enhancement, restoration, inpainting, quality assessing | 58 |
| P4: Image and/or video coding/decoding and international coding standards | 45 |
| P5: Image digital watermarking, forensic, image information hiding, etc. | 42 |
| P6: Multiple/super-resolutions (decomposition/interpolation, resolution conversion) | 19 |

The selected papers on image engineering have been further classified into five categories: image processing (IP), image analysis (IA), image understanding (IU), technique applications (TA), and surveys.

In Table 1.1, the statistics for IP are also provided. The listed numbers are the numbers of papers published each year, and the percentages in parenthesis are the ratio of IP papers over all IE papers. Almost one-third papers related to image engineering are in the image processing area in these years. So far, image processing has achieved the most important progresses.

This survey series is characterized not only by categorizing the selected documents but also by statistically comparing and analyzing them, so that it is helpful for determining the direction of image engineering research and formulating the work decisions, in addition to contributing to the literature search.

The papers under the category IP have been further classified into six subcategories. The names of these six subcategories and the average numbers of papers per year for each subcategory are listed in Table 1.2.

1.3 Image Processing System

Image processing has been widely used. This book mainly introduces some basic techniques for image processing. Various image processing systems can be constructed by combining these techniques and can be used to solve different practical problems.

1.3.1 A Block Diagram of System

The constitution of a basic **image processing system** is represented in Figure 1.9. The seven modules shown in this figure have each a specific function, namely image acquisition (imaging), synthesis (image generation), processing, display, printing, communications, and storage. The system input includes image acquisition and generation, while the system output includes both display and printing. It should be noted that not every actual image processing system includes all of these modules. On the other hand, some special image processing system may also include other modules.

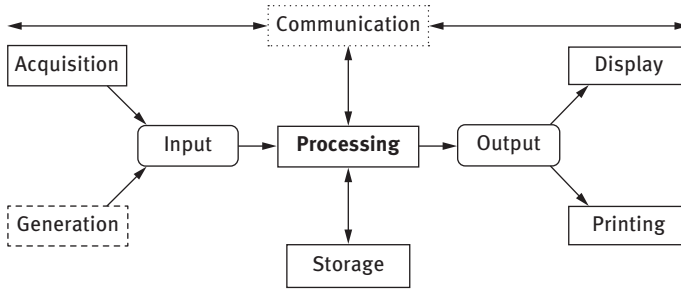


Figure 1.9: A configuration diagram showing an image processing system.

In Figure 1.9, the modules with dotted frames are associated with the image processing system, but the reader may refer to other books (see Further Reading at the end of this chapter) for introduction. The modules with solid frames, including the equipment needed for the respective functions, will be introduced briefly below.

1.3.2 Image Acquisition Equipment

Image acquisition is realized with certain equipment, also known as the imaging equipment, which transforms the objective scene into an image that could be processed by computer. In fact, the image can be collected from objective scene or generated (synthesized) from the known data. The latter is mainly the concern of computer graphics. For the image processing system, the common purpose of both is to get the discrete image that can be put into the computer for subsequent processing.

1.3.2.1 Acquisition Equipment Performance

The input of the image acquisition equipment at work is an objective scene, while the output is an image reflecting the nature of the scene. In general, there are two acquisition devices for image acquisition. One is a physical device (sensor) that is sensitive to the electromagnetic radiation energy of a spectral band (e.g., X-ray, ultraviolet, visible, infrared), which generates the (analog) electrical signal proportional to the received electromagnetic energy, and the other is called a digitizer, which can convert the above (analog) electrical signal to a digital (discrete) form.

In the acquisition of visible light image, for example, the acquisition equipment projects the scene onto the image, which can be modeled by pinhole imaging in simple cases, so the objects in scene and their locations in image have corresponding geometry relationship. In addition, the brightness changes in scene should be reflected in the image, which requires the establishment of a certain illumination model, and links the scene brightness with the gray scale of images. The geometrical relation is finally associated with the **spatial resolution** of the image, whereas the illumination model is finally related to **amplitude resolution** of the image.

In addition to spatial resolution and amplitude resolution of the acquired image, the several indicators in the following are also often used to represent the properties of acquisition device (Young *et al.*, 1995).

- (1) Linear response: It refers to whether the relationship between the intensity of input physical signal and the strength of output response signal is linear.
- (2) Sensitivity: The absolute sensitivity can be represented by the minimum number of photons detected, while the relative sensitivity can be represented by the number of photons required to make the output to change one level.
- (3) SNR: It refers to the (the energy or intensity) ratio of desired signal with unwanted interference (noise) in collected images.
- (4) Unevenness: It refers to the phenomenon that physical input signal may be constant while the digital form of output is not constant.
- (5) Pixel shape: It is the form of pixel region, which is generally square, but other shapes (e.g., hexagonal) may also be possible.
- (6) Spectral sensitivity: It is the relative sensitivity to radiation of different frequencies.
- (7) Shutter speed: It corresponds to the acquisition shooting time.
- (8) Read-out rate: It refers to the read (transmission) rate of signal data from the sensitive unit.

1.3.2.2 Solid-State Acquisition Devices

Solid-state array is a widely used collection device, which is composed of discrete silicon imaging elements, known as photosensitive primitive. Such a photosensitive element could produce the output voltage proportional to the input light intensity received. Solid-state array can be divided into two types according to the geometry organization: line scanner and flat-bed scanner. Line scanner comprises a row of photosensitive primitive. It relies on the relative motion between the scene and the detector to obtain 2-D images. The flat-bed scanner has photosensitive primitives lined square and can directly obtain 2-D images. A distinctive feature of solid planar sensor array is that it has a very fast shutter speed (up to 10^{-4} s), so many sports (with wild movement) can be frozen down. There are three commonly used devices.

CCD Device Camera with **charge-coupled device** (CCD) is one of the most widely used image acquisition device. Its main component, that is, CCD sensor, is a solid-state imaging device that uses the mode of charge storage and transfer as well as readout for work, whose output is converted to a digital image by the digitizer (achieved by inserting a special hardware card in the computer).

The number of units in a CCD sensor array is 768×494 in the US standard (US RS-170 video norm), 756×582 in the European standard (European CCIR norm). According to different chip size, the unit size is often between in $6.5 \mu\text{m} \times 6 \mu\text{m}$ to $11 \mu\text{m} \times 13 \mu\text{m}$.

CCD sensor's advantages include the following: It has precise and stable geometry. It is small in size, high in strength, and resistant to vibration. It has high sensitivity (especially cooled to a lower temperature). It can be made of many resolutions and frame rates. It is able to imaging with invisible radiation.

CMOS Device Complementary metal oxide semiconductor (CMOS) sensor includes a sensor core, an analog-digital convertor, output registers, control registers, and gain amplifiers. The photosensitive pixel circuits in sensor core can be classified into three kinds. One is photodiode-type passive pixel structure, which is formed by a reverse biased photodiode and a switch tube. When the switch tube is turned on, the photodiode is connected to the vertical column lines, the amplifier located at the end of the column line reads out column line voltage. When the photodiode stored signal is read, the voltage is reset, then the amplifier transforms the charge proportional to optical signal into voltage output. Another is photodiode-type active pixel structure, which has more than the passive pixel structure an active amplifier on the pixel unit. The last one is raster active pixel architecture. The signal charges are integrated in raster, the diffusion point was reset before output. Then, the raster pulses are changed, and the raster signal charges are collected and transferred to the diffusion points. The voltage difference between the reset level and the signal voltage level is the output signal.

Compared with the conventional CCD imaging devices, CMOS imaging device integrates the entire system on a single chip, which reduces the power consumption and device size, and the overall cost is lower.

CID Device Charge-injection device (CID) sensor has an electrode matrix corresponding to image matrix. There are two isolated electrodes to produce potential wells at each pixel location. One electrode is connected to all the electrodes (and their corresponding pixels) in the same row, and the other electrode is connected to all the electrodes (and their corresponding pixels) in the same column. In other words, in order to access a pixel, its rows and columns should be selected.

The voltages of the above two electrodes can be respectively positive and negative (including zero), and there are three kinds of situations for their combination with each other, corresponding to three working modes of CID. The first is integration mode. In this case the voltage of the two electrodes are both positive, optoelectronics will accumulate. If all the rows and columns remain positive, the entire chip will give an image. The second is non-elimination mode. In this case the voltages of the two electrodes are negative and positive, respectively. The photoelectrons accumulated by the negative electrode can be migrated to the positive electrode and will inspire a pulse in the circuits connected to the other electrode, whose magnitude reflects the number of photoelectrons accumulated. The photoelectrons migrated will remain in the potential well, so the pixels can be read out repeatedly without removing them through a round-trip migration of charges. The third one is an elimination mode. In

this case the voltages of the two electrodes are both negative. The accumulated photoelectrons will overspill or inject into a silicon chip layer between the electrodes, and this will excite pulses in the circuit. Similarly, the amplitude of the pulse reflects the cumulative number of photoelectrons. However, this process will exclude migrated photoelectrons out of potential well, so it can be used to “clearing” to make a chip ready to capture another image.

The circuit in the chip controls the voltages of row and column electrodes to acquire an image and to read out with the elimination mode or the non-elimination mode. This allows the CID to access each pixel in any order, and at any speed in reading sub-image of any size.

Compared with the conventional CCD imaging device, CID imaging device has much lower light sensitivity. On the other side, it has the advantages of random access, no blooming, etc.

1.3.3 Image Display and Printing

For image processing, the result of processing is still an image and is mainly used to display for human viewing. So the **image display** is very important for the image processing system. The image display is an important step in the communication between the system and the users.

The commonly used display devices in image processing systems include the cathode ray tube (CRT), liquid crystal display (LCD) monitors and TVs. In the CRT, the horizontal and vertical positions of the electron beam gun are controlled by the computer. In each deflected position, the intensity of the electron beam gun is modulated by the voltage. The voltage at each point is proportional to the corresponding grayscale value at this point. In this way, the grayscale image is converted to a brightness change mode, and this mode is recorded on a cathode ray tube screen. The images entering the monitor can also be converted to hard copy slides, photos, or transparencies.

In addition to the monitor, various printing devices, such as a variety of printers, can also be considered as an image display device. Printers are generally used for low-resolution output image. A simple method of early printing grayscale images on paper is to use the repeated printing capabilities of standard-line printers; the gray value at any point in the output image is controlled by the number of characters and the density of the dot printing. Printers that are currently in use, such as thermos-sensitive, dye-sublimation, ink jet, and laser printers, can print higher-resolution images.

1.3.3.1 Halftone Output

Some printers can output now continuous tone at the same spatial position, such as continuous-tone dye-sublimation printers. However, because of their slower speed and the requirement of special materials (special paper and ink), their applications

have certain limitations. Most print devices can only directly output binary image, such as a laser printer whose output has only two gray scales (black for print output and white for no-print output). To output the grayscale image on a binary device and to keep their original gray level, a technique called halftone output should be used.

Halftone output technology can be viewed as a transforming technology from grayscale image into a binary image. It intends to convert all kinds of gray values into binary dot patterns, which can be output by the printing devices that can only directly output binary point. In the meantime, it also utilizes the integrated nature of the human eye, by controlling the output in the form of binary dot pattern (including the number, size, and shape) to obtain a visual sense of multiple gray levels. In other words, the output image produced by halftone technology is still the **binary image** in a very fine scale, but is perceived as grayscale image in the coarse scale, because of local average effect of the eye. For example, in a binary image each pixel only takes white or black, but from a distance, the human eye can perceive a unit composed of multiple pixels, then the human eye perceives the average gray value of this unit (which is proportional to the number of black pixels).

Halftone technology is mainly divided into two categories: amplitude modulation and frequency modulation. They are introduced in the following sections.

1.3.3.2 Amplitude Modulation

Initially proposed and used halftone output technology is called **amplitude modulation** (AM) halftoning, which adjusts the output size of the black dot to show the different shades of gray. The gray level of early pictures on newspapers is represented by using different sizes of ink dots. When observed from a distance, a group of small set of ink dots could produce some light gray visual effects, and a group of large collections of ink dots could produce some dark gray visual effect. In practice, the size of the dots is inversely proportional to the gray values to be represented, that is, the dots in bright image area are small, while the dots in the dark image areas are large. When the dots are small enough, and are viewed far enough away, the human eye will obtain more continuous and smooth gradation image based integration features. The normal resolution of newspaper picture is about 100 points per inch (dot per inch, DPI), and the normal resolution of book or magazine picture is about 300 DPI.

In amplitude modulation, the binary points are regularly arranged. The size of these dots changes according to the gray scale to be represented, while the dot form is not a decisive factor. For example, the laser printer simulates different shades of gray by controlling the ratio of ink coverage, while the shape of ink dots is not strictly controlled. In actual utilization of amplitude modulation technology, the output effects of binary dot pattern depend not only on the size of each point but also on the spacing of the grid related. The smaller the gap, the higher will be the resolution of the output. Granularity of the grid is limited by the printer's resolution, which is measured by dots per inch.

1.3.3.3 Frequency Modulation


In **frequency modulation (FM)** halftone technology, the size of the output black dots is fixed, but the spatial distribution of dot depends on the desired gradation (frequencies occurring within a certain area or interval between points). If the distribution is dense, darker gray will be obtained; if the distribution is sparse, lighter gray will be obtained. In other words, to obtain a darker gray effect many points (which synthesize a printing unit, also known as printing dots corresponding to one pixel in the image) should be arranged close to each other. With respect to AM halftoning technology, FM halftone technique can eliminate moles (Moiré) pattern problems due to the superposition of two or more regular pattern generated in AM halftoning techniques (Lau and Arce, 2001). The main drawback of frequency modulation technique is related to the increase of halftone dot gain. Dot gain is increments of printing unit cell size relative to the size of the original amount, which lead to reduced or compressed grayscale range of printed images, and this will reduce detail and contrast.

Recently, with the increase of printer resolution (>1,200 dpi), FM halftone technique has reached the limit. People began to study techniques combining AM and FM halftone techniques to obtain the point sets whose size and spacing are both changing as the alteration of output gradation. In other words, the size and spacing between the basic points of printing units are required to change with the required gray level. This will not only generate spatial resolution comparable to AM halftone technology but also obtain the effect of Moore pattern cancellation similar to FM halftone technique.

1.3.3.4 Halftone Output Templates

A concrete implementation of halftone output technique is first to subdivide the image output units, by combining the nearby basic binary points to form the output unit. In this way, each output unit will contain a number of basic points, if some basic binary points output black, other basic binary points output white, then the effect of different gray levels can be obtained. In other words, to output different gray levels, a set of **halftone output templates**, each corresponding to an output unit, need to be established. Each template is divided into a regular grid, and each grid point corresponds to a basic binary point. By adjusting the respective basic binary point as black or white, it is possible to make each template to output different gray levels, so as to achieve the goal of outputting grayscale images.

Example 1.4 Halftone output templates

By dividing a template into a grid of 2×2 , the five different shades of gray can be output in accordance with Figure 1.10. By dividing a template into a grid of 3×3 , the ten different shades of gray can be output in accordance with Figure 1.11. Because there are $C_k^n = n!/(n-k)!k!$ kinds of different ways to put k points into n units, the number of ways in these figures are not unique. Note that in both figures, if a grid is black in a certain gray level, then this grid will be still black for all gray levels that are greater than this gray level in output. 

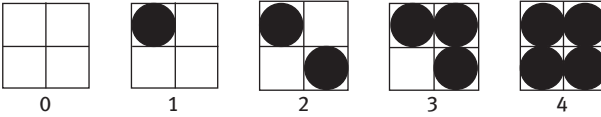


Figure 1.10: Dividing a template into a grid of 2×2 to output five gray scales.

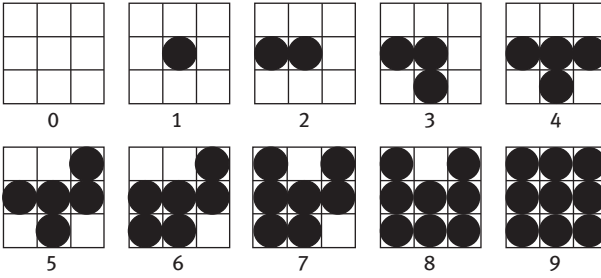


Figure 1.11: Dividing a template into a grid of 3×3 to output ten gray scales.

According to the above method of dividing the template into the grid, for the output of 256 types of gray levels, a template will need to be divided into a 16×16 units. It is seen that the visible spatial resolution of the output image will be greatly affected. Halftone output technology is only worth used under the circumstances that the output gray values of output device itself are limited. Suppose that each pixel in a 2×2 matrix may be black or white, each pixel needs one bit to represent. Taking this 2×2 matrix as a unit of halftoning output, then this unit requires 4 bits and can output five gray levels (16 kinds of modes), $0/4$, $1/4$, $2/4$, $3/4$, and $4/4$ (or written 0, 1, 2, 3, 4), respectively. However, if a pixel is represented by 4 bits, this pixel may have 16 kinds of gray scales. It is seen that if the halftone output using the same number of memory cells, the smaller the output scales the larger the output size.

1.3.3.5 Dithering Technology

Halftone output technology improves the amplitude resolution of the image by reducing the spatial resolution of the image, or increases the image gray levels by sacrificing the numbers of space points. It is seen from the above discussion that if the output image with more gray scales is required, the spatial resolution of the image will be greatly reduced. On the other side, if a certain spatial resolution needs to be maintained, the output gray levels will be relatively small, or to keep the spatial details the number of gray levels cannot be too large. However, when a grayscale image has relatively small number of gray levels, the visual quality of the image will be relatively poor, such as the appearing of a false contour phenomenon (see examples and discussions in Section 2.4.2). To improve the quality of the image, dithering technique