Introduction to Holographic Imaging

全息成像概论

Wei Sui

韦 穗 编著

北京师范大学出版集团
BEIJING NORMAL UNIVERSITY PUBLISHING GROUP
安 徽 大 学 出 版 社

Introduction to Holographic Imaging

全息成像概论

Wei Sui

韦 穗 编著

北京师范大学出版集团
BEIJING NORMAL UNIVERSITY PUBLISHING GROUP
安 徽 大 学 出 版 社

图书在版编目(CIP)数据

全息成像概论＝Introduction to Holographic Imaging:英文/韦穗编著.
—合肥:安徽大学出版社,2013.1
ISBN 978-7-5664-0589-0

Ⅰ.①全… Ⅱ.①韦… Ⅲ.①全息成像—概论—英文 Ⅳ.①TP72

中国版本图书馆 CIP 数据核字(2012)第 222566 号

全息成像概论
Introduction to Holographic Imaging

韦 穗 编著

出版发行:北京师范大学出版集团
安 徽 大 学 出 版 社
(安徽省合肥市肥西路 3 号 邮编 230039)
www.bnupg.com.cn
www.ahupress.com.cn
经 销:全国新华书店
印 刷:中国科学技术大学印刷厂
开 本:184mm×260mm
印 张:13.5
字 数:328 千字
版 次:2013 年 1 月第 1 版
印 次:2013 年 1 月第 1 次印刷
定 价:35.00 元
ISBN 978-7-5664-0589-0

策划编辑:李 梅 武溪溪
特约编辑:章权兵
责任编辑:武溪溪 徐兆星
责任校对:程中业
装帧设计:李 军
美术编辑:戴 丽
责任印制:赵明炎

Preface

On the sense that 70-80 percent of the information human gets comes from visual cue, the science and technology for imaging form a large part of information science. Today's imaging industry is being challenged to find more scientific and attractive ways to present the information, it will be the 3D imaging and that holographic imaging is the ultimate 3D visualization tool.

The holography, the science of recording and reconstructing the field of a light wave and a complex electromagnetic wave field with even higher frequencies, was invented by Dr. Dennis Gabor in 1948, which is so fundamental that he eventually won, in 1971, the Nobel Prize in Physics.

Holography is assembled from Greek words that approximate the meaning "entire recording". "Entire" in this context is meant to distinguish the holography from the photograph. As we know that the oscillation of the field of a light wave fronts approach 10^{15} Hz, none of the existing light-sensitive devices can directly record both the amplitude and phase of a light wave field. In traditional photography, intensity of the light is captured and the crucial phase information encoding the sense of depth or shape is discarded, while in holography both amplitude and phase can be recorded even though the recording media respond only to light intensity.

Over the years, holography has been advanced to a stage where it can facilitate developments in countless optical and non-optical techniques. For example, Holography can be used with X-Rays, to form three dimensional images of both bones and organs. Holographic Data Storage techniques can store an extremely large amount of data on small areas. Holographic optical tweezers use computer-generated holograms to create arbitrary three-dimensional configurations of optical traps useful for capturing and moving mesoscopic objects. In adaptive optics, light is modulated by Holography to correct for aberrations in a variety of optical systems such as the human eye or the atmosphere. Very recently it is shown that light can be focused through strongly opaque scattering materials by sending in spatially shaped wavefronts. Holographic optical elements (HOE) can perform the functions of mirrors, lenses, gratings, or combinations of them, and they are used in myriad technical devices, such as optical interconnection and switching, manipulating nanoparticles, and bio-sensors.

Holography is also a technique employed to make three-dimensional images. Researchers working on virtual reality systems and 3D computer graphics visualization have realized that our current visual interface has not reached its full potential. There is no doubt that a 3D imaging market is developing and holography is a very realistic form of visualization due to its capability to properly convey the depth cues that we use to interpret three-dimensional objects.

The chapters in the book are organized as follows.

The first chapter will gave a discussion of the performance of the human visual system especially 3D one and brief survey on a variety of 3D display techniques—stereoscopic, volumetric and holographic ones. The basic holography concepts are also introduced here from the perspective of a historical background, where Chinese magic mirrors, the device of capable of producing holographic object from sun light dates back to the middle age, is also highlighted.

The topics involved are highly multidisciplinary but holography is basically built on quite complex physical laws of optics. Therefore, some fundamental background on the wave optics is focused in Chapter Two and it is expected that readers should be knowledgeable in basic principles of optics: Maxwell's equations, wave equation, Helmholtz wave equation, scalar diffraction theory, Fresnel and Fraunhofer approximations and polarization, etc. For our purpose in this book, we will describe electro-optical characteristics of liquid crystals in this chapter. Liquid crystal device is the only technology able to modulate intensity, phase and polarization, there is no doubt that liquid crystal will continue to play an important role in the era of information technology.

The great part of the book is on those following including optical holography, computer-generated holograms and holographic video display from a novel perspective of combining optics with computation optimally.

Chapter Three is a summary of the basic types of classic optical hologram, not to intend to cover a comprehensive survey. It includes several classical optical holograms developed by great pioneers, such as in-line, off-axis, rainbow holograms and reflection type. Then the holographic stereogram which, in their basic form, is a synthetic hologram made of thousands of images corresponding to as many as the points of view on a three-dimensional scene. This approach is widespread in Chinese landscape painting, such as "The Qing Ming Festival" (1085-1145) and "The Qian long Emperor's Southern Inspection Tour" (1770). And it is very delightful to introduce the device, named "holographic functional screen" by Dr. Frank C Fan in AFC Technology Co. Ltd in Shenzhen, which is the largest holographic stereogram today in the world I believe. One technology termed holographic screen is also introduced here, which may open up a new way for 3D display. The practical aspects of holography are finally described, including light sources, the characteristics of recording media and process for making a simple hologram with kits.

Chapter Four concentrates on Computer-generated hologram, which combines flexible computing with optics to escape some limitations of traditional methods done by coherent light plus wet chemical processing in recording phase. Brown and Lohmann pioneered computer-generated hologram (CGH) in the mid 1960s. A pure phase encoded CGH, termed kinoform was afterward proposed by Lesem and it is finding increasing use in commercial lenses nowadays. In 1989, MIT Media Laboratory Spatial Imaging Group created the first real-time 3-D holographic images where a new type of computing, called "diffraction specific computation", was invented for faster rate and less bandwidth. These relevant topics are specialized into cell-oriented, phase-only and computation based on propagating sections respectively. Among the challenging tasks in holographic imaging, one of the major obstacles for implementing 3D holography imaging, if not the major one, is the lack of capturing naturally lit scenes in real time. A non-interferometric sampling of the diffraction field or a novel framework for phase retrieval is therefore briefly introduced. Finally, we will explore digital holography (DH) in which a hologram is digitally recorded in real time by a digital charge-coupled device (CCD), and then numerically reconstructed. Therefore, it combines the benefits of the physical optics with sophisticated computational methods to gain substantial performance and thus the holography is becoming computational.

Chapter Five describes state-of-the-art techniques of holographic video display. An electro-optical apparatus could display three-dimensional moving images in real time, invented first by Professor Stephen A. Benton who brought holography from the age of film to the digital age. The first system capable of displaying 3-D holographic video is made of acoustic optic modulators and stimulates much activity in this field. A variety of DMD (digital micro-mirror device) and LCOS (Liquid Crystal on Silicon) based display systems devised by a many number of research groups then began to emerge. Heart of those display systems is spatial light modulator (SLM), and a liquid-crystal (LC) based SLM, as an instance, is briefly discussed here for addressing the principal characteristics and some major challenges involved, and then some representative systems are depicted. There include acoustic optic modulators based display system, DMD (digital micro-mirror device) based display system and LCOS (Liquid Crystal on Silicon) based display system. Our group is working on practical research on developing prototypes of the dynamic holographic display based on DMD and LCOS and I am going to share the results of our projects here with the readers but also our perspective on how these results may be best turned into future research successes. What we realized is that using commercial SLMs for the holographic video is not suited mainly because of the small diffraction angle and low resolution. To be fair, it is not really the fault of the current devices that they are not perfectly suited for 3D application as they were made with two-dimensional displays in mind; three-dimensional displays were only an afterthought. The research done so far has demonstrated that we are well on the way to produce the new technology.

This book comes from my in-class lectures for senior/first-year graduate level students as well as my team's own research in the area supported by the National Natural Science Foundation of China under Grants (60473102 and 60872106). It has been well recognized that holography has become a major pillar of modern optics and imaging and is a valuable subject for introducing students to the modern optics or hybrid optics/electronics of both science and technology. Emotions overwhelm me to write this book when thinking about giving my lectures as well as my research in the area for industrial society and being rewarded a very appreciation.

In keeping with the introductory nature of the book, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. I hope this book can be useful for anyone desiring to learn about and develop the holographic imaging and relative technology which is still an emerging technology with much scope for future investigations.

Wei Sui

June 2012

Contents

Preface 1

Chapter 1 Holography: The Ultimate 3D Visualization Tool 1

1.1 Human 3D Perception 2

1.1.1 Anatomy 3

1.1.2 Stereopsis 5

1.1.3 Accommodation and Convergence 7

1.1.4 Motion Parallax 9

1.1.5 Pictorial Information 9

1.1.6 Some Photometric Visual Parameters 11

1.2 3D Visualization Systems 13

1.2.1 Stereoscopic Displays 14

1.2.2 Autostereoscopic Displays 17

1.2.3 Volumetric Displays 20

1.2.4 Holography 21

1.3 Historical Background 23

1.3.1 A Two-step Lensless Imaging Process 24

1.3.2 White-light Holography 26

1.3.3 Computer-generated Hologram 27

1.3.4 Holographic Video Display 28

1.3.5 Chinese Magic Mirrors 29

1.3.6 The Tentacled Holographic Entity 30

Chapter 2 Wave Optics 33

2.1 The Basic Nature of Light-wave 34

2.1.1 Maxwell's Equations and Wave Equation 35

2.1.2 Complex Representation and Helmholtz Wave Equation 36

2.1.3 Plane and Spherical Wave 38

2.1.4 Angular Spectrum Representation of Plane Waves 40

2.2 Scalar Diffraction Theory 41

2.2.1 Huygens-Fresnel Principle 43

2.2.2 Fresnel and Fraunhofer Approximations 45

2. 2. 3 Another Derivation of Fresnel Approximations ······ 49
2. 3 Polarization ······ 50
2. 3. 1 Polarization ······ 50
2. 3. 2 Polarizer, Rotator and Polarizing Beam Splitter ······ 52
2. 3. 3 Electro-optical Characteristics of Liquid Crystals ······ 54

Chapter 3 The Basic Types of Optical Hologram ······ 60
3. 1 Classical Optical Holography ······ 60
3. 1. 1 Diffraction Grating ······ 61
3. 1. 2 In-line Holography (Gabor Configuration) ······ 64
3. 1. 3 Off-axis Holography (Leith-Upatnieks Configuration) ······ 68
3. 1. 4 Rainbow (Benton) Holograms ······ 69
3. 1. 5 Reflection (Denisyuk) Holograms ······ 71
3. 2 Holographic Stereogram ······ 73
3. 2. 1 What Is a Holographic Stereogram ······ 74
3. 2. 2 Holographic Functional Screen ······ 78
3. 2. 3 Holographic Screen for Image Projection ······ 80
3. 3 Practical Aspects of Optical Holography ······ 82
3. 3. 1 Light Sources for Holography ······ 82
3. 3. 2 Holographic Recording Media ······ 86
3. 3. 4 Making a Simple Hologram: Integraf's Holography kits ······ 88

Chapter 4 Computer-generated Holograms ······ 92
4. 1 Cell-oriented Computation ······ 93
4. 1. 1 Lohmann-type Detour Hologram ······ 94
4. 1. 2 Burckhardt Amplitude Encoding ······ 97
4. 1. 3 Two-phase Encoding ······ 98
4. 1. 4 Fourier Holograms ······ 100
4. 1. 5 An Example of Display Application ······ 103
4. 2 Phase-oriented Computation ······ 105
4. 2. 1 Lesem's Kinogram ······ 106
4. 2. 2 Phase Manipulation in Imaging ······ 109
4. 2. 3 Iterative Phase Retrieval ······ 113
4. 3 Computation of Wave Field Propagating ······ 117
4. 3. 1 Numerical Techniques for Fresnel Diffraction ······ 118
4. 3. 2 Diffraction-specific Fringe Computation ······ 121
4. 3. 3 Non-interferometric Computation of the Diffraction Field ······ 124
4. 4 Digital Holography (DH) ······ 129
4. 4. 1 System Setup ······ 130

4. 4. 2 Limitations and Challenges in DH Recording ······ 131
4. 4. 3 Reconstruction Algorithms ······ 135

Chapter 5 Holographic Video ······ 139
5. 1 Liquid-crystal Based SLM Device ······ 141
5. 1. 1 Introduction ······ 141
5. 1. 2 Deformation Effects of Nematic Liquid Crystals ······ 143
5. 1. 3 Coding Domains and High Diffraction Efficiency & Wide Angle ······ 148
5. 1. 4 Problems Associated with a Pixelated Device ······ 150
5. 2 Display by Acoustic-optical Modulator ······ 154
5. 2. 1 Scophony ······ 156
5. 2. 2 Mark Display System ······ 157
5. 2. 3 Acousto-optical Bragg Display Architecture ······ 162
5. 3 DMD-based Display System ······ 164
5. 3. 1 Digital Micromirror Device Architecture ······ 165
5. 3. 2 An Experimental Setup and Diffraction Analysis ······ 167
5. 3. 3 Performance Achieved ······ 171
5. 3. 4 Discussions ······ 173
5. 4 LCOS-based Display System ······ 176
5. 4. 1 LCOS Device and Electronics System ······ 177
5. 4. 2 Performance Calibration Methods of LCOS ······ 180
5. 4. 3 Computational LCOS ······ 184
5. 4. 4 Color Holographic Display ······ 186

References ······ 190

Chapter 1

Holography: The Ultimate 3D Visualization Tool

Visual media have been used to express and communicate ideas for thousands of years. We nowadays receive many impressions from the surrounding world as images from technical systems, such as PC displays, TV and cinema screens, etc. Looking at major trends in the evolution of display technologies, for example in televisions: black/white, color TV, high resolution TV; the strong development in materials, electronics and optics advance to the threshold of a generation of machines to match of imaging displays to the ultimate human visual perception—the 3D displays. In other words, while real-time 2D display devices have historically traded off image quality and resolution to meet technical limitations set by state-of-the-art and cost constraints, this is becoming less and less the case, the display concept uses new principles: the physiology and psychology of human visual factors has been judged in the first place. Three-dimensional (3D) perception is an intrinsic part of the human experience. While most people gain the majority of their spatial information through vision, and approximately 90% of the population benefit from 3D perception. Here is a demand to push the limits towards 3D display.

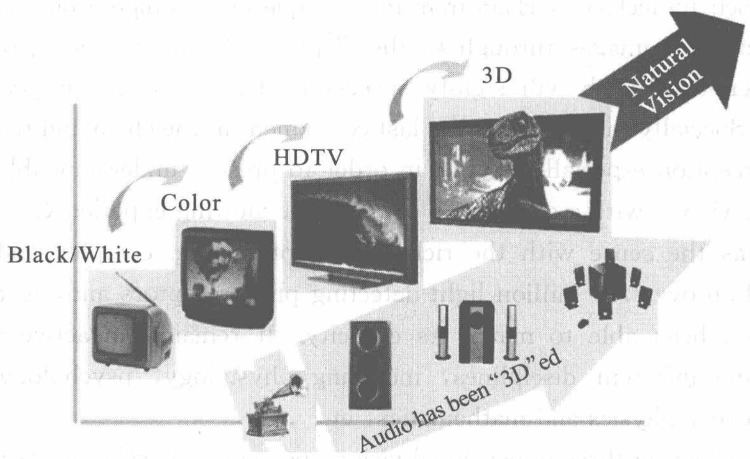

Figure 1. 1 Today's display industry is being challenged to find more scientific and attractive ways to present the information; it will be the 3D display. Moreover, audio has been "3D"ed.

The importance of understanding and manipulating three-dimensional data sets goes in a number of fields such as computer-aided design, engineering, medical imaging, navigation, and scientific research. Possible applications for a three-dimensional visual experience to the arts and entertainment industry are endless.

An information-efficient 3D display system must stimulate the viewer in the most efficient way possible. A true 3D technology should provide all of the depth cues that the human visual system (HVS) uses for comprehending three dimensional objects, including motion parallax, binocular disparity, focal as well as accommodation and convergence effects. Furthermore, it can be viewed simultaneously by any number of users, without the aid of special headgear or position trackers.

Therefore, it is important to begin the development of 3D techniques with a discussion of the performance of the human visual system. Then a short survey is made of 3D display techniques (such as (auto) stereoscopic, volumetric displays and holographic display). The chapter will express the argument that in terms of the physiology and psychology of human visual factors, holography is potentially superior to all other 3D display techniques—whether they be stereoscopic or volumetric. Some selected events in the History of Holography are also introduced in this chapter to give a clear understanding of information nature of holography. The events involved are a two-step lensless imaging process, white-light holography, computer-generated hologram, Holographic video display and Chinese magic mirrors.

1.1 Human 3D Perception

Imaging activity includes a chain from image acquisition, compression, coding transmission and reproduction of images through to the display. Central to these components is the viewers' experience which will signify success or failure of the proposed technological innovations. Specially the display is the last component in the chain and requires knowledge of human perception especially 3D one in order to present understandable and compelling images to the viewer with a completely comfortable viewing experience.

Vision, as the sense with the richest perception, is a complex and highly evolved system based on over 100 million light-detecting photoreceptors and, to date, no sensing technology has been able to match its capacity. It remains an active area of research involving many different disciplines, including physiology, psychology, neuroscience, computer science, physics and mathematics, etc.

When considering three-dimensional vision, perceptual psychologists are faced with an interesting paradox. The physical parameters of the human visual system, such as the field of view, spatial resolution, visible spectrum, and so on, are also naturally limited. How can, for example, the essentially two-dimensional mosaic of retinal receptors curved around the back of an eyeball give rise to the perception of a three-dimensional world? (See Figure 1.2 for the synthesized retinal cones.)

In addressing this problem, psychologists have adopted the empiricist notion that complex ideas have to be built up through the association of simpler ones. Therefore, it is assumed that the third dimension is reconstructed by the brain through associating visual sources of information, often called cues.

In human vision, 3D perception is triggered by a large number of cues. Among them are monocular cues (sometimes also called psychological cues), such as pictorial information for depth, accommodation, and motion cues, binocular ones, such as convergence (angular disparity) as well as stereopsis (horizontal disparity). In natural viewing situations, 3D perception is an ever-present cue in the visual perception. Generally, and in addition to stereopsis, the physiological depth cue of the mutual interplay between accommodation and convergence is considered to be the most important one for depth perception.

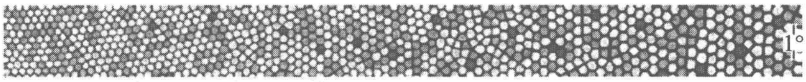

Figure 1.2 Starting at the fovea center on the left, the first 1° of the synthesized retinal cones.

1.1.1 Anatomy

Figure 1.3 shows the anatomy of an eyeball. The eye is nearly spherical, about 25 mm in diameter. The eye is wrapped in three main layers: the outer sclera that passes into the cornea at the anterior part. The cornea is the transparent part through which the light rays enter the eye. The sclera is the "white" of the eye that is mainly protective in function.

The middle layer consists of the choroid that passes into the ciliary's body and the iris. The choroid is deeply pigmented with melanin reducing reflecting stray light in the eye. The ciliary's body is responsible for the accommodation of the lens. The pigmentation of the iris is responsible for the color of the eye. The size of the opening of the iris, the pupil, is variable and under control of the autonomic nervous system. The pupil gives the aperture of the eye and plays an important optical role ranging from about 8 mm diameter in low light conditions down to about 2 mm diameter in full sun-light.

The innermost layer is the retina. The retina is the visible light sensor in the human eye and an extension of the central nervous system and connected to the brain by the optic nerve. It contains two types of photoreceptors: rods and cones. The rods are more numerous (120 million) and more sensitive to light than the cones. On the other hand, multiple rods are connected to a single nerve fiber, and such fiber can be activated by any one of about a hundred rods, which reduces the visual acuity. The 6 to 7 million cones are concentrated on the macula, a central yellow spot on the retina, about 3 mm in diameter. In the center of the macula, there is a 0.3 mm diameter rod-free area with very thin densely packed cones, known as fovea. The cones in the fovea are thinner, with diameters of 3 μm down to 1.5 μm, and more densely packed than anywhere else in the retina. Also, cones in the fovea are individually connected to nerve fibers. This makes the fovea the area on the retina capable of the highest visual acuity. Outside of this central region, the eye's spatial resolution drops significantly. By studying cone densities, it has been found that the spatial resolution the human eye can resolve is cut in half at about 2 degrees from the point of fixation, and at 20 degrees, the resolution is cut by a factor of ten. For this reason, the eyeball must move continuously, so that light from the object of primary interest always falls onto the fovea.

The inside of the eye can be divided into three parts: the anterior chamber between the cornea and the iris filled with a watery liquid, the aqueous humor. The posterior chamber is the part between the iris and the ciliary's body and the lens, filled with aqueous humor, too. The third part is the vitreous chamber filled with a jellylike fluid called vitreous humor.

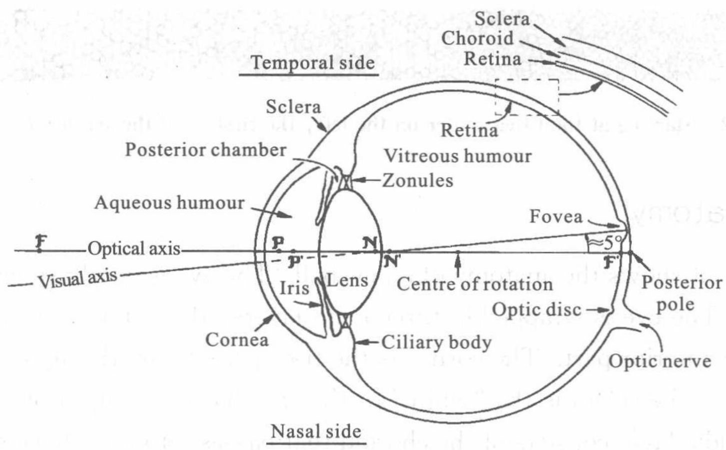

Figure 1. 3 Horizontal section of the right eye as seen from above
Reference: [Atchison] Cornea; iris; lens; pupil, retina; optic nerve, fovea, vitreous, optical axis.

The ability of the eye to resolve fine detail, visual acuity, is closely related to the density of photoreceptors in the retina, and the usual, straightforward way to determine and describe it is the relative detail size resolved when looking at a Snellen letter chart or Landolt rings. The nearer you are to the object being viewed, the smaller the level of detail that can be determined. For a normal eye, this limit angular separation is about one minute of arc (1/60 degree of arc) or 290 micro radians (what is known as the ocular resolution). See Figure 1. 4. A typical viewing situation, for example, places the viewer at about 600 mm from the display; at this distance, the eye can resolve $600 \times 0.000290 = 0.175$ mm. A point of light that is angularly smaller looks identical to a 0. 175 mm spot. Two small spots confined to less than 0. 175 mm appear as a single point of light. In history, the images produced by computer technology have far worse resolution, and this is usually compensated for by using different anti-aliasing techniques. However, optically produced holographic images generally exhibit resolution far beyond the abilities of the eye.

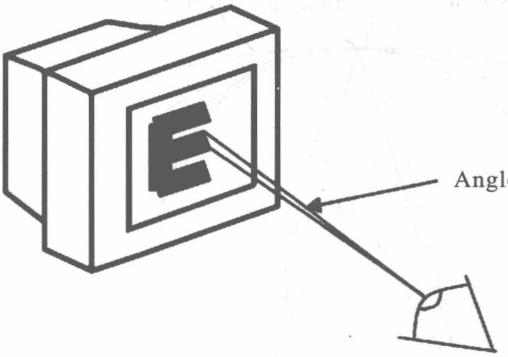

Figure 1. 4 Visual acuity of human eye is 1/60th of a degree of the visual context

1.1.2 Stereopsis

"Stereo" is a Greek work meaning "spatial" or "three-dimensional". Due to the fact that our eyes are separated by 6. 3 cm on average (also known as Inter Pupillary Distance, or IPD), each eye receives a slightly different perspective of the same scene. At every particular moment, each of two eyes perceives only a small fraction of the incoming wavefront limited by the size of the pupil (about 3 mm×3 mm). The retina images of two eyes are perceived and transferred to the brain by optical nerves. The brain understands the difference between those two views as cues for depth, and automatically fuses those two images to get a "center" view, which was not actually seen by either eye. The Mind's ability to create three-dimensional visual world out of two separate images is called stereopsis or binocular vision, giving the immediate impression of depth. The geometry of the binocular vision is sketched in Figure 1. 5.

The circle in which are situated all points perceived as single, while focusing on the point in the space point of fixation, is called horopter. The horopter takes the form of a circle. Points which are not on the horopter will have a retinal disparity. Disparities in front of the horopter are said to be crossed and disparities behind the horopter uncrossed. As long as the disparities do not exceed a certain magnitude, the two separate viewpoints are merged into a single percept (i. e. fusion). The small region around the horopter within which disparities are fused is called Panum's fusional area (see Figure 1. 5) i. e. , where the two retinal images are fused into a single image in depth. The limits of Panum's fusional area are not constant over the retina, but expand at increasing eccentricity from the fovea. At the fovea the limit of fusion is equal to a maximum disparity of only one-tenth of a degree, whereas at an eccentricity of 6°, the maximum disparity is limited to one-third of a degree and at 12 degrees of eccentricity without eye movements the maximum value is approximately two-third of a degree.

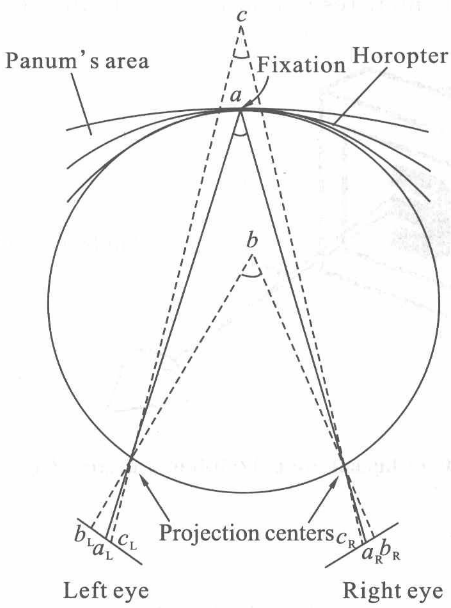

Figure 1. 5 **The geometry of the binocular vision when viewing the natural world. When you focus on a point *a* in space with both eyes, that point becomes the zero-disparity point. Other points in space that are closer or farther in depth will have different retinal projections in the two eyes relative to the zero-disparity point. Suppose that point *b* located somewhere in front of point *a*, in this case, the point *b* will appear further to a_L in the left eye image than to a_R in the right eye image.**

Typically, monocular visual field is 160° (w) × 135°(h), binocular visual field is 200°(w)×135°(h). Figure 1. 6 illustrates the monocular visual and combined field of view. In nature, many vertebrates have vision systems covering a wide with variable spatial resolution. This type of vision allows for an optimal use of the brain resources and simplifies the optics of the eye. Put on other creatures that predatory creatures have forward facing eyes to give good depth perception and good targeting; prey creatures have side facing eyes to give good all-round vision.

The number of distinguishably different views (called the parallax resolution) in a visual field is closely related to the visual acuity. This does not mean however that the vision outside the parallax resolution does not exist. The resolution of the perceived image, derived from the intensity on the retina, degrades for higher viewing angles, but a low-resolution image may still extend to more than 100° of viewing angle and called peripheral vision.

Estimates of the effective range of stereopsis vary across the literature, but it is clear that stereoscopic information becomes less effective as distance increases and retinal disparities become smaller. For distances beyond 30 meters disparities become negligible.

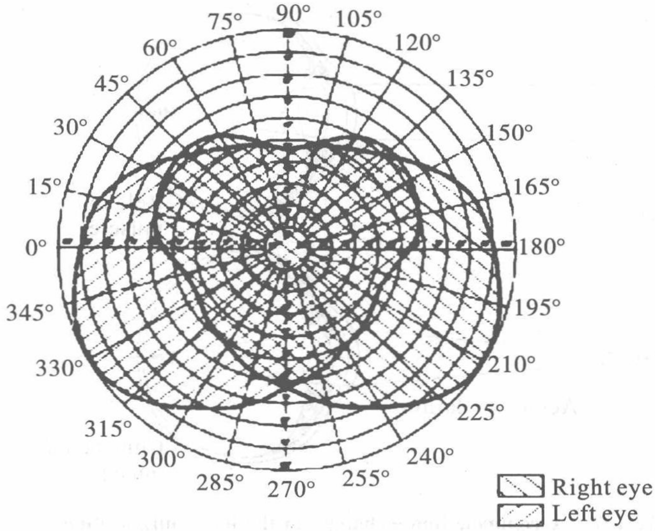

Figure 1. 6 The field of vision of the human

1.1.3 Accommodation and Convergence

The ability of the eye to change its effective focal length to image objects over a range of distances is known as fine focusing, or accommodation. Accommodation enables a person of normal vision to focus on object from infinity to a near point, on which an eye can only accommodate correctly. In a normal eye near point might be about 7 cm for a teenager, 12 cm or so for a young adult, roughly 28 to 40 cm in the middle-aged and about 100 cm by 60 years of age. The eye looses accommodation as it ages, called presbyopia. Accommodation is a weak depth cue, effective only at distances less than two meters and often coupled with other cues.

In the human eye there are two focusing elements: the cornea has a fixed power of about 40 dioptres, while the lens, which is adjustable by the surrounding ciliary muscles, brings the total power to around 60 dioptres when relaxed for distant vision and around 70 dioptres when fully tensed for near vision (In fish the adjustment is achieved by moving the lens, and in some birds it is achieved by changing the surface of the cornea).

Here the diopter is the unit of measure for the power of a lens or optical system, the abbreviation for which is usually abbreviated D. The diopter power of a lens is simply the reciprocal of its effective focal length, when the focal length is expressed in meters. For example, a lens with a 1-m focal length has a power of 1 diopter; a 1/2-m focal length, 2 diopters.

Convergence, by contrast, is the simultaneous movement of both eyes toward the point of interest or the inward rotation of the eyes to converge on objects as they move closer to the observer. The optical axes of both eyes converge on this point to image the object onto the respective fovea regions.