Chapter

1

Introduction and Digital Image Fundamentals

SYLLABUS:

Introduction and Digital Image Fundamentals : The origins of Digital Image Processing, Examples of Fields that Use Digital Image Processing, Fundamentals Steps in Image Processing, Elements of Digital Image Processing Systems, Image Sampling and Quantization, Some basic relationships like Neighbours, Connectivity Distance Measures between pixels, Linear and Non Linear Operations.

Chapter Outline

1.1 INTRODUCTION

Digital image processing, the manipulation of images by computer, is a relatively recent development in terms of man's ancient fascination with visuals. In its short history, digital image processing has been applied to practically every type of imagery, with varying degree of success. Several factors combine to indicate a lively future for digital image processing. A major factor is the declining cost of computer equipment. Both processing units and bulk storage devices are becoming less expensive year-by-year. A second factor is the increasing availability of equipment for image digitizing and display. There are indications that its cost will continue to decline. Several new technological trends promise to further promote digital image processing. These include parallel processing made practical by low-cost microprocessors and the use of charge-coupled devices (CCDs) for digitizing, storage during processing and display and large, low cost image storage always. Another impetus for development in this field stems from some exciting new application on the horizon. Certain types of medical diagnosis, including differential blood cell counts and chromosome analysis, are nearing a state of practicality by digital techniques. The remote sensing programs are well suited for digital image processing techniques. Thus, with increasing

PIONEER IN SIGNAL PROCESSING

Harry Nyquist (2/7/1889–4/4/1976)

Harry Nyquist received his Ph.D. from Yale in 1917. From 1917 to 1934, he was employed by Bell Labs where he worked on transmitting pictures using telegraphy and on voice transmission. He was the first to quantitatively explain thermal noise. He invented the vestigial sideband transmission technique still widely used in the transmission of television signals. He also invented the Nyquist diagram for determining the stability of feedback systems.

availability of reasonably inexpensive hardware and some very important applications on the horizon, one can expect digital image processing to continue its phenomenal growth and to play an important role in the future.

1.2 VARIOUS DEFINITIONS RELATED TO DIGITAL IMAGE PROCESSING (DIP)

Image

An image may be defined as a two-dimensional functional $g(x, y)$. Here x and y are spatial (plane) coordinates.

Gray level or Intensity

With respect to a two dimensional function $g(x, y)$, the amplitude of g at any pair of coordinates (x, y) is known as the intensity or gray level of the image at that point.

Digital Image

When $g(x, y)$ and the amplitude levels of g are all finite, discrete quantities, the image is defined as a digital image.

Pixels

A digital image is composed of a finite number of elements, each of which has a particular location and value. These elements are referred to as picture elements, image elements, pels, and pixels. In fact pixel is a term which is most widely used to denote the elements of a digital image.

Digital Image Processing (DIP)

The digital image processing (DIP) refers to processing digital images by means of a digital computer. The digital image processing encompasses a wide and various field of applications. We can also say that this field of digital image processing encompasses processes whose inputs and outputs are images and in addition encompasses processes that extract attributes from images including the recognition of the individual objects.

1.3 EVOLUTION OF DIGITAL IMAGE PROCESSING (DIP)

The very first application of digital images was in the newspaper industry. In this application, the pictures were sent by submarine cable between the two cities. Invention of the Bartlane cable picture transmission system in the early 1920s reduced the time required to send a picture across the Atlantic from more than a week to less than three hours. Specialized printing equipment coded pictures for cable transmission and then reconstructed them at the receiving end. The early Bartlane systems were capable of coding images in five distinct levels of gray. This capability was increased to 15 levels in 1929. As a matter of fact the history of digital image processing is intimately tied to the development of the digital computer. In fact, digital images require so much storage and computational power that progress in the field of digital image processing has been dependent on the development of digital computers and of supporting technologies that include data storage, display and transmission. The first computer powerful enough to carry out meaningful image processing tasks appeared in the early 1960s. In parallel with space applications, digital image processing techniques began in the late 1960s and early 1970s to be used in medical imaging, remote earth resources observations and astronomy. The invention in the early 1970s of computerised axial tomography (CAT), also called computerized tomography (CT) for short is one of the most important events in the application of image processing in medical diagnosis. From the 1960s until the present, the field of image processing has grown vigorously. In addition to applications in medicine and the space program, digital image processing techniques now are used in a broad range of applications. Computer procedures are used to enhance the contrast or code the intensity levels into color for easier interpretation of X-rays and other images used in industry, medicine, and the biological sciences. Similarly successful applications of image processing concepts can be found in astronomy, biology, nuclear medicine, law enforcement, defence, and industrial applications. The continuing decline in the ratio of computer price to performance and the expansion of networking and communication bandwidth via the world wide web and the Internet have created unprecedented opportunities for continued growth of digital image processing.

1.4 MOTIVATION AND PERSPECTIVE

As a matter of fact, the birth of digital computer has introduced to the society of a machine which is much more powerful than human beings in numerical computation. In a computer, the human capability of processing non-numerical information received from the environment as well as society can be incorporated with equal or more efficiency. This led to evolution of a new subject called artifical intelligence, which has a large area of common internet and motivation with another subject known as pattern recognition. A major portion of information received by a human from the environment is visual. Hence, visual information by computer has been drawing a very significant attention of the researchers over the last few decades. In fact, the process of receiving and analyzing visual information by the human species is called as sight, perception or understanding. In a similar way, the process of receiving and analyzing visual information by digital computer is called digital image processing and scene analysis. The term 'image' rather than 'picture' is used here, because the computer stores and processes numerical image of a scene. Although 'pattern recognition' and 'image processing' have a lot in common, yet they were developed as separate disciplines. Two broad classes of techniques, *i.e.*, 'processing' and analysis have evolved in the field of digital image processing and analysis. Processing of an image includes improvement in its appearance and efficient representation. So, the field consists of not only feature extraction, analysis and recognition of images, but also coding, filtering, enhancement and restoration. The entire process of image processing and analysis starting from the receiving of visual information to the giving out of description of the scene, may be divided into three major stages which are also considered as major sub-areas and are given below :

(i) Discretization and Representation

It converts visual information into a discrete form which is suitable for computer processing. It also approximates visual information to save storage space as well as time requirement in subsequence processing.

(ii) Processing

Processing improves image quality by filtering etc., compressing data to save storage and channel capacity during transmission.

(iii) Analysis

Analysis extracts image features, quantifying shapes, registration and recognition.

In the initial stage, the input is a scene (*i.e.*, visual information) and the output is corresponding digital image. In the secondary stage, both the input and the output are images where the output is an improved version of the input. Also, in the final stage the input is still an image but the output is a description of the contents of that image. Figure 1.1 shows a schematic diagram of different stages.

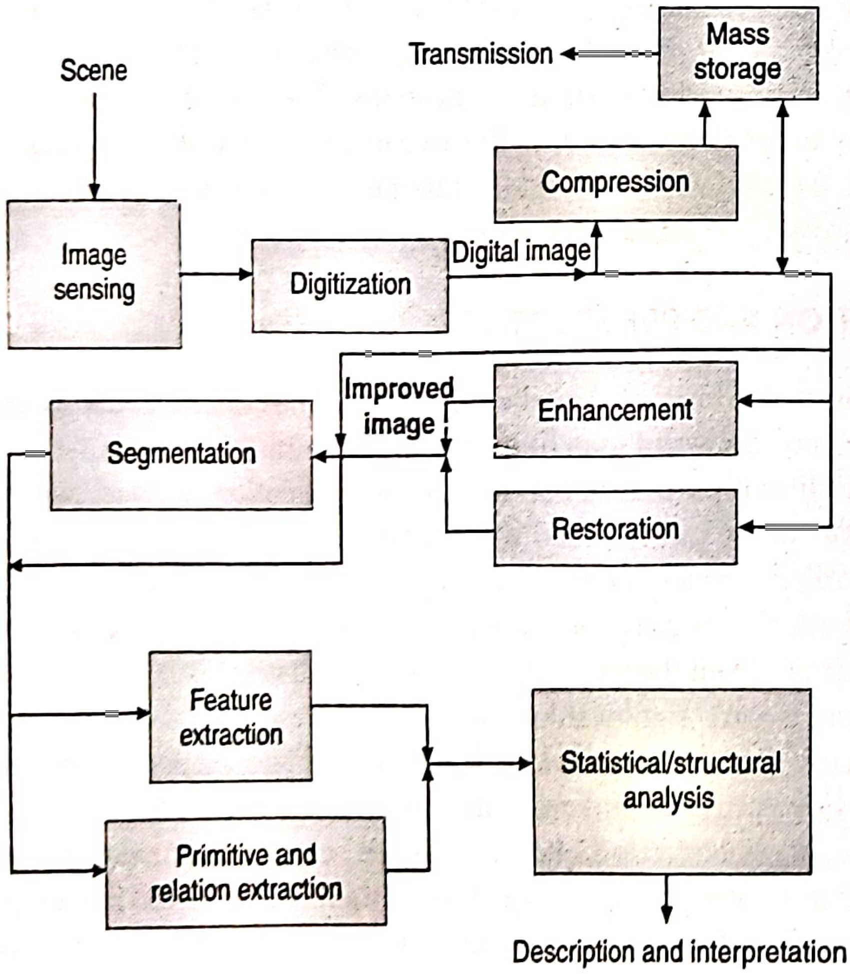


Fig. 1.1 Different stages of image processing and analysis scheme. Information flow along the outgoing link from each block.

A successful man is one who can lay a firm foundation with the bricks that others throw at him.
—David Brinkley

1.5 PRACTICAL ASPECTS OF DIGITAL IMAGE PROCESSING

Human beings are primarily visual creatures who depend on their eyes to gather information around them. Of the five senses that human beings have, sight is what we depend upon the most. Not many animals depend on their visual systems; the way human beings do.

Bats use high frequency sound waves. They emit sound waves which reflect back when they encounter some obstruction. Cats have poor vision but an excellent sense of smell. Snakes locate prey by heat emission and fish have organs that sense electrical fields.

1.5.1 What Happens when we Look at an object?

The eye records the scene and sends signals to the brain. These signals get processed in the brain and some meaningful information is obtained. Let us take a simple example when we see fire, we immediately identify it as something hot. Two things have happened here:

(*i*) The scene has been recorded by the eye.

(*ii*) The brain processed this scene and gave out a warning signal.

This is image processing.

We start processing images from the day we are born. Hence, image processing is an integral part of us and we continue to process images till the day we die. So, even if this subject seems to be new, we have been sub-consciously doing this, all these years. The human eye brain mechanism represents the ultimate imaging system. Apart from our vision, we have another important trait that is common to all human beings. We like to store information, analyse it, discuss it with others and try to better it. This trait of ours is responsible for the rapid development of the human race.

Early human beings strove to record their world by carving crude diagrams on stone. All the drawings that we see in old caves is just that; storing images seen, trying to analyse them and discussing it with others in the tribe. Let us consider figure 1.2. This art developed through the ages by way of materials and skill. By the mid-nineteenth century, photography was well established. Image processing that we study starts from this era.

Fig. 1.2

Though it was stated earlier that the human eye-brain mechanism represents the ultimate imaging system, image processing as a subject involves processing images obtained by a camera. With the advent of computers, image processing as a subject grew rapidly. Images from a camera are fed into a computer where algorithms are written to process these images. Here, the camera replaces the human eye and the computer does the processing. Hence, image processing as an engineering subject is basically manipulation of images by a computer.

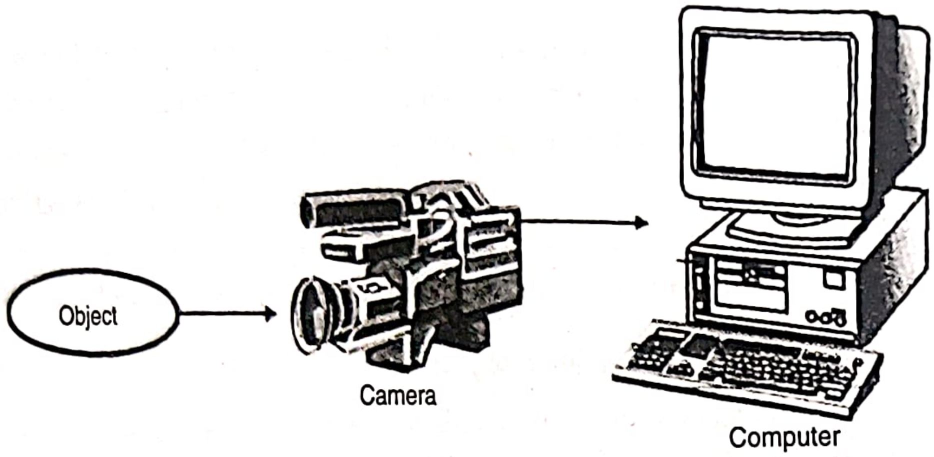


Fig. 1.3

1.6 IMAGES

(GGSIPU, Delhi, Sem. Exam; 2008-09) (10 Mark

Let us now define what we mean by an image. The world around us is 3-dimensional, whi images obtained through a camera are 2-dimensional. Hence, an image can be defined as 2-dimensional representation of a 3-dimensional world. Consider the image shown figure 1.4.

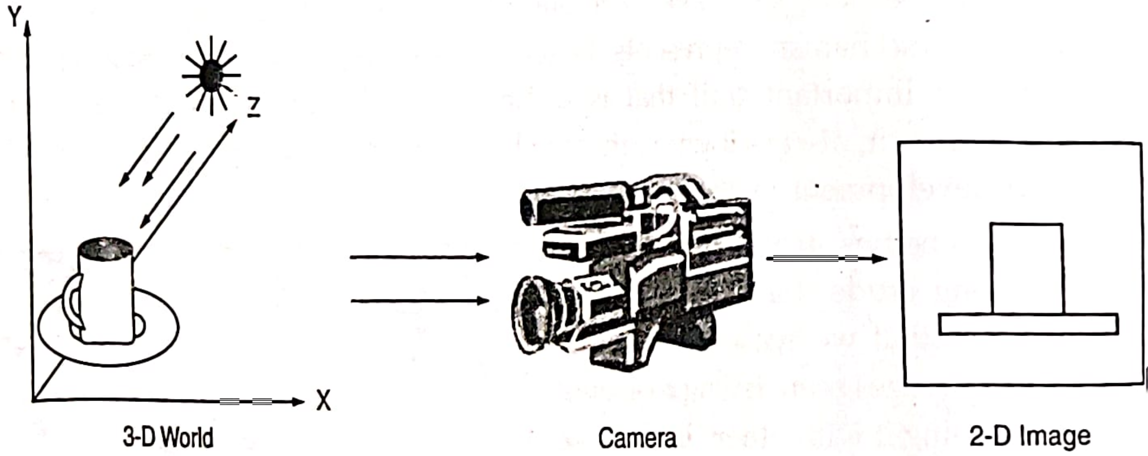


Fig. 1.4

In moving from the 3-dimensional world to the 2-dimensional image, we loose dimension. Depth of information is lost. As can be seen from the figure 1.4, the handle of tea cup is missing. All family pictures, photographs on identity cards etc. are 2-dimensio If this statement is not clear, let us take a simple example.

1.6.1 Example of a 1-Dimensional and a 2-Dimensional Signal

Consider a voltage signal shown in figure 1.5. We are all familiar with a signal of this kind. Here the voltage is varying with respect to time. This is a typical 1-dimensional signal. If we want to locate a dot on the wave, all we need to know is its corresponding time.

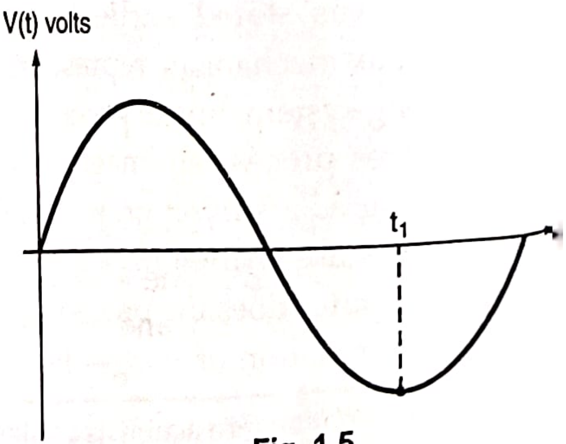


Fig. 1.5

Let us see why images are 2-dimensional functions. Consider the image shown in figure 1.6.

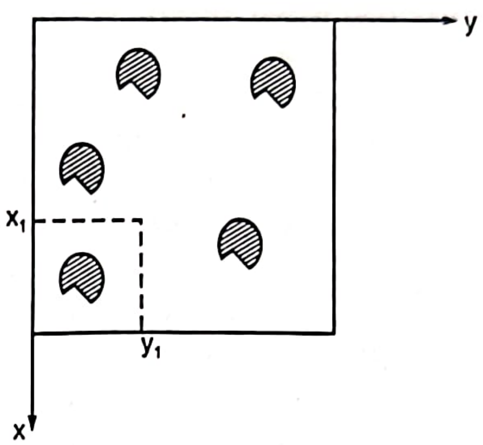


Fig. 1.6

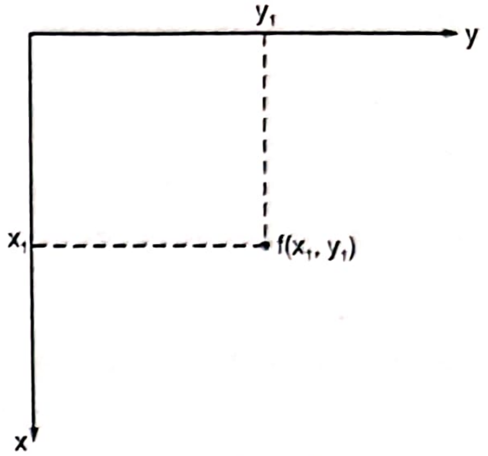


Fig. 1.7

In this case, to locate the dot shown, we need to know its position in two directions (x and y) in figure 1.7. Hence, all images that we see are 2-dimensional functions. A typical image is represented as shown in figure 1.7. Here, (x_1, y_1) are the spatial coordinates and f is the gray level (colour in the case of colour image) at that point. Hence, gray level f varies with respect to the x and y coordinates.

1.7 THE ELECTROMAGNETIC SPECTRUM

The apparatus shown in figure 1.8 will work only if light is incident on the object. What we call light is actually a very small section of the electromagnetic energy spectrum. The entire spectrum is shown in figure 1.8.

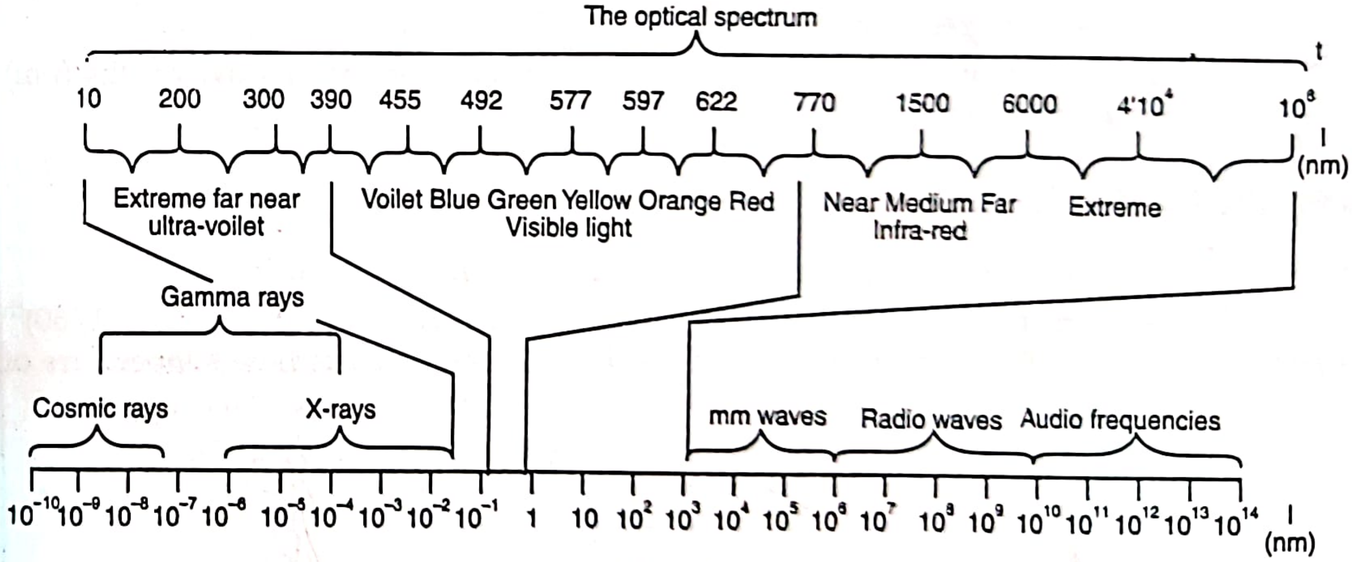


Fig. 1.8

Electromagnetic energy, as the name suggests, exists in the simultaneous form of electricity and magnetism. These two forms of the same energy are transmitted together as electromagnetic radiation. One cannot exist without the other. A flow of electric current always produces magnetism, and magnetism is used to produce electricity. Electromagnetic radiation is propagated outwards from its source at a velocity of 300,00,0000 meter second (3×10^8 m/sec). Although our natural source of electromagnetic radiation is the there are also a number of man-made sources which among many others, include tun filament lamps, gas discharge lamps and lasers. Light is a band of electromagnetic radi mediated by the human eye and is limited to a spectrum extending from 380 nm to 76(Most of the images that we encounter in our day to day life are taken from cameras w are sensitive to this range of the electromagnetic spectrum (380-760 nm). We must not f though, that there are cameras which are capable of detecting infrared, ultraviolet X-rays and radio waves too.

The electromagnetic spectrum can be expressed in terms of wavelength and frequ The wavelength (λ) and the frequency (f) are related by the expression.

$$\lambda = \frac{c}{f}$$

Here c is the speed of light = 3×10^8 m/sec.

EXAMPLE. 1.1. *Calculate the frequency of oscillation of green light.*

Solution : It has been known that green light has a wavelength of approximately 50((500×10^{-9} m)

Its frequency of oscillations can be calculated using Equation (1.1).

$$\lambda = \frac{c}{f}$$

$$f = \frac{c}{\lambda} = \frac{3\times10^8 \text{ m/sec}}{500\times10^{-9} \text{ m}}$$

$$f = 6 \times 10^{14} \text{ Hz}$$

i.e., the frequency of green light is 600,000,00,000,000 cycles/sec.

Hence, it is more convenient to discuss electromagnetic in terms of wavelengths ((rather than frequencies (Hz).

1.8 UNITS OF INTENSITY

We know that for an object to be seen, some amount of light has to fall on it.

The unit of luminous intensity (I) is candela (cd) (SI unit) which by definition, is (1/(of a square centimeter of the surface of a black body radiator at the absolute temperatur 2045 K.

Important Point: *A black body radiator is one that absorbs all the radiation incident upon it a has no reflecting power. The radiation from a heated black body source is called black bo radiation and is always quoted in Kelvin.*

The unit is called candela because initially it was defined as a standard candle burn a specific amount of wax per hour. There is another important unit apart from candela we encounter. This unit is called lux.

1.9 THE HUMAN VISUAL SYSTEM

It is important for designers and users of image processing to understand the characteris of the human vision system. For efficient design of algorithms whose output is a photograph or a display viewed by a human observer, it is beneficial to have an understanding of the mechanism of human vision.

Many interesting studies have been carried out and the subject of visual perception has grown over the years. We begin with the structure of the human eye.

Figure 1.9 shows the horizontal as well as the vertical cross-section of a human eye ball. The front of the eye is covered by a transparent surface called cornea. The remaining outer cover, sclera, is composed of a fibrous coat that surrounds the choroid, a layer containing blood capillaries. Sclera is the white portion of the eye.

Inside the cholorid, is the retina which is composed of two types of photoreceptors. These photoreceptors are specialised to transduce light rays into receptor potentials. These photoreceptors are called rods and cones (named due to their shape). Rods are long and slender while cones are shorter and thicker. Nerves connecting the retina leave the eyeball through the optic nerve bundle. Light entering the cornea is focussed on the retina surface by a lens that changes shape under muscular control to perform proper focussing of near and distant objects. The iris acts as a diaphragm to control the amount of light entering the eye.

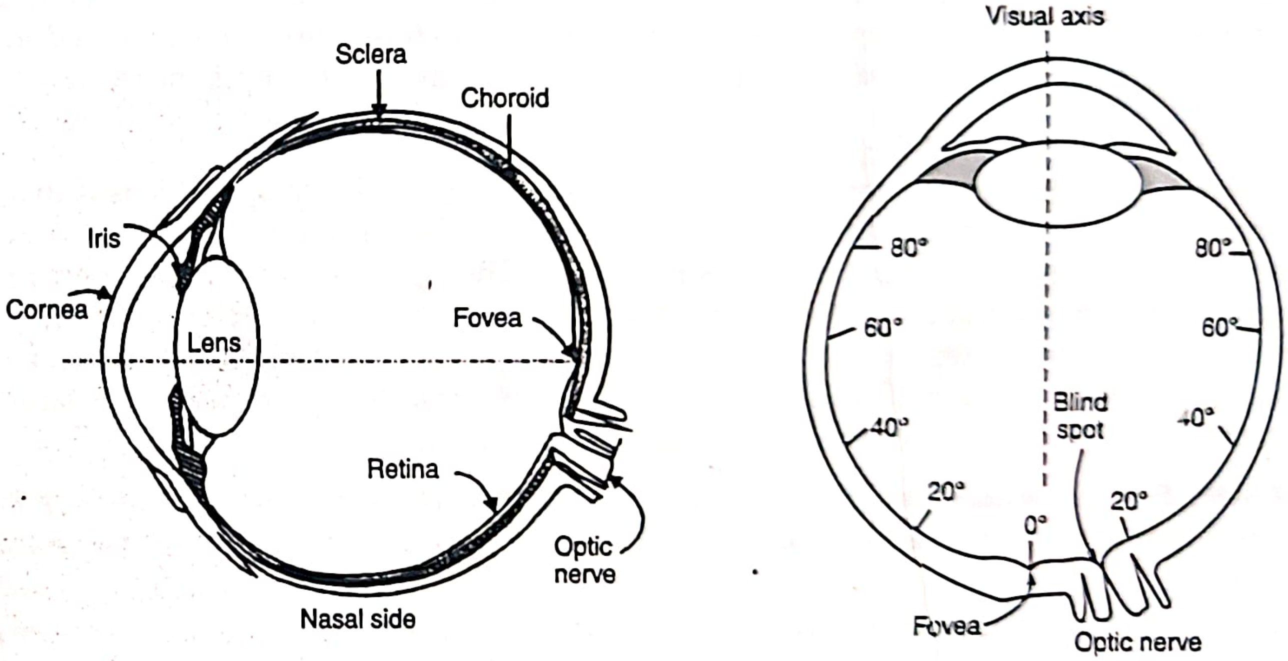


Fig. 1.9

Each retina has about 6 million cones and 120 million rods. Rods are most important for black and white vision in dim light. They also allow us to discriminate between different shades of dark and light and permit us to see shapes and movements. At low levels of illumination, the rods provide a visual response called Scotopic Vision. The fact that we can see in the dark is due to this scotopic vision.

Cones provide colour vision and high visual acquity (sharpness of vision) in bright light. Cones respond to higher levels of illumination, their response is called Photopic Vision. In the intermediate range of illumination, both rods and cones are active and provide Mesopic Vision.

In moon light, we cannot see colour because only the rods are functioning. The distribution of rods and cones in the retina are shown in figure 1.10.

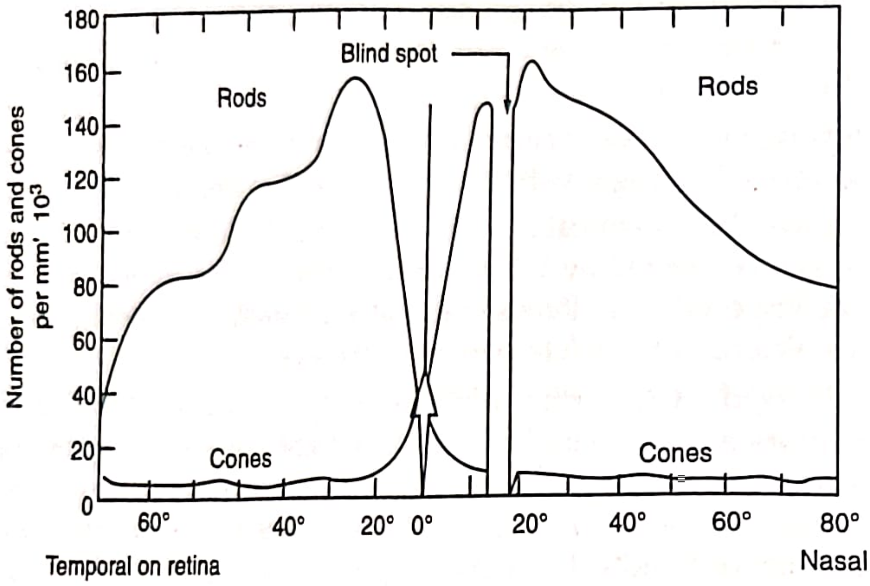


Fig. 1.10 Permetric angle, degree

At a point near the optic nerve, called fovea, the density of the cones is the greatest. Due to this, it is the region of sharpest photopic vision. The photoreceptors are connected to the nerves and these nerves combined together, leave the eyeball as the optic nerve.

1.9.1 Image Formation In Eye

The main difference between the lens of the eye and an ordinary optical lens is that the former is flexible. The shape of the lens is controlled by the tension of the ciliary muscles. These muscles help in focussing of objects near or far. The distance between the centre of the lens and the retina (focal length) varies from 14 mm to about 17 mm. When the eye focuses on an object far away (approx. > 3 m) the lens exhibits its lowest refractive power (Focal length = 17 mm). When the eye focuses on near by objects, the lens of the eye is strongly refractive (Focal length = 14 mm). Let us take an example:

EXAMPLE 1.2. *Consider an observer looking at a lamp-post which is at a distance of 50 m. If the height of the lamp post is 10 m, find the size of the image formed in the retina (Retinal image).*

Solution : Since the image is far away, the focal length is approximately 17 mm. We use the similarity of triangles.

Let the retinal image be r

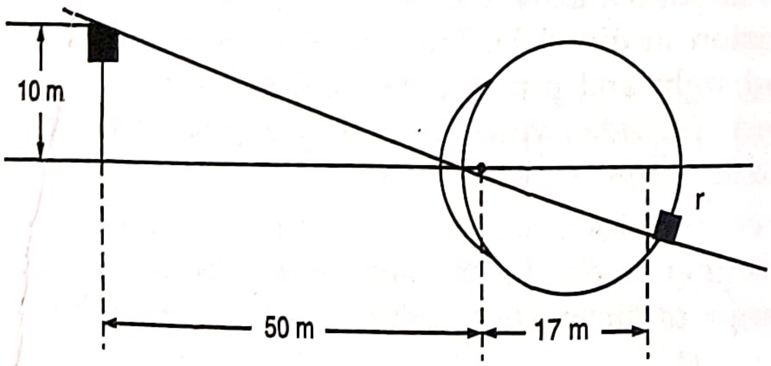


Fig. 1.11

$$\frac{10}{50} = \frac{r}{17}$$

$$r = 3.4 \text{ mm}$$

∴ The height of the retinal image is 3.4 mm

If the same image is observed at a distance of 100 m, we get

$$\frac{10}{100} = \frac{r}{17}$$

$$r = 1.7 \text{ mm}$$

1.9.2 Visual Phenomena (GGSIPU, Delhi, Sem. Exam., 2008-09)(10 marks)

The human eye is complex system and the images that we perceive are also equally complex. We shall now explain the visual phenomena.

What the human eye senses are in general intensity images-Intensity, Brightness and Contrast are three different phenomena. Intensity of a light source depends on the total amount of light emitted by it. Hence, intensity is a physical property and can be measured. Brightness on the other hand is a psycho-visual concept and hence is actually a sensation to light intensity. Contrast may be defined as the difference in perceived brightness.

1. Contrast Sensitivity

The response of the human eye to changes in the intensity of illumination is known to be non-linear.

Consider the simple experiment :

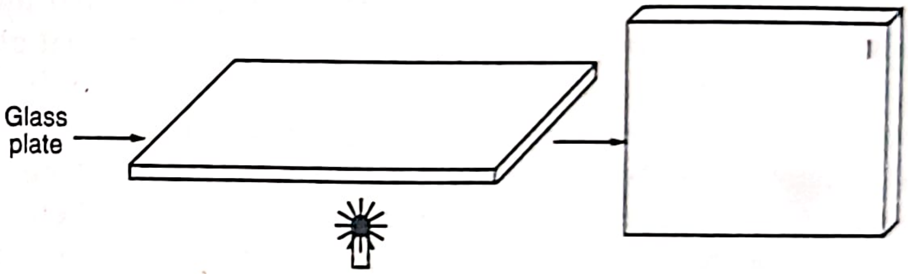


Fig. 1.12

We take a diffuser (opaque) glass plate and illuminate it from the bottom with constant illumination I.

The observer is asked to look at this glass plate, from the top. At the centre of this glass plate, the intensity of illumination is increased from I to $I + \Delta I$. The observer is now asked to observe whether he or she can detect this increase.

If the observer cannot detect the change, the intensity is further increased by another increment of ΔI. This procedure is continued till the observer detects the difference. This is known as the just Noticeable Difference (JND).

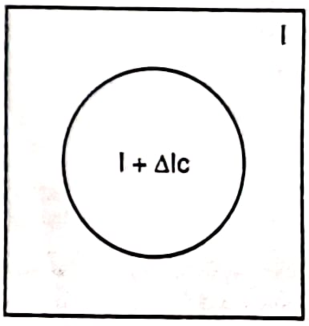


Fig. 1.13

This ratio of $\frac{\Delta I_c}{I}$ is called the Weber ratio

$$\text{Weber ratio} = \frac{\Delta I_c}{I}$$

Here, I is constant and I_c is the incremented value.

A low Weber ratio implies that even a small variation (ΔI) was detected by the observer. A higher Weber ratio implies that large variations ($\Delta I + \Delta I + ...$) were required for the observer to notice the change.

Hence, a low Weber ratio means that the observer has good discernible vision. At proper illuminations, the Weber ratio of a group of people in more or less constant at 0.02. Weber ratio also depends on the illumination I.

As can be seen from the graph, the weber ratio is large at very low as well as very high levels of illumination. This should not come as a surprise. Our discrimination quality reduces when we are in a room that is not well lit. At the same time our discrimination quality also reduces when there is too much light.

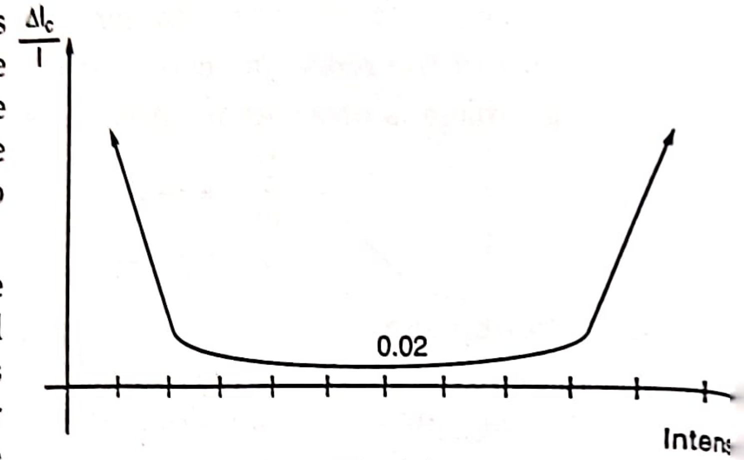


Fig. 1.14

2. Brightness Adaptation

The range of light intensity levels to which the human visual system can adapt is enorm of the order of 10^{10} from the scotopic threshold to the glare limit. It simply means we see things in the dark and also when there is a lot of illumination. It has been shown the intensity of light perceived by the human visual system (subjective brightness) logarithmic function of the light intensity incident on the human eye.

The curve in the figure 1.15 represents the range of intensities that the human vi system, can adapt. When illumination is low, it is the scotopic vision that plays a domi role while for high intensities of illumination, it is photopic vision which is dominant.

As can be seen from the figure, the transition from scotopic vision is gradual an certain levels of illuminations, both of them play a role. To cut a long story short, dynamic range of the human eye is enormous. But there is a catch here. The eye ca operate over the entire range simultaneously, *i.e.*, at a given point of time, the eye can observe a small range of illuminations. This phenomena is known as Brightness adapta The fact that our eyes can operate only on a small range, can be proved by a simple experi on ourselves.

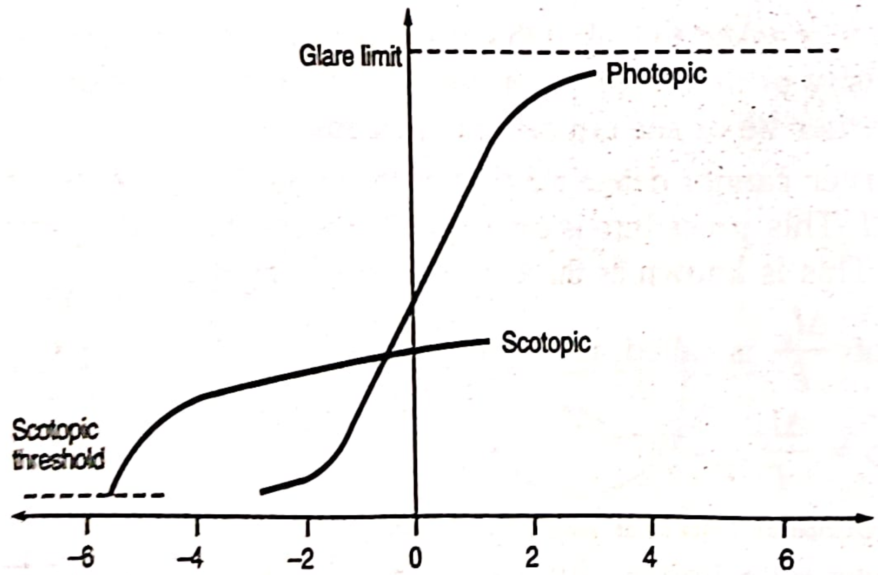


Fig. 1.15

Success often comes to those who dare and act. It seldom goes to the timid who are ever afra consequences.
—J.L.N

Stare at the sun for a couple of seconds, the eye adapts itself to the upper range of the intensity values. Now, look away from the sun and you will find that you cannot see anything for sometime. This is because the eye takes a finite time to adapt itself to this new range. A similar phenomenon is observed when the power supply of our homes is cut-off in the night. Everything seems to be pitch dark and nothing can be seen for sometime. But gradually our eyes adjust to this low level of illumination and then things start getting visible even in the dark.

3. Acquity and Contour (Mach Bands)

Mach band are named after the Austrian physicst Ernst Mach. (1838-1916).

Consider a set of gray scale strips shown in figure 1.16.

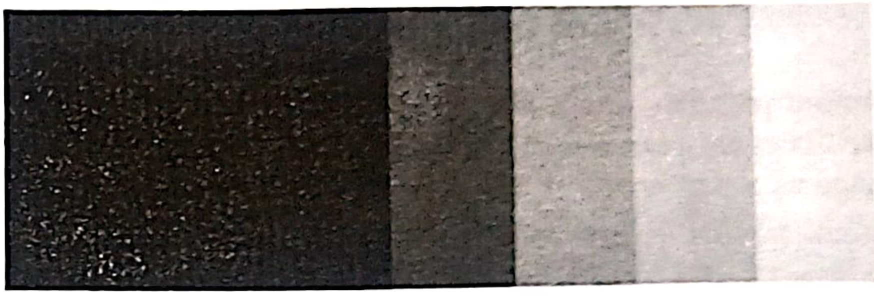
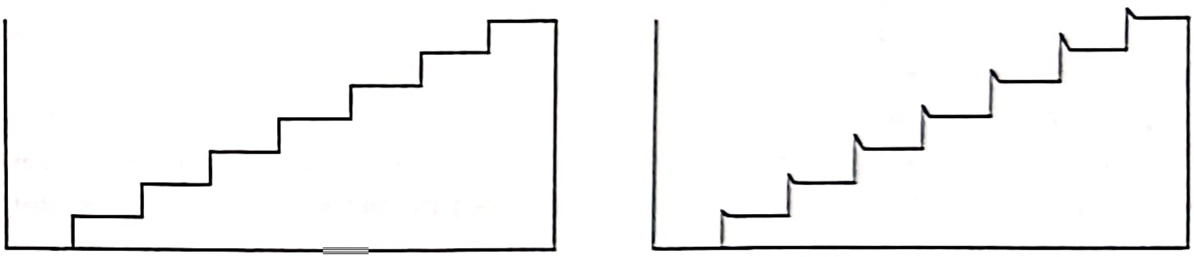


Fig. 1.16

Each of the eight strips have uniform intensities within the strip. This can be seen if we place our hand on all the other strips and observe only one strip at a time. But when we look at all the eight strips together, visual appearance is that each strip looks darker at its right side than its left. This is called the **Mach band effect.**

The actual and the perceived intensity charts are shown in figure 1.17 (*a*) and (*b*).



(a) Actual intensity

(b) Perceived intensity

Fig. 1.17

The intensities tend to overshoot at the right hand edges. The overshoot is a consequence of the spatial frequency response of the eye. The human eye possesses a lower sensitivity to high and low spatial frequencies than to mid range frequencies. The implication of this is that perfect edge contours in an image can be sacrificed to a certain extent as the human eye has an imperfect response to high spatial frequency brightness transitions.

4. Simultaneous Contrast

Let us consider the image shown in figure 1.18. Each of the small circles have the same intensity, but because the surrounding gray level of each of the circles is different, the circles do not appear equally bright. Hence, the intensity that we perceive are not actually the absolute values.

The happiness of every country depends upon the character of its people rather than the form of its government. — Thomas C. Haliburton

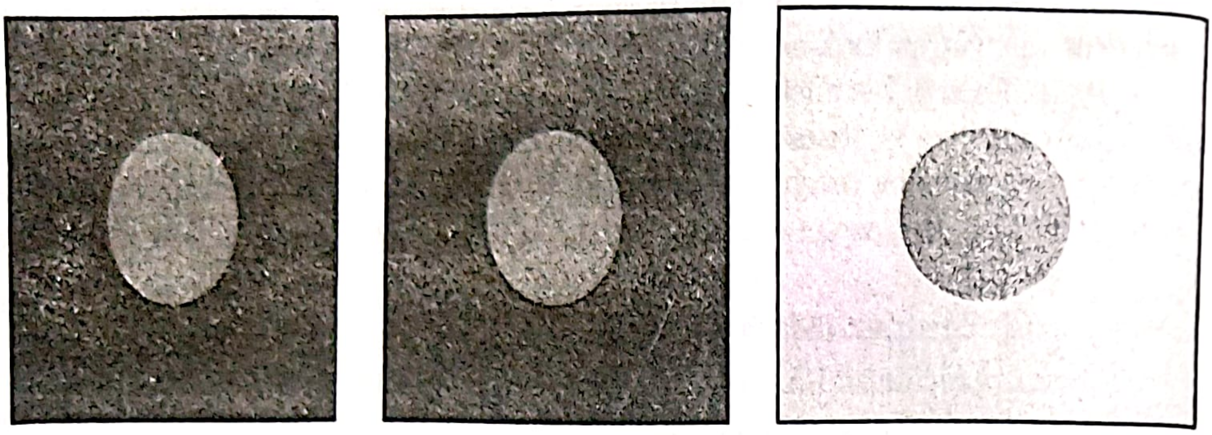


Fig. 1.18

5. Integration

Another important property of our eye is that it integrates the scene as a whole. This is a property that facilitates programming. When we look at a picture, we do not look at each point, but the image as a whole.

Let us take an example, read the following lines as fast as you can.

"According to a recheearch at an Elingsh University, it doesn't matter in what order the letters in a word are the only important thing is that the first and the last letter is at the right place. The rest can be total mess and you can still read it without a problem. This is because we do not read every letter by itself but the word as a whole."

You could read it, inspite of the spelling mistakes only because of the integration property of the eye.

Before, we end one issue needs to be sorted out. A very common question that people ask is what is the difference between image processing, computer graphics and computer vision?

Image processing deals with manipulation of images. A input image is modified into a new image. Computer graphics deals with creation of images. In computer graphics, models (2D or 3D) are created using mathematical functions (Descriptors). Computer vision which is also known as Machine vision deals wtih the analysis of image content. Computer vision is used to automate a process.

Table 1.1

Output / Input	Image	Description (Mathematical function)
Image	I.P.	C.V.
Description (Mathematical function)	C.G.	-

From the Table 1.1

Image processing	→	Input (Image)	-	Output (Image)
Computer graphics	→	Input (Description)	-	Output (Image)
Computer vision	→	Input (Image)	-	Output (Description)

Life is a continuous process of adjustment. — Indira Gandhi

1.10 SCENES

(*i*) Scene

The term 'scene' stands for a land-scape or a view as seen by a spectator. The scene, indoor or outdoor, we see around us is, in general, three-dimensional, *i.e.*, each point in the scene may have different depth from the observer. However there are scenes which can be considered as two-dimensional, *i.e.*, points comprising the scene have equal depth. Some examples of two dimensional scenes are as under :

(*a*) Flat terrain seen from satellite situated at a very high altitude,

(*b*) The shadow of objects created by X-rays,

(*c*) Flat polished surface of objects or thin slices seen through microscope.

(*d*) Documents printed on paper.

1.11 APPLICATIONS

As a matter of fact, digital image processing and analysis techniques are used today in a variety of problems. Many application oriented image analyzers are available and are working satisfactorily in real environment. The following are a few major application areas :

1. Office Automation

This includes optical character recognition, document processing, cursive script recognition, logo and icon recognition, identification of address area on envelops etc.

2. Industrial Automation

Industrial automation area includes automatic inspection system, non-destructive testing, automatic assembling process related to VLSI manufacturing, PCB checking, robotics, oil and natural gas exploration, seismography, process control applications etc.

3. Bio-Medical

Bio-medical area includes various fields such as ECG, EEG, EMG analysis, cytological, histological and stereological applications, automated radiology and pathology, X-ray image analysis, mass screening of medical images such as chromosome slides for detection of various diseases, mammograms, cancer smears, CAT, MRI, PET, SPECT, USG, and other tomographic images, routine screening of plant samples, 3-D reconstruction and analysis etc.

4. Remote Sensing

It includes natural resources survey and management, estimation related to agriculture, hydrology, forestry, mineralogy, urban planning, environment and pollution control, cartography, registration of satellite images with terrain maps, monitoring traffic along roads, docks and airfields etc.

5. Scientific Applications

Scientific applications include high energy physics, bubble chamber and other forms of track analysis etc.

6. Criminology

It includes finger print identification, human face registration and matching, forensic investigation etc.

7. Astronomy and Space Applications

It includes restoration of images suffering from geometric and photometric disto- computing close-up picture of planetary surfaces etc.

8. Meteorology

This particular area includes short term weather forecasting, long term climatic c detection from satellite and other remote sensing data, cloud pattern analysis etc.

9. Information Technology

This includes fascimile image transmission, videotex, video-conferencing and videop etc.

10. Entertainment and Consumer Electronics

This includes HDTV, multimedia and video-editing etc.

11. Printing and Graphic Arts

This includes colour fidelity in desktop publishing, art conversation and dissemin etc.

12. Military Applications

This includes missile guidance and detection, target identification, navigation of pilo vehicle, reconnaissance and range finding etc.

Important Point : *H e it may be noted that in addition to the above mentioned areas, ano important application o mage processing techniques is improvement of quality or appearan a given image.*

1.12 COMPONENTS OF AN IMAGE PROCESSING SYSTEM

Digital image processing is basically modification of images on a computer. The components of an image processing system are shown below.

1. Image Acquisition
2. Image Storage
3. Image Processing
4. Display
5. Transmission (if required)

We shall discuss each one in detail.

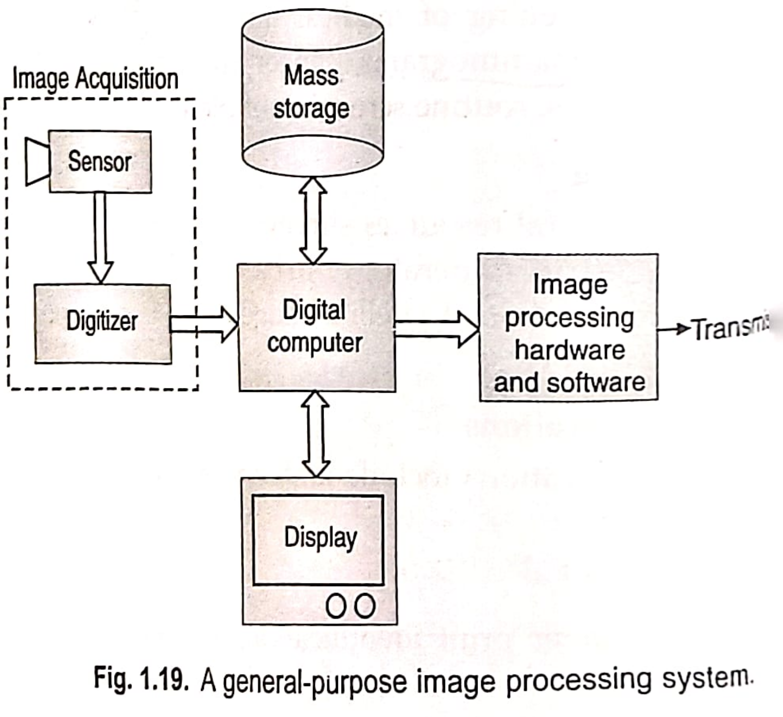


Fig. 1.19. A general-purpose image processing system.

1. Image Acquisition

Image acquisition is the first step in any image processing system. The general aim of image acquisition is to transform an optical image (real world data) into an array of numerical data which could be later manipulated on a computer.

Image acquisition is achieved by suitable cameras. We use different cameras for different applications. If we need an X-ray image, we use a camera (film) that is sensitive to X-rays. If we want an infra-red image, we use cameras which are sensitive to infra-red radiations. For normal images (family pictures etc.) we use cameras which are sensitive to the visual spectrum. In this book we shall discuss cameras (sensors) which are sensitive only to the visual range.

Quantum detectors

Quantum detection is the most important mechanism of image sensing and acquisition. It relies upon the energy of absorbed photons being used to promote electrons from their stable state to a higher state above an energy threshold. Whenever this occurs, the properties of that material get altered in some measurable way. Planck/Einstein came up with a relationshhip between the wavelength of the incident photon and the energy that it carries.

$$e = \frac{hc}{\lambda} \quad \text{...(1.2)}$$

where e = Energy carried by a photon

h = Planck's constant, 6.626×10^{-34} Js

c = Speed of light, 3×10^{8} m/sec

λ = Wavelength of the incident radiation

On collision, the photon transfers all or none of this quantum of energy to the electron. The equation (1.2) is very important as it tells us that the maximum wavelength to which the quantum detector will respond is determined by the energy threshold and hence by the material selection.

Of the several modes of operation of quantum detectors, the most important ones are

(*a*) Photoconductive (*b*) Photovoltatic

(*a*) Photoconductive

The resistance of photoconductive materials drop in the presence of light due to the generation of free charge carriers. An external bias is applied across the material to measure this change. The principle of photoconductivity is used in Vidicon imaging tubes.

Vidicon imaging tubes

Vidicon is a vacuum tube used for image acquisition. Figure 1.20 is the schematic diagram of the vidicon tube image sensor. The light image is focused on a transparent signal plate coated on the inside with a photoconductive target material. The front face of the signal plate is coated with SnO_2 (tin oxide) which forms the conducting layer. This plate is biased to a positive potential of about 50 V. The target coating is maintained at approximately 0 V by a mesh grid which is placed behind it.

Change is not made without inconvenience even from worse to better. —Richard Hooker

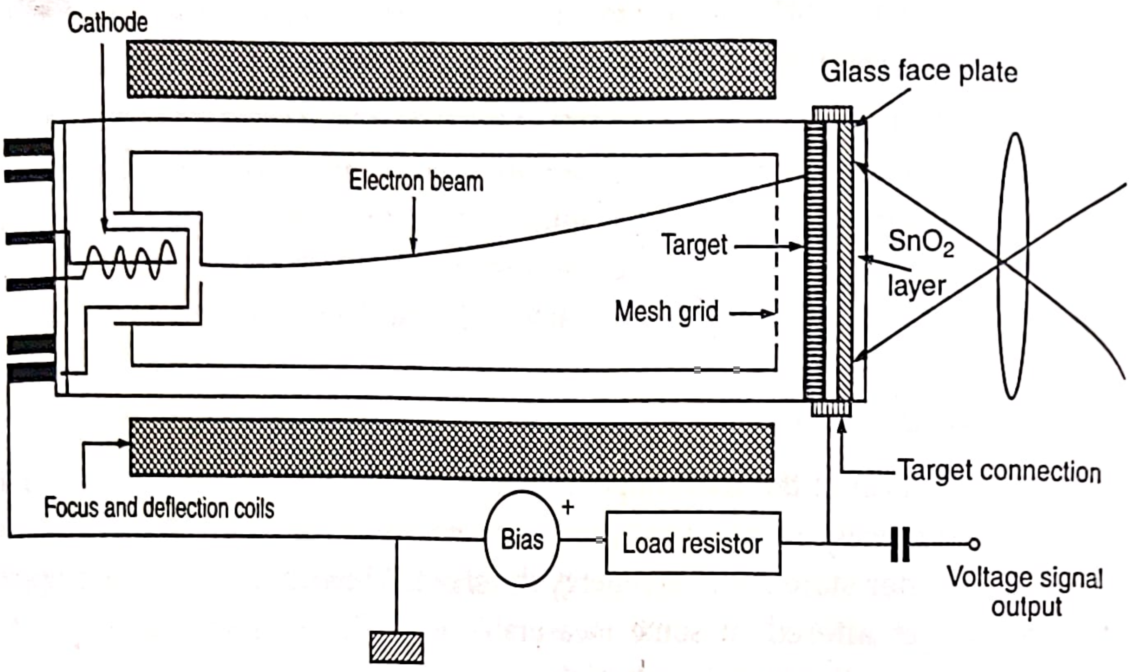


Fig. 1.20

Due to this the signal plate and target behave as a continuous array of capacitors contai a photoconductive dielectric. When there is no light incident on the target, its resistan very high due to which the charge across the capacitor is maintained. However, when l strikes the target, the dielectric material becomes leaky and the target side voltage rises. target is now scanned by a low velocity electron beam. When this beam strikes the dischar capacitor, current flow to restore the target side to its original voltage of 0 V. This cu also flows in the external bias circuit, which produces a voltage drop in the load resist

In order to produce the output necessary for broadcast video applications, the ele beam is scanned across the surface of the target by electromagnetic deflection coils. (Defle coils were encountered when you studied CRO, (cathode ray oscilloscopes), in your l semesters). The original vidicons use antimony-trisulphide, which is a photocondu material, as their target coatings. Other forms of vidicon are made using more complex t materials. The silicon target vidicon achieves improved sensitivity and a spectral resp similar to that of the human eye.

The biggest drawback of the vidicon tube is that it uses the concept of deflection to position the electron beam. These deflection coils make the vidicon bulky and are respor for major power drain. Since the coils are magnetic, the vidicon also becomes sensiti external fields.

(b) Photovoltaic

Photovoltaic devices consist of semiconductor junctions. They are solid state a composed of discrete silicon imaging elements known as *Photosites*. Photovoltaic devices a voltage output signal that is proportional to the intensity of the incident light. No ext bias is required as was in the case of photoconductive devices.

The technology used in solid-state imaging sensors is based principally on charge co devices, commonly known as CCDs. Hence, the imaging sensors are called CCD sen

The solid state array (CCD) can be arranged in two different configurations.

(b.1) Line array CCD (b.2) Area array CCD.

(b.1) Line Arrays

The line array represents the simplest form of CCD imager and has been employed since the early 1970s. Line arrays consist of a one-dimensional array of photosites.

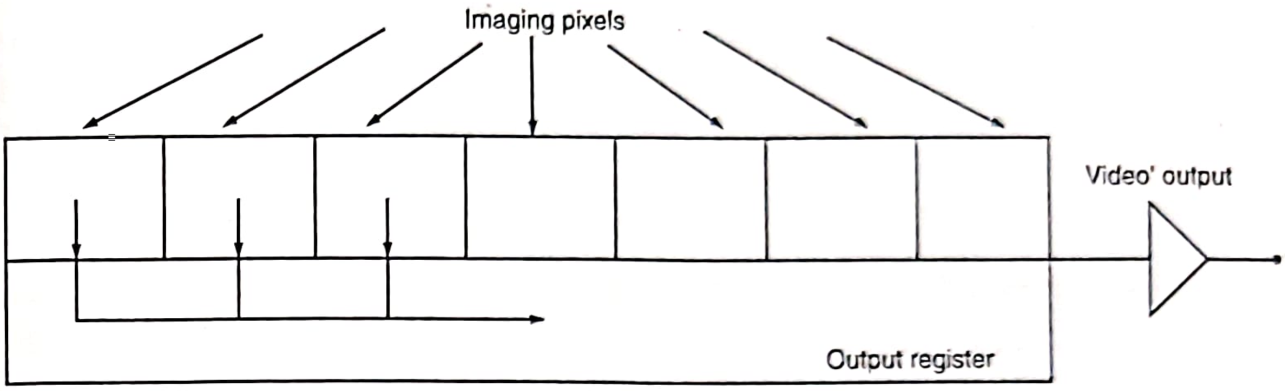


Fig. 1.21

A single line of CCD pixels are clocked out into the parallel output register as shown in figure 1.21. The amplifier outputs a voltage signal proportional to the contents of the row of photosites. One thing to note is that line array CCD scans only one line (hence is one dimensional). In order to produce a two-dimensional image, the line array CCD imager has to be used as a scanning device by moving this array over the object by some mechanical activity.

This technique is used in flat bed scanners (the scanners that you come across in your laboratory or in a cyber cafe). A line array CCD can have anything from a few elements to upto 6000 or more.

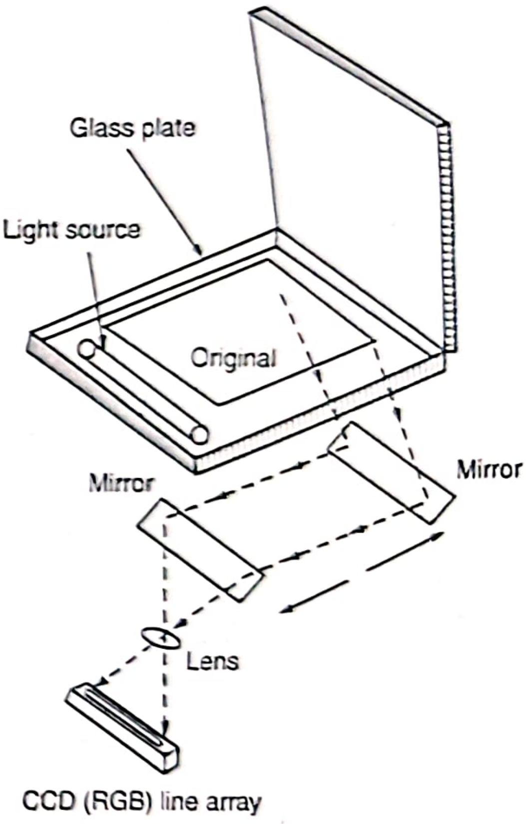


Fig. 1.22

(b.2) Area Arrays

The problem with line arrays is that it scans only one line. To get a two-dimensional image, we need to mechanically move the array over the entire image.

Area arrays or matrix arrays consist of a two-dimensional array of photosites. They make it possible to investigate static real world scenes without any mechanical scanning. Thus, much more information can be deduced from a single real time glance than would be possible with line arrays. Area arrays can be seen in all the digital cameras that we use for video imaging. The area arrays are move versatile than the line arrays, but there is a price to be paid for this. Area arrays are higher on cost and complexity.

Area sensors come in different ranges, *i.e.*, 256 × 256, 490 × 380, 640 × 480, 780 × 575. CCD arrays are typically packaged as TV cameras. A significant advantage of solid state array sensors is that they can be shuttered at very high speeds (1/10,000 series). This makes them ideal for applications in which freezing motion is required.

To accomplish great things, we must not only act, but also dream: not only plan, but also believe.
— **Anatole France**

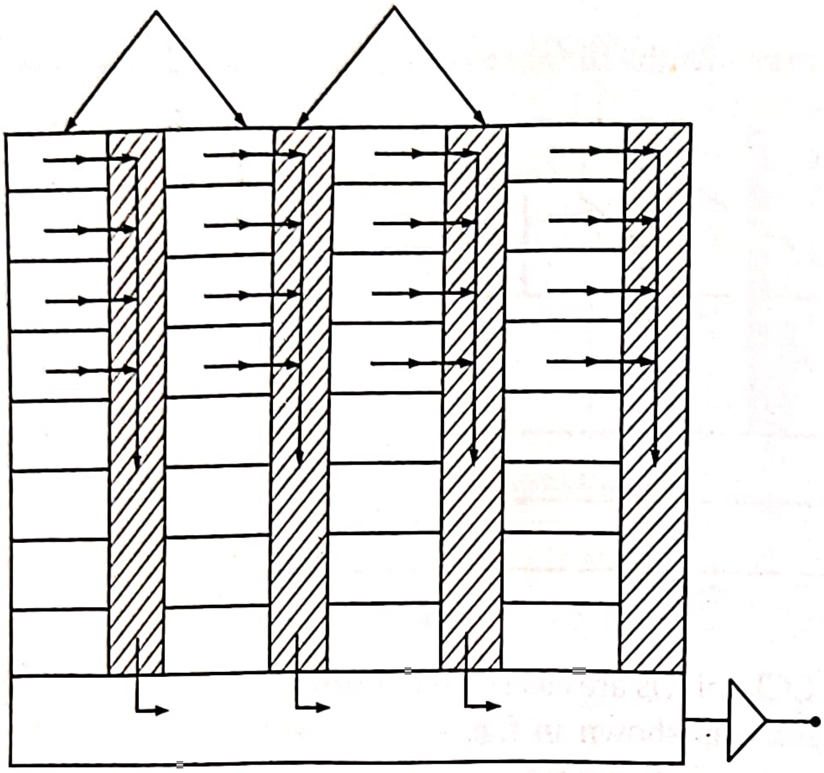


Fig. 1.23

2. Image Storage

All video signal are essentially in analog form, *i.e.*, electrical signals convey luminance and colour with continuously variable voltage. The cameras are interfaced to a computer where the processing algorithms are written. This is done by a frame grabber card. Usually a frame gabber card is a printed circuit board (PCB) fitted to the host computer with its analog entrance port matching the impedance of the incoming video signal. The A/D converter translates the video signals into digital values and a digital image is constructed. Frame grabber cards usually have a A/D card with resolution of 8-12-bits (256 to 4096 gray levels). Hence, a frame grabber card is an interface between the camera and the computer.

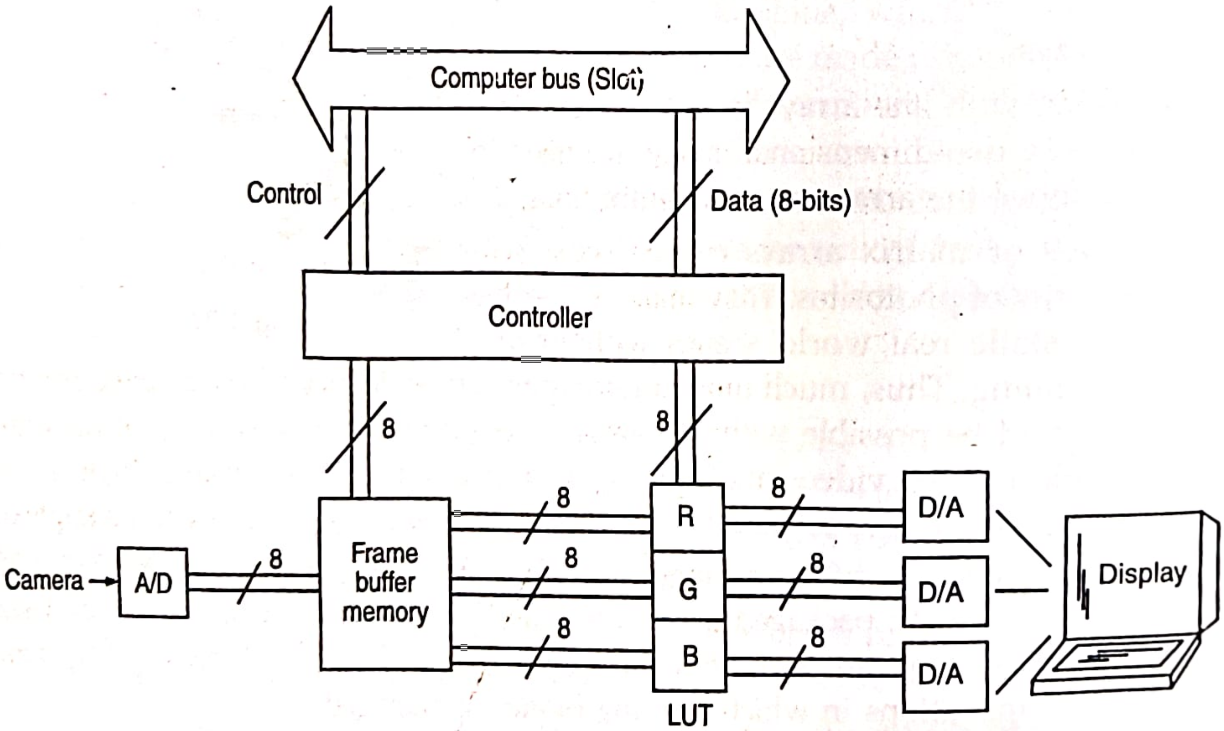


Fig. 1.24 Simplified diagram of a frame grabber card

Frame grabber card has a block of memory, separate from the computers own memory, large enough to hold any image. This is kown as the *frame buffer memory*. Image data usually in the form of bytes (8 bits), is written into the frame grabber memory under the computer control, usually by DMA transfers. The contents of the memory are continuously read out at video rate (30 frames/sec.), passed through the D/A converter and displayed on the monitor.

The output has a colour map or a colour Look Up Table (LUT) to permit pseudo colouring. The table consists of 8-bit values for each of the red, green and blue guns of the monitor. The commercially available frame grabber cards have additional features such as ability to zoom regions of the image and pan the images. The frame buffer memory can be upto 5 MB. Images being 2-dimensional functions, occupy a lot of space and hence the storage space on the host computer has to be large. Let us try to find out as to how much space is actually taken by images.

Each image is stored as a matrix, where every value of the matrix represents the grey level at that point. Suppose the image (matrix) is of size $A \times B$ and suppose we recquire C bits to represent each element of the matrix. Memory space required to store this image is approximately equal to $A \times B \times C$ bits.

Suppose we have D such images then total number of bits $= A \times B \times C \times D$ ...(1.3)

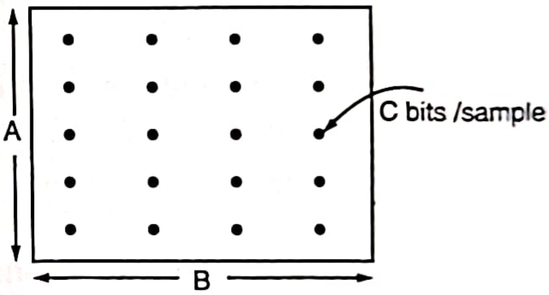


Fig. 1.25

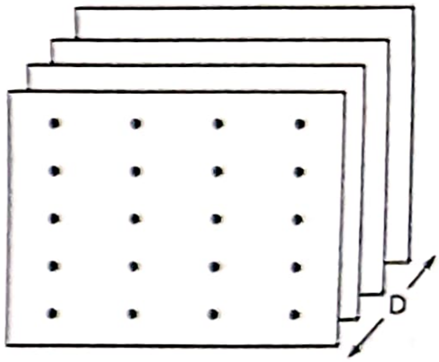


Fig. 1.26

Thus the formula $\approx ABCD$ gives us a fairly good idea of the amount of space required.

	A	B	C	D	Number of bits
Low quality video phone	64	64	8	6	$\approx 0.2 \times 10^6$ bits
Digital broadcast TV	720	576	25	8	$\approx 83 \times 10^6$ bits
HDTV	1920	1150	50	8	$\approx 883 \times 10^6$ bits

With the advent of the PCI bus, the host computers memory could now be used as the frame buffer memory. This is because the PCI bus faciliates fast communication. Hence, the image could now directly be stored on the computer RAM. Due to this, the frame buffer memory has become more or less obselete. Only the very high end frame grabber card still have a small frame grabber memory embedded on them.

Images being two-dimensional functions, occupy a lot of space and hence it is advisable to have a computer with a sizeable hard disk and also a good RAM. Proceesed images could be stored on magnetic floppies or CDs. Archival data are stored on magnetic tapes.

3. Image Processing

Systems ranging from microcomputers to general purpose large computers are used in image processing. Dedicated image processing systems connected to host computers are very popular nowadays. Processing of digital images involve procedures that are usually expres in algorithmic form due to which most image processing functions are implemented software. The only reason for specialized image processing hardware is the need for sp in some applications or to overcome some fundamental computer limitations. The tre though is to merge general purpose small computers with image processing hardware. stated in the earlier section, frame grabber cards play the important role of merging image processing hardware with the host computer. One thing that we should remember image processing is characterized by specific solutions. Hence, there is no one way to proc images. A technique that works well in one area can be totally useless in some oth applications. The image processing software that is used in this book is MATLAB.

4. Display

A display device produces and shows a visual form of numerical values stored in computer as an image array. Principle display devices are printers, TV monitors and CRT Any erasable raster graphics display can be used as a display unit with an image processir system. However, monochrome and colour TV monitors are the principal display devic used in modern image processing systems.

These raster devices convert image data into a video frame. One major problem is, must refresh the screen at a rate of about 30 frames per second to avoid flicker. since som computers are unable to transfer data at such high speeds, it is a good idea to buy a hig end frame grabber card which has frame buffer memory on it.

If you want to build a image processing the system a home, you should have a Vide Graphics Card (VGA) attached to a computer and a monitor that supports that VGA car One could then use a simple camera that comes along with the system.

5. Transmission

There are a lot of applications where we need to transmit images. The stages in th transmission of an image over a channel or network are shown in figure 1.27.

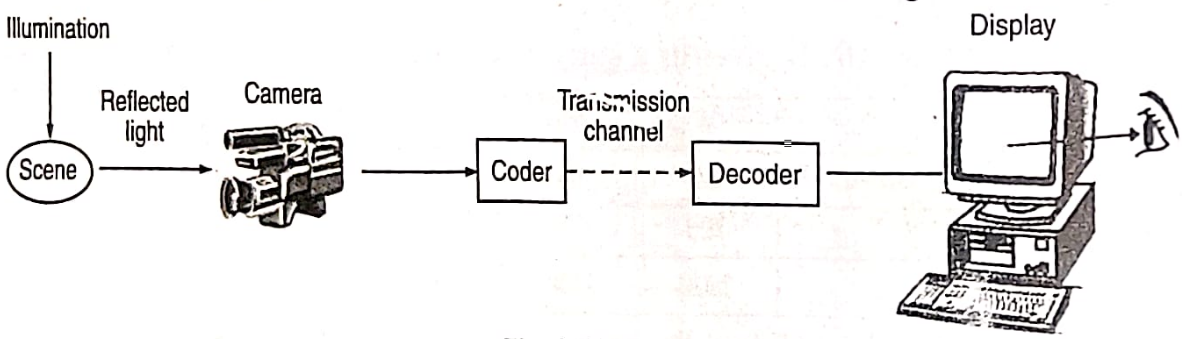


Fig. 1.27

The image sequence from the camera is coded into as concise a representation as possib for transmission over the channel.

Most transmission in broadcast television are still in analog form and analog codir methods are used to make it as efficient as possible. NTSE. PAL and SECAM are the 3 maj coding systems used in various parts of the world (USA uses NTSE, while India uses PAL Digital image coding is a high activity area. In image processing; it is concerned with efficie transmission of images over digital communication channels. A variety of indigenous ide have been developed in recent years. Coding is influenced by the type of the channel us to carry the image signals. Several different types of transmission channels are encounter in practice including cables, terrestrial radio, satellites, and optical fibres.

Gamma

In the image transmission chain, there are many elements which exhibit a non-linear behaviour. If x is the input and y is the output, then

$$y = cx^{\gamma}$$

$$c = \text{Constant}$$

$$\gamma = \text{Gamma of the device}$$

The camera, the display device and eye all have non-unity gammas (all are non-linear). Hence, to make sure that the perceived gray scale in the displayed image is correct, it is necessary to insert an additional compensating, non-linear device called the gamma corrector.

We have discussed a lot of things so far and it is advisable at this stage to have a branch diagram of these topics.

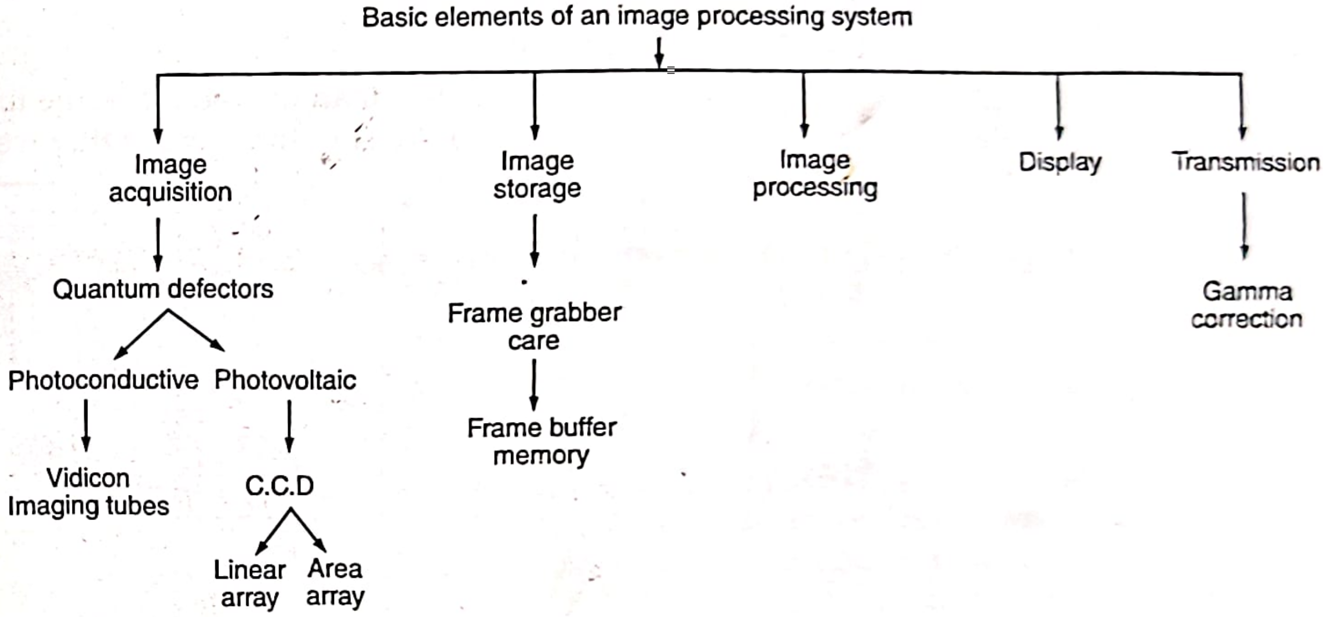


Fig. 1.28

1.13. IMAGE TYPES

It was stated earlier that images are 2-dimensional functions, refer figure 1.29.

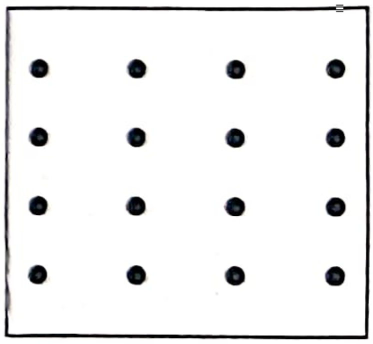


Fig. 1.29

Images can be classified as follows:

1. Monochrome images (Binary images)
2. Grey scale images
3. Colour (24-bit) images
4. Half-toned images

1. Monochrome image

In this, each pixel is stored as a single bit (0 or 1). Here, 0 represents black while 1 represents white. It is a black and white image in the strictest sense. These images are also called bit mapped images. In such images, we have only black and white pixels and no other shades of gray.

2. Gray Scale Image

Here, each pixel is usually stored as a byte (8-bits). Due to this, each pixel can have values ranging from 0 (black) to 255 (white). Gray scale images, as the name suggests have black, white and various shades of gray presents in the image.

3. Colour Image (24-bit)

Colour images are based on the fact that a variety of colours can be generated by r the three primary colours viz. Red, Green, and Blue, in proper proportions. In colour i each pixel is composed of RGB values and each of these colours require 8-bits (one by its representation. Hence, each pixel is represented by 24-bits [R(8-bits), G(8-bits), B(8

A 24-bit colour image supports 16, 777, 216 different combination of colours.

Colour images can be easily converted to gray scale images using the equation

$$X = 0.30\,R + 0.59\,G + 0.11\,B$$

An easier formula that could achieve similar results is

$$X = \frac{R+G+B}{3}$$

4. Half Toning

It is obvious that a gray scale image definitely looks better than the monochrome as it utilizes more gray levels. But there is problem in hand. Most of the printers that w (inkjet, lasers, dot matrix) are all bi-level devices, *i.e.*, they have only a black cartridge and can only produce two levels (black on a white back-ground). In fact, most of the printing jobs are done using bi-level devices.

You have all read newspapers at some point of time (hopefully). The images do look like gray level images. But if you look closely, all the images generated are basically using black colour.

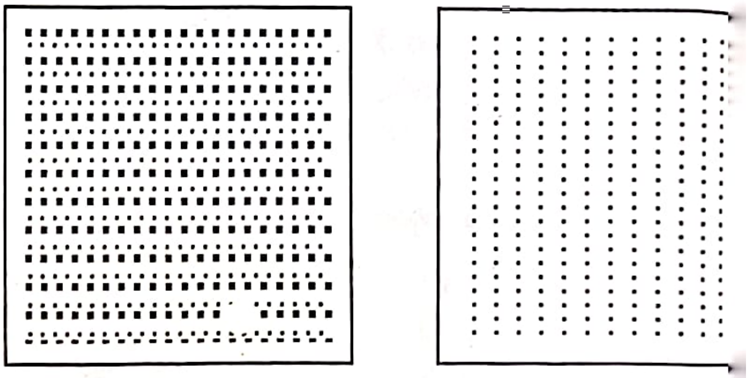


Fig. 1.30.

Even the images that you see in most of the books (including this one) are gene using black colour on a white background. Inspite of this we do get an illusion of seeing levels. The technique to achieve an illusion of gray levels from only black and white is called half-toning.

The human eye integrates the scene that it sees. Consider a simple example. Con two squares of say 0.03 × 0.03 sq. inch. One of these squares contain a lot of black dots the other square contains fewer black dots. When we look at these squares from a dis the two squares give us a perception of 2 different gray levels. This integration prope the eye is the basis for half toning. In this, we take a matrix of a fixed size and depe on the gray level required, we fill the matrix with black pixels.

Let us take an example.

Consider a 3 × 3 matrix. This matrix can generate an illusion of 10 different gray when viewed from a distance.

Here, the first block represents white, the last block represents black and all the blocks represent intermediate values of gray. So, in the case, while printing, if we enco gray level 0, we plot 9 pixels which are all white. If we encounter gray level 1, we l pixels of which only one pixel is black and so on.

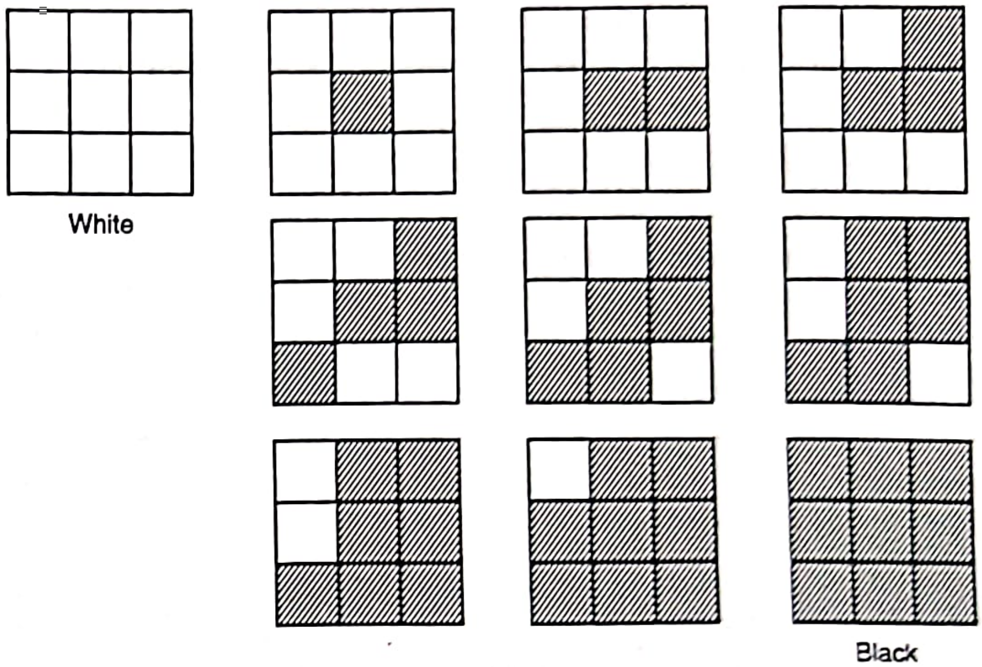


Fig. 1.31.

As is evident a 3 × 3 matrix will generate 10 different gray levels.

The dots that are placed in the 3 × 3 matrix example can be in any order. But we need to follow two rules.

1. Dots should be arranged in such a manner so that they don't form straight lines. Lines are very obvious to the viewer and hence should be avoided.

Example, suppose in an image we have 4 consecutive gray levels of value 3, and if we use a code a shown in figure 1.32 the half toned image would look like figure 1.33.

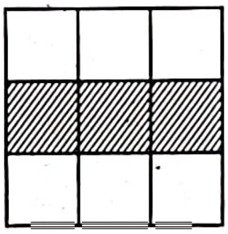


Fig. 1.32

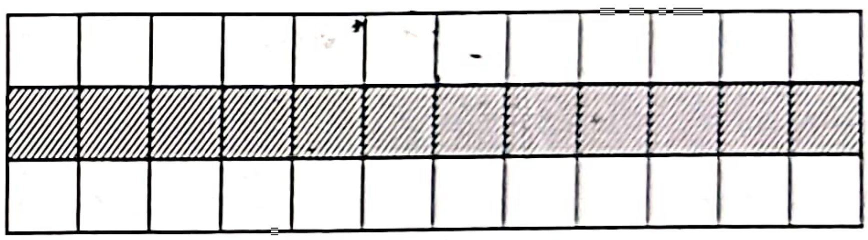


Fig. 1.33

It can be seen that it does not look like a gray level. It looks like a straight black line. Hence, lines should be avoided while defining the matrices.

2. If a pixel in a particular matrix is black for gray level i, it should be black, for all further levels $j > i$. This reduce false contouring.

Half toning gives excellent results and we do perceive a gray level image just by using black pixels on a white background.

The logic to implement a half-toned image from a gray level image is given below.

1. Define the size of the half-toned matrices based on the number of gray levels the original image has.
2. Generate the matrices starting from all white pixels to all black pixels.
3. Read the original image. For every gray level value read, plot the corresponding matrix.

Remember, the physical size of the half-toned image will always be bigger than the original images as for every single gray level value, we output an entire matrix.

1. Image Sensor

An image sensor intercepts the radiant energy propagating from the scene and transform it to produce an intensity image.

Following two different technologies are most common :

(*i*) Photochemical

(*ii*) Photoelectronic

Photochemical methods have the advantage of combining image formation and recording on a single entity called 'photographic film'. Photoelectronic methods, on the other hand separate the recording process from image formation and detection. However, in the second method, recorded image can be converted more easily to a form which is suitable to computer processing.

Devices used as Image Sensors

The devices used as image sensors range from still camera to multispectral scanner on board in satellites. Television cameras are widely used and are easy to operate. There are as many as five different systems used in television imaging as under :

(*i*) Image orthicon tube

(*ii*) Vidicon tube

(*iii*) Iconoscope tube

(*iv*) Image dissector tube

(*v*) Charge transfer devices

Charge-Coupled Devices

Most popular amongst the charge transfer devices is charge-coupled devices which are commercially called as CCD camera. They behave similar to an array of metal-oxide semiconductors field-effect transistors (MOSFET) in a sense that both have a source, a drain and a depletion region. When an image is formed on a CCD array, the photons incident on the semiconductor accumulate charges in the depletion region. Hence, during image scanning the CCD image plane can be considered as a monolithic array of charged capacitors. Now these charges are transferred to output by applying a series of clock pulses between the source and the drain. This transfer can be made either one line at a time or a complete frame at a time. In the second case, a frame buffer would be required to avoid data loss.

Multispectral Scanners

Multispectral scanners also use the same technology except some filters corresponding to different wavelength bands are added and a full size image is recorded for each spectral band. Apart from there optical image sensors image can also be captured in devices like, X-Ray, scanner, radar, ultrasonic ranger, magnetic resonance imaging (MRI) system and so on.

2. Digitizer

A digitizer produces digital image composed of discrete intensity values at discrete position. In other words, a digitizer is a device for converting the output of the physical sensing device into digital form. For instance, in a digital video camera, the sensors produce an electrical output proportional to light intensity. The digitizer converts these outputs to digital data. Most of the image sensors (photoelectronic devices) mentioned above either have suitable built in digitizers or provide signal that can be digitized straightway by an A/D converter. But, some sensors (*e.g.*, still cameras) are purely analogue devices and their responses must be digitized before being fed to a computer.

3. Digital Computer

In an image processing system, the computer is a general purpose computer. In fact, systems ranging from microcomputers to general purpose large computers are used in image processing. In dedicated applications sometimes, specially designed computers are used to achieve a required level of performance. In fact, dedicated image processing systems connected to host computers are very popular nowadays. Special co-processor card (with hardware implemented image processing operators) and parallel processors are also being included in many small systems to gain speed. Depending on this requirement, various image processing architectures are designed and are available in the market. For example, machines for scientific research are different from commercial ones, as to solve a particular problem may need a special architectures. On the other hand in industrial applications, a machine needs to do a particular job in real time without the concern for its general use.

4. Image Processing Hardware and Software

Specialized image processing hardware, generally, consists of the digitizer plus hardware which performs other primitive operations such as an arithmetic logic unit (ALU), which performs arithmetic and logic operations in parallel on entire images. Also, software for image processing consists of specialized modules which perform specific tasks. In fact, a well-designed package also includes the capability for the user to write code that, as a minimum, utilizes the specialized modules. More sophisticated software packages allow the integration of those modules and general purpose software commands from at least one computer language.

5. Mass Storage

As a matter of fact, in the mass storage capability is of utmost importance is an image processing system. For instance an image of size 1024 × 1024 pixels in which the intensity of each pixel is an 8-bit quantity, requires one megabyte of storage space if the image is not compressed. However, practically dealing with millions of images requires an adequate storage in an image processing system which is a big challenging task.

In various image processing applications, the digital storage may be subdivided into following three major categories :

(*i*) Short-term storage for use during image processing

(*ii*) On line storage for comparatively fast recall

(*iii*) Archival storage*

Measurement of Storage

Basically, storage is measured in bytes (eight bits), K bytes (one thousand bytes), M bytes (one million bytes), G bytes (meaning giga, or one billion bytes) and T bytes (meaning tera, or one trillion bytes).

---

* Archival storage is characterized by infrequent access.

6. Display Unit

A display device produces and show a visual form of numerical values store computer as image array. Principal display devices are printer, T.V. monitor and CRT erasable raster graphics display device can be used as display unit with an image proc system. However, T.V monitors (B/W or colour) are most common display devices These raster devices convert image data into a video frame. In some cases, It is essen have stereo display and these are implemented in the form of headgear containing two displays embedded in goggles worn by the user.

7. Hard Copier

Hard copier are also non-erasable display devices. They leave permanent impress the output image on the media, and hence the name. These devices basically are pr ranging from line printers to thermal and laser printers, and the medium ranges from ord to specialized papers. Most of the printers are bi-levels and specialized techniques are to generate different intensity or shades.

1.14 THE TERMINOLOGY OF DIGITAL IMAGE PROCESSING

Images occur in various forms, some visible and other not, some abstract and others some suitable for computer analysis and other not, and it is important to have an aware of the different types of images. The lack of this awareness can lead to considerable conf among people communicating ideas about images when they have differing concep what an image is. Since images form an overwhelming part of our experiences from b there is a tendency to take them for granted. This section is intended to establish a founda upon which images of all forms can be discussed without confusion. Our definitions do establish a standard for the field but are introduced to make this book self-consistent.

Before we can define digital image processing, we must agree upon a definition fo word *image*. Whi'e most people have a notation of what an image is, a precise definiti somewhat elusive. Among several definitions of the word in Webster's Dictionary are following: "An image is a representation, likeness, or limitation of an object or thing, a r or graphic description, something introduced to represent something else." Thus, in a ge sense, an image is a representation of something else. A photograph of Abraham Lincol instance, is a representation of an American president as he once appeared before a ca An image contains descriptive-information about the object it represents. A photog displays this information in a manner that allows the human eye and brain to visualiz subject itself. Notice that under this relatively broad definition of image fall "representations" not perceivable by eye.

Images can be classified into several types based upon their form or method of genera In this regard, it is instructive to employ a set theory approach. If we consider the set o objects (figure 1.34), the images form H subset. There is a correspondence between image in the subset and the object that it is used to represent. Within the set of images, t is a very important subset containing all the visible images, those that can be seen perceived by eye. Within this set exist several subsets representing the various metho generation. These include photographs, drawings, and paintings. Another subset con the optical images, that is, those formed with lenses, gratings, and holograms.

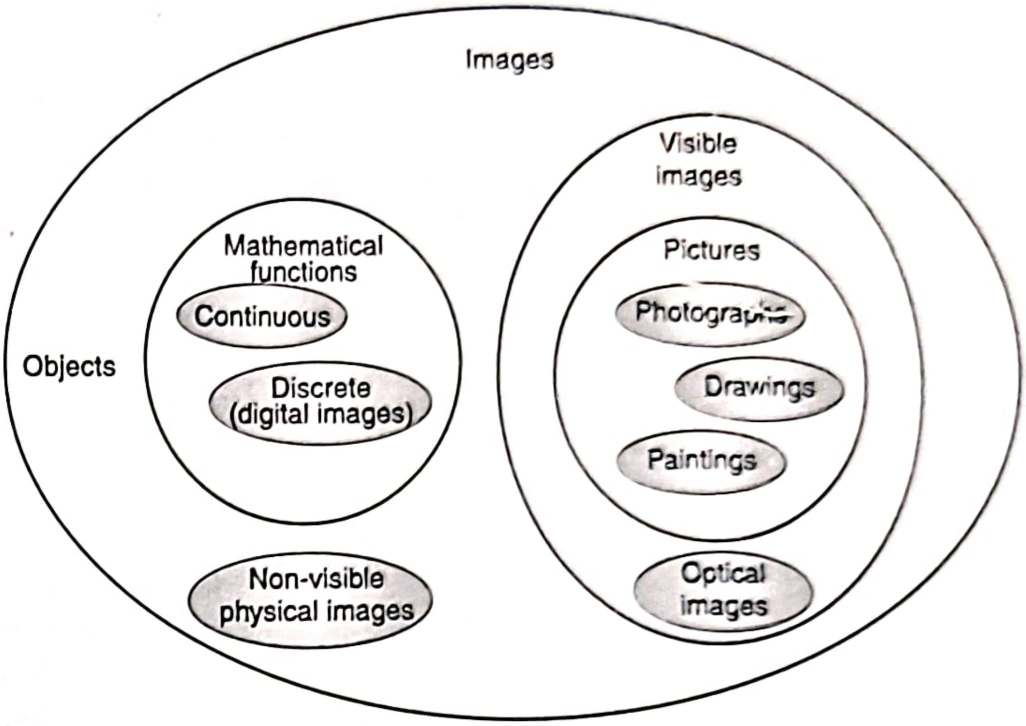


Fig. 1.34 Types of images

The physical images are distributions of measurable physical properties. For example, optical images are spatial distributions of light intensity. These can be seen by the human eye and are visible images as well. Examples of non-visible physical-images are temperature, pressure, elevation and population density maps. A subset of the physical images is multispectral. These are images having more than one local property defined at each point. An example is the tricipital image as it is reproduced in color photography and color television. Whereas the black and white image—has one value of brightness at each point, the color image has three values of brightness, one each in red, green, and blue. The three values represent intensity in different optical spectra which the eye perceives as different colors.

Another subset of images contains the abstract images of mathematics, the continuous functions and the discrete functions or digital images. Only the digital images can be processed by computer.

A *picture* is a restricted type of image. Webster 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." For our purposes we take the word picture to mean a distribution of matter that is visible when properly illuminated. In the vernacular of image processing, however, the word *picture* is sometimes used as equivalent to the word *image*.

According to Webster, the word *digital* relates to "calculation by numerical methods or by discrete units." We can now define a *digital image* to be a numerical-representation of an object (which may itself be an image).

Processing is the act of subjecting something to a process. *A process* is a series of actions or operations leading to a desired result. Thus, a series of actions or operations are performed upon an object to alter its form ... example is a car wash ... automobiles are processed to change them from dirty to clean.

Now we can define *digital image processing* as subjecting numerical representa objects to a series of operations in order to obtain a desired result. In the case of pictu processing changes their form to make them more desirable or attractive, or to acco some other previously defined goal.

For purposes of discussion, it is convenient to restrict the general definition of a image. Unless otherwise stated, we shall use the restricted definition of a digital which is *a sampled, quantized function of two dimensions which has been generated by means, sampled in an equally spaced rectangular grid pattern, and quantized in equal inte gray level.* Thus a digital image is now a two-dimensional rectangular array of qu sample values. In discussing images not so restricted, we shall make use of the fol four generalizations:

1. Non-optical digital images generated from other than optical images;
2. High-dimensional digital images defined on three or more dimensions (this in multispectral images in which there is more than one gray level value at each
3. Non-standard sampling, in which the domain of the image is sampled by a s other than the equally > spaced rectangular grid;
4. Nonstandard quantization, where the quantizing levels i arc not equally spa

An image is usually a condensation or summary of the information in the ob represents. Ordinarily, an image contains less information than the original object. The an image is an incomplete, yet in some sense adequate, representation of the object

Digital image processing starts with one image and produces a modified version image. It is therefore a process that takes an image into an image. *Digital intake ana* taken to mean a process that takes a digital image into something other than a digital such as a set of measurement data or a decision. For example, if a digital image con number of objects, a program might analyze the image and extract measurements objects. The term *digital image processing,* however, is loosely used to cover both proc aim analysis.

Digitizing is the process of converting an image from its original form into digita The term *conversion* is used in a non-destructive sense because the original image destroyed but is used to guide the generation of a digital image. The reverse opera *display,* that is, the generation of a visible image from a digital image. Commonly equivalents are the words "playback," "reconstruction," and "recording." The process is non-destructive since displaying a digital image does not destroy the data. There ar *volatile* and *permanent* displays. The latter produce *hard-copy* output.

We take *scanning* to mean the selective addressing of specific locations within the d of an image. Each of the small sub regions addressed in the scanning process is ca *picture element,* which is abbreviated by the word *pixel.* When digitizing photographic in *scanning* is the process of sequentially addressing small spots on the film. The term sca is loosely taken as an equivalent to the term "digitizing." The rectangular grid sca pattern is known as a *raster.*

Sampling is defined as measuring the gray level of an image at a pixel location. digitizing images, it is frequently desirable to employ devices that convert one pl quantity to another. An example is the photomultiplier tube, which converts light energy into electrical energy. Devices of this type are called *transducers* and the process itself, *transduction.*

Quantization is the representation of a measured value by an integer. Since digital computers process numbers, it is necessary to reduce the continuous measurement values to discrete units and represent them by numbers.

The steps of scanning, sampling, transduction (if necessary), and quantizing are sufficient to generate a numerical representation of an image and therefore constitute the steps in digitization. We may reverse the process to display a digital image. With the ability to convert images into digital form and back into visible form, we are able to define and execute digital processing steps and observe the results.

When a process generates an output image from an input image, there must exist a correspondence between points in the two images. Each pixel in the output image must correspond to one pixel in the input image. Thus, when the operation is applied to one point or a neighbourhood centered upon one point in the input image, the resulting gray level value is stored in the *corresponding point* in the output image.

The operations that can be performed on digital images fall into several classes. An operation is a *global operation* if it is applied equally throughout the entire digital image. A *point operation* is one in which the output pixel value depends only on the value of the corresponding input pixel. Point operations are sometimes called *contrast manipulation* or *stretching.* A *local operation* is one in which the output pixel value depends on the pixel values in a neighbourhood of the corresponding input point.

The notion of *contrast* refers to the amplitude of gray level variations within an image. *Noise* is broadly denned as an additive (or multiplicative) contamination of an image. The *sampling density* of a digital image is the number of sample points per unit measure in the domain. *Gray scale resolution* is the number of gray levels per unit measure of image amplitude. *Magnification* refers to the size relationship between an image and the object or image it represents. It is defined only for linear geometrical relations where one can define the same metric in the domains of both images and where the size relationship is uniform over the entire image. Magnification is a meaningful relationship between input and output digital images in a processing step. However, the magnification from a physical image to a digital image is not a meaningful concept, and sampling density should be used.

1.15 SOME PHILOSOPHICAL CONSIDERATIONS

When one approaches a topic such as digital image processing, he cannot do so without bringing with him a set of notions and attitudes—in other words, a philosophy. In this section, we discuss three topics that are constructive in this regard.

The Continuous Versus Discrete Philosophy

There are two approaches one may take when considering image processing operations. We can think of the digital image as a set of discrete sample points (which it actually is), each having individual importance, or we may think in terms of the continuous function which the digital image represents. The theory underlying many of the processing operations is based on the analysis of continuous functions. Other operations are most easily thought of as logical operations performed on individual points. Thus it is important to be able to think of digital images in either way, but without confusion.

of tools consisting of formal theory, proved heuristics, and untested ideas. The solution often results from a combination of techniques. Whether or not the immediate problem is solved, the list of available techniques usually grows. Frequently, a heuristic is solidified in theory after its successful application, and new theoretical methods often suggest processing and analysis approaches. Both success and failure tend to increase the list of techniques, although failures are less frequently reported.

Processing Efficiency

Digital image processing can only be done with the use of a significant physical resource, namely the hardware system itself. For this reason, one usually must optimize the productivity of his machine time by avoiding, in so far as possible, unprofitable runs. This can best be done by carefully thinking through each processing step before execution. The user should be able to predict, in general terms, the results of each processing step before it is executed. In this way the user increases the probability of success and avoids unprofitable computer run.

The "prediction beforehand" approach contrasts with haphazard experimentation. There are so many possible image processing operations that the chances of selecting a successful one at random are quite remote. Certainly some intelligent experimentation may be required before the final result is obtained. This book is concerned with developing insight into image processing so that the reader may make intelligent and efficient use of his equipment. When one finds himself in a situation where system time is less expensive than his own personal time, then "artistic" experimentation may be justified. This, however, requires little instruction and is not treated here.

The "prediction beforehand" approach, of course, does not preclude surprises. It is quite likely that some factor unaccounted for in the planning will emerge to produce quite an unexpected image. Each time this happens, it offers the user an excellent chance to increase his knowledge of image processing, if he takes time to track it down.

Functional Requirements for Digital Image Processing

The following is a list of requirements, a general-purpose image processing system should meet to be effective in its application:

1. The hardware must be adequate for the problems attempted. Inadequate sampling in the spatial domain and inadequate gray scale quantization may not make success unattainable, but can render failure inconclusive. Processing algorithms usually assume that the image function is continuous. If the sampling and quantization used do not justify this assumption, performance may suffer considerably. Thus, the fear of large data quantities can be a threat to a successful solution. When system noise levels degrade the image, success is again in jeopardy. While image analysis requires a high-quality image digitizer, image processing requires a high-quality image display device as well.
2. For general-purpose work, the software system should allow simple library call-up and execution of processing and analysis programs. Convenient tape or disk storage of input and output digital images and library programs is a practical requirement.
3. The library programs should be maintained with an eye toward versatility. The power of the system is greatly enhanced if existing programs can be used to try out new approaches to old or new problems.

4. The program library should be easily expandable to include new programs as they are developed. In this way, the system experiences continual growth.

1.17 A SIMPLE IMAGE FORMATION MODEL

(*i*) Two-dimensional Image Representation

As discussed earlier, an image can be represented by a two-dimensional function which is of the form $g(x, y)$. Here, (x, y) are the spatial coordinates and g represents the value or amplitude at spatial coordinates (x, y). This amplitude g is a positive scalar quantity, the physical meaning of which can be determined by the source of a particularly image.*

Given that an images is generated from a physical process then its values will be proportional to energy radiated by physical source**. Because of this fact, two dimensional image represented $g(x, y)$ should be finite and non zero. Mathematically, we can state that

$$0 < g(x, y) < 8 \quad \text{... (1.6)}$$

(*ii*) Characterization of Two-Dimensional Function $g(x, y)$

The two-dimensional function $g(x, y)$ may be characterized by following two components:

(*a*) The amount of source illumination incident on the scene being viewed,

(*b*) The amount of illumination reflected by the objects in the scene.

Now, the component described in (*a*) is called as the illumination component and is denoted by $i(x, y)$ whereas the component described in (*b*) is called as the reflectance component and is denoted by $r(x, y)$. Therefore, these two components (functions) are combined as a product to yield $g(x, y)$, *i.e.*,

$$g(x, y) = i(x, y)\, r(x, y) \quad \text{... (1.7)}$$

Here,

$$0 < i(x, y) < \infty \quad \text{... (1.8)}$$

$$0 < r(x, y) < 1 \quad \text{... (1.9)}$$

In equation (1.8), the nature of i(x,y) is determined by the illumination source. In equation (1.9), $r(x, y)$ is determined by the characteristics of the imaged objects. Also, equation (1.9) shows that reflectance is bounded by 0 (*i.e.*, total absorption) and 1 (*i.e.*, total reflectance)

Important Point : *It may be noted that the expressions given in equations (1.8) and (1.9) are also applicable to image formed via transmission of the illumination through a medium, such as a chest X-ray.*

(*iii*) Gray Level

As discussed earlier the intensity of a monochrome image at any coordinate (x_o, y_o) is called the **gray level** of the image at that point. This gray level is represented by letter '*l*'. This means that

$$l = g(x_0, y_0) \quad \text{... (1.10)}$$

Looking at equations from (1.7) to (1.10) it is obvious that gray level l lies in the following range :

$$L_{min} \leq l \leq L_{max} \quad \text{... (1.11)}$$

* Most of the images of interest in the book are monochromatic images.

** Electromagnetic waves.

(iv) Requirement on Gray Level

Theoretically the only requirement on L_{min} is that it should be positive and requirement on L_{max} is that it should be finite.

Practically, we have

$$L_{min} = i_{min}\, r_{min} \quad \dots (1.12)$$
$$L_{max} = i_{max}\, r_{max} \quad \dots (1.13)$$

The typical limits for indoor values in the absence of additional illumination, may be stated as under :

$$L_{min} \cong 10, \text{ and}$$
$$L_{max} \cong 1000$$

(v) Gray Scale

The internal $[L_{min}, L_{max}]$ is popularly known as gray scale. In common practice, this interval is numerically shifted to the new interval $[0, L - 1]$. In this interval, we consider two cases :

(a) $l = 0$ is treated as black,

(b) $l = L - 1$ is treated as white on gray scale.

✍ **Important Point :** *It may be noted that all the intermediate values are shades of gray varying from black to white.*

1.18 INTRODUCTION TO SAMPLING AND QUANTIZATION

We know that an image is basically a two-dimensional representation of the three-dimensional world. We also know that images may be acquired using a Vidicon or a CDD camera or using scanners. The basic requirement for image processing is that images obtained should be in the digital format. For example, one cannot work with or process photographs on identity cards unless he/she scans it using a scanner.

The scanner digitizes the photograph and stores it on the hard disk of the computer. Once this is done, one can use image-processing techniques to modify the image as per requirement. In a Vidicon too, the output which is in analog form requires to be digitized in order to work with the images. In brief, to perform image processing, we need to have the images on the computer. This will only be possible when we digitize the analog pictures.

Now that we have understood the importance of digitization, let us see what this term actually means.

The process of digitization involves following two steps :

(i) Sampling

(ii) Quantization

In other words, Digitization = Sampling + Quantization.

We already know about these terms from previous semesters in subjects like Principles of Communication Engineering, Signals and Systems and Signal Processing which dealt with 1-dimensional signals. Let us take a brief look at these concepts and move ahead to the 2-dimensional domain.

1.18.1 Sampling

We consider a band-limited signal. Although real world signals are rarely band limited, we can produce one by passing the signal first through a low-pass filter known as an anti-aliasing filter.

✍ **Important Point :** *A signal is said to be band limited, if its Fourier Transform (FT), F(u), is zero outside a bounded region.*

To understanding sampling, we first need to understand convolution involving impulse functions. If $f(t)$ is a step signal shown in figure 1.36 and $g(t)$ is a train of impulses ($g(t)$ is also known as a COMB function), then the convolution of the two is given by $f(t) \otimes g(t)$. Let us see what happens when we convolve $f(t)$ with $g(t)$.

Proof :

We know that the convolution of $f(t)$ and $g(t)$ is given by

$$y(t) = \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau = \int_{-\infty}^{\infty} g(\tau)\, f(t-\tau)\, d\tau$$

or
$$y(t) = \int_{-\infty}^{\infty} [\delta(t-T) + \delta(t) + \delta(t+T)]\, f(t-\tau)\, d\tau$$

$$= \int_{-\infty}^{\infty} \delta(t-T)\, f(t-\tau)\, d\tau + \int_{-\infty}^{\infty} \delta(t)\, f(t-\tau)\, d\tau + \int_{-\infty}^{\infty} \delta(t+T)\, f(t-\tau)\, d\tau$$

But, $\int_{-\infty}^{\infty} \delta(t-T)\, f(t-\tau)\, d\tau = \delta(t - T) \otimes f(t)$ [This is impulse at $t = -T$ convolved with $f(t)$]

And, $\int_{-\infty}^{\infty} \delta(t+T)\, f(t-\tau)\, d\tau = \delta(t + T) \otimes f(t)$

[This is impulse at $t = + T$ convolved with $f(t)$]

This gives us the figures as shown in figure 1.36.

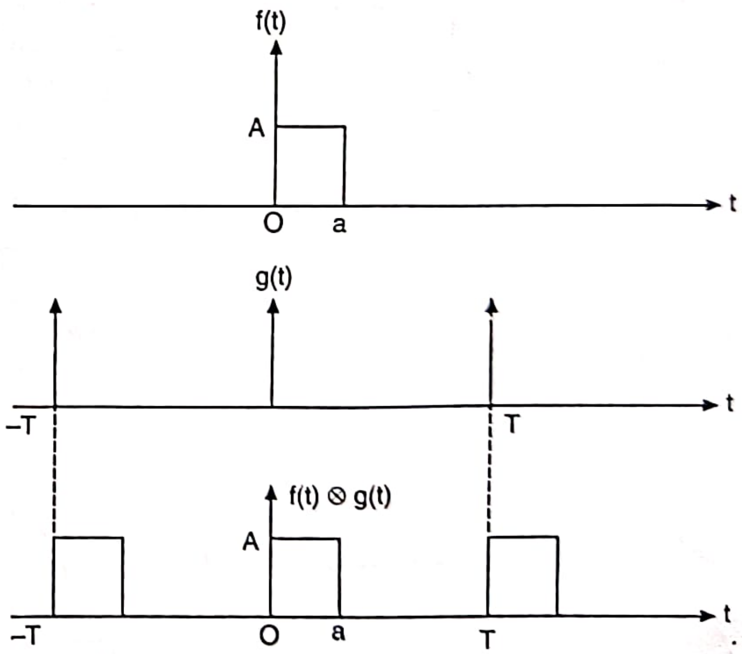


Fig. 1.36.

We observe that the convolution replicates the signal $f(t)$ at every impulse $g(t)$.

Another important property that one needs to know is that convolution in one domain is equal to multiplication in the other, *i.e.*, convolution in the time domain is equal to multiplication in the time domain is equal to convolution in the frequency domain.

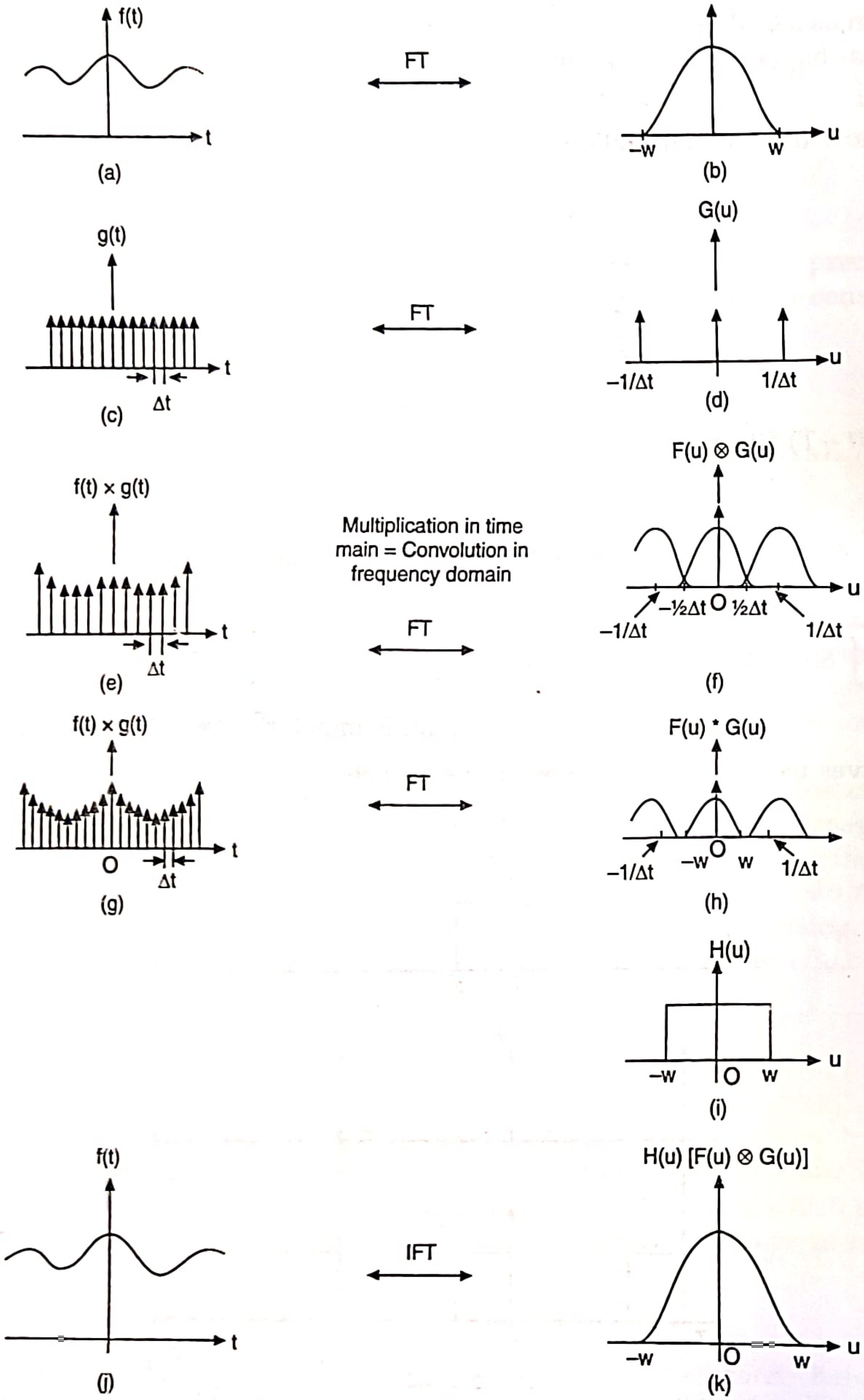


Fig. 1.37.

Let us consider a band limited signal as shown in figure 1.37.

As is seen in figure 1.37, if we use figure 1.37 (*c*) as the sampling period, we encounter overlapping or aliasing in the frequency domain (figure 1.37 (*f*)). This is due to undersampling. If we decrease the sampling period (increase the sampling frequency) as in figure 1.37 (*g*), we can eliminate aliasing in the frequency domain (figure 1.37 (*h*)). If we now multiply figure 1.37 (*h*) with a gating function $H(u)$ (figure 1.37 (*i*)] we can select only the required part of the spectrum (figure 1.37 (*k*)). We take the inverse Fourier transform to get back the original signal $f(t)$ (figure 1.37 (*j*)).

All this was possible because the sampling period was small (sampling frequency was large). Hence, to avoid aliasing, the sampling frequency should be greater than or equal to 2 × Bandwidth (2 × *W*). In other, $\Delta t \leq \frac{1}{2W}$. This is the Whittaker-Shannon sampling theorem. Only, if this condition is satisfied, we can recover the original signal. These 1-D concepts can be easily extended to the 2-D domain. A function $f(x, y)$ is called a band limited function if its Fourier transform $F(u, v)$ is zero outside a bounded region in the frequency plane, *i.e.*,

$$F(u, v) = 0; \quad u > u_0, v > v_0$$

1.18.2 Quantization

As a matter of fact, the values obtained by sampling a continuous function usually comprise of an infinite set of real numbers ranging from a minimum to a maximum depending upon the sensors calibration. These values must be represented by a finite number of bits usually used by a computer to store or process any data. In practice, the sampled signal values are represented by a finite set of integer values. This is known as quantization. Rounding of a number is a simple example of quantization.

With these concepts of sampling and quantization, we now need to understand what these terms mean when we look at an image on the computer monitor.

Higher the spatial resolution of the image, greater is the sampling rate, *i.e.*, lower is the image area $\Delta x \, \Delta y$ represented by each sampled point. Similarly, higher the gray level resolution (tonal resolution) more are the number of quantized levels.

Hence, spatial resolution gives us an indication of the sampling while gray level resolution (tonal resolution) gives us an indication of the quantization.

Spatial resolution ⟶ Sampling

Gray level resolution ⟶ Quantization

We have already stated that an image can be considered as a 2-D array. Image $f(x, y)$ is arranged in the form of $N \times M$ array

$$f(x, y) = \begin{bmatrix} f(0,0) & f(0,1) & \cdots\cdots & f(0, M-1) \\ f(1,0) & f(1,1) & \cdots\cdots & f(1, M-1) \\ f(2,0) & f(2,1) & \cdots\cdots & f(2, M-1) \\ \vdots & & & \\ f(N-1,0) & f(N-1,1) & \cdots\cdots & f(N-1, M-1) \end{bmatrix}_{N \times M}$$

Hence, every image that is seen on the monitor, is actually this matrix. Each element of the matrix is called a *pixel*. Whenever we see an image on the screen of the computer, it is actually a matrix which consists of N × M pixels and each pixel is considered to be a sample. Hence, more the pixels, more the samples, higher the sampling rate and hence better the spatial resolution. The value of each pixel is known as the gray level.

The computer understands only ones and zeros. Hence, these gray levels need to be represented in terms of zeros and ones. If we have two bits to represent the gray levels, only 4 different gray levels (2^2) can be identified viz. 00, 01, 10, 11, where 00 is black, 11 is white and the other two are different shades of gray. Similarly, if we have 8-bits to represent the gray levels, we will have 256 gray levels (2^8). Hence, more the bits, more are the gray levels and better is the tonal clarity (quantization). The total size of the image is $N \times M \times m$, where m is the number of bits used.

1.19 DIGITIZING IMAGES

Since computers can process only digital images, and nature affords image in other forms a necessary precursor to digital image processing is the conversion of images into digital form. The specialized equipment for digitizing images is, by and large, what transforms an ordinary computer center into an image analysis laboratory. For image processing applications display devices are also required. Image display, however, is obtainable from a line printer although this process is rather cumber-some.

Unit relatively recently, image digitizing equipment was so expensive and complex that only a few centers had such a capability. Advances in technology, however, are making image digitizers less expensive and their use more widespread. Widely diverse configuration of apparatus have been used to convert images into digital form. In this section, we discuss the element of an image digitizer and examine several implementations. The aim is to develop an insight into the capabilities, and limitations of the various approaches.

1.19.1 The Elements of a Digitizer

An image digitizer must be able to divide an image into picture elements and address each individually, measure the grey level of the image at each pixel, quantize that continuous measurement to produce an integer, and write out the set of integers on a data storage device. To accomplish this, a digitizer must have five elements. The first is a sampling aperture, which allows the digitizer to access picture elements individually while ignoring the remainder of the image. The second element of an image digitizer is a mechanism for scanning the image. This process consists of moving the sampling aperture over the image in a predetermined pattern. Scanning allows the sampling aperture to address pixels in order. one at a time.

The third element is a sensor, which can measure the brightness of the image at each pixel through the sampling aperture. The sensor is commonly a transducer that converts light intensity into an electrical voltage or current. The fourth element, a quantizer, converts the continuous output of the sensor into an integer value. Typically, the quantizer is an electronic circuit called an *analog-to-digital converter*. This unit produces a number that is proportional to the input voltage or current.

The fifth element of an image digitizer is the output medium. The gray level values produced by the quantizer must be stored in an appropriate format for subsequent computer processing. Technically, the output medium could be omitted if the image were being processed "on-line." Image digitizer is frequently done "off-line" from the main computer system, however, and the output medium is necessary. The output medium can be magnetic tape, magnetic disk, data cards, or even punched paper tape. Because of the size of typical digital images, the latter two formats are seldom practical.

1.20 CHARACTERISTICS OF AN IMAGE DIGITIZER

While image digitizers differ in the apparatus they use to perform their function, they may be equated on the basis of their relevant characteristics. Two important characteristics are the size of the sample aperture and the spacing between adjacent pixels. If the digitizer has a lens system with variable magnification, the sample size and spacing at the image size capability of the instrument. In the case of a film scanner, the maximum input size might be 35-millimeter (mm) film, or perhaps 11-by 14-in. X-rays. At the output, image size is specified by the maximum number of lines and of samples per line. Thus, a digitizer might be able to produce digital images having up to 1000 lines of 100 samples each.

A third significant characteristic of an image digitizer is the physical parameter that it actually measures and quantizes. In case of film scanners, as an example, the instrument can measure and quantize either transmittance or optical density. Both are functions of the darkness or lightness of the film, but in certain applications one may be better than the other. The linearity of the digitization is also an important parameter. For instance, if the instrument digitizes light intensity, one should know to what accuracy the gray levels are proportional to the actual brightness of the image. The validity of subsequent processing may be jeopardised by a non-linear digitizer. It is the number of gray levels to which the instrument can quantize the image. Early image digitizers hade only two gray levels : black and white. In current practice, 8-bit (256-level) data is common, and considerably higher resolution is possible with recent instrumentation.

Lastly, one of the most important characteristics of a digitizer is its noise level. If a uniformly gray image is presented to a digitizer, the noise inherent in the system will cause variations in the output even though the input is constant. Noise introduced by the digitizer is a source of image degradation and should be small relative to the contrast of the image.

These characteristics constitute a brief specification sheet for an image digitizer. They provide a basis upon which to compare different instruments or to decide whether a given instrument is adequate for a particular job. In some applications, digitizing images with relatively few lines, samples, and gray levels and with appreciable non-linearlity and a high noise level may be adequate. But, many of the important applications of digital image process processing require a high-quality image digitizer—one capable of digitizing large image to many gray levels with good linearity and a low noise level. In later sections, we discuss image digitizer requirements in light of processing applications.

1.21 TYPES OF IMAGE DIGITIZERS

An important and highly versatile type of image digitizer is the so-called digitizing camera, which has a lens system and can digitize an image of any object presented to it. An example is a television camera interfaced to a computer. Such a device can digitize not only physical objects but also other images is the film scanner. This is an instrument made specifically for scanning images on film. Film scanners can digitize an image of an object only after it has been photographed initially by a film camera. Historically, film scanners have played a predominant role in image processing, but current practice favours direct digitizing cameras.

There are two important digitizing philosophies, "scan-in" digitizing and "scan-out" digitizing. In a scan-out system (figure 1.38), the entire object or film image is illuminated continuously, and the sampling aperture allows the sensor to "see" only one pixel at a time. In a scan-in-system (figure 1.39), only one small spot of the object is illuminated, and all the transmitted light is collected for the sensor. In this case, the object is scanned with the illuminating beam, and the sensor is spatially non-specific.

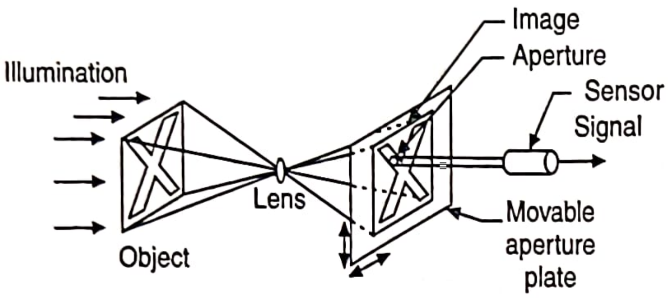


Fig. 1.38 A scan-out digitizer.

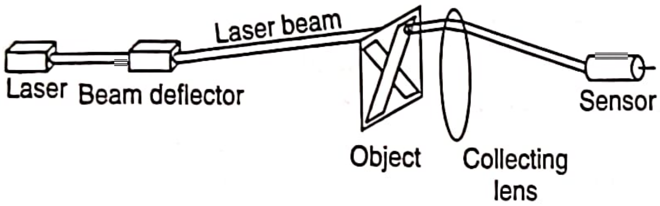


Fig. 1.39 A scan-in digitizer.

There is a third philosophy—a combination of the previous two. In a *scan-in/scan-out* system, the object is illuminated by a moving spot and sampled through a moving aperture that follows the spot. Such a system reduces the effects of glare and has found some application in digitizing microscope images. The complexity of such systems, particularly in tracking the illuminating spot with the sampling spot, has limited their application.

1.22 IMAGE DIGITIZING COMPONENTS

As discussed before, an image digitizer must have a light source, a light sensor, and a scanning system. Furthermore, either the light source of the light sensor, or both, must be behind a sampling aperture. In this section, we discuss various types of light sources, light sensors, and scanning systems. Also, in the following section, we put them together to form complete image digitizers.

1.22.1 Light Sources

The most common man-made light source is the incandescent bulb. For scan-out systems, incandescent is convenient for general illumination of the object or image being digitized. For scan-in work, the filament of a small bulb can be imaged with a lens to form a small bright spot.

Highly concentrated beams of light can be produced with a laser. The laser generates a narrow, intense, coherent beam of light by first raising the atoms of an active material (helium, neon, ruby, etc.) to a high-energy state and then stimulating a simultaneous transition back to the normal state. This transition gives rise to a high-intensity beam of coherent light that is easily focussed and deflected. While the laser could be used for general illumination in a scan-out system, its principal advantage lies in producing small high-intensity spots for scan-in digitizers.

Certain phosphorus emit light when irradiated with an electron beam. If an electron beam is focussed to a small spot on the face of a phosphor-coated glass plate (figure 1.40), light is emitted from that spot. The phosphor that coats the face of the cathode-ray tube (CRT) is a crystalline compound doped with certain impurities. The phosphor is deposited on the face of the tube over a transparent aluminium film. This film is positively charged and forms an anode that attracts the electron beam. The impact of the energetic electrons excites the atoms of the host phosphor, raising some of their electrons to high-energy states. As these electrons decay back to their normal state, light is emitted. The spectrum (color) and persistence (decay rate) of the light generated can be controlled in the manufacture of the phosphor. A wide variety of emission spectra and persistence times from less than 1 microsecond to several seconds is available.

The brightness of the light spot produced by the electron beam is roughly proportional to the average beam current density. The phosphor is made up of granules and is therefore subject to grainness and scattering of light within the phosphor layer. Currently available cathode-ray tubes have a resolution limit of about 30 to 70 line pairs (cycles) per millimeter.

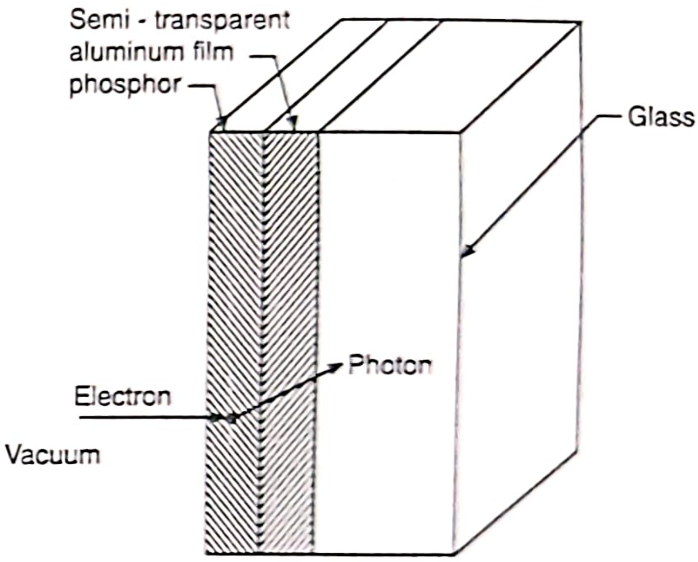


Fig. 1.40 CRT target

The relatively recent solid-state light-emitting diodes (LEDs) also form compact and convenient light sources. LEDs are typically made of gallium arsenide semiconductor. They emit light at controlled intensity form a spatially small source. This also makes them promising candidates for use in scan-in systems.

1.22.2 Light Sensors

Light sensors produce an electrical signal proportional to the intensity of light falling upon them. Three physical phenomena give rise to three types of light sensors : photoemissive devices, photovoltaic cells, and photo-conductors. Photoemissive substances emit electrons with irradiated with light ; photovoltaic substances, such as silicon and selenium solar cells, generate an electrical potential when exposed to light ; and photoconductors, such as cadmium sulfide and cadmium selenide exposed to light ; and photoconductors, such as cadmium sulfide and cadmium selenide, show a drop in their electrical resistance when exposed to light. Photodiodes and phototransistors change their junction characteristics under the influence of light.

1. Photoemissive Devices : Phototubes and Photomultiplier Tubes. The phototube (figure 1.41) has a positively charged anode and a negatively charged cathode coated with layers of oxides of the alkaline metals (silver, cesium, antimony, sodium, bismuth, and rubidium).

When photons of sufficient energy ($\lambda < 1$ micron or so) strike the photocathode, electrons are freed from the surface. Under the influence of the electric field, they migrate to the anode, producing a current flow through the device. This current is proportional to the photon flux incident on the photocathode. The current is sensed by the external circuit and may be sampled and quantized.

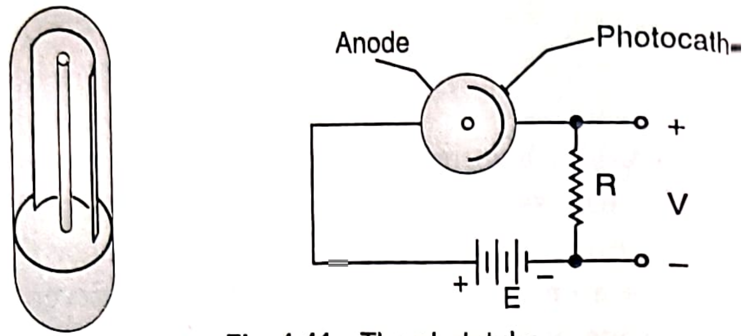


Fig. 1.41 The phototube.

The photomltiplier tube (figure 1.42) has a photoemissive face that forms a semitranspar photocathode. Behind the cathode are a series of dynodes charged with progressively hig positive voltages. Primary electrons freed from the photocathode by photons are accelerated toward the first dynode. The impact of the first dynode free secondary electrons, producing a multiplying effect. The resulting electrons are then attracted toward the second dynode, and the process continues until the electrons from the last dynode are collected on the anode to produce a current in the external circuit. The photomultiplier tube behaves similarly t phototube except that it is more sensitive because of the multiplying effect of the dyn One primary electron may give rise to as many as a million electrons in the external cir This high sensitivity makes the photomultiplier tube useful for digitizing at low light le

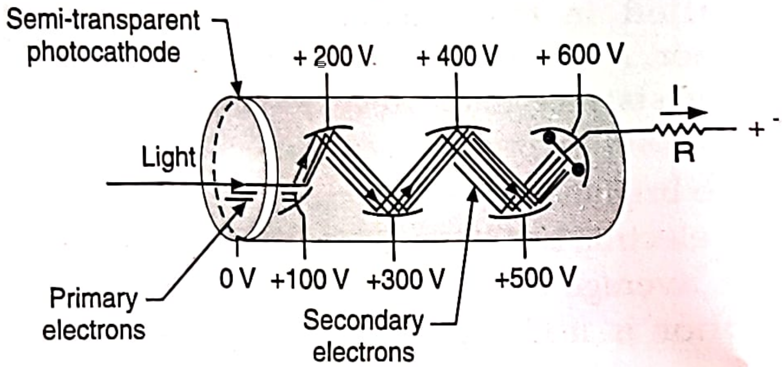


Fig. 1.42 The photomultiplier tube.

2. Photovoltaic Cells. Solar cells are semiconductor junction devices made of silicc selenium. A junction potential exists at the interface between the *P*-type semicondu Impinging photons mobilize carries near the junction, which more under the influence o junction potential to produce a current flow in the external circuit. The open-circuit vo of the cell is primarily due to the junction potential of the semiconductor. The short-ci current, however, is roughly proportional to light intensity. Photovoltaic cells are usefu solar power applications, but their slow response makes them undesirable for image digiti applications.

3. Photoconductive Devices. The common photoconductive cells are made of cadm sulfide or cadmium selenide semiconductor doped with *N*-type impurities. They are junction devices but, when connected to an externally supplied field, they conduct unde influence of the externally applied electric field. These devices exhibit resistance depen on light intensity. Over a wide range, the logarithm of resistance is inversely proportion the logarithm of light intensity measured in footcandles. These devices are stable and relat accurate and have found wide use in photographic lightmeters. Their slow response li their use for image digitizing purposes.

4. Photodiodes and Phototransistors. The photodiode (figure 1.43) is a solid-state *P-N* junction that can be exposed to light. In operation, the junction is reverse-biased and exhibits a high impedance. One layer of the device (for instance the *P*-layer) is made very thin so that light can penetrate to the junction. Impinging photons release electron-hole pairs. In the depletion layer, where the electric field is strong, these mobilized carriers do not recombine but migrate under the influence of the field so create a current in the external circuit. The current is proportional to the photon flux. Since the reverse-biased junction presents a high impedance, the current is controlled by the light intensity and is relatively independent of the externally applied voltage. The depletion layer is made comparatively thick to capture long wavelength photons.

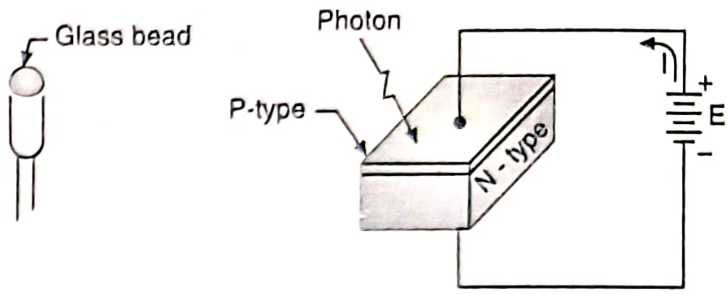


Fig. 1.43 The photodiode.

The avalanche photodiode achieves higher sensitivity than the ordinary photodiode through an electron multiplication effect. The avalanche photodiode is back-biased almost to the point of breakdown. Electrons freed by impinging photons are accelerated by the intense field to velocities at which they have ionizing collisions, freeing more electrons. This effect can produce gain factors as high as 1000, considerably increasing the sensitivity of the device.

The phototransistor (figure 1.44) is mounted in clear plastic or in a can with a lens on top to permit light to access the transistor junction. Impinging photons release electron-hole pairs in the collector-base junction. The movement of these carriers constitutes base current in the transistor. The collector current is proportional to the base current but is amplified by the current gain factor of the transistor. Externally, the phototransistor behaves like the photodiode except with higher sensitivity. Design requirements for speed and linearity, however, dictate compromise in transistor design and limit available current gains.

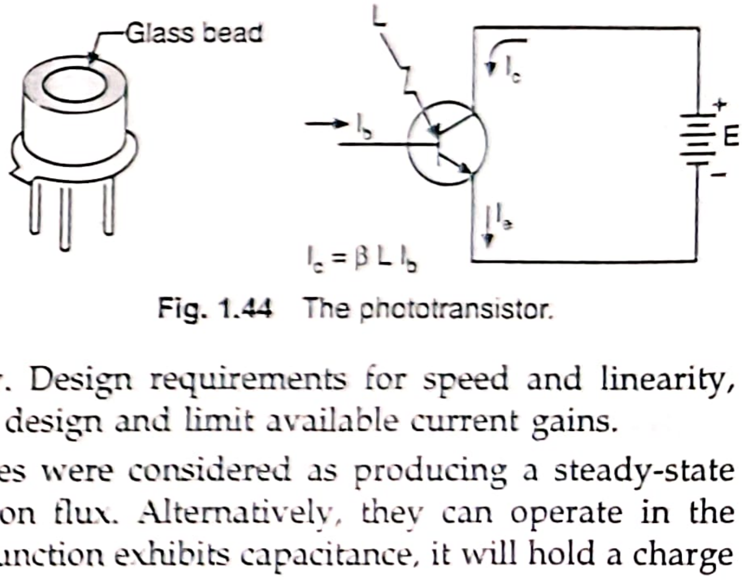


Fig. 1.44 The phototransistor.

In the previous discussion, photodiodes were considered as producing a steady-state current proportional to the incident photon flux. Alternatively, they can operate in the "integrating mode". Since the photodiode junction exhibits capacitance, it will hold a charge of the reverse-biased polarity. Subsequently, photoconduction bleeds off the charge at a rate proportional to incident photon flux. If the photodiode is periodically recharged to some reference voltage, the charge (number of electrons) required is proportional to the integral of incident photon flux over the period between charges. Thus, in the integrating mode, the photodiode sense not instantaneous photon flux but photon flux integrated over a certain period of time.

Two factors limit the dynamic range of photodiodes operating in the integrating mode. First, the small junction capacitance limits the initial charge that can be stored. Secondly, the "dark current", which flows even without incident light, gradually discharges the photodiode.