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Brief Survey on Three-Dimensional Displays: from Our Eyes to Electronic Hologram

Abstract:

In this paper, a brief survey on three-dimensional display technologies is reported. The survey starts from the basic consideration on how a human visual system can perceive depth, as the missing dimensional component, from two-dimensional planar images. As these visual depth cues have been identified, efforts are directed to construct displays that are able accommodate as many cues as possible. Numerous displays have been built in this respect, however, only two are presented in this paper: lenticular sheet and parallax barrier. This approach, however, does not comprehensively solve the problem since these apparatus can not reproduce the original object wavefront that contains phase of the wave within which the information of object's spatial location is embodied. Holography, conceived for the first time in 1948, is able to fulfill this necessity, and it is the main reason up to now holography remains considered as the only true three-dimensional display. The remaining part of this paper is subjected to discussion on holography. Discussions will be structured chronologically and will cover both progresses in both recording and displaying media, as well as the development in techniques whose long-time goal is to produce a real time holographic display.

1. Introduction

Vision, as the sense with the richest perception, has attracted attention for study even since the earliest recorded civilization. Of this wide subject, three-dimensional perception received a significant consideration because the limitation nature of image. An image is essentially a two-dimensional planar form that human, however, can perceive the observed objects as occupying three-dimensional space. An interesting phenomenon takes place i.e. a dimensionality reduction from three-dimensional real world space to two-dimensional planar shapes. According to history, study in this topic has even begun in ancient Greek philosopher era when Euclid in A.D. 280 reported depth perception from images perceived by human eyes must be related to pair of eyes of human visual system [1]. According to Euclid' s proposition depth perception can be derived from simultaneous impression of two different perspective, due to pair of eyes, to object under observation. Euclid proposal has laid the fundamental basis in three dimensional/ depth perception studies in modern era. In conjunction to volumetric imaging apprehension, the necessity of recording media to 'freeze' and store a segment of time of visual perception came into way since human brain is undoubtedly a real time processor: any incoming information just flow and apprehended continuously. Photographic plate invention in 19th century could accommodate the necessity with, however, the depth imaging remained in search.

This project paper reports a brief and breadth study on three-dimensional displays. The discussion initially begins with depth sensation perceived from planar images, termed as depth cues. According to interdisciplinary and separated studies from psychology, physiology, mathematics and related information studies, depth cues can be divided into two main categories: psychological depth of cue, which derived from a two-dimensional planar image and physiological depth of cues, which related to physiology of human visual system [1,2]. The latter depth of cues is stronger in providing depth of cues than the first cues do [1]. The three-dimensional displays are in intention to be designed to cover as many cues as possible within the apparatus. Due to broad range of designed equipment to meet this condition, the discussion on this topic is limited to only two major displays: lenticular sheet and parallax barrier [1,2].

As the science evolved, physics has contributed a revolutionary idea in constructing a three-dimensional display. Rather than building a means that provides as many depth cues as possible, physics has pointed out the shortcoming nature of any imaging detector. Imaging detector

responds only to amplitude but not the phase term of object's wavefront, i.e. phase information always lost during the recording stage [3,4,5]. Phase information can be mathematically shown contains the information of the spatial location of a point on the object's surface of where the wavefront emanating from. Preserving this information term enables one to reconstruct the points that constitute the object, the depth information can therefore be recovered [3,4,5]. Invoking this idea, Prof. Dennis Gabor, 1971 Nobel Laurate in Physics convinced for the very first time in 1948 the wavefront reconstruction technique and coined his invented technique as holography [3,4,5].

This subsequent part of this paper will deal with holography as the real three-dimensional imaging technique. The earliest Gabor's technique in his era, however, was not easily realizable and was not promising due to unavailability of coherent light source as the main requirement to perform his method [3,4]. For almost 20 years Gabor's method remained unexplored until the invention of laser as the most widely used coherent light source in the late 1950s, and the staggering experiment of Prof. Emmet Leith and Juris Upatnieks from Willow Run Laboratory of University of Michigan [3,4]. For the first time a visually 'enjoyable' three dimensional and holographic based image could be seen, attracted the attention of long lining patrons to annual Optical Society of America meeting in 1964 at where their holographic work was displayed [6]. Gabor and Upatnieks work also explicitly implored for the first time the Shannon's information theory, as well linear systems consideration, in analyzing hologram formation [3,4].

The demand of compact, ubiquitous hologram grew significantly after the spectacular work of Leith and Upatnieks. In this conjunction, the related notable work was from (former Sovyet Union) Prof. Yuri Denisyuk which based on Gabriel Lipmann's photographic work. Denisyuk was able to build a reflection hologram, instead of transmission hologram mode proposed by Gabor and Leith and Upatniek's. Denisyuk's hologram can selectively reflect a particular wavelength when illuminated with polychromatic white light. His work opened a possibility of using non-coherent polychromatic light instead of stringent coherent light necessity, as dictated by the early Gabor's requirement [7].

Major breakthrough in holographic display also occurred in 1969 when S. A. Benton from Polaroid Company discovered rainbow hologram [7,8,9,11]. The available hologram that time was not bright enough to be seen and he concluded it was due to a huge amount of displayed spatial information when a hologram is illuminated. Based on physiology of human visual system, he considered vertical parallax was redundant and could be removed [7,9,11]. The reduction of this parallax information significantly increased the hologram brightness in spite of colorful image yielded under polychromatic light illumination. His technique widely termed as rainbow hologram, which becomes the ample format of hologram today. The embossing technique invented in later years enables hologram to be printed in any planar surface [8,9].

To extend the limited parallax appearance of a hologram T. H. Jeong in 1967 showed the possibility of full rotation view hologram using numerous single photographic images and recorded holographically as a sequence of strip hologram [8,9,10]. This idea became profound when later years L. Cross synthesized a famous 360-degree discrete hologram called a 'Kiss II' for artistic display [9]. The latter technique was called holographic stereogram, invoking the term stereogram to illustrate this method composes several stereogram perspectives into a single holographic plate [10,11,12].

This paper will also briefly discuss the hologram-making methods after the Gabor's invention. These methods, however, are carried out using the same planar recording medium: photographic or celluloid plane. Anyone, who ever dealt with photographic work as the author experienced by himself, will realize the inconvenient stages before the image can be seen. Furthermore, the time-consuming photographic developing stage definitely hampers the realization of real-time imaging. As the computer became more powerful and less costly beginning in the 1970s, the quest of using computer to synthesize hologram also raised. The first attempt to answer this question was the work of Lohmann using an aperture at which its area can be adjusted to accommodate the object amplitude and shifted to four-quadrant direction to capture phase information [13,14]. Lohman's work then named as 'Computer-Generated Hologram' and became the 'popular' term for holographic pattern generation using method other than photographic work. Following Lohman's was the kinoform to synthesize phase-only hologram [3]. These two methods, as the earliest non-photography holographic method, will be also described here in this paper.

In the final part, the paper will briefly describe methods to pave the ways in implementing electronic holography. One of the contemporary methods is the opticall scanning holography work developed from Poon and Korpel's work in 1992 [15]. They could show the possibility of electronically synthesizing a hologram by means of acousto-optics crystal to produce time-varying Fresnel zone plate, as the holographic pattern of a point, based on heterodyning technique [15,16]. This is further analyzed mathematically by Prof. Poon in 1985 [17]. The technique enables the flexibility to electronically record hologram and subsequently stored and reconstructed the pattern computationally. Another method is the holographic video based on computational holographic stereogram developed in Media Lab [3,18]. The holographic stereogram pattern is computed and then fed to acousto-optic modulator to form the corresponding holographic pattern for diffracting the incoming laser beam into a point in a prescribed volume [18,19]. In spite of great reduction of holographic information by sacrificing vertical parallax along with size of object volume, this display however inevitably remains requiring a massive computational works to calculate the holographic fringe pattern [3,18,19].

The most foreseeing future application of these techniques is three-dimensional TV, which might be the first and initial final point of advanced three-dimensional study in the long-lasting search spanning from 300 years BC until now the 21st century [1,2]. However, numerous other applications of the real-time three-dimensional displays have been waiting such as medical imaging, scientific visualization, haptic interaction [20] until the future 'holodeck' concept in science-fiction TV series 'Star Trek'.

The purpose of this paper is not to provide new information. Some discussion in this paper also might be shallow that the author strongly encourages the reader to probe further in the specified field. The main goal of this paper is to provide the compendious basic concept of depth and spatial cues in human visual system that people historically have pursued in creating a display to cover as many cues as possible. Also, in relation to the lecture class, which only describes hologram as the three-dimensional technique, this paper is expected to provide the reader a more thorough perspective of three-dimensional imaging technique other than holographic method. In conclusion it can be shown that hologram is the only technique that can virtually provide three-dimensional perception to human visual system due of its unsurpassed ability to reconstruct the object three-dimensional wave.

2. Depth Cues

Modern psychological and physiological studies confirm Euclid's concept, described in Section 1, as one of physiological depth cues. The physiological depth cues itself is one of two groups of cue that provoke spatial perception. Other category of cue is psychological depth cues, which is essentially spatial perception obtained when someone looks at a two-dimensional picture. In this attempt depth information can be gathered even merely using one eye. This is possible because the depth is not derived from disparity of images captured by both eyes but from (previous) 'knowledge' of the observer to the image.

2.1. Psychological Depth Cues

Since visual system is the 'direct interface' between the environment, where the physical phenomena occurs and brain as the information processor, it is plausible to assume that the physiology of visual system strongly influences the perception of depth cues. To some degree, however, from a pair of planar images formed in both eye retinal areas depth perception can also be constructed by the presence of experience and imagination. This mainly affected by the mental of the observer when the observation takes place, thus the depth cues bear the term 'psychological' to distinct with stronger physiological cues.

As the experience and imagination, not the anatomy of visual system, play a significant role in this type of clue, depth sensation can be acquired even with using merely one eye. It is the

reason sometimes the psychological depth cues is also referred to monocular psychological depth cues, which consists several monocular cues. They will be briefly outlined in the following.

2.1.1. Retinal Image Size

As the magnification takes place in image formation due to distance from eye to object, the size object will appear differently in the retina. Based on the apparent object size, an observer can infer the distance, as well as depth, of the object.

2.1.2. Aerial Perspective

If we observe a wide-open scene, we subsconsciously perceive hazy or blur object as located farther from us. Less hazy and blur object will receive the opposite recognition. This perception is based from common knowledge that light from farther landscape will undergo more scattering from small particles in air than that at closer distant, as we can infer from landscape in Fig 1.

2.1.3. Linear Perspective

Related to previous cue, we can also infer the depth from change of image size as the object is located farther i.e. farther buildings will appear smaller than the closer ones. This also shown in Fig 1.

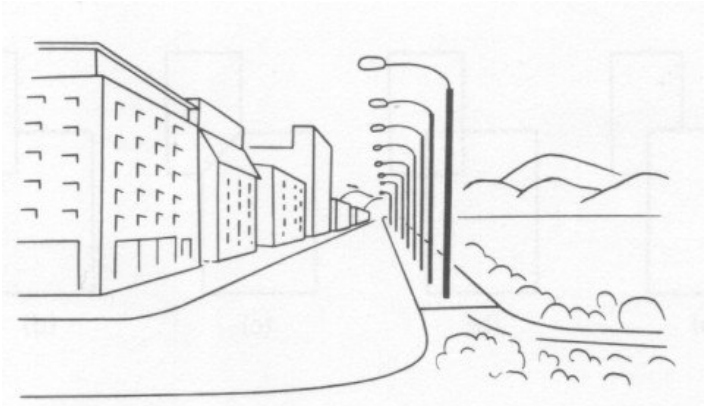


Figure 1. Picture to illustrate aerial and linear perspective cues (source: Okoshi 1976)

2.1.4. Overlapping or Occlusion

If there are two overlapped objets, the observer will perceive the object with continuous edge pattern as located closer as shown in Figs 2 (a) and (d), while no cues offered in Figs 2 (b) and (c). This idea can be extended for more than two objects. Occlusion is considered the most important monocular depth cue [21].

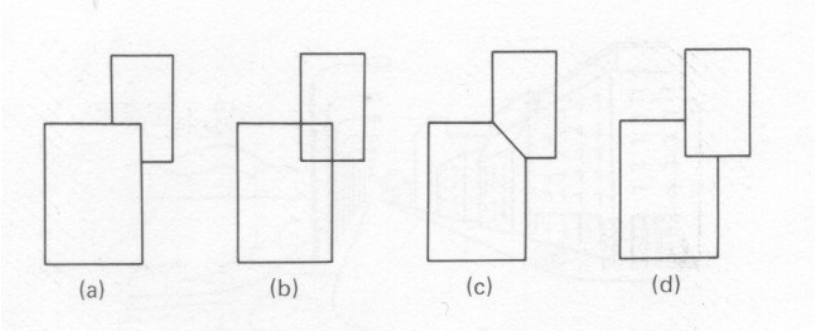


Figure 2. Overlapping or occlusion cue (source: Okoshi 1976)

2.1.5. Shades and Shadows

Depending on which part the object are located, shades and shadows can result in concavity or convexity relative on the observer's orientation. This is illustrated in following figure. Most of the observers will immediately associate Fig 3(b) with of window on a jail. The shadow on the ceiling of window tunnel signals that the part is out of sunlight and turns dark. Therefore it suggests a concavity. On the other hand Fig 3(a) mostly is linked with a tomb-like shape lying on a flat surface. The sunlight is always assumed to fall from above and the 'opposite' side is shadowed indicating it is out of sun reach. A convexity is noticed.
Interestingly, when we turn the figure upside down the perception becomes opposite to those of previous observation.

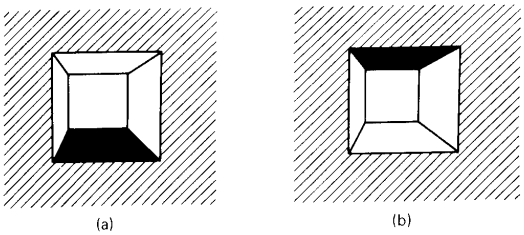


Figure 3. Shadows and shades depth cues (source: Okoshi 1976)

2.1.6. Texture Gradient

Change of roughness of texture can also be harnessed to infer depth, as shown in fig. To certain degree, we might consider this cue as part of linear perspective.

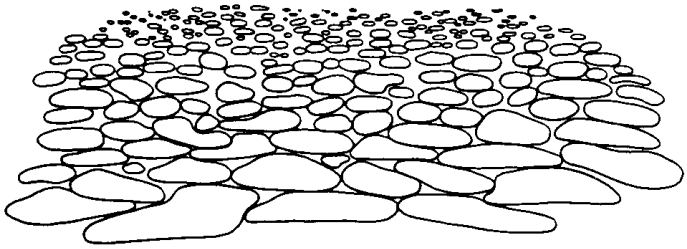


Figure 4. Depth cue from texture gradient (source: Okoshi 1976)

2.2. Physiological Depth Cues

Out of total ten, modern psychology groups the depth cues into two main categories. Six of them have been elucidated in previous section. The following is the brief description of the remaining four cues, which is considered as the stronger cues

2.2.1. Accommodation

The distance from retina, part of the eyes at which the visual sensation is initiated, to crystalline eye is fixed. In order to adjust the focal length distance the eyes itself must be able to adjust the required focal length until the sharpest image is obtained. The change is carried out by alteration of muscular tension that binds the lens. This ability is called accommodation and since this change is independent of both eyes the cue is monocular. This cue is effective only for distance less than two meters [2].

2.2.2. Convergence

While pointing to a particular spot on the object surface, muscular tension of both eyes will independently adjust the focal length and rotate the eyeball to cause optical axes of both eyes intersect on the observed point. Angle made by this fixation process is called convergence angle.
Research shows there is a strong interaction of convergence to accommodation but not vice versa. How far the eyes converge will influence the degree of accommodation. The opposite is also valid although weaker than the earlier, which can be inspected from a simple monocular experiment. From the study, it takes around 0.2-0.3 s for convergence to adapt to the precipitous distance change information, from infinity to 0.2 m, provided by accommodation mechanism.
If the two-pupil separation is P_O , distance from eyes to object is a and angle of convergence is α (shown inn Fig. 5), then

$$\alpha = \frac{P_O}{a}[rad] \text{ or } 57.3\frac{P_O}{a}[\deg], \tag{1}$$

or

$$\left|\frac{d\alpha}{da}\right| = \frac{P_O}{a^2}, \tag{2}$$

which suggests change of convergence angle is inversely proportional to squared distance. This confirms experimental results that ne-degree convergence angle change, for typical pupil distance 6.5 cm, takes place on these two extreme distance changes: distance change from ∞ to 3.58 m and from 25 to 23.4 cm.

Together with accommodation, convergence remains an effective cue for distance less than 10 m.

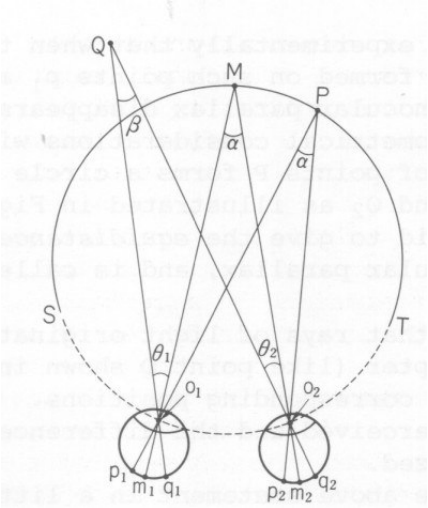


Figure 5. Convergence by triangulation of eyes (source: Okoshi 1976)

2.2.3. Binocular Disparity (Parallax)

When head is at rest position, two eyes will fixate at a point of interest on the object surface. Rays of light from that point will fall on the fovea centralis, the most light-sensitive area of eye. Points other the fixation spot, however, will not always be focused down to center of retina but to different corresponding locations in the retina. This effect is called binocular disparity or binocular parallax, and depth inference due to this cue is called stereopsis.

Stereopsis can be analyzed from convergence angles of different points [2]. With reference to Fig. 6, using only two points for simplicity, we can conjecture the distance of those two points by [2]

$$\Delta D = D_\beta - D_\alpha = \frac{P_O}{2\tan\left[\tan^{-1}\left(\frac{P_O}{2D_\alpha}\right) - \frac{\theta}{2}\right] - D_\alpha}, \quad (3)$$

or for very small θ

$$\Delta D \cong \frac{D_\alpha^2 \theta}{P_O}. \quad (4)$$

From vernier experiment, the minimum detectable angular disparity is around round 10 seconds of arc [1]. By using Eq (4) typical lowest depth of resolution for a certain distance can be calculated. With typical values of P_O and convenient display viewing distance of 6.5 cm and 46 cm, respectively and invoking more conservative value of minimum disparity angle 30 seconds of arc ($1.45\ 10^{-4}$ radians) [2] , the minimum depth of resolution is found to be 0.47 mm.

Study also indicates that for a moderate viewing distance, stereopsis is the dominant depth cue to produce depth sensation.

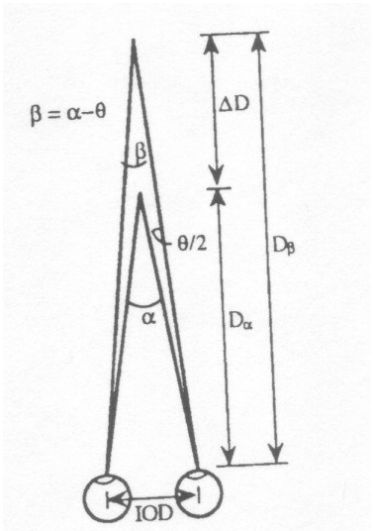


Figure 6. Depth resolution from convergence and binocular disparity (source McKenna & Zeltzer, 1992)

2.2.4. Motion Parallax

An observer however is indeed free to move, not limited to fix his/her head, while viewing an object. Allowing an observer while watching, as long as the movement is less than eye pupil diameter, permits him or her to have multiple perspectives of the object [1,2,22].

In general, motion parallax is defined different angular velocity of objects at different depths from the observer. Closer objects move across field of view faster than the farther object does. Hence depth can be inferred from this cue inversely proportional relationship between apparent object's speed with distance.

Motion parallax is recognized as a powerful method to identify object shape and relative depth distance. Since human visual system perception is more sensitive intensity change which visually seen as edges in order to identify shape, motion parallax simultaneously serves as a cue for depth as well as shape.

Furthermore since this cue can be seen as combination of several perspectives of binocular disparities, the presence of motion parallax cue will generate binocular parallax cue as well but not vice versa [21].

2.3. Range of depth cues coverage

According to McKenna and Zeltzer's investigation, depth cues have a certain range in which they become effective and more dominant than the others. The following discussion is based on their noticeable description [2].

For moderate to far distance (over 10 meters), accommodation and convergence give depth information from matching the depth of the scene instead of differentiating relative depth for shorter distance. For example in a flight simulator by collimating light from emanating from close display surface, the image will appear as if it came from great distance.

In shorter distance binocular parallax can be dominant, or at least important depth of cue. For an unfamiliar object, in which the pictorial depth cue can not resolve the depth information, binocular disparity mechanism provides an identification method not merely by differentiating depth of points on the object but also from this depth ability to separate fore and background images. Binocular disparity, however, can be the only cue for depth dominating over other cues. Random dot stereogram is a profound example.

Binocular disparity will serve as dominant cue when the psychological cues are severely ambiguous. Also this cue will aid well in low bandwidth or noisy images that no relation present between noise components on both images by increasing the signal-to-noise ratio.

In much greater distance where triangulation is difficult to perform, motion parallax allows the observer to infer depth by 'looking around objects and obscuring elements. Experiments show the presence of motion parallax improves the ability of the subject to locate target in space using 2-D images.

For most cases of 2-D still imaging the only depth cues are the psychological depth cues. At least two pictorial cues must be provided by display: linear perspective and image size.

In practice, there will be no single or dominant cue that provokes a proper depth perception. For instance in a flight simulator, pictorial depth cues are needed to form a realistic long-range view an appropriate level of atmospheric scattering needed to be presented. This in turn will create hazy and fog impression as main feature of aerial perspective. It is also important to present appropriate size of objects and more importantly the texture of terrain's objects. Familiar size of object will inform the trained pilot the aircraft height while the proper texture assists the pilot to approximate the ground surface contour. From the physiological counterparts, especially for higher speed, the motion parallax becomes increasingly important. In simulation that includes short-range view, such as refueling simulation, stereopsis needed to be employed as well.

3. Examples of Three-Dimensional Displays

Three Dimensional Displays in general can be grouped into two main categories: stereoscopic and autostereoscopic [1,2]. The first refers to displays that require additional viewing aid to provoke spatial sensation. This kind of display is widely available in market. Most of the commercial display, other than hologram which will be explained later, that bears '3-D' or 'three dimensional' labels are in the category of stereoscopic. One of the examples of this apparatus is the famous 'View Master', which currently under registered trademark of Fisher-Price. The principle of this viewing aid, however, roots back to the 'stereoscope', invented by Sir James Wheatstone the first 3-D display recorded in history. Stereoscope employs two pictures, each designated for left and right eye separately. The pictures are of the same object but taken slightly translated to mimic image disparity of both eyes. Indeed in this viewing aid binocular disparity becomes the dominant depth cue. The movie with 3-D label also exploits the same principle: the picture was taken by two cameras, one slightly translated from the other. Image captured, for instance, for left camera is filtered with vertical polarizer that only allows vertical polarization of incoming light to be recorded and horizontal polarization for right eye. The viewing glass is constructed to imitate the camera ideas: left side of the glass is the vertical polarizer sheet and horizontal-oriented sheet for right side. When a viewer watches the 3-D movie, left and right eye will receive slightly different perspective, which is the neccessity of depth sensation provided by binocular disparity cue. We can verify the different filter orientation of the glass by noting different

colors of the left and right sides: different polarization molecules that constitute the sheets will reflect different color.

In the following examples, the discussion will be narrowed only on autostereoscopic displays. In opposite to stereoscopic display, this type of display does not require any viewing aid to see 3-D effect.

3.1. Lenticular sheet

3.1.1. Integral Photography [1]

If we move our head or body to get motion parallax cue, assuming both eyes fixate to a point in space, it is essentially similar to 'sample' the object space. The 'sampling period' to get one perspective is approximately about the size of eye's pupil. It is clear that the smaller the angular displacement, the finer perspective we can capture, which increases the resolution.

This idea to increase angular perspective was adopted into photography. Rather than moving the camera, an array of small lenses is placed at a focal distance in front photographic film. Finer sampling will be carried out by this array than a single lens does. This method is known as integral photography technique, proposed for the first time by a notable French optics investigator M. G. Lipmann in 1908. Imaging principle of this apparatus is shown in Fig. 7 as follows: suppose the array consists of 10,000 fly's eye lens sheet and assume that this system takes a picture of a man with a red rose is clipped on his suit shown in Figure. Subsequently, at the photographic film 10,000 red dots, viewed from different various directions, will be recorded. These 10,000 red spots will follow the similar paths as those on the recording stage at the reconstruction stage. A viewer in the left (in front of the lens array) will see a red notch towards the direction of the original position of the flower and this means the viewer will observe a something red floating in space where the original red dots originated from.

The problem in integral photography is the depth inversion, known as pseudoscopic image which is opposite to image we normally see as orthoscopic images. This problem also occurs in holography when we attempt to observe the real image (this will be discussed later). One proposal to overcome this flaw was from Ives in 1931 using the scheme shown in Fig. 7. His technique usually called as two-step integral photography

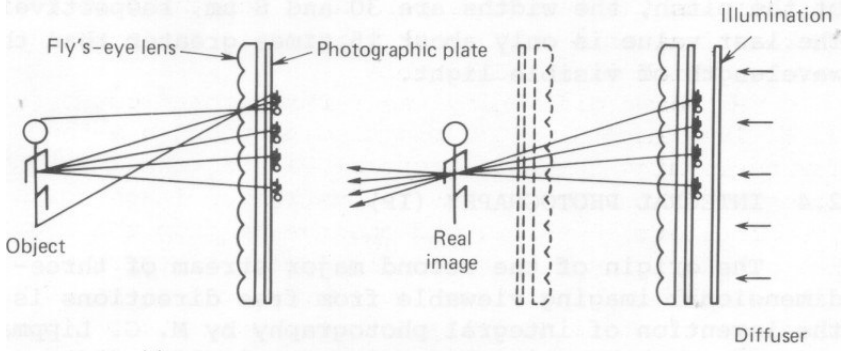
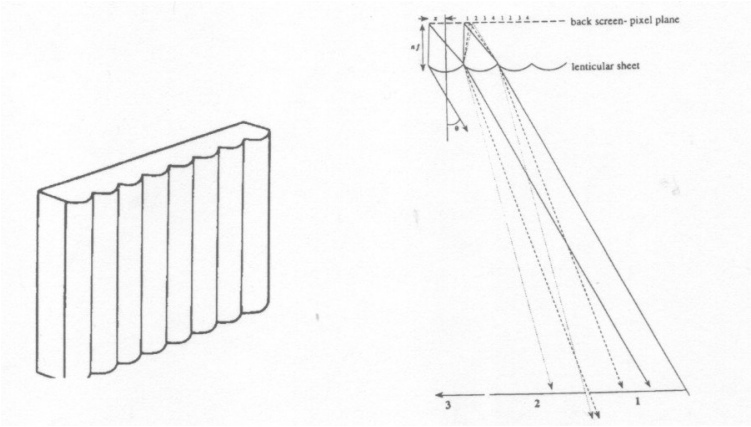


Figure 7. Integral Photography (a) Recording, (b) Playback. Dashed lens sheet refers to pseudoscopic image conversion suggested by Ives (source Okoshi 1976)

3.1.2. Lenticular sheet

The lenticular sheet system is a simplification of the predecessor integral photography type (20 years before the lenticular sheet was proposed). Vertical orientation of the lens sheet is sacrified leaving only horizontal direction. Original tiny lenses therefore can be replaced by sheet of convex cylindrical lens having focusing power only in horizontal direction imitating the nature of human eye, which grasps only the horizontal parallax. Typical (horizontal) lens sheet is shown Fig. 8(a).



(a) (b)

Figure 8. (a) Lenticular sheet as a compound of (horizontal) cylindrical lens (source Okoshi 1976), (b) Image formation in lenticular sheet display (source McKenna and Zeltzer, 1992 adapated from Hamasaki 1980)

At the play back stage, the vertically oriented image is located again at one focal length behind the lens sheet. In the diagram shown in Fig 8 (b) four strip images, or vertical pixel in CRT display, behind the lens will be deflected out from single lens axis at angle θ. The deflection angle depends θ on focal length *f* and shift of the image strip from lens axis *x* [2]

$$\theta = \frac{x}{f} \tag{5}$$

Directing the image in several subzones will allow parallax cue when an observer traverses horizontally across the display. Tiny shift between vertical strips will be perceived by left and right eyes as different images that cue of binocular disparity, as well as convergence, is supported. Since, however, the image is located at focal distance the deflected image will be collimated that an observer will see the image as if it were at infinity. No accommodation cue available in this display.

Disadvantage of this type of display is the requirement of high resolution in horizontal direction. If the sheet is employed in CRT display, the highest resolution is limited by display resolution (pixel size). Other problems arise from the lens. Smaller lens is prone to due to aberration and diffraction problems that the deflection is not parallel but with some angle. This in turn limits the number of subzones that can be differentiated from one to each other [2]. Alignment is also an issue since imperfect alignment will not image the strips onto its appropriate subzone [2].

As reported by McKenna and Zeltzer, they employed lenticular sheet with focal length of 1.9 mm and dividing the image into 8 zones from a display of 2560x512 pixels. At viewing distance of 460 mm, the viewing zone subtends at 31.6 degrees and the gap between subzone is about 4°[2].

3.2. Parallax Barrier

The diagram of parallax barrier is shown in Fig 9. It employs vertically oriented slits and the picture behind the slit is fine strip alternating images for left and right eyes. The slits limit part of the image the eye should see. Each eye will see different perspective. The depth can be inferred by binocular parallax and convergence cues [1,2].

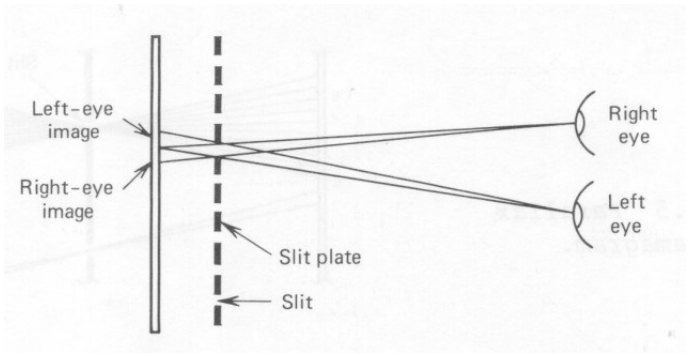


Figure 9. Parallax Barrier arrangement (source Okoshi 1976)

This type display, however, has several drawbacks [1,2]. The use of the slit inevitably reduces the image brightness, even entirely blocks the image. Second problem is the small shift begins to introduce diffraction effect. Left or right eye will not only perceive the corresponding image but also the smeared adjacent image due to diffraction. Third problem associated with the slit pitch. The slit pitch *p* must meet the requirement

$$p < \frac{viewing\ distance}{3500}. \qquad (6)$$

For example, if the slit width is 0.1 of the pitch for viewing distance 250 mm the slit width should less than 8 μm – only 15 times the visible wavelength [1]. Similar to lenticular sheet, this display can not provide accommodation [2].

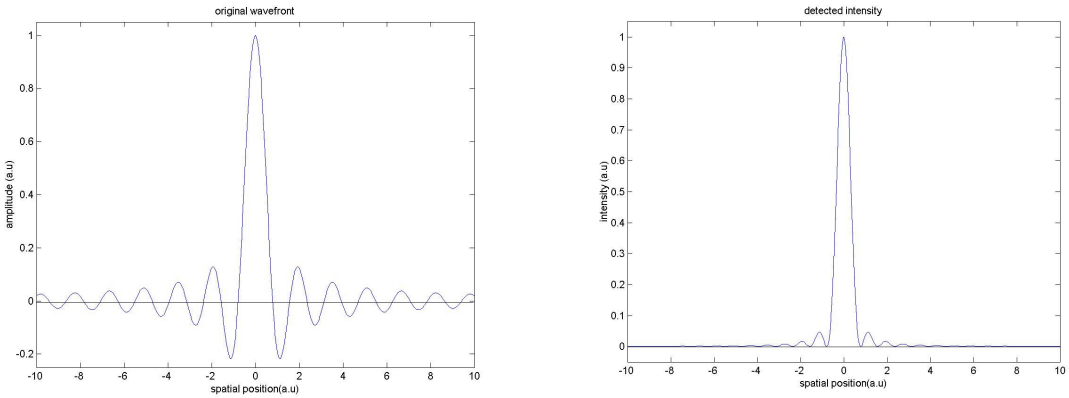
4. Wavefront reconstruction

On the previous two examples of three-dimensional display, the analysis is based on ray or geometrical optics. Further analysis using wave optics reveals some missing information that previous analysis can not provide.

Everything that our eyes, or light detector, see in the universe is the reflected light impinging to the observed object. Since according to wave optics light is (electromagnetic wave), every light detector, including our eyes, physically detects the wave emanating from the object. Light wave, however, oscillates at a very high frequency, visible light frequency for instance is in order of hundreds of Tera Hertz (Tera = 10^{12}). Time response of any available detector is extremely much slower to respond the instantaneous undulation of light, that the response is merely the average of the wave within the detector's time response.

This averaging process also changes the initial shape of the object's wave, or usually called as wavefront. Based of Huygens theory, the direction of where the points on the object that emanates the wave also determine the shape of the object's light wave. Therefore a change in the wavefront will deteriorate the spatial information of the wave and the intrinsic spatial location of the object points is not recovered. Depth (spatial) information can be only inferred using psychological depth cues as described in section 2.1.

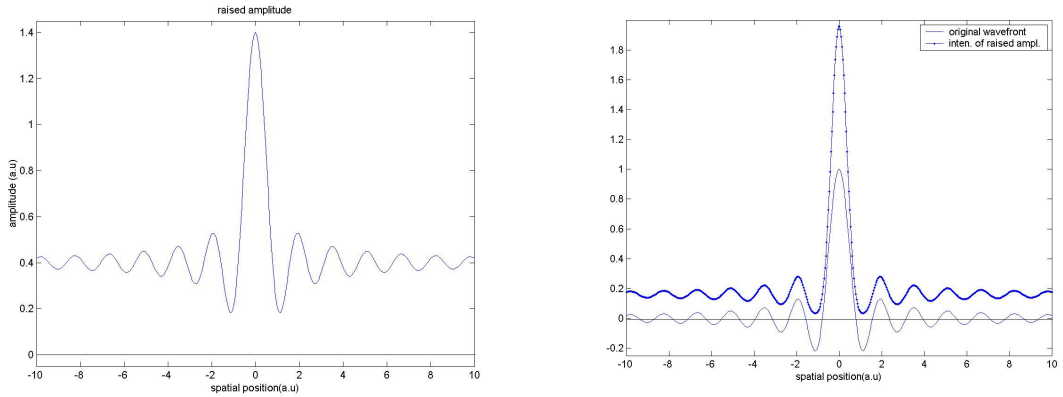
Caulfield illustrates the change of the wavefront shape in the Figure 10 [24]. Suppose the original wavefront is the shape shown in Fig 10(a). The averaging process of light detector produces the deteriorated shape from the original in Fig 10(b).



(a) (b)

Figure 10 (a) Original wavefront, (b) Detected intensity at the light detector

If we somehow can devise the light detector such that the amplitude of every point in the incoming wavefront is larger than zero, as shown in Fig 11 (a), then the detected intensity, with higher intensity value, should maintain similar shape to that of initial incoming wavefront, as shown in Fig 11(b). Dennis Gabor' s got this idea in 1948 in order to overcome spherical aberration problem in his electron-microscope system.



(a) (b)

Figure 11 (a) Amplitude-raised original wavefront (b) Detected intensity of the raised wavefront compared to original shape of object waves.

Preserving the shape of wavefront will maintain the spatial information of the point objects that the three-dimensional information can be retrieved. Gabor coined his invention as holography stemmed from two Greek words: *Holos* and *Graphien*, which literally means entirely draw or write. In this context both amplitude and phase term, that contains the wave spatial information, is completely recorded. This technique is in opposite to conventional light detector, that merely preserves the amplitude of object's wave and detected as intensity.

As the wave's phase term, in which the information of spatial position is embodied, is maintained the true 3-D senastion can be displayed in holography. This also can be pointed out from the way a human's eyes observe incoming wavefront. First: the alteration of eye's lens shape that the incoming wavefront shape falls onto retina. Second: wavefront sampling by both eyes at two slightly different positions. Third method is similar to second method but performed at many different locations [22]. These three mechanisms are essentially physiological depth cues: the first method is accommodation, the second is binocular disparity and motion parallax as the third method. Hence we can draw conclusion that in order for a display to be capable of presenting the true three-dimensional perception, the display must be able to reconstruct and

rebuild the original object's wavefront. Since holography, up to now, is the only technique that enables us to reconstruct the object wavefront ,it is appropriate to say that holography is the true three dimensional imaging techniques.

5. Off-axis holography

Description on initial Gabor's experiment on holography at 1948 will not be described here. Some papers and texts reveal his invention in further details [3, 6, 8, 23]. The first hologram, however, showed a poor result due to obstruction of bright zeroth order light to the observed image diffracted at higher order.

Until almost 20 years later holography was out of attention. In 1964 two researchers at Willow Run Laboratory of University of Michigan, Emmet Leith and Juris Upatnieks identified similarities between their work in synthetic aperture radar and holographic technique proposed by Gabor. Working through communication theory analysis they identified that the image is essentially modulated on reference beam, similar situation as that on information-modulation onto carrier wave. Overlapping between zeroth and first order can therefore be precluded if the frequency of reference beam, as the carrier wave, is high enough that it will be shifted to prevent superimposition with the object frequency content. In order to increase the spatial frequency of the light, the reference beam must be titled and not parallel to optics axis as performed in Gabor's original technique. Leith and Jupatnieks technique is called off-axis holography to distinguish with the on-axis Gabor's method.

If the tilted angle is θ, the reference beams spatial frequency f is related to light wavelength λ through the expression

$$f = \frac{\sin\theta}{\lambda}, \tag{7}$$

From equation above, it is clear that larger θ will separate the image farther the blocking zeroth order. Also selecting lower wavelength will increase the reference beam frequency. This, however, is at the expense of the necessity of high spatial frequency content of the recording medium. The necessity sets the upper limit of angular separation of undiffracted and diffracted beam.

For instance, with wavelength red laser light of 0.6 μm and titled angle of 45° the recording medium must be able to capture the reference beam spatial frequency of 1000 line-pairs/mm [5]. The available photographic recording media, however, have much higher resolving power. For example, one of the most widely used holographic plates Agfa 8E75 HD has resolving power about 4,000 cycles/mm and typically most of the silver-halide emulsions have resolving power about 2,000 line-pair/mm [4]. Notwithstanding, the method proposed by Leith and Upatnieks has opened for the first time the possibility of seeing the true three-dimensional image. Their first hologram was displayed in 1964 annual meeting of Optical Society of America creating long line of patrons who wished to see it. The era of hologram started ever since, shifted from laboratory work to art and aesthetic entities.

As indicated in section 3.1.2 the lenticular sheet and parallax barrier lack of accommodation depth cue. In fact, prior to hologram all the acclaimed three-dimensional displays were always lack of accommodation [1]. Hologram provides all depth cues due to wavefront reconstruction nature of its operation [21].

6. Reflection Hologram

The holographic discussion in previous section refers to transmission recording and reconstruction mode. In this scheme, the holographic fringe pattern will be formed and three-dimensional image will appear when the reference beam illuminates the photographic plate from the same side.

In 1962, Yuri Denisyuk, from former Sovyet Union inspired of the previous works from Bragg in light diffraction and that of Lippman in photography, created other holographic mode called the reflection hologram. In his work, Gabriel Lipmann layered the backside of photographic film with highly reflective alluminum film. Incoming object beam will be reflected and interfered with the beam itself. This process creates a standing wave within the emulsion in the form of interference grating. If a polychromatic light falls upon the medium, a particular wavelength will be rfelected as long as the angle and wavelength fulfills the Bragg condition. The Lippman photographic plate therefore is wavelength selective. Invoking the Lipmann's idea to create the grating, Denisyuk arranged the object and reference beam to interfere within the emulsion. The resulting interference pattern in this mode is the holographic fringes. Split (two) beam Transmission and Reflection hologram recordings setup is shown in Figure 12 (a) and (b). Figure 12 (d) shows the direction of reconstructed image if the reflection hologram is illuminated. Note that in transmission mode the reference and object come from the same side while the opposite occurs in reflection mode.

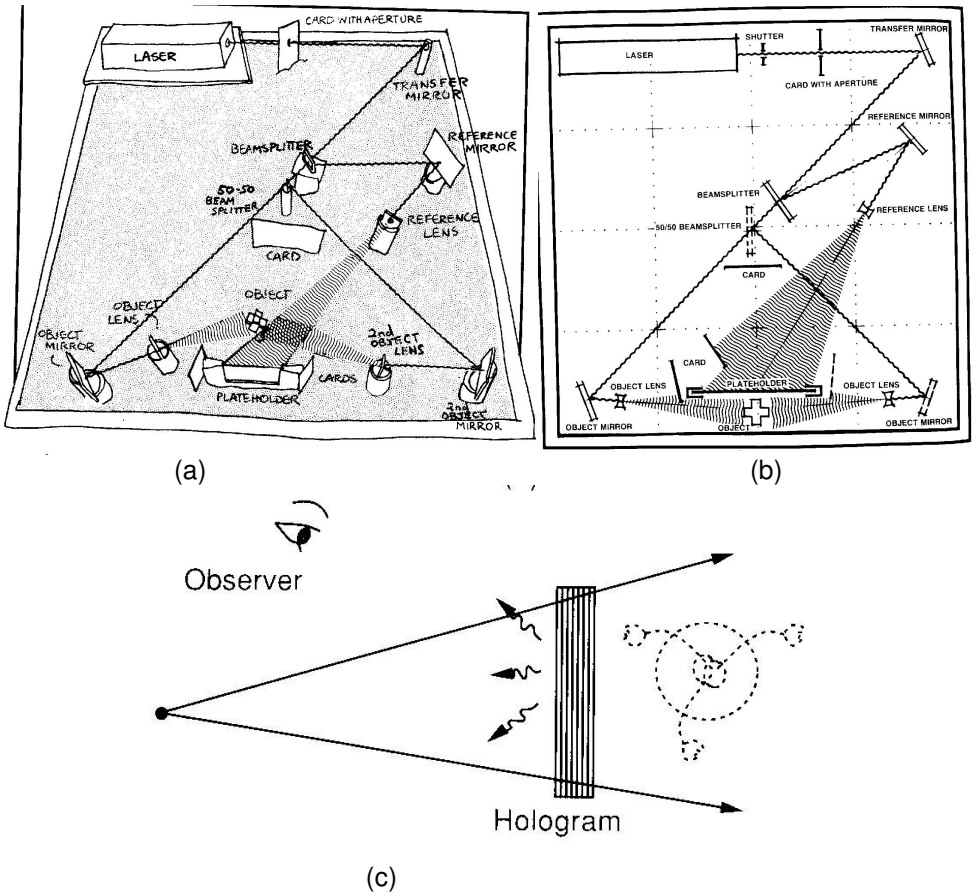


Figure 12. Typical hologram recording set-up of (a) transmission and (b) reflection mode using split (two) beams, (c) Reconstruction of reflection type hologram (source a and b Unterseher et. al 1982, c Goodman 1996)

In transmission mode hologram, different wavelength of reference beam at the reconstruction stage and that of recording stage will turn the hologram to undergo astigmatism due to dissimilar axial and lateral magnification. Advantage of reflection over transmission hologram is when the hologram is illuminated by white light, it will automatically select the reflected wavelength as long as the wavelength fulfills due to Bragg condition [3,4]. Disadvantage of this type of hologram is smaller fringe spacing. The fringe spacing Λ within the recording medium can be calculated using the relation

$$\Lambda = \frac{\lambda}{2\sin\left(\frac{2\theta}{2}\right)}, \tag{8}$$

where θ is the angle between object and reference beam. When θ approaches 180°, as in the typical arrangement of reflection hologram recording, the fringe spacing will be about half of the wavelength within the emulsion [3,4]. Other problem is the shrinkage of the emulsion particle during the chemical developing and drying stage [4]. The color of the hologram in reconstruction will therefore be different from that in recording step. Usually if red laser used in the recording step, the reflected wave will turn into green [4].

7. Information content in a hologram

Hologram has a superior ability to provide the real true three-dimensional images, all of physiological and psychological depth cues are naturally displayed and rich of perspective images viewed at continuous angles entailed with other cues. It might, however, raise the question on the amount of information within a hologram.

The answer to that question is information content in a hologram is extremely humongous. This can be shown in following equations following discussion by St.-Hillaire [23]: as hologram is physically a grating, then hologram should satisfy grating equation

$$\lambda f_h = \sin\theta, \tag{9}$$

with f_h is the maximum spatial frequency of fringes and λ is wavelength of diffracted light and θ is the angular extent of viewing zone. From Shannon's sampling theorem the minimum sampling frequency is twice of the maximum frequency of signal to be sampled

$$f_s = 2f_h = 2\frac{\sin\theta}{\lambda}, \tag{10}$$

and for one-dimensional (for instance horizontal-parallax-only) hologram of width d the number of required sample N is

$$N = df_s = \frac{2d\sin\theta}{\lambda}. \tag{11}$$

For a full (horizontal and vertical) parallax of width d the minimum total number samples N_t must be

$$N_t = \frac{4dw\sin^2\theta}{\lambda^2}. \tag{12}$$

For example a 100 x 100 mm^2 hologram with maximum diffraction angle 30° according to Eq 12 requires a minimum of 2.5 x 10^{10} samples for a single frame. If a real time hologram of 60 frames/second with 8-bit resolution can be implemented, the system requires minimum of 12 x 10^{12} bits/second [23], definitely beyond the ability of conventional high-resolution display data rate of 2 Gbits/sec [2]. It is the reason that the real-time holographic image display can hardly be implemented.

8. Rainbow Hologram

Motivated by demand to build a reduced information-content hologram [8], in 1968 S.A. Benton a researcher at Polaroid Company, realized that vertical parallax can be sacrificed in order to lessen the information content. He developed a holographic recording technique that only allows horizontal parallax by placing a horizontal slit to transfer the (first) master hologram onto the (second) image hologram. This is shown in Fig 13.

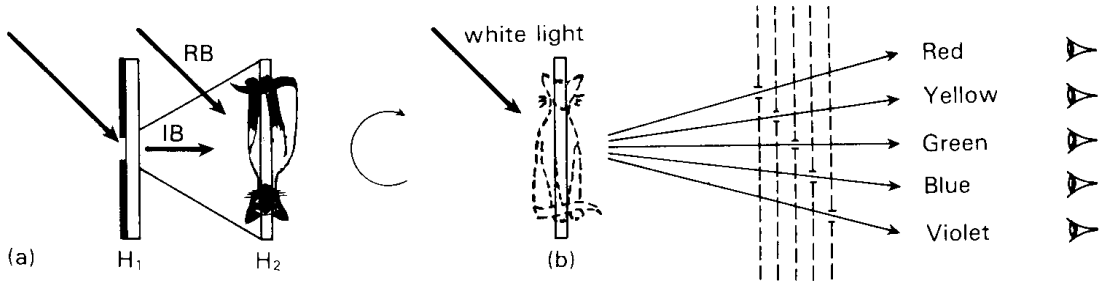


Figure 13 (a) Additional recording stage in making rainbow hologram (b) color spectrum (rainbow) appearance as the viewer looking up and down (source Saxby 1988).

The master hologram (H1) is made through similar procedure in making the common transmission hologram. Master hologram H1 subsequently illuminated by anti-reference beam, the reference beam coming from reversed direction to that of previous recording stage, with a horizontal slit placed in front of H1. The beam coming out of H1will produce real image and this image will serve as the object for the next hologram H2 (called image hologram). The direction of reference beam for H2 is similar to that for H1. This stage is shown in Fig 13 a.

Similar to reconstruction of hologram that will display the initial object, at the reconstruction stage of a rainbow hologram the image will appear very sharp when viewed at the exact location of the slit used in making the second hologram. Within the slit pupil, image appears bright and clear, otherwise it looks blur. Apparently, the Benton's technique is also the solution to common problem of limited image depth in transmission-mode full aperture transfer hologram (shown in Fig 14). This hologram has a shallow depth of image. Part of object deeper than the depth will exhibit color smear if observed at slightly different perspective.

When a rainbow hologram is illuminated with white light and the observer moves up and down within the slit area, he/she will see sharp and bright images at, however, different colors. Within the slit area, the color of image will be the same as the one used in recording. Shifting vertically, within the slit area, the image will remain sharp but color will change continuously as one in rainbow, shown in Fig 13 b.- where this technique bears the name [3,4,8]. Outside the slit the image will look blur.

9. Embossed Hologram

As the hologram became widely available, moving from laboratory to marketable commodities the demand of mass production of hologram, particularly as printable media, also grew up drastically. The holographic techniques discussed so far employ light sensitive (high-resolution) chemical emulsion layered upon glass or celluloid plane. Inevitably, a method to transfer hologram from photographic film onto any commercial product surface is required.

In 1974 Michael Foster proposed a mechanical method to duplicate the hologram [8]. The hologram as the product of his method was called embossed hologram. This embossing technique has enabled us to see hologram printed on surfaces of any commercial entities including the use of hologram for identification and security since hologram can be massively produced and duplicated.

The schematic diagram of embossing technique is shown in Fig 14. The process [4,8] begins with holographically recording the subject onto photoresist surface. Fringes will be printed as a relief structure on the material. Creating fringe pattern on a photoresist material requires a powerful laser that it must be carried out by a special company, not a homemade lab.

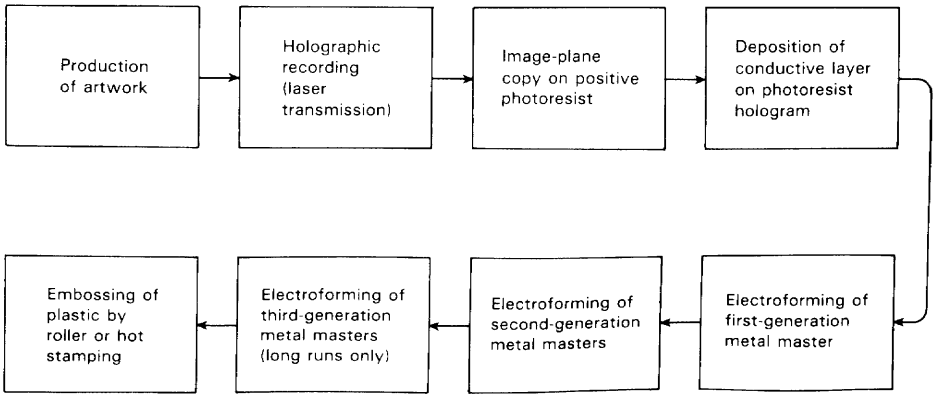


Figure 14. Steps in producing embossed hologram (source Saxby 1988)

Result of this stage is a photoresist master hologram that subsequently undergoes electroforming stage. In this step the master hologram is made to be conductive by spraying metal, usually silver on the photoresist surface. The sprayed master now is immersed in a tank containing pure nickel and a current is flown into the tank. The thin layer of nickel now is deposited on the top of the photoresist master. At this stage the metal master hologram has been formed and the photoresist master can be removed. The metal master hologram acts like a 'stamper' that a new second-generation metal master can be formed using this first generation by repeating electroforming stage.

The metal master hologram foils now is to be embossed on a surface. The typical process to emboss hologram is called hot-foil blocking or hot stamping that now becomes the standard method to print hologram onto papers, legal documents, credit cards. The process is shown in Fig 15. Using this process big companies such as American Banknote and Bradbury Wikinson can press up to 5000 cycles/hour [8], turning hologram into mass production. The resulting hologram will be a reflection type and with the total thickness of about 3 microns blended with the product surface there is no other way to remove it unless by breaking the product [8].

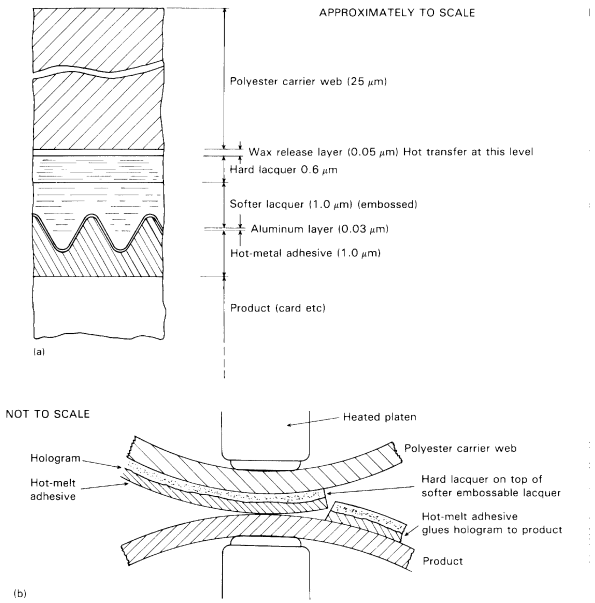


Figure 15. Hot stamping process to print metal hologram onto a surface (source Saxby 1988)

10. Multiplex Hologram

Related to section 7 regarding huge amount of information contained in a hologram, in communications typically the main way to reduce bandwidth, and subsequently the information content, is by multiplexing. Since hologram is also a means to deliver information it is also possible to multiplex smaller holograms onto larger hologram. The fact that a hologram can provide infinite number of parallax that is actually indistinguishable by eye's angular resolution, determined by pupil separation and viewing distance [27], brings multiplexing into consideration: the object is sampled at discrete perspective and record the finite views onto a hologram. As the taking pictures at a number of views is a common activities in stereography, the more popular term for multiplex hologram becomes holographic stereogram. Some initial proposals in this technique were from McCrickerd and George in 1968 and De Bitteto in 1969 [3,4,8,10] which the corresponding set-up is schematically shown in Fig 16.

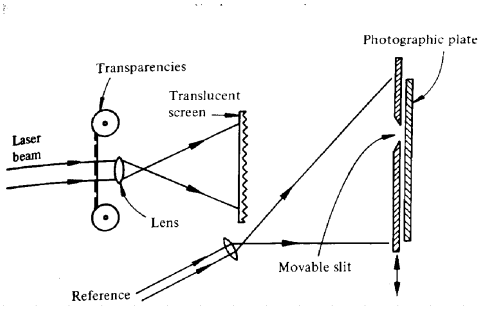


Figure 16. Holographic stereogram set-up proposed by De Bitteto (source Hariharan 1996, adapted from De Bitetto 1969)

Multiple photograph views of the object are recorded in a transparancies. As the 'object' for hologram is the diffuser or translucent screen which is a single transparency frame illuminate d by laser light. As one transparency frame is advanced, the movable slit also progresses to multiplex holographic record of one frame. At the reconstruction stage, the hologram will present discrete horizontal parallax and no vertical parallax available.

A somewhat more artistic holographic stereogram technique was proposed by Cross. The object was placed on turntable and photographed for a full rotation at discrete angles, as shown in Fig 17 (a). In the recording step, Instead of using movable slit the multiplexing is carried out by the use of cylindrical lens that directs the projection of a frame into a vertical strip image. This is shown in Fig 17 (b). Similar to De Bitteto' s method, the hologram will contain contagious vertical smaller hologram and exhibit only parallax view.

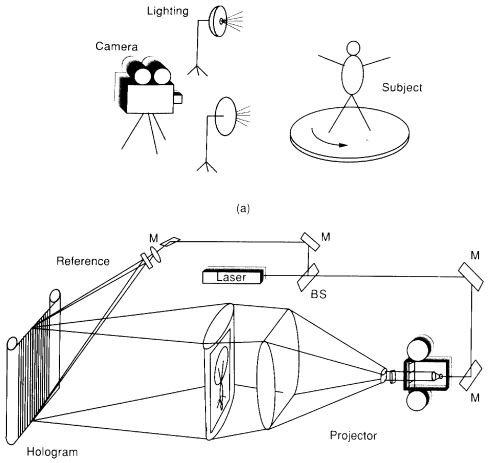


Figure 17 (a) Recording of perspective sequence of the object, (b) Transferring the sequence as hologram (source Goodman 1996).

Typically the reconstruction of Cross hologram is made by wrapping the hologram onto a cylindrical surface and locating a white light source to illuminate the hologram. White light illumination will cause color change appearance as an observer moves the head up and down.
Figure 17. Displaying a Cross holographic stereogram (source Goodman 1996)

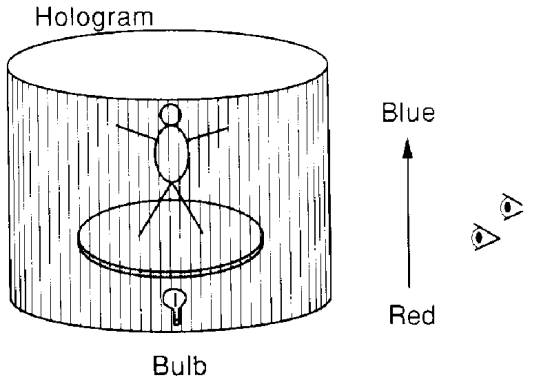


Figure 17. Displaying a Cross holographic stereogram (source: Goodman 1996)

11. Computer Generated Holography

As one has experienced the procedures in making hologram using photographic plate, he/she might consider the work as labor intensive and somehow time consuming. The latter fact hinders photographic plate based hologram to be implemented as real-time display. It is common that eventually we expect a method that enables a hologram is recorded onto a non-photographic plate with much shorter the recording time. Stimulating by the swift progress in electronic-based display, efforts were directed to methods in sampling the holographic fringes, mimicking steps in the digital image processing. As the hologram becomes available in discrete form, the computer can then generate the discrete representation of the pattern. The final step is to plot the generated pattern on a transparency and illuminate it to produce the desired hologram.

The earliest computer generated hologram (CGH) method was the binary detour phase technique proposed by Lohmann and Brown in 1966 [3,4,14]. The following derivation refers to brief but explainable description in Goodman's text [4] to synthesize Fourier hologram. The physical realization of the hologram is a cell in which there is an open aperture within the cell. The width of the opening determines the amplitude while the offset of center of the aperture relative to the center of the cell encodes the phase. The goal of the encoding is to create the final image in the form of

$$U_f(u,v) = \sum_{p=0}^{N_X-1}\sum_{q=0}^{N_Y-1}\left|a_{pq}\right|e^{j\phi_{pq}}e^{j\frac{2\pi}{\lambda f}(up\Delta x+vq\Delta y)}, \tag{13}$$

where $U_f(u,v)$ is the final image amplitude produced by hologram, and

$$a_{pq} = U_h(p\Delta x, q\Delta y) = \left|a_{pq}e^{j\phi_{pq}}\right|, \tag{14}$$

with a_{pq} is the Fourier coefficient and $Uh(p\Delta x, q\Delta y)$ is the field pattern at hologram plane. Eq. 13 and 14 show the final image field is a sum of the image constituent Fourier components with its corresponding amplitude and phase.

The aperture in the cell is a rectangular that can be expressed with

$$t_A(x,y) = rect\left(\frac{x-x_0}{w_x}\right)rect\left(\frac{y-y_0}{w_y}\right) \quad . \tag{15}$$

If this aperture is illuminated with by an inclined plane wave

$$U_p = e^{-j2\pi\alpha x}, \tag{14}$$

with α equals to sin2θ/λ, and 2θ is the angle between plane wave propagation vector and normal of hologram, the transmitted field will be

$$U_t(x,y) = e^{-j2\pi\alpha x} rect\left(\frac{x-x_0}{w_x}\right) rect\left(\frac{y-y_0}{w_y}\right), \tag{16}$$

and at Fourier plane the field becomes

$$U_f(u,v) = \frac{w_X w_Y}{\lambda f} \sin c\left[\frac{w_X(u+\lambda f\alpha)}{\lambda f}\right] \sin c\left[\frac{w_Y v}{\lambda f}\right] e^{j\frac{2\pi}{\lambda f}[(u+f\lambda\alpha)x_0 + vy_0)]}. \tag{17}$$

The variables follow the diagram in Fig 18.

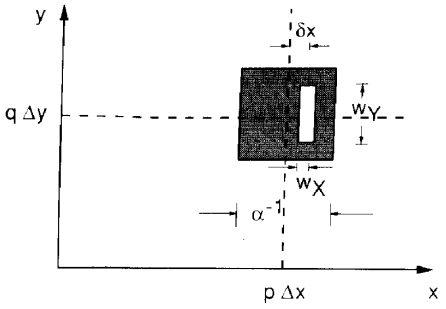


Figure 18. Cell and aperture structure in binary detour-phase CGH method (source Goodman 1996)

If the width of the aperture w_X is chosen to be much smaller than reconstruction beam period or $w_X << \alpha^{-1}$ then the first sinc term can be removed. Also if the size of the region of interest in image plane is much smaller than the width sinc functions, both sinc terms can be replaced with unity. Overall approximations give simpler linear term

$$U_f(u,v) = \frac{w_X w_Y}{\lambda f} e^{j2\pi\alpha x_0} e^{j\frac{2\pi}{\lambda f}[(ux_0 + vy_0)]} \tag{18}$$

Since the goal is construct cells that represent Fourier components expressed in Eq. 13, we need to establish the index assignment to every element. Choosing p and q as the index, the center of (p,q)th cell can be written as $(x_0)_{pq} = p\Delta x$ and $(y_0)_{pq} = q\Delta y$. Using these indexed centers to Eq 18 becomes

$$U_f(u,v) = \sum_{p=0}^{N_X-1}\sum_{q=0}^{N_Y-1} (w_X)_{pq}(w_Y)_{pq} e^{j2\pi p} e^{j\frac{2\pi}{\lambda f}(up\Delta x + vq\Delta y)}. \tag{19}$$

In Eq. 19 it is assumed α^{-1}, period of the reconstruction beam, is equal to width of a cell Δx. The term $e^{j2\pi p}$ serves as to accommodate the phase due to the shift, or in other words when the center of the aperture coincides with the center of the cell, the second exponential term can be set to one. Comparing Eq 19 with Eq 13, the amplitude of the Fourier harmonics can be trimmed by modifying width of aperture in y-direction w_Y. Aperture width in x-direction can not be adjusted since it needs to fulfill the condition $w_X << \alpha^{-1}$.

By shifting the aperture in x-direction, its center position becomes $(x_0)_{pq} = p\Delta x + (\delta x)_{pq}$, Eq. 19 now, due to the shift, becomes

$$U_f(u,v) = \sum_{p=0}^{N_X-1}\sum_{q=0}^{N_Y-1}(w_X)_{pq}(w_Y)_{pq}e^{-j2\pi\frac{(\delta x)_{pq}}{\Delta x}}e^{j\frac{2\pi}{\lambda f}\left(up\Delta x+u(\delta x)_{pq}+vq\Delta y\right)}. \quad (20)$$

If, once again, the region of interest in the image plane is small enough that $\frac{L_U(\delta x)_{pq}}{2\lambda f} << 1$, where $-L_U/2$ to $L_U/2$ is the region of interest of the image in u direction, the exponential term in Eq. 20 for u direction $e^{j\frac{2\pi}{\lambda f}u(\delta x)_{pq}} \approx 1$, leaving only

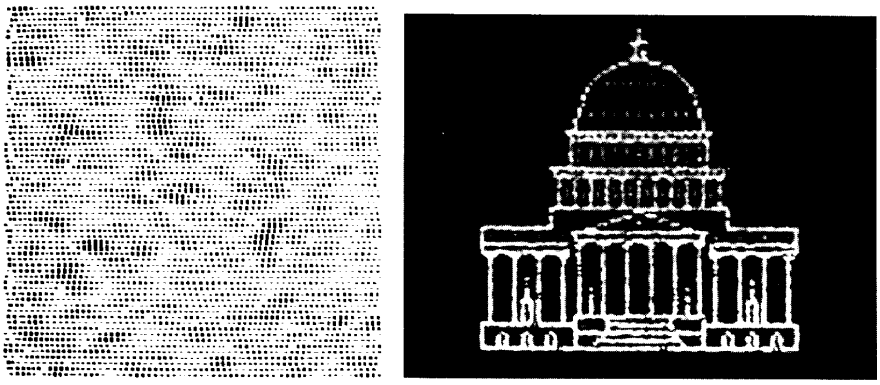
$$U_f(u,v) = \sum_{p=0}^{N_X-1}\sum_{q=0}^{N_Y-1}(w_X)_{pq}(w_Y)_{pq}e^{-j2\pi\frac{(\delta x)_{pq}}{\Delta x}}e^{j\frac{2\pi}{\lambda f}(up\Delta x+vq\Delta y)} \quad (21)$$

By comparing to Eq 13, the phase of (p,q)th cell ϕ_{pq} is related to the shift of the aperture $(\delta x)_{pq}$ through

$$\phi_{pq} = -\frac{2\pi(\delta x)_{pq}}{\Delta x}, \quad (22)$$

with amplitude of (p,q)th harmonics is proportional to width of aperture in y-direction or $(w_Y)_{pq}\alpha|a_{pq}|$.

Example of CGH pattern generated using this method is shown in Fig. 19, where Fig 19 (a) is the plotted calculated pattern on a transparency and Fig 19 (b) is the hologram after plotted pattern in Fig 19 (a) is illuminated by laser light.



(a) (b)

Figure 19 (a) Plotted CGH pattern on a transparency (b) Image after transparency is illuminated (source Goodman 1996, pictures courtesy of A. Lohmann and were reprinted by permission International Business Machine Corp.).

12. Electronic Holography

Despite its capability to record holographic pattern not onto a time-consuming process photographic plate, binary hologram remains need a significant amount of time to transfer the pattern on the plastic sheet or any transparent material. Other problem the resolution of ink plotter

or any means to write the pattern on the transparent surface sets the upper limit of CGH resolution although one can encode computationally in finer detail.

The progress in optical modulator enables one to create a beam-modulating pattern electronically, which can be conveniently carried out in computer. In the following is the discussion of two of the most recent displays using acousto-optics modulator (AOM): scanning holography and holographic video. Description of AOM is not given here, it can be found in several standard optical information processing texts such as reference 4 and 5.

12.1. Scanning Holography

If a three-dimensional imaging system can be modeled as a linear system, then the imaging system holds superposition property: any arbitrary output is composed of responses of any individual element that constitutes the input. Furthermore, if the system can replicate the holographic pattern of a point then the complete holographic pattern of an object can be generated since an object can be viewed as a collection of a large number of points.

The point hologram is called Fresnel Zone Plane (FZP) [4,7,8]. If this pattern is scanned over an object and the scanning result is detected, we will obtain a scanned version of hologram of the object. Poon and Korpel proposed a method to create FZP by superimposing plane wave and spherical wave of different temporal frequency and named the pattern as time-dependent FZP [5.15,16,17]. In further development the time-dependent FZP (TDFZP) is implemented in a system called Optical Scanning Holography [5,15] in which TDFZP is scanned over the object in recording stage. The scanned object will modulate the TDFZP that the detected signal collected by photodetector will be a heterodyne current in the form [5,16]

$$i_{scan}(x,y;z,t) \approx \sin\left\{\frac{k_0}{2z}\left[(x-x_0)^2+(y-y_0)^2\right]-\Omega t\right\}, \tag{23}$$

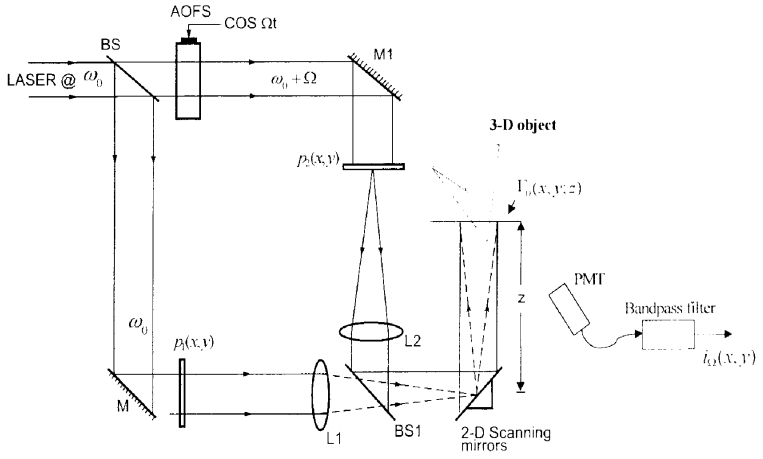


Figure 20. Basic configuration of optical scanning holography set-up (source Poon & Banerjee 2000)

where Ω is the difference of temporal frequency of plane and spherical waves, and k_0 is wave number. The current in Eq 23 is due to a point object with offset (x_0, y_0) located z_0 from focal plane of lens L1, as shown in Fig. 20.

After demodulation and bias adding that enables the demodulated signal to be stored in square-law device [15], the stored information will be

$$t(x,y) \approx 1 + \sin\left\{\frac{k_0}{2z}\left[(x-x_0)^2 + (y-y_0)^2\right]\right\}. \quad (24)$$

The expression above is similar to familiar mathematical expression of FZP recorded on a photographic plate [5,15]

$$t(x,y) \approx A + B\sin\left\{\frac{k_0}{2z}\left[(x-x_0)^2 + (y-y_0)^2\right]\right\}, \quad (25)$$

with $A = a^2 + \left(\frac{k_0}{2\pi z}\right)^2$ and $B = \frac{ak_0}{\pi z}$, a is the reference wave amplitude. This shows the OSH capability of producing the point source hologram.

This system possesses several advantages. First is definitely its ability to gain holographic information in electronic format that can be sampled and stored conveniently in a computer. Other advantage is since the data is gathered through one-dimensional scanning, the light detector can be merely a photodetector. This set-up also inherently records carrier-frequency hologram, the holographic pattern modulated in spatial carrier frequency as proposed by Leith and Upatnieks to prevent overlapping between zeroth order and real image [15].

Application of OSH includes pioneering in 3-D fluorescence microscopy [27] as the first hybrid between the coherent holographic technique and incoherent fluorescence microscopy. Instead of using plane and spherical wave with temporal frequency of ω_0 and $\omega_0+\Omega$, in this application on both interferometer arms are plane waves with temporal frequency of $\omega_0-\Delta\Omega/2$ and $\omega_0+\Delta\Omega/2$. As the object is two solution drops consists of high density fluorescence latex beads located at different axial depth at separation of about 2 mm. With scanning area of approx. 2 x 2 mm^2, using $\Delta\Omega = 2\pi$ x 10.7 MHz the system can resolve lateral and axial resolution of 7.7 and 200 μm.

12.2. Holographic video

In 1989, spatial imaging group at Media Lab MIT reported that they have synthesized holographic display in real-time (video) format [3,23,28]. The system is inspired by the previous hologram displays: the binary detour phase, holographic stereogram and rainbow hologram.

The core of the system is the multichannel AOM that diffracts the incoming expanded laser beam to points in space corresponding to a section of a horizontal line of a hologram. This is similar to rainbow hologram effect that the viewer will see the sharpest image, with all depth cues, when his/her eyes located at the slit used previously in the recording stage.

The idea of fringe generation in this system is similar to idea of computer graphics: working backwards to create desired image from the initial description of what the object should look like. This idea is equal to the one in binary detour phase hologram that the area and shift of the aperture are determined from the desired Fourier components to be appear on the image.

Process in making holographic stereogram can now be synthesized in computer [25,26,28]. The calculated hologram is now needed to be implemented as an input signal to AOM. In order to do this, the calculated pattern is now decomposed into the so-called basis fringe: a small holographic element that has uniform a spectral content and diffract the light at the same angle [28]. The element bears name 'basis' after the concept of any signal into orthogonal basis functions [28].

Since the displayed image is a hologram only of a horizontal strip portion, then the complete image can be displayed if there is a mechanism to stack every hologram line on the top of each other. This necessity is facilitated by the vertical scanning mirror [23, 28]. The horizontal array is required to compensate the drift of beam when it traverses inside the AOM that the image will appear stationary [23,28]. Configuration of MIT holographic video is shown in Fig. 21.

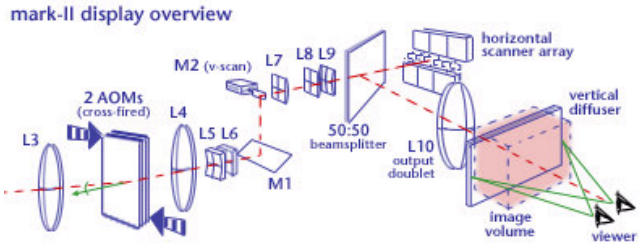
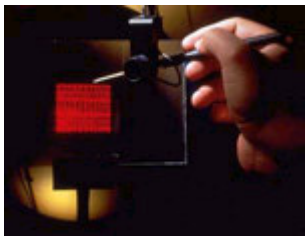


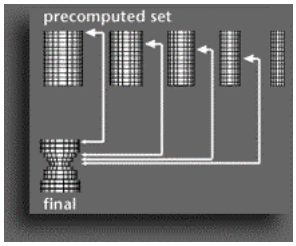
Figure 21. Configuration of second generation MIT holographic video display (source: http://spi.www.media.mit.edu/groups/spi/HVmark2.htm)

The first generation of MIT holographic display was capable of displaying cubical image 25x25x25 mm with 15° view zone at 20 frames/second. The second generation although with only monochromatic illumination and lower frame rate it is able to generate bigger volumetric image of height, width and depth of 80,140 and 150 mm, respectively.

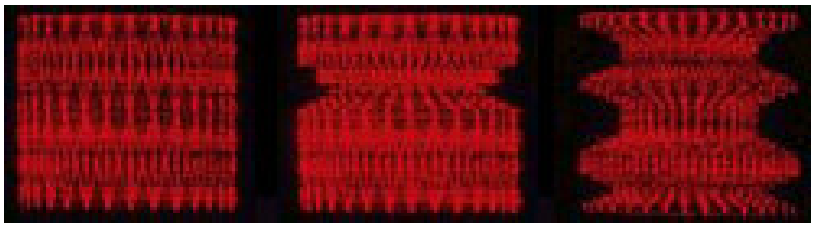
One of the most interesting application of this display is the haptic (force feedback) hologram developed also in the same lab [20]. As one 'applies a force' on the hologram, the system will calculate the new 'deformed' hologram and update the fringe calculation, as well as applying repulsive force to simulate friction in real carving. Instead of calculating the entire holographic pattern, based on the model to be shaped, the holographic system can provide a pre-calculated set of fringe to speed up the fringe calculation: the most update shape is sum of the possible element in the pre-computed holographic shapes. Faster fringe calculation enables the haptic operator to always refresh the hologram apparent as well as the counter-force to the operator. Assume at the same time there exits a system at different location that is simultaneously working on the real object, at the end of haptic operation the desired object can be obtained as shown in Fig 20 d.



(a)



(b)



(c)



(d)

Figure 22 (a). Force applied to hologram (b) Pre-computed hologram shapes, (c) Dynamics of apparent changes of the hologram due to force 'applied onto' (d) The real object has been completely carved to get the desired shape
(source http://spi.www.media.mit.edu/groups/spi/HHlathe.htm)

13. Conclusion

Often our sense of depth is taken for granted [2], therefore in this survey depth cues issue is first to be explored in first two sections. There are ten depth cues, six of psychological, which based on observer's mental and prior knowledge and four of physiological cues. The latter is considered being able to provoke spatial perception stronger than the knowledge-based cues. The goal of 3-D display design is to construct a display that is able to present as many depth-cues as possible, particularly the physiological cues. Examples of two 3-D displays prior to invention of hologram, lenticular sheet and parallax barrier, are presented in section 3. Prior to hologram, all three-dimensional displays were only able to provide parallax and binocular disparity as well as convergence. Studies show that eyes respond to incoming wavefront in various mechanisms such that four physiological cues can be obtained as described in section 4. Hence the only way a display can provide all physiological cues is to present the wavefront of the original object. So far, hologram is the only means which is capable of reconstructing the wavefront of the object.

Next part of the discussion is on various techniques to improve hologram itself since the first Gabor's hologram had a low quality of image. One of the degrading factors is a severe overlapping of non-diffracted light and image-carrying diffracted beam. Brief discussion in overcoming this problem is given in section 5, the Leith and Upatnieks proposal a tilted reference beam to prevent the overlapping. Using this technique enabled hologram for the first time became visually joyful in viewing that provoked true spatial perception. The existing hologram, however, looked impractical since it required a large space for set-up table even just reconstruction a mid size hologram frame. There existed a demand that hologram can be reconstructed only by simple polychromatic light source such as sunlight, incandescent lamp. Inspired by the previous work by Lipmann, Denisyuk proposed a method to extract holographic image that can selectively choose the wavelength when the hologram was illuminated with white light. Other feature of the technique that the light source can be placed in the same side as the viewer since the image retrieval mode was reflective, instead of transmissive. This is briefly discussed in section 6.

Leith and Upatnieks proposed method has a drawback of raising the spatial frequency content of hologram that also eventually increases the information content of hologram. Section 7 exposes a simple method to calculate information content of hologram. A method to reduce information content of hologram, as well as method to increase image brightness, was proposed by S. A. Benton. The method is called rainbow hologram and shortly presented in section 8. Now hologram is ubiquitously found everywhere, from cereal box until credit card even in money bill. The technique that enables hologram to be printed on any surface is called embossed hologram, which is quantitatively described in section 9.

Leith and Upatnieks method of using tilted reference beam to separate image and zeroth order beam was inspired by the common way in communication to use carrier wave to shift the object's spectral from the DC term. Comparability of holographic signal analysis with communication theory brought other idea to reduce information through multiplexing, which is common in communication, to holography. Two major multiplexing hologram techniques from De Bitetto and Cross are also briefly discussed in section 10.

As one has experienced holographic work, it makes sense if the experimenter would like to have a non-photographic hologram work. Photographic work is procedural intensive, performed in dark room which might be inconvenient to certain individuals and time consuming that hampers the ultimate goal of research in producing real-time holography. Storing a chemical based emulsion also requires a certain handle that might become a painstaking activity if the number of stored plate grows. On the other hand as the speed and performance always improves, computer becomes the backbone in imaging work. It is plausible that efforts were directed to enable computer to generate holographic pattern. The first computer generated hologram (CGH) method was proposed for the first time by Lohmann and Paris in a binary format pattern. The method was called binary detour phase hologram. The holographic data could then be conveniently stored in computer, avoiding physical storage as one for photographic hologram.

At the time the binary detour phase was proposed, a dynamic optical modulator was not widely available. The pattern was printed on a transparency using plotter or ink printer that inherently set the upper limit of image resolution. As the electronic-based optical modulator

becomes widely available these days, some new holographic methods using dynamic modulator have been proposed. The proposed methods usually categorized as electronic hologram, which discussed in section 12 and only two of the methods along with their applications are described in this paper. Both method use acousto-optics modulator (AOM) is the dynamic medium.

The first method is optical scanning holography (OSH) proposed by Poon and Korpel described in section 12.1, in which a time-dependent Fresnel Zone Plate (TDFZP) is created by superimposing plane and spherical wave of slightly different frequencies. The detected signal becomes the hologram of sampled point scanned across the object. Complete scanning of the object means the scanning has collected the complete hologram of the object and ready to be reconstructed. This set-up has been employed to improve performance of fluorescence microscopy.

Other method is holographic video from MIT Media Lab, which combines several previous holographic techniques. It is essentially the electronic format of holographic stereogram in which the fringe generation follows the concept in computer graphics: working backwards from the description of the object and then perform the calculation to obtained the desired image. The calculated pattern is subsequently fed to AOM to diffract the expanded beam as a hologram of a slice in the object. To obtain the entire object the hologram lines are multiplexed, the same technique in holographic stereogram. An interesting application of this computer extensive method is haptic or force-feedback interaction between hologram and user. Possibility of this application is such as telesurgery where the patient is not present in the operation table but the doctors will 'operate' the hologram of the object. On the other location a decicated robot for surgery, for instance will perform similar action the doctors do at distant.

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