

Pinhole Imaging based Solutions for Stereoscopic 3D and Head Worn Displays

by

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Dedicated to the soul of my guardian;

MOM ...

ABSTRACT

Two well-known existing problems of stereoscopic displays are the accommodation-convergence conflict and the lack of natural blur for defocused objects. We present a new technique that we name Super Stereoscopy (SS3D) to provide a convenient solution to these problems. Regular stereoscopic glasses are replaced by SS3D glasses which deliver at least two parallax images per eye through pinholes equipped with light selective filters. The pinholes generate blur free retinal images so as to enable correct accommodation, while the delivery of multiple parallax images per eye creates an approximate blur effect for defocused objects. Experiments performed with cameras and human viewers indicate that the technique works as desired. In case two pinholes equipped with color filters per eye are used, the technique can be used on a regular stereoscopic display by only uploading a new content, without requiring any change in display hardware, driver or frame rate. Apart from some tolerable loss in display brightness and decrease in natural spatial resolution limit of eye due to pinholes, the technique is quite promising for comfortable and realistic 3D vision, especially enabling the display of close by objects that are not possible to display and comfortably view on regular 3DTV and cinema.

We propose a simple virtual reality (VR) type head-worn display (HWD) system, where a pinhole array relays the image on a smart phone display to the retina of a user without requiring any lenses. The sub-images relayed through the pinholes are seamlessly tiled on the retina without ghost (double) images or blank regions by using an optimized pinhole design and by pre-processing the images shown on the cell phone. A proof-of-concept prototype with a 3 mm exit pupil successfully verifies the developed theory and demonstrates the delivery of full color images within a diagonal field-of-view (FoV) of 45 degrees at a resolution of about 4 cycles per degree.

The experiments also demonstrate the interesting possibility that there are multiple options for the display content that generates a desired retinal image, including those obtained with random decisions. The system is low-weight, very low-cost, and can deliver diffraction-limited images across a wide FoV. However, the spatial resolution is moderate due to small pinhole size. Also, pupil tracker sensors and a dynamically configurable pinhole array are needed to handle changing pupil size and locations.

ÖZETÇE

Stereoskopik ekranların iyi bilinen iki sorunu; göz merceği uyumsuzluğu ve odaklanılamayan nesnelerde doğal blörün olmamasıdır. Biz bu sorunlara uygun bir çözüm olması için Süper Stereoskopi (SS3B) adını verdiğimiz yeni bir teknik sunuyoruz. Sıradan stereoskopik gözlükler yerine, ışık seçici filtrelili iğne deliklerinin üzerinden her bir göze en az iki paralaks görüntü gönderen, SS3B gözlükler kullanılmaktadır. İğne delikleri blörsüz retinal görüntüler üreterek göz merceği uyumunu sağlamakta ve bu sırada çoklu paralaks görüntülerin göze ulaştırılmasıyla odaklanılamayan nesneler için kısmi blör etkisi oluşmaktadır. Kamera ve insan gözlemcilerle yapılan deneyler tekniğin istendiği gibi çalıştığını göstermektedir. Her göz için renk filtrelili iki iğne deliğinin kullanıldığı durumda bu teknik, sıradan stereoskopik ekranlarda herhangi bir donanım, sürücü veya kare hızı değiştirmeden sadece yeni içerik yüklenerek kullanılmaya uygundur. Görüntüdeki kabul edilebilir parlaklık düşüşü ve iğne delikleri sebebiyle gözde oluşan doğal uzamsal çözünürlük azalması dışında, bu teknik konforlu ve gerçekçi 3B görüntü için, özellikle sıradan 3BTV ve sinemalarda görüntülenmesi mümkün olmayan yakın objelerin gösterilmesinde umut vadetmektedir.

Bu tezde, bir basit başa takılan gösterge ile sanal gerçeklik (SG) sunmaktayız ve bu sayede lense gerek kalmadan akıllı telefonun ekranındaki görüntüyü, iğne delikleri sayesinde kullanıcının retinasına aktarıyoruz. Optimize edilmiş olan iğne delikleri tasarımı ve cep telefonunda gösterilen görüntülerin ön-işlemesi sayesinde, alt-görüntüler, iğne deliklerinden retinaya, çift görüntü ve boş alanlar olmaksızın, sorunsuz bir şekilde bölünmüş olarak aktarılır. Kavram ispatı prototipi 3mm göz bebeği çıkışı için tasarlanmış ve teoriyi başarılı bir şekilde doğrulamaktadır. Bu prototipin, her derecede 4 döngüsü var ve 45 derecelik çapraz görüş alanında tam renkli görüntülerin aktarılabilmesini göstermektedir. Bu deney aynı zamanda, istenen

retina görüntüsünü oluşturan ekran içeriğini oluşturmanın (rastgele kararlar sonucu alınanlar da dahil) ilgi çekici birden fazla seçeneğinin göstermektedir. Sistem hafif ve düşük bütçeli olmakla birlikte geniş görüş alanı içine kısımla sınırlandırılmış görüntüler aktarabilmektedir. Ancak, uzaysal çözünürlük küçük iğne deliği boyutundan dolayı orta kalitededir. Ayrıca, değişen göz bebeği büyüklüğü ve yeri için göz bebeği takip algılayıcıları ve dinamik olarak ayarlanabilen iğne delikleri gerekmektedir.

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ABBREVIATIONS

3D	:	Three Dimensional
IPD	:	Inter-Pupillary Distance
PMS	:	Polarization Maintaining Screen
LHCP	:	Left-Handed Circular Polarizer
RHCP	:	Right-Handed Circular Polarizer
SMV	:	Super Multi-View
MEMS	:	Micro Electro-Mechanical System
SS3D	:	Super Stereoscopic 3D
HWD	:	Head Worn Display
OML	:	Optical Microsystems Laboratory
LCD	:	Liquid Crystal Display
FoV	:	Field of View

Chapter 1

INTRODUCTION

This thesis is divided into two research projects and both of them are offering solutions for common problems in 3D display and head mounted display technologies by using engineered pinholes. To better understand this research, the following chapter gives general information about the fundamental principles of the research conducted. An important element of this research is the human eye. Understanding the functionality of the human eye and some terminologies related to the eye is a necessity to conduct this research. Next, the micro projector (PicoP) used in our 3D displays is explored. At the end of this chapter, an interesting phenomenon called the pinhole effect and its mechanism is explained, which is the main basis of different solutions throughout this thesis.

In Chapter 2, a new technique called ”*Super Stereoscopic 3D (SS3D)*” is proposed to help resolving the well-known accommodation-vergence conflict. There were already some solutions offered for this problem in the literature. But, all of them were insufficient and had difficulties such as optical complexity, hard implementation, and not being able to provide proper parallax. The main motivation of this part of the research is to offer a solution, which overcomes the accommodation-vergence conflict using pinholes providing simulated natural blur besides being easy to implement. SS3D provides two different views for a single eye using color-coded double pinhole array. This leads to more comfortable and more realistic 3D experience.

Nowadays technology is moving towards miniaturization and personalization. One of these technologies is head mounted displays. The Head Worn Display (HWD) technology is heading towards wider Field of View (FoV) and more realistic experience

along with more comfortable form factor. There are many solutions suggested such as solutions using relay lens(es) and also lens-free solutions. Chapter 3 offers a comfortable solution using a pinhole array placed in front of the eye and a smart phone as the display. This technique benefits from special content creation procedure and forms a seamless overlap-free image on the retina. The motivation here is to find a design which is comfortable and light weight besides forming wide FoV seamless image on the retina.

1.1 Human Vision System

This research is based on having a thorough understanding of the eye and human vision system working mechanism. This section, in particular, is appropriated for human vision system explaining the structure of the eye, how we perceive objects in 3D and some essential terminologies. A healthy person has a pair of eyes which are separated from each other with a distance named Interpupillary Distance (IPD). This value differs from person to person depending on their age, gender, and their physique varying between $50 - 75 \text{ mm}$ with a mean of 63 mm [1]. Each eye is able to see a different portion of the visual scenery with some overlapping regions in its field of view. This difference can be experienced by looking via a single eye at a time at a fixed scene. Later in this section, the benefit of having a pair of eyes separated creating different images with different perspectives will be discussed.

1.1.1 The Eye

Many investigations have been conducted on the anatomy of the eye, its shape and its dimensions. There are different models for the eyes dimensions and variety of measurements. As an example, Table 1.1 introduces two models suggested by Navarro et al. [2] and Eugene Hecht [3]. Figure 1.1 shows a schematic image of the eye showing different parts of the eye. The forefront layer of the eye is the *Cornea* which has an important role as the first refractive element of the eye having the main part in the eyes refracting power [4, 5]. The next layer after the 0.5 mm thick biological tissue

is the *Aqueous Humour*, filling the gap between the cornea and the eye-lens with a water-alike liquid. The aperture stop of the eye is the *Iris* which has a circular hole in the center called the *Pupil*. The iris has different colors and different patterns which differ from person to person. The next component of the eye is the *Lens* which is a transparent gradient index biological tissue. The eye lens is a *Bi-convex* lens able to change its focal length depending on where the eye is focused on using sets of muscles located on the edges of the lens. Passing through the eye lens, the inner part of the eyeball is located filled by a liquid having an index close to water named the *Vitreous Humour*.

Table 1.1: A comparison of two eye models suggested by Navarro et al. and Eugene Hecht.

Eye Component	Parameter	Navarro	Hecht
Cornea	Front Radius (mm)	7.72	7.26
	Back Radius (mm)	6.5	5.58
	Thickness (mm)	0.55	0.45
	Refractive Index	1.367	1.376
Aqueous Humour	Thickness (mm)	3.05	2.79
	Refractive Index	1.337	1.336
Lens	Front Radius (mm)	10.2	8.67
	Back Radius (mm)	-6	-6.33
	Thickness (mm)	4	4.98
	Refractive Index	1.42	1.386-1.406
Vitreous Humour	Thickness (mm)	16.4	15.78
	Refractive Index	1.336	1.337

The last component is the most important element for human vision termed the *Retina*, which acts as the eyes detector. The retina contains two different photoreceptors as *Rods*, which are larger in number and more sensitive but not in color, and *Cones* that are less in number and more sensitive in color. Assuming F' is the origin of the retina, there is a region about 5° toward the temporal side called the *Fovea* having the highest concentration of cones in the eye. By getting further from the foveal region the cone density decreases.

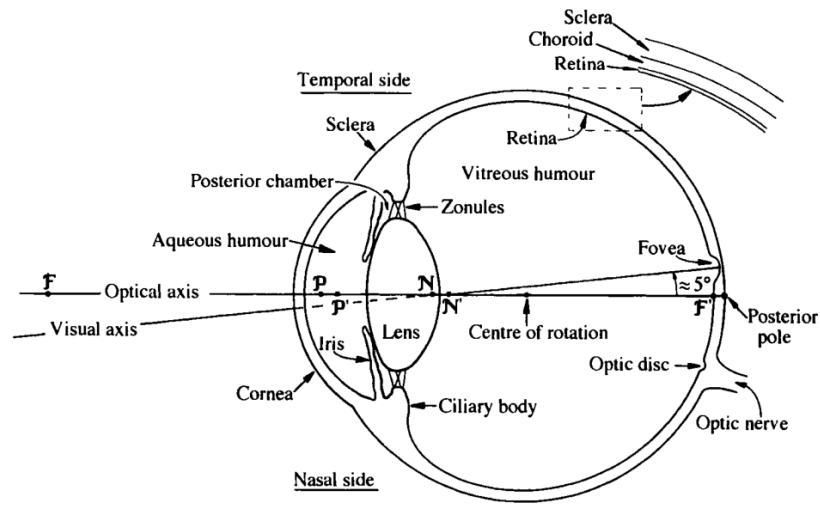


Figure 1.1: Schematic of different parts of the eye and its axes

1.1.2 Some Terminology

In this section, I describe some necessary and frequently used terms related to the human visual system.

- **Horofter** refers to the locus of points in space imaged on the same corresponding points on both left and right retinas. Figure 1.2, shows that F and P are the corresponding points on the retina for the fovea and a point in space, respectively. The horofter is the locus of points in space, P, in which values for $\frac{X}{Z}$ and $\frac{Y}{Z}$ are the same for both eyes [6].

- **Accommodation** is mainly used for the eye changing its focus point. When the eye is focused at infinity, the eye lens is relaxed and its thickness is minimum. When an object moves toward the eye and gets closer, in order to form a blur-free image on the retina, the lens get squeezed from the edges by its muscles called *Ciliary Ligaments*. This tensile stress on the eye lens forces the eye lens to increase its thickness and reduce its radius of curvature resulting in increasing the lens power. The main driving force for the accommodation procedure is the retinal blur in the foveal region [7].

- **Vergence** is the horizontal rotational movement of the eyeball either converging towards or diverging from each other. The main stimulus for this move is the disparity.

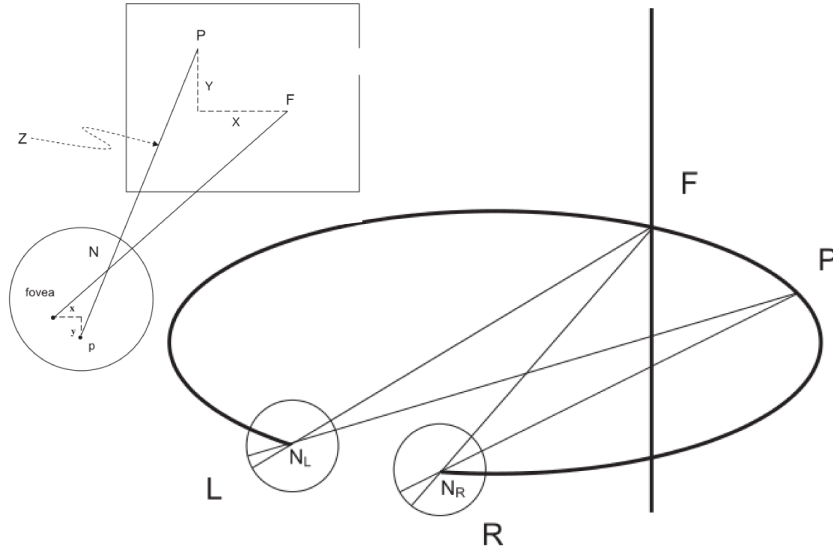


Figure 1.2: Scheme showing the definition of horopter in human visual system

Due to having two eyes separated from each other, the retinal image of a fixed seen formed in the right eye is a little different and shifted compared with the left eye's retinal image. This means that the same corresponding points in space do not fall into the same corresponding point on the retina which causes disparity. In order to decrease this disparity the brain forces the eye to rotate [7].

- **Accommodation-Vergence Conflict:** In a real life scenario, while looking at an object, eyes accommodate that object and change their vergence to form a single blur-free image on the retina done through a close feedback loop shown in Figure 1.3. In the upper part of the figure, which is related to accommodation, the input is the amount of blur in the foveal region. By changing the focal length of the eye lens and rechecking the amount of blur the loop goes on until it reaches the threshold. The story is the same for vergence, but the stimulus is the disparity. The most interesting part of this control system is that the accommodation affects the vergence of the eye and vice versa. According to this correlation, naturally, wherever the eye focuses on it will change its vergence towards that point [8]. The configuration of the eyes in a real scene is similar to Figure 1.4A.

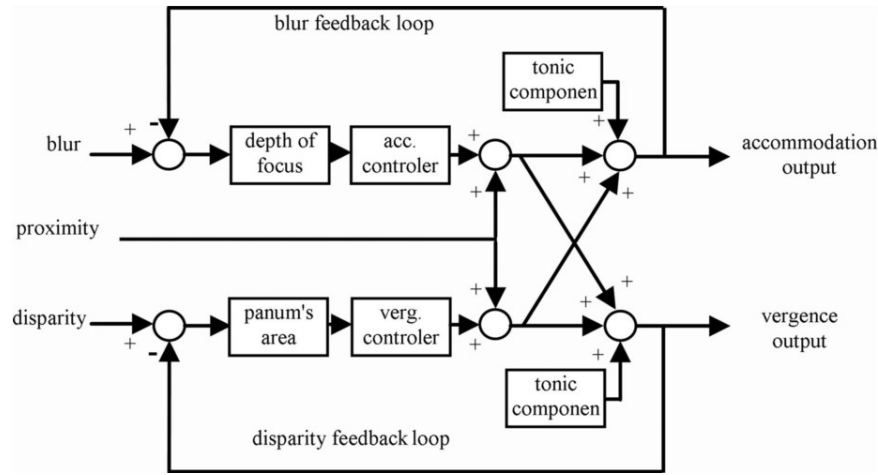


Figure 1.3: Close feedback loop showing the accommodation-vergence working principle

In an artificial 3D scene like movies shown in the cinema, the accommodation-vergence of the eye will not always fall onto the same point. In the cinema the eye is usually accommodated on the cinema screen since the content is the sharpest on the screen, so the blur will be minimized. On the other hand, due to the disparity on the screen, the virtual object will be formed outside or inside the screen forcing the eye to change its vergence to that specific point [9]. This difference between the locations of eye accommodation and vergence is called *Accommodation-Vergence Conflict* illustrated in Figure 1.4B.

1.1.3 How Do We Perceive Depth?

The important factor in human perception is various depth cues, which are in two main categories: Monocular and Binocular cues [7]. These cues help the brain to perceive the depth of a scene in a correct manner. One well-known monocular cue is *Motion Parallax*, occurring when objects that are at different distances from us appear to move at rates that are different while we are moving. We judge an objects distance based on how quickly an object moves. The closer an object is to us, the quicker it appears to move. The further an object is from us, the slower it appears to move. Another cue is the eye changing its accommodation resulting in having a better

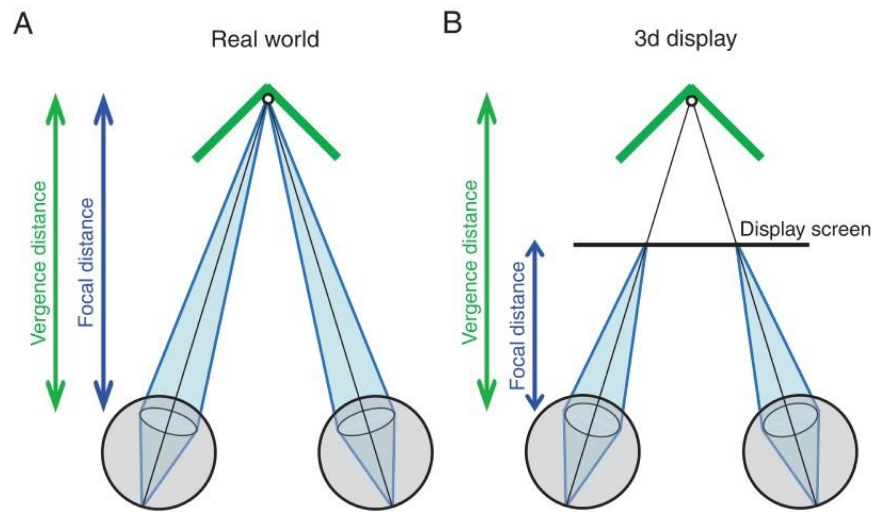


Figure 1.4: Showing the eye's accommodation-vergence relation in (A) real life scenario and (B) in artificial 3D scenes

understanding of the distance. Also, there are several other monocular cues such as, linear perspective, aerial perspective, shading, and texture gradient.

The next category of perceptual cues is binocular cues which covers two main cues: Stereopsis or retinal disparity or binocular parallax and Convergence [7]. The image formed on left and right eyes retina is different. By using two images of the same scene obtained from slightly different angles, it is possible to triangulate the distance to an object with a high degree of accuracy. Each eye views a slightly different angle of an object seen by the left and right eyes due to the horizontal separation of the eyes. If an object is far away, the disparity of that image falling on both retinas will be small. If the object is close or near, the disparity will be large. It is stereopsis that tricks people into thinking they perceive depth when viewing 3D movies. On the other hand, convergence is another means to understand the depth pattern of a scene discussed in Section 1.1.2.

1.2 Laser Scanning Pico-Projectors (*PicoP*)

The main part of developing the SS3D technique in this thesis was using an off-the-shelf laser-based scanning pico projector manufactured by Microvision Inc. [10]. For years, the collaboration between OML and Microvision resulted in many innovations in the MEMS industry and display technologies. As shown in Figure 1.5, the device combines three primary colors, Red, Blue, and Green, generated by the laser with a specially coated prism to create a high color gamut white light. Then, with a set of optics the white light goes to the MEMS scanning mirror and the image will be scanned pixel-by-pixel in two axes with a pre-defined raster pattern.

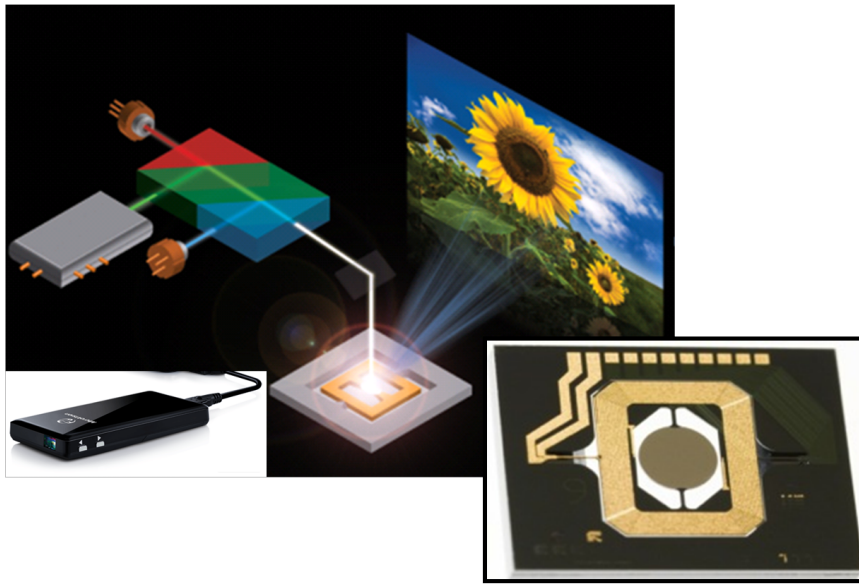


Figure 1.5: The photonic modules working principle and the MEMS scanning mirror (on the right) used in the PicoP

This pico-projector is laser based and does not use objective lenses to form an image; therefore, the output image is always in focus, even with changing the viewing distance. The light sources are Gaussian beam lasers propagating in free space with a beam waist of 0.5 mm in perpendicular axis and 0.3 mm in the parallel axis. The output light is polarized such that red and blue have the same polarization and are perpendicular to green. This factor gives the ability to selectively use the light for imaging and creating a 3D experience. On the other hand, the small dimensions for

the photonics module enable miniaturization.

1.3 Pinhole Effect

The human single eye is able to adapt to changes in depth from about $15\text{ cm} - \infty$ and form a sharp image on the retina within this range. Also, since the eye pupil's diameter differs from $2.5 - 8\text{ mm}$, the depth of field of the eye changes according to [11]. The principle governing the problem is the same principle present in photography as the $f_{\#}$ of a lens following a simple equation:

$$f_{\#} = \frac{f}{D}$$

in which, f is the focal length of the eye lens and D is the diameter of the pupil [12]. The larger this number, the larger the depth of field will be. This means for a fixed pupil size, if eye focuses on a near point the depth of field will be smaller than when it is focused on a far point. Also, more importantly, for a fixed focal length, the smaller the pupil gets, the larger the depth of field becomes.

Placing a tiny hole as the aperture stop ¹ of an optical system leads to benefiting from an effect so called *The Pinhole Effect*. This method was used centuries ago to create a simple camera. The camera consisted of a hollow box with a sensitive film on one side and a small hole in front of it as the stop without using any lens. The film was exposed the reflection of the sunlight from the scene for a specific amount of time and the result was a sharp, large depth of field image of the scene. Nowadays, using pinholes apertures are used in the laser business to shape the beam and electron microscopy techniques in order to capture large depth of field images.

Another interesting use of this effect is to let the eye focus on objects closer than its allowable focus range. While looking at an object located in an allowable range (more than 15 cm), the eye tries to change its optical power to form a sharp image on the retina as shown in Figure 1.6a. When the display gets closer and closer to about

¹Aperture Stop for an optical system is the stop that limits the light entering the optical system [4]

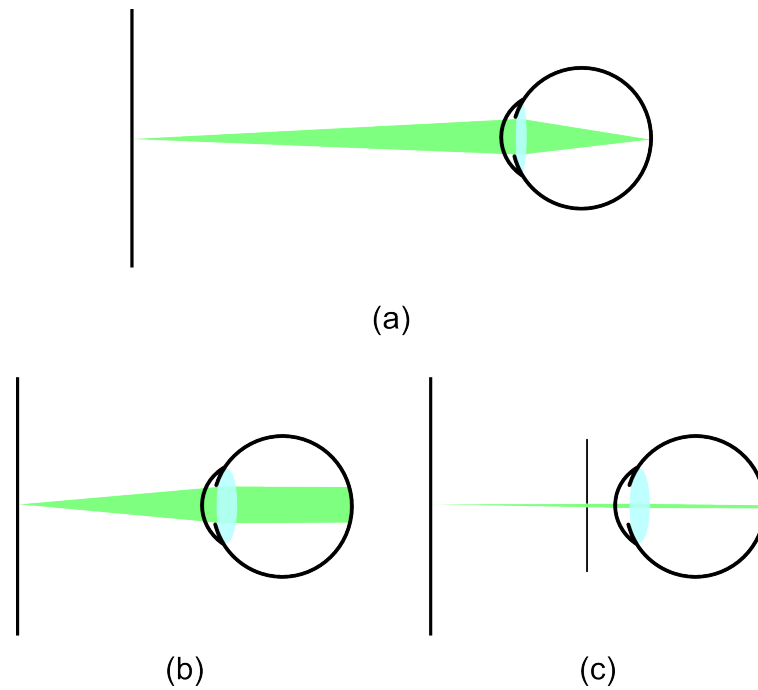


Figure 1.6: Showing the eye forming an image on the retina when the object is (a) in the focus range of the eye, (b) very close to the eye, and (c) placing a pinhole smaller than the pupil as the aperture stop.

few *cm* the eye is not capable of focusing on the object and the resulting image on the retina will be a blurred region illustrated in Figure 1.6b. By placing a pinhole in front of the eye, as in Figure 1.6c, the visible spot size on the retina reduces below the blur threshold of the retina and the image will be sharper. The first visible drawback of this method is the limited FoV of the optical system.

Chapter 2

SUPER STEREOSCOPY TECHNIQUE FOR COMFORTABLE AND REALISTIC 3D DISPLAYS

This chapter is mainly focused on a new method called SS3D for experiencing more comfortable and realistic 3D. Investigating the available solutions for artificial 3D experience as stereoscopic and auto-stereoscopic display principles is the starting point of this chapter. In the following sections, basic concepts of SS3D are described such as the methodology of the technique, the role of monocular parallax in perceiving SS3D, the effect of pinhole design on having realistic and comfortable 3D experience, testing this method with designed experimental setups, and the corresponding analysis for the design.

2.1 Stereoscopic 3D in the Literature

The horizontal parallax of the eye results in forming slightly shifted images on the retina. This is called stereopsis and was introduced in Section 1.1.3 as one of the binocular cues. This principle was understood for several centuries and also was used in paintings, but in 1852 Sir Charles Wheatstone [13] proposed the stereoscopic vision in a modern fashion with an invention similar to stereoscopic 3D televisions. His first invention in the field is a device composed of mirrors, and two perspective images. With the help of his mirrors, he has been able to direct each image to a single eye as in Figure 2.1. The basis of the existing 3D displays in movie theatres still relies on this foundation. From the beginning, many different techniques were derived to

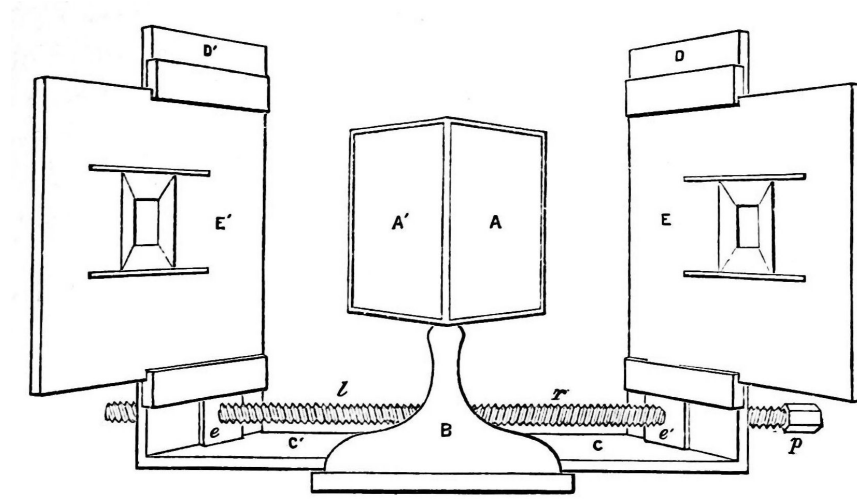


Figure 2.1: Sketch showing the invention of the first stereoscopic display, which was built by Sir Charles Wheatstone

provide stereoscopic imagery [7, 14]. Most frequently used stereoscopy methods require special aids in front of the viewer's eyes. In most cases, the required aid is in the form of glasses. Some of these binoculars benefits from the polarization state of the light, or wavelength of the light. Besides, light selectivity can also be achieved through time multiplexing, which is another form derived from the polarization techniques. But there are also other possibilities, which do not require any special aids in front of the viewer's eyes generalized as auto-stereoscopic displays. Some of these techniques are introduced in more detail in the following sections in two main categories: Glass-based Stereoscopic and Glass-free Stereoscopic (Auto-stereoscopic) displays. Using glasses with specific filters in them is the most common and economic way of implementing stereoscopic 3D. Although there are several different designs in this family, here some important types are mentioned in this section.

2.1.1 Color Interlaced (Anaglyph)

One of the most primitive methods to produce artificial 3D experience is using anaglyph method. The first method to produce anaglyph images was developed in 1852 by Wilhelm Rollmann in Leipzig, Germany [15]. This process consisted of capturing two

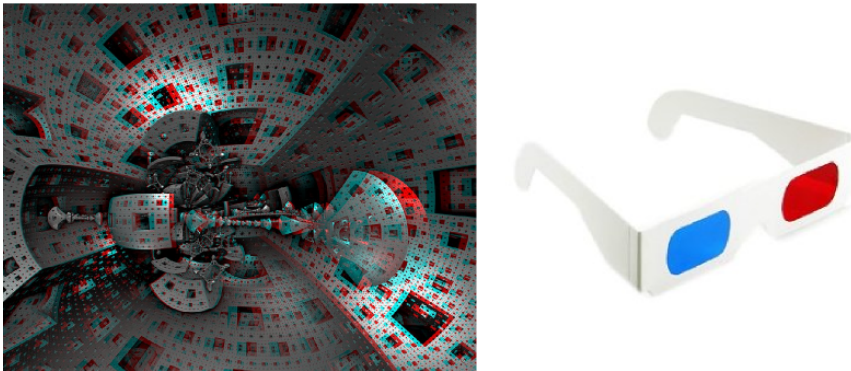


Figure 2.2: Showing an anaglyph 3D image as an example and an anaglyph glass used to observe the image.

slightly shifted images of a scene and then color code the images such that the image assigned to the left eye is red coded and the right one is cyan. Then, these two images are superimposed on each other to form the final image. The viewer would then use coloured glasses with red filter (for the left eye) and cyan color filter (right eye) [7]. Figure 2.2 shows an anaglyph 3D image with one type of glass for viewing the image. Obviously there are some advantages and drawbacks to this method. The advantages of this technique are its simplicity in content creation, hardware, and most importantly there is no need to use high frequency displays for viewing the content. However, the main drawbacks of this method are high crosstalk level and low color quality.

2.1.2 Polarization Interlaced

Another method which is common for stereoscopic 3D is polarization interlaced stereoscopic displays which are used intensively in cinemas and 3D theatres. The working methodology is very simple and consists of passive polarization glasses, a projector with a liquid crystal polarization rotator with at least 120 Hz refresh rate or two 60 Hz refresh rate projectors displaying right and left views separately, and a polarization maintaining silver screen. The projectors project the left and right contents with LHCP and RHCP respectively. These two projectors must be registered properly with a point at infinity for the resulting 3D image to be perceived properly.

After the light is reflected back from a polarization maintaining screen, contents come to viewer's eyes wearing the passive glasses with matching polarization filters. Consequently, each eye perceives its corresponding view resulting in a 3D fusion in the brain. Two of the most important commercial companies developing these technologies and designing 3D theatres are RealD [16] and IMAX [17].

2.1.3 Time-multiplexing (Shutter Glasses)

In the time-multiplexed approach, the left and right eye images are displayed on the screen in an alternating fashion. Each eye receives light only on alternate frames which leads to flicker unless the frame rate is increased to at least twice the frequency where flicker is not perceived. Those displays are typically operated at 120 Hz or greater. The viewer is required to wear battery-powered active shutter glasses, which are synchronized to the content being displayed [18]. Active glasses are more costly, heavier than inexpensive passive glasses, and require careful handling. On the other hand, the crosstalk level using this technique is among the lowest which makes the image quality very high.

2.1.4 Mixed Polarization

Mixed Polarization is a new method first introduced by OML laboratory in 2012 by Akşit et al. [19]. The system consists of a projection source with a display refresh rate of 60 Hz produced by Microvision Pico-projectors, an active polarization rotator synced with the input content, a pair of commonly used passive 3D glasses, and a polarization maintaining silver screen. Inherently the PicoP has orthogonal polarization states between green and red-blue. The active polarization rotator rotates each the polarization 90° per frame. For instance, the right eye's i^{th} frame content will be in green and the $(i + 1)^{th}$ frame will be in red-blue as illustrated in Figure 2.3. Main advantages are being portable, simple to implement, and most importantly using only a single 60 Hz projector showing the desired content. Nonetheless, the main disadvantage is using a polarization maintaining silver screen for projecting the content.

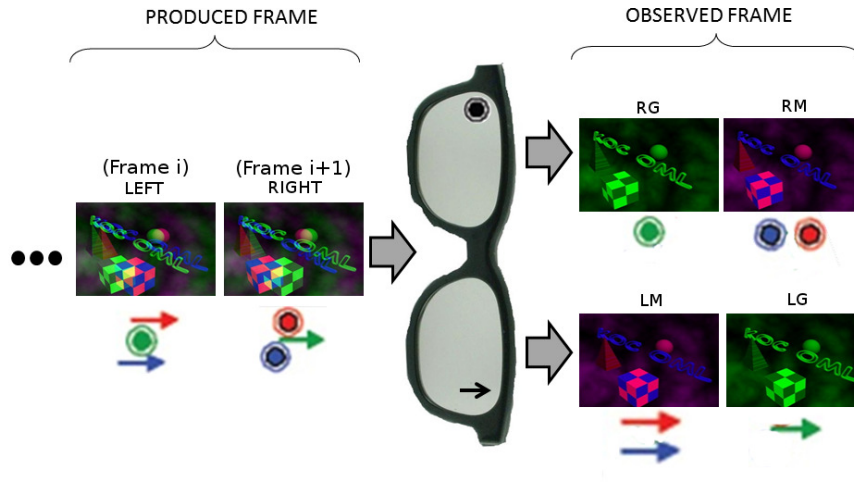


Figure 2.3: Showing the perceptual order of the content via mixed polarization technique

The presence of the silver screen adds complexity and more crosstalk to the system.

As a summary, Table 2.1 shows advantages and drawbacks of different stereoscopic 3D techniques using glasses mentioned above.

Table 2.1: Comparing four types of glass-based stereoscopic 3D techniques.

Method	Required Hardware	Adv. vs. Disadv.
Anaglyph	Color-coded glasses; Regular 60 <i>Hz</i> projectors or displays	(+) Easy to implement, cheap (-) Low color quality
Polaroid-based glasses	Single 120 <i>Hz</i> or two 60 <i>Hz</i> projection; Passive glasses; Polarization maintaining screens	(+) Cheap passive glasses (-) High refresh rate projection or difficult content registration; Special screens required
Time-multiplexing (Shutter Glasses)	120 <i>Hz</i> or higher refresh rate required; Active shutter glass	(+) Extremely low crosstalk (-) High refresh rate; Expensive hardware
Mixed Polarization	Regular 60 <i>Hz</i> projectors; Passive glasses; Polarization maintaining screens	(+) Standard refresh rate; Cheap hardware (-) Special screens required

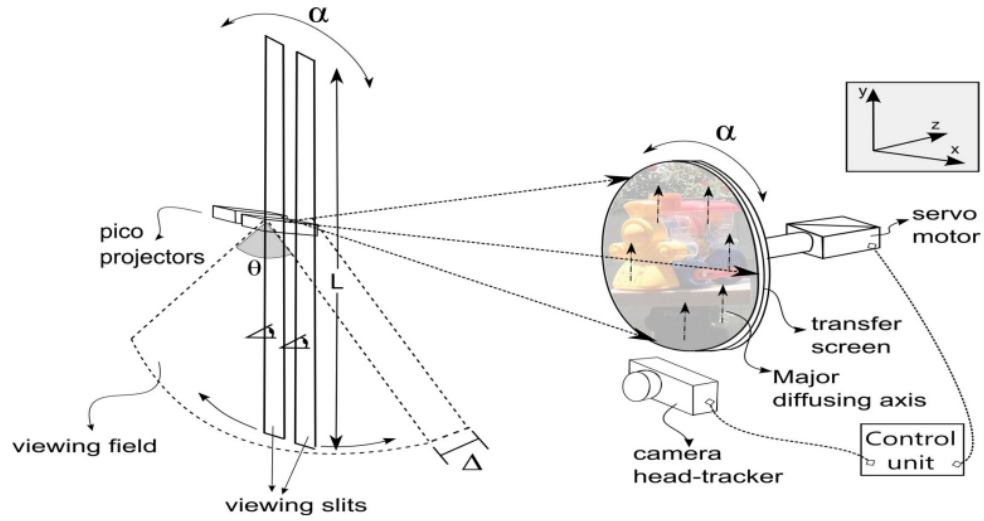


Figure 2.4: System sketch showing the elements and the created viewing field of the display

2.1.5 Rotating Multi-View Auto-stereoscopic Display

This technique is a novel auto-stereoscopic display developed by Eldeş et al. [20] in OML. The display consists of two projectors, a rotating transfer screen, and a head-tracking unit. Projectors are placed horizontally above the viewer's head separated as IPD from each other. The left and right projectors project left and right perspectives, respectively. Using a vertical diffuser sheet on top of the screen assists to produce two vertical slits at the viewer plane resulting in a viewer standing in the projector plane perceiving stereo images. Figure 2.4 shows the working system of the display. The tracking unit tracks the position of the head and dynamically changes the angle of the viewing slits via rotating the screen using the control unit. These dynamic changes helps the viewer to perceive stereo images while having free head movement.

2.1.6 Super Multi-View (SMV) Displays

The second category of displays is auto-stereoscopic display meaning there is no need for a passive or active glasses. There are several types of these displays available such as light field displays [21], parallax barrier based displays [22], holographic displays [23].

An auto-stereoscopic displays with suggested solution to both accommodation-vergence conflict and lack of motion parallax is classified as Super Multi View (SMV) displays [24]. SMV displays provide high number of images with narrow interval of parallax to overcome the mentioned problems. Figure 2.5 shows the working principle of SMV displays. In this technique, the horizontal separation between views is decreased such that each view is smaller than the pupil diameter. Light coming from at least two slightly shifted views enters simultaneously the eye. It is claimed that this will evoke the natural accommodation-vergence response of the eye to provide smoother and more realistic 3D experience.

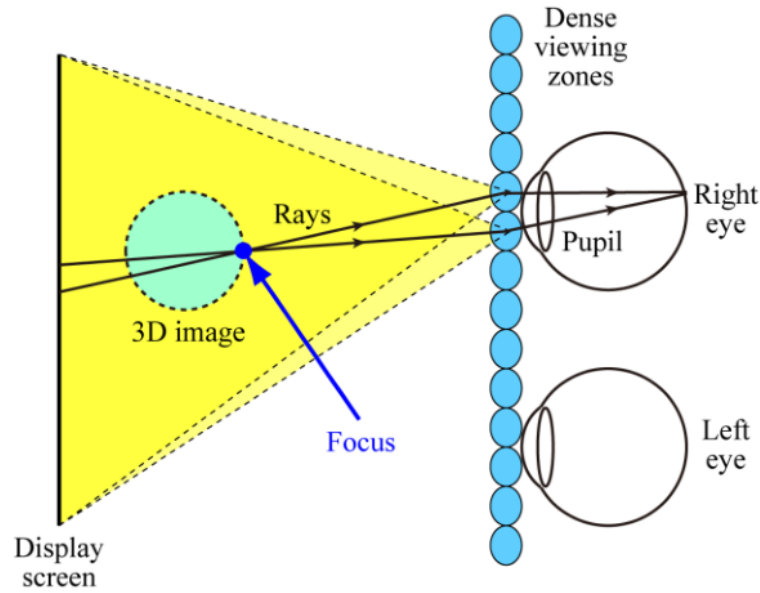


Figure 2.5: Showing the Super multi-view (SMV) display technique

2.2 SS3D Methodology

The single eye perceives slightly different perspectives from each point of the pupil itself which are infinite. Dividing the pupil into discrete points and allowing different perspectives passing through each of them mimics the eye pupil resulting in more comfortable and realistic 3D. A similar idea to ours has been presented under the name Super Multi View (SMV) displays discussed in Section 2.1.6. However, due to the multi-view and auto-stereoscopic nature of their proposal, experimental demonstrations require quite complex hardware and demonstrated only limited success as the viewing slits produced at large distances from the display screen cannot be sufficiently small due to optical limitations. Therefore, we decide to benefit from both pinhole effect to overcome the accommodation-vergence conflict and separating view with two pinholes to mimic the natural blur in the eye for more realistic 3D. The basis of this method is using double pinholes covered with color filters to separate different perspectives for a single eye.

2.2.1 Working Principle

We initially used filters were linear polarization filters matching the PicoP polarization vectors. Maintaining the polarization vectors direction is very crucial, therefore, imperfections in the screen and filters decrease the quality. Another problem is the head freedom of movement. Since the filters are linearly aligned, by the rotation of the head, filter's alignment will change and the perceived content will be mixed. Consequently, Anaglyph color filters were chosen to be used as filters. Benefits of using these filters are integrability with polarization filters to separate two eyes from each other, no need for a special screen, polarization independent, and ease of implementation.

One of the monocular cues of visual depth perception is depending on the fact that movement of the head produces relatively large apparent displacement of nearby objects in the opposite direction and relatively small displacement of distant objects in the same direction. This is so called *Monocular Parallax* which is one of the basic

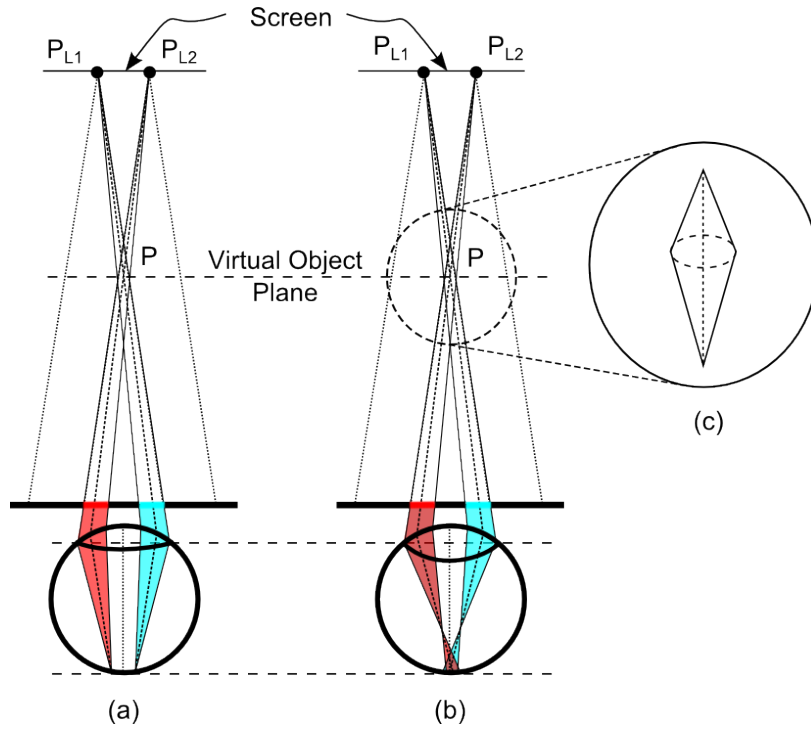


Figure 2.6: Showing the effect of separating the content using color filters on the retinal image in a single eye while the eye is focused on (a) the screen and (b) the virtual object plane. (c) The resulting voxel is elongated diamond shape at the virtual object plane.

working functions in our method. Figure 2.6 shows the main principle governing the SS3D. In Figure 2.6a the image of two points on the screen (P_{L1} and P_{L2}) after passing through color filters on the retina is two sharp points while the eye is focused on the screen. By changing the accommodation of the eye towards the virtual object plane, the resulting image on the retina is a combined red-cyan spot as illustrated in Figure 2.6b. This spot is the image of the formed diamond shape voxel, P , at the virtual object plane which is an acceptable blur to eye. This effect is better understood when binocular vision is involved. Figure 2.7 demonstrates a comparison between regular stereoscopic 3D and SS3D.

The binocular disparity on the screen drives the eyes to converge to the object plane which should be the correct accommodation point. In regular stereoscopic 3D, when eyes are focused on the virtual object plane, the resulting image on the retina

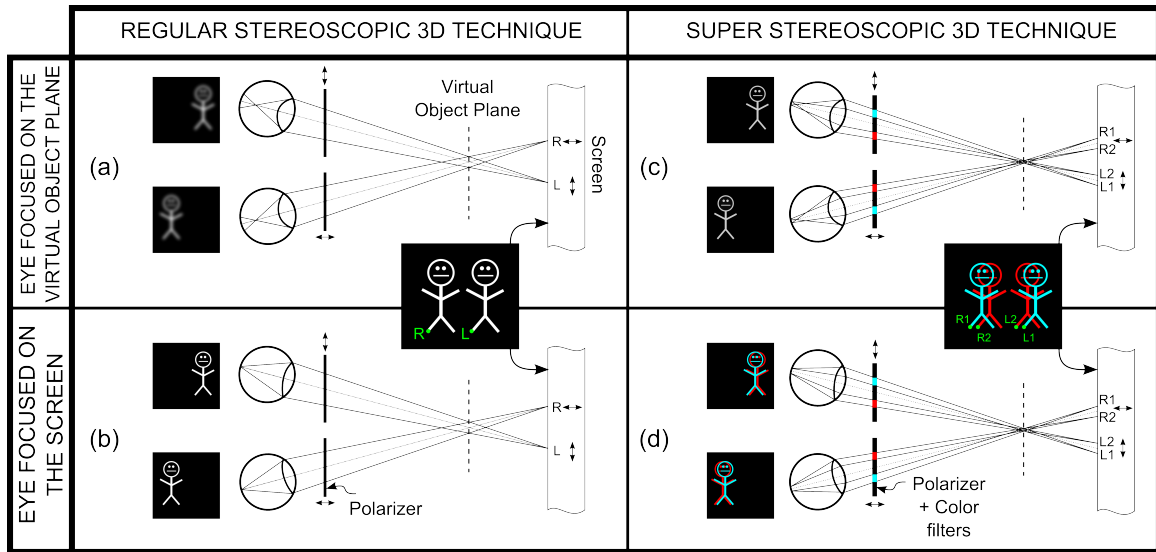


Figure 2.7: Retinal image formations in regular stereoscopic 3D and SS3D systems. In regular stereoscopic 3D displays, eyes converge on the virtual object. However they cannot stay focused on virtual object plane since in that case retinal images are blurred as in (a), so they change their focus to the screen in order to sharpen retinal images as in (b), resulting in A/C conflict. In SS3D, the pinholes lead to retinal images which are always sharp, hence eyes can stay focused on the virtual object plane, as in (c), eliminating the A/C conflict. In fact, when eyes are focus on a different plane, parallax images get separated from each other, as in (d), providing an approximate blur effect.

is blurred due to the voxel size, Figure 2.7a. To eliminate this blur, eyes change their accommodation toward the screen where the content is sharper as shown in Figure 2.7b. This mismatch between the accommodation and convergence point causes a conflict described in Section 1.1.2. Unlike regular stereoscopy, In SS3D, when the eyes are focused on the screen, the retinal image is a sharp, separated, and red-cyan double image as in Figure 2.7d. Therefore, eyes try to change their refractive power to find the best accommodation point which is the virtual object plane where the retinal image is acceptably sharp as displayed in Figure 2.7c. This is due to the small voxel size and the image being all in focus because of the pinhole effect.

2.2.2 Content Creation Procedure

One prominent strength of this technique is being capable of using the same hardware as the regular stereoscopic 3D with minor modifications. Parts needed to be modified are the content shown on the screen and glasses used by the user. In this technique, at least two pairs of views are required for each frame. Figure 2.8 shows the positions of the camera to capture the proper content. L and R represent the general position of the camera for left and the right eye separated by IPD. For each eye the camera is slightly shifted to capture different views for a single eye shown as L1 and L2, for instance. Depending on the scene and the depth profile, the separation between L1 and L2 is determined.

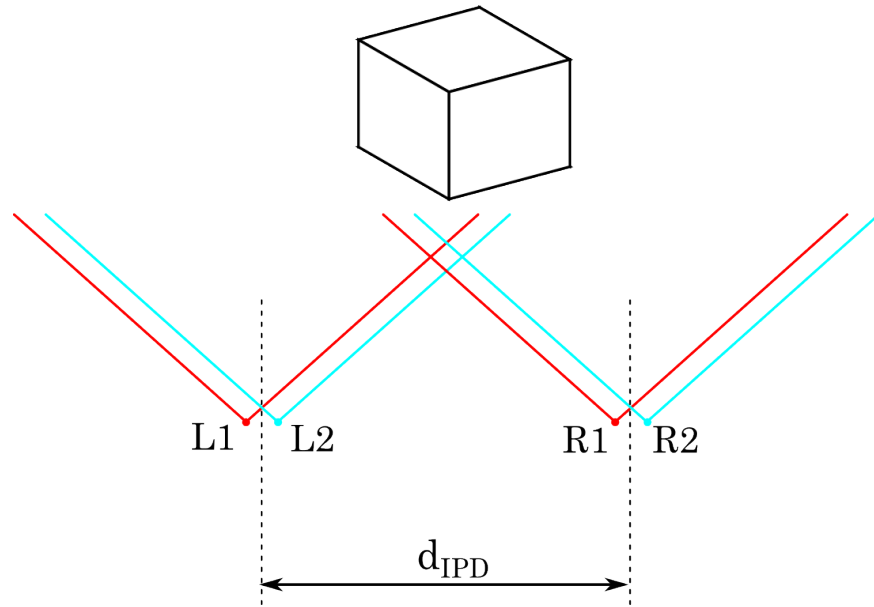


Figure 2.8: Demonstrating camera positions and their color coding required to generate proper content for SS3D .

To generate contents for demonstration, a virtual 3D scene has been created with the open source *Blender* software. The scene is consist of two pumpkins locating at 115 *cm* and 50 *cm*, respectively, and a goose locating at 100 *cm*. The content creation procedure is shown in Figure 2.9 using same camera positions mentioned in Figure 2.8. Each frame of the display content consists of four parallax images of a single 3D scene, Figure 2.9a. Two of these images are for the left eye, and other two are for the right

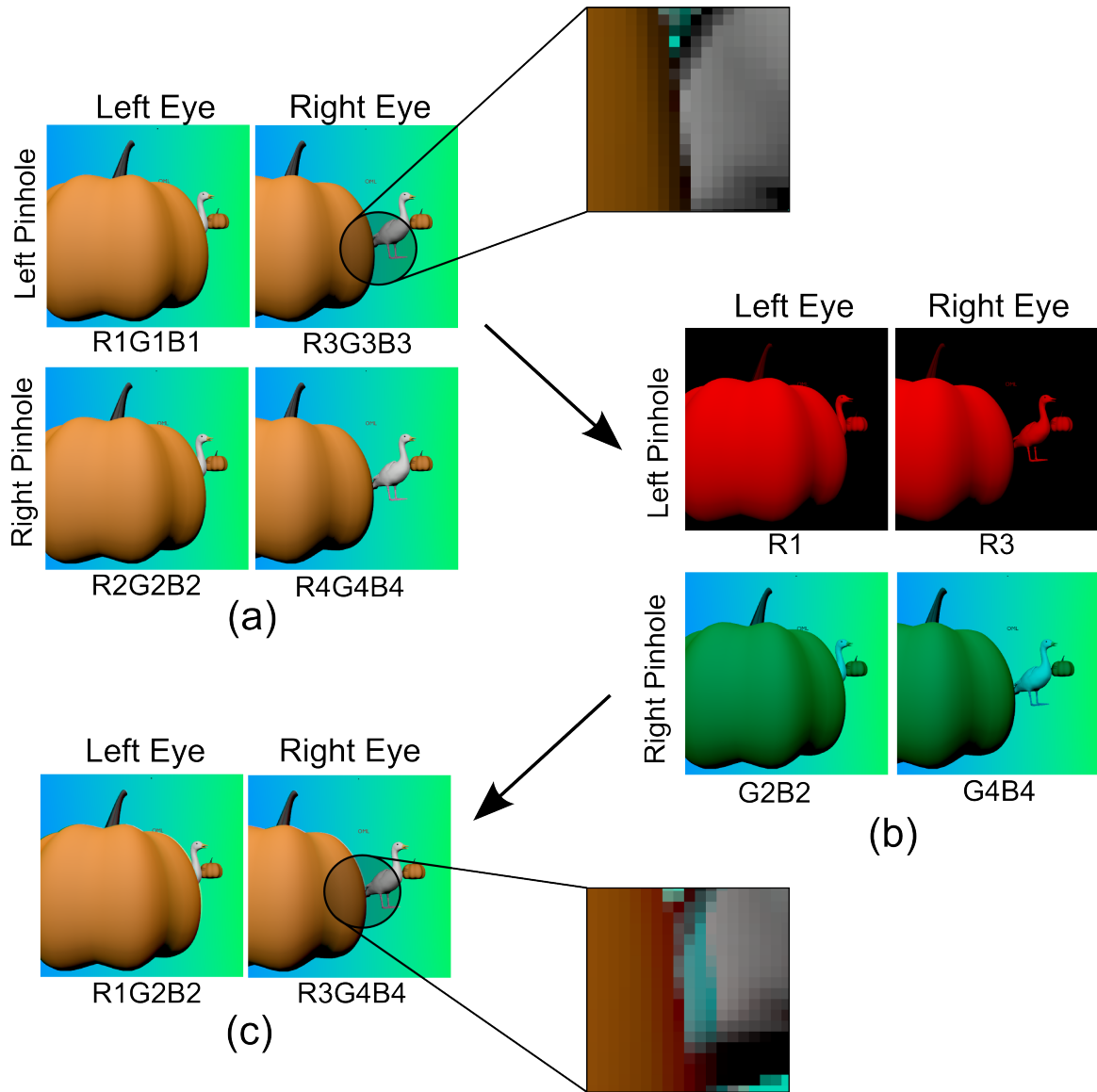


Figure 2.9: Content creation procedure. (a) Images exported directly from rendering software, (b) images after discarding the relevant color channels, and (c) final images obtained by superimposing the preserved channels. The magnified portion in (c) illustrates the color shifts formed due to superimposition of parallax images. No such color shift is present in the magnified portion of (a).

eye. For any of the eyes, the green and blue channels of the left pinhole image and the red channel of the right pinhole image are discarded as in Figure 2.9b. The kept channels are superimposed to create an RGB image which is then fed to the associated pico-projector Figure 2.9c. As shown in the zoomed section of the final image, there is

a color shift in the image which is not present in the initially captured image. This slight color shift is due to the monocular parallax applied for each eye.

2.3 Analysis

Pinhole diameter, eye-relief distance, and pinhole separation are important design parameters for SS3D glasses. Pinhole diameter is the main parameter determining the voxel width, hence the ability of the system to trigger correct accommodation response. From a geometrical optics perspective, as the pinhole diameter is made smaller, the voxel width gets smaller and image blurring on the retina is reduced. However, from a wave optics perspective, as the pinhole diameter gets smaller, diffraction effects become predominant and as a consequence retinal images get blurred. Moreover, the captured light power decreases with shrinking pinholes. Therefore, there is an optimum size for the pinhole diameter. Figure 2.10 shows the mentioned geometrical (solid lines) and wave optics (dashed lines) relation between the voxel width and the pinhole diameter for objects locating at different virtual object planes.

Eye-relief and pinhole separation distances are the main determinants of SS3D glasses' FoV. The FoV obtained using SS3D glasses is shown in Figure 2.11. As seen, there is a Full Field of View (FoV_f) where the image is seen through at least one of the pinholes, and there is a portion of it where the image can be seen through both pinholes called as Super Stereoscopic 3D Field of View (FoV_{ss}). It is easy to see from the figure that decreasing the eye relief increases both FoV_f and FoV_{ss} , but obviously there is a lower limit to this since a too close eyeglass will be disturbing to the user. On the other hand, increasing pinhole separation increases FoV_f and decreases FoV_{ss} , hence, a compromise can be made here depending on the application, as long as the screen is included in FoV_{ss} . Finally, note that due to the presence of pinholes in front of the eye, the FoV of a single naked eye (which is about $95 - 115^\circ$ horizontally) is somewhat decreased. However, this is not a significant reduction when typical applications are considered. For instance, for a viewer standing 1 m away from a 20" display, the used portion of the FoV is only about 30° , which can easily

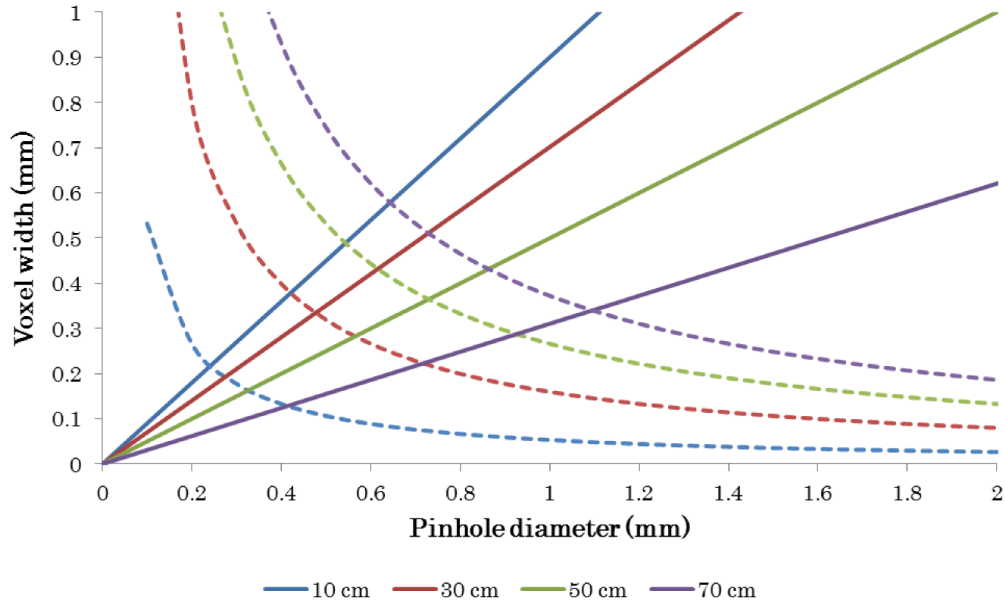


Figure 2.10: Showing the voxel width vs. pinhole diameter calculated using geometrical optics (solid lines) and wave optics (dashed lines) for a virtual object located at different virtual object planes. The screen is 1 *m* away and the pinhole separation is 2 *mm*.

be provided with SS3D glasses with reasonable selections of eye relief and pinhole separation distances.

The pinhole separation is also the main determinant of the amount of artificial blurring introduced for defocused objects. If the pinholes are too close to each other, the parallax images overlap on the retina for a greater range of distances, so the blur effect is weak. On the other hand, if the pinholes are placed too wide, the retinal images get separated too quickly, giving the impression of double vision rather than blur. Therefore, there is also a trade-off in addition to the FoV criterion. Our trials with different dimensions and comparing FoVs indicate that using 0.6 *mm* for pinhole diameter and a separation of 1.4 *mm* for 5 *mm* eye relief is a good choice.

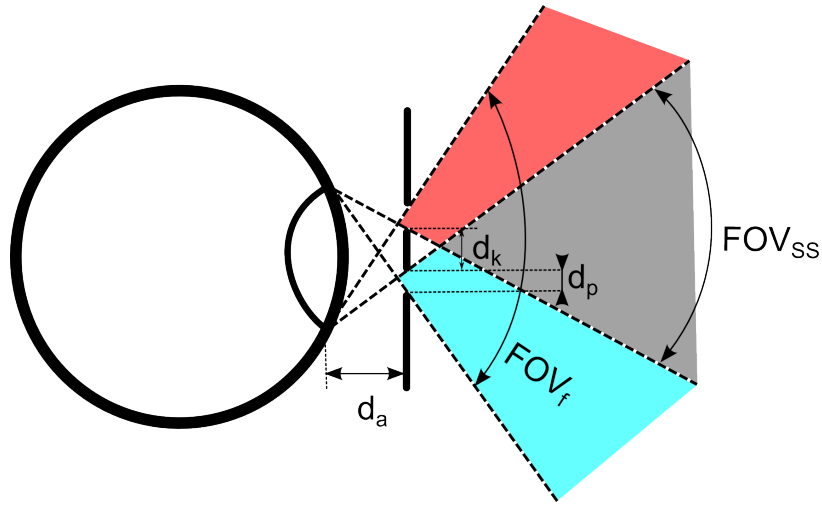


Figure 2.11: Showing the FoV of SS3D glasses (top view), where d_k is the pinhole separation, d_p is the pinhole diameter, and d_a is the eye-relief distance.

2.4 Experimental Results & Discussion

In Section 2.2.1, it is claimed that the eye prefers to change its accommodation from the screen to the object plane while having color coded pinholes placed in front of it. To prove this concept experimentally for a single eye, an LCD screen was placed 60 *cm* away from a camera. In front of the camera, we placed two pinholes. The pinholes used for this experiment have a diameter of 1 *mm* and the distance between pinholes' center is 2 *mm*. The left and right pinholes are equipped with red and cyan color filters, respectively. Three sets of red and cyan bars, Figure 2.12a, have disparities such that from top to bottom, three virtual white bars are supposed to appear at 35, 50 and 60 *cm*. When the camera is focused at three different depths, the images with no pinholes appear sharp only at the screen, Figure 2.12b, and are substantially blurred at other planes, Figure 2.12c and d, illustrating that in conventional stereoscopy it is not possible to achieve correct accommodation. Using the pinholes in front of the camera, each bar appears white and sharp at the corresponding virtual object plane, illustrating that in SS3D it is possible to achieve correct accommodation, Figure 2.12f and g. We also see the formation of double partially overlapping images in the case

of pinholes when the accommodation is shifted away from the virtual object plane, illustrating that in SS3D we achieve more natural vision with an approximate blur effect.

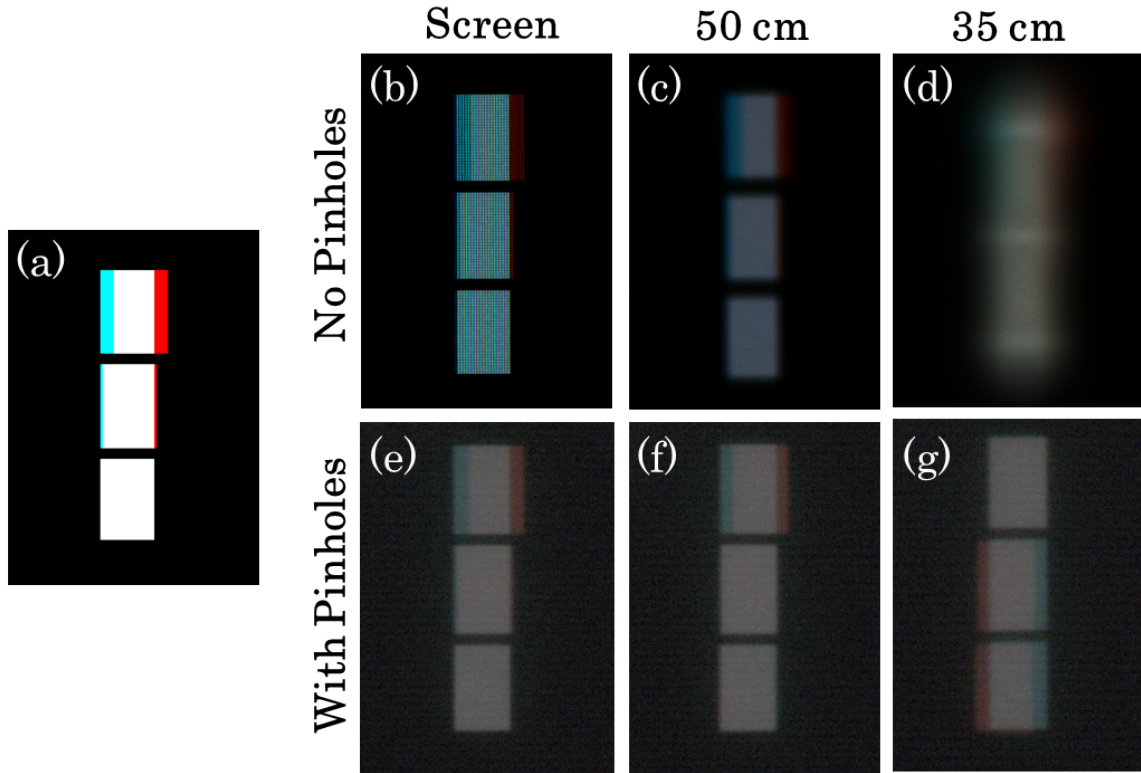


Figure 2.12: Camera-based experiment illustrating SS3D concept for one eye. (a) is the content shown on the screen. The camera is focused (b) on the screen without pinholes, (c) at 50 *cm* without pinholes, (d) at 35 *cm* without pinholes, (e) on the screen with pinholes, (f) at 50 *cm* with pinholes, (g) at 35 *cm* with pinholes. Images are enhanced for better visualization.

As a preliminary test of the proposed technique, an experiment has been conducted with 15 subjects among students of Koç University. The subjects were not informed about the SS3D technique before the test. Several prototypes have been made during the research which three of them are demonstrated in Figure 2.13. Figure 2.13a is a design which consist of 10 vertical slits with periodic red-cyan color filters attached on them. At the first glance, this design seems a good choice for passing more light due to larger openings, but in the vertical direction the effect on AC conflict reduces because of having a large aperture size. To overcome this problem the next design was

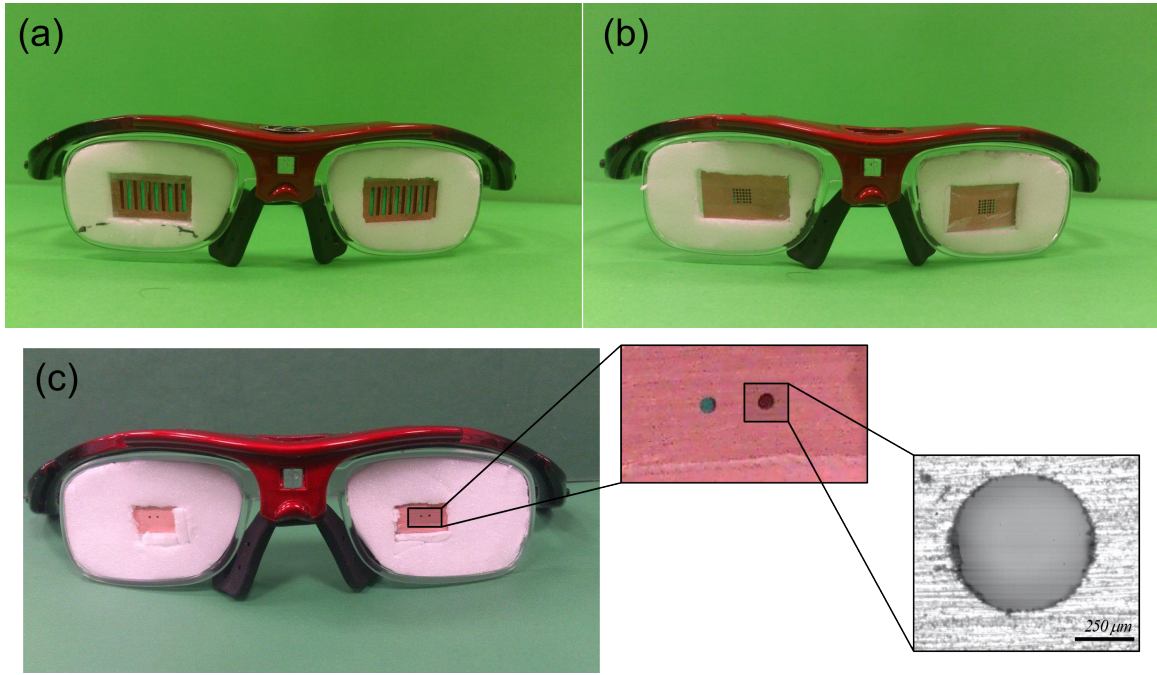


Figure 2.13: Prototype glasses having (a) 10 vertical slits with same color filters each one slit in between, (b) 5×6 array of pinholes, and double pinholes with pinhole diameter of 0.6 mm and pinhole separation of 1.4 mm .

proposed as in Figure 2.13b using pinhole array. The problem here was having several pinholes side by side with only two different filters result in the final images being mixed and not being perceived as stereo. As a solution to both mentioned problems, the design shown in Figure 2.13 was built. This design uses two pinholes covered with red and cyan filters with pinhole diameter of 0.6 mm and pinhole separation of 1.4 mm , as illustrated in zoomed areas of Figure 2.13c. Although the brightness in this design decreases, the AC conflict and receiving stereo images are well fixed. Therefore, this design was used as the final prototype for the further tests.

The prototype eyeglasses do not have any polarizers or shutters as it is tested using a 3D display system that is already capable of separating left and right views without requiring the viewer to wear any glasses. This 3D display system was also developed in our lab [20]. As illustrated in Figure 2.14a, our 3D display uses two pico-projectors developed by Microvision Inc. and placed above the viewer's head. The projection

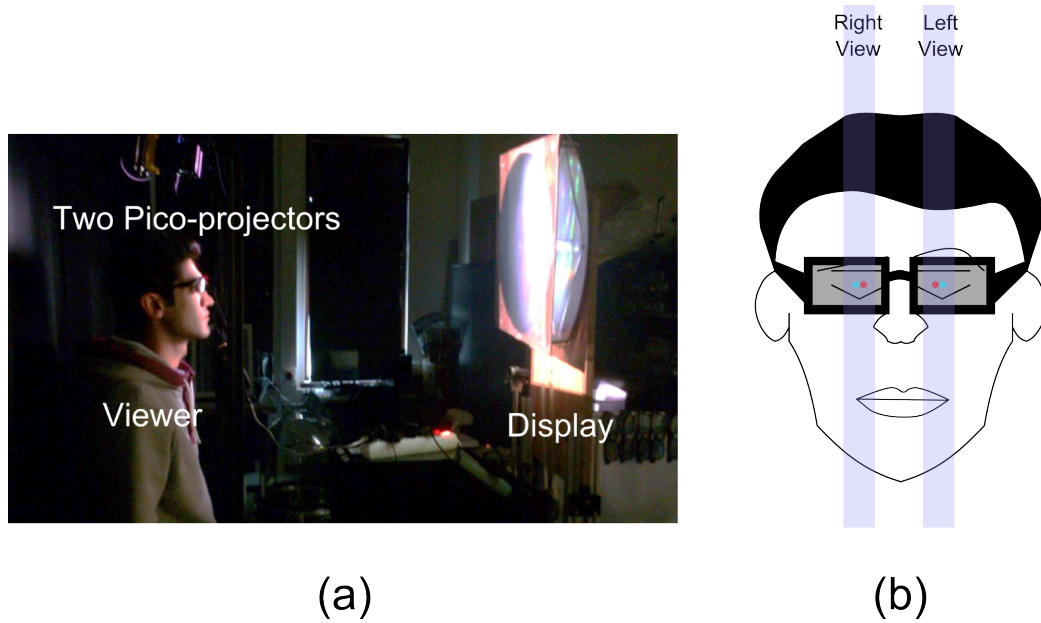


Figure 2.14: (a) The setup used for testing, and (b) a sketch showing how the display separates right and left views on a viewer's eyes wearing SS3D glasses.

screen contains a retro-reflective film and a vertical diffuser. The screen produces two vertical viewing slits for left and right eyes. Viewer's head is also tracked with a camera and the viewing slits are automatically aligned with the viewer's eyes by rotating the screen, allowing head motion. If desired, the content can be updated in synchronism with head position to provide both horizontal and vertical motion parallax. Figure 2.14b shows the separated right and left views via the display used for the test on a viewer's eye wearing SS3D eyeglasses. The content shown in Figure 2.9 was displayed on the display. The screen was placed at 100 *cm* away from the viewing position, and the disparities are calculated such that the large pumpkin appears at 50 *cm*. The subjects were first asked to wear SS3D eyeglasses and align the glasses with their IPD and their eye's optical axis such pinholes are symmetrically aligned in front of each eye pupil. Secondly, they were asked to focus on their thumbs and move it to a position where the big pumpkin is also in focus. At that position, the distance between their thumb and the screen was measured. The average of these measurements turned out to be 50.5 *cm* with a standard deviation of 15.7 *cm*. This

initial experiment and impressions of subjects indicate that SS3D technique seems promising for improving the 3D depth perception.

2.5 Publication Record

Out of this part of the research, 1 journal paper and 2 conference papers have been published. Also one Turkish patent has been issued. Here goes the list of the published articles:

1. Kaan Akşit, Amir Hossein Ghanbari Niaki, Erdem Ulusoy, and Hakan Urey. "Super stereoscopy technique for comfortable and realistic 3D displays." *Optics Letters* 39, no. 24 (2014): 6903-6906. ([Link](#))
2. Kaan Akşit, Amir Hossein Ghanbari Niaki, and Hakan Urey. "P187L: Late News Poster: Improved 3D with Super Stereoscopy Technique." *SID Symposium Digest of Technical Papers*. Vol. 45. No. 1. 2014. ([Link](#))
3. Kaan Akşit, Amir Hossein Ghanbari Niaki, Osman Eldes, and Hakan Urey. "Super stereoscopy 3D glasses for more realistic 3D vision." In *3DTV-Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON)*, 2014, pp. 1-3. IEEE, 2014. ([Link](#))

Chapter 3

PINHOLE ARRAY BASED HEAD WORN DISPLAY WITH ARTIFACT-FREE IMAGE RELAY

This chapter is mainly focused on a new comfortable light weight HWD design which relays images using a pinhole array placed in front of the eye and a smart phone as the display to form a seamless image on the retina. Investigating different available solutions for near-to-eye displays would be the starting point of this chapter. In the following sections, basic concepts of this design are described. First, the methodology of this technique including design of the pinhole array and content creation flow is discussed. Later, the experimental results are displayed explored in more detail including some analysis of the system.

3.1 Near-to-Eye HMDs in the Literature

Nowadays with advances in miniaturization technologies, electronics is becoming more compact. This has revolutionized our experience in human-computer interface and interaction. The tendency of integrating smart devices with human life and personalizing these technologies has been arisen for decades. One of these well-known technology trends is Head Worn Augmented Reality (AR) and Virtual Reality (VR) displays. The main goal of these HWDs is to provide a wide field of view, an acceptable resolution, and comfortable form factor [25, 26]. Since eyes cannot focus distances closer than 25 *cm*, a screen located only a few centimeters away from the eye will form a blurred image on the retina. Variety of solutions has been offered to overcome this

issue. Here these solutions are categorized as solutions using lens(es) and lens-free solutions.

3.1.1 Solutions Including Relay Lens(es)

One common solution is using relay lens(es) so that the refractive power of the eye lens is supplemented and a focused retinal image is formed. There are several designs suggested for low and wide FoV displays [26] and also variety of products are available in the market which some of them are mentioned in this section.

One of these commercially successful products is Oculus VR headset [27]. The design is similar to ski goggles with large high definition screens. The screen displays two side by side images for each eye. A set of lenses is placed on top of the screen, focusing and reshaping the picture for each eye, and creating a stereoscopic 3D image. The system has sensors tracking head movement and adjusts the image accordingly. The result is the sensation that you are looking around a 3D world.

Google cardboard [28] is another example of near-to-eye VR displays using a pair of lenses in front of the eye aiding the human accommodation and a smart phone acting as the screen. The image shown on the screen is simply a stereo pair which forms a correct image on the retina after going through the lens. Aside its simple design, personalized design and light weight, the FoV is limited and the resulting image is with chromatic and spherical aberrations caused by the single lens itself.

3.1.2 Lens-free Solutions

Due to mentioned above drawbacks, there has been many researches conducted investigating lens-free solutions. There are several different approaches in the literature and some of them are mentioned here. Achieving wide FoV, light and comfortable form factor, and easy production with lower price are prominent streams in this research area. Lanman et al. [29] introduced a light field based solution using a thin OLED microdisplay with a microlens array attached to it. Sharp retinal images are represented using out-of-focus rendered light field images. Light field computed image



Figure 3.1: (a) An array of point light sources, (b) the optically see-through built prototype, and (c) a photograph taken through the prototype showing what the eye sees

is shown on the display which is a light field display, also thin OLEDs were used as well, assisted by the microlens array the image formed on the retina is sharp. As an advantage, this prototype provides the eye with continuous accommodation throughout a finite depth of field. Besides its advantages, there are some limitations to their proposed technique. The small diagonal display size limits the setup's overall FoV, the computation cost for this method is high as well, and the pixel size of the used displays are some limitations.

Another lens-free solution has been suggested by Maimone et al. [30] which is wide FoV compact augmented reality eyeglasses. These eyeglasses consist of a pair of LCD and an array of point light sources implemented as an edge-lit, etched acrylic sheet. The point light sources are coded through the LCD such that they act as see-through projectors. A virtual encoded aperture on the LCD aids the point projectors to cover the 2D area in front of the eye and create a wide FoV. Rearranging the image into sub-images according to the printed point light sources configuration helps viewers to perceive a correct image in their accommodation range. The main innovation in this system is the use of coded defocused point sources via an LCD as pinlights. Figure 3.1 illustrates the pinlight near to eye AR display. Drawbacks of this method are color multiplexing to form full RGB image and present artifacts are disturbing besides not providing a seamless image to the eye.

Moon et al. [31] proposed a holographic HMD with RGB light emitting diodes. Figure 3.2 shows the designed geometry and zemax model of the proposed holographic

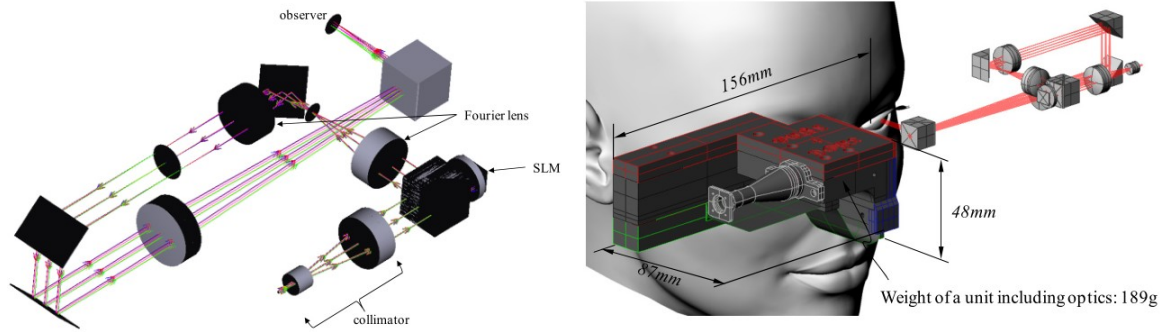


Figure 3.2: The zemax layout of the holographic HMD design (left) and the conceptual design for the display (right)

HMD. A field-sequential technique is used along with a high refresh rate liquid crystal on silicon (LCoS) SLM synchronized with fast modulation RGB LED light sources to generate full color holography. The design consist of three main parts: RGB LEDs coupled with multi-mode fibers to make the design more compact, an SLM and Fourier Filter, and eye piece lenses. Akşit et al. [32] suggest a slim near-eye display using pinhole aperture arrays integrated with a smart phone. In this solution an array of pinholes are drilled and placed on the display which can also be a smart phone. The content shown on the screen is computed according to the pinhole configuration same as light field displays. The sub images on the screen after passing through the pinhole array, the image on the retina would be correct. The hardware of this design is quite similar to our hardware design. Despite their easy to implement, light form factor, and quite similar design, their retinal image quality is hindered by the artifacts which are formed due to the overlap between elemental images relayed through different pinholes.

3.2 Our HMD Design Methodology

The refractive power of the eye lens is not sufficient to focus on a display placed directly a few centimeters away from the eye. In such a case, a blurred retinal image is formed, as illustrated in Figure 3.3a and 3.3b. Our solution to this issue is to place a number of pinholes between the display and the eye. The effect of a single pinhole is demonstrated in Figure 3.3c. The pinhole limits the transmitted bundle of rays so that a point on the display is imaged as a small blurred spot on the retina. As a result, the retinal image is seen as sharp, as displayed in Figure 3.3d. If the pinhole is directly placed on the eye lens, such as via a contact lens introduced by Innovega Inc. [33], there will essentially be no limit on the FoV. However, when there is a separation between the eye lens and the pinhole planes (so that a contact lens is avoided and a comfortable eye clearance is provided), a single pinhole provides only a limited FoV. To increase the FoV, the number of the pinholes could be increased to form a 2D array. However, using a pinhole array does not lead to a seamless retinal image in a straightforward manner. In particular, when a desired image is directly placed on the display (i.e., in an unprocessed form), the final retinal image appears fragmented and distorted rather than seamless, as in Figure 3.3e. The formation of a seamless retinal image therefore requires more advanced optical analysis and appropriate pre-processing of display content.

The general working principle of our design is shown in Figure 3.4. In order to provide a seamless retinal image without artifacts, the desired image is pre-processed and segmented into several sub-images between which some darkened regions are introduced. The resulting image is such that when it is shown on the display and viewed through the pinhole array, a seamless image forms on the retina. However, to achieve this result, the pinhole array needs to satisfy some requirements, and the content on the display should be properly computed, as we explain in the following sub-sections.

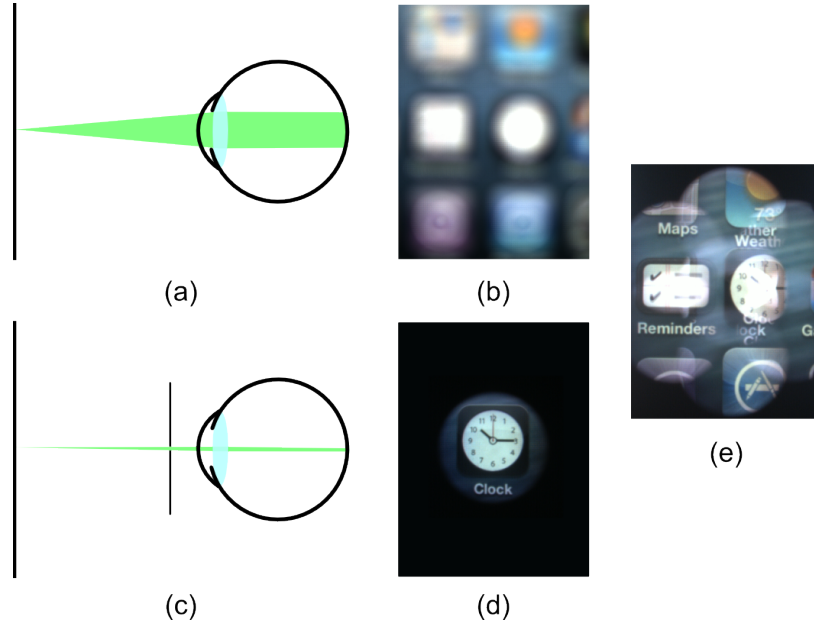


Figure 3.3: Lensless image relay with pinholes. (a) An eye looking directly at a near-to-eye display placed a few centimeters away. (b) Resulting blurred retinal image. (c) An eye looking at a near-to-eye display via a single pinhole. (d) Resulting sharp retinal image with a limited FoV. (e) Wide FoV retinal image formed via a pinhole array. The image suffers from overlap artifacts since the content on the display is not processed yet.

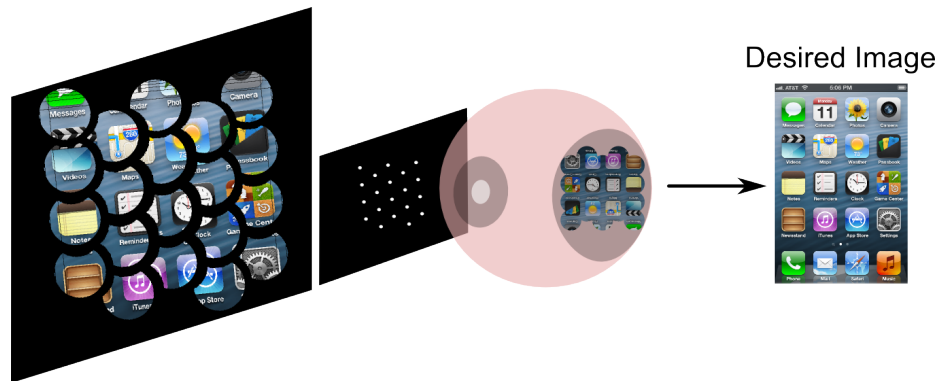


Figure 3.4: The general working principle of the proposed HWD concept. The pinhole array performs the image relay. The desired content is not directly placed on the display, but rather appropriately processed into a new image. In particular, the desired image is segmented and some dark regions are inserted between the segments. When the resulting image is uploaded to the display and viewed through the pinhole array, a seamless retinal image forms.

3.2.1 The Design

Main parameters which should be considered in our offered HMD are screen-pinhole array distance, eye-relief distance, pinhole diameter, pinhole separation (configuration), and the pupil diameter. The merit of function here is achieving higher FoV and resolution while keeping the design comfortable. For the screen-pinhole array distance, the larger the better since larger portion of the screen would be visible. The limiting factor is the total size of the design which increases and is undesired. On the other hand, smaller eye-relief is better since it gives larger FoV. However, when the pinhole array gets closer to the eye, it contact the eyelashes which cause discomfort for the viewer. The summation of screen-pinhole array and eye-relief distance is the total display thickness which must be constant. This criterion leads to a trade-off between these two variables. Based on our findings, pinhole array placed 10 *mm* is an optimal choice taking into account the comfortability and FoV. If this parameter decreases the FoV will increase but it will hit eyelashes which makes it uncomfortable. For the screen-pinhole array distance 35 *mm* has been chosen.

The next variable to be considered is the pinhole diameter which is very important. From geometrical optics point of view, the smaller the pinhole, the smaller the resulting spot size and the better the resolution. Further, from diffraction optics point of view, the smaller the aperture size the larger the spot size which is worse for the resolution. Moreover, smaller pinhole diameter passes less light resulting in less brightness in the perceived image. As explained, the correct pinhole diameter is an optimization between diffraction and geometrical spot size while taking into account the brightness. Figure 3.5 shows how a spot is formed on the retina when a point source passes through a pinhole in front of the eye both from diffraction and geometrical optics point of view. In the figure, α_{diff} represents the spread angle due to diffraction and α_{geo} is the angular spot formed by the geometrical propagation of the light. According to Strehl ratio [34], 10% diffraction spread is acceptable for an optical system, so:

$$\alpha_{\text{diff}} < 0.1\alpha_{\text{geo}} \implies \frac{\lambda}{d_{\text{pinhole}}} < 0.1 \times \frac{d_{\text{pinhole}}}{d_{\text{screen}}}$$

where λ is the wavelength of the light which is assumed to be 500 nm , d_{pinhole} is the pinhole diameter, and d_{screen} is the screen-pinhole array distance. Inserting the values mentioned gives $d_{\text{pinhole}} > 420 \text{ }\mu\text{m}$ as a criterion for the pinhole diameter. Pinhole diameter larger than this would help in case of diffraction and brightness, but in terms of resolvable spot and pinhole effect, larger pinhole diameter is worse. Consequently, the near to optimal diameter for pinholes chosen in this design is 0.4 mm .

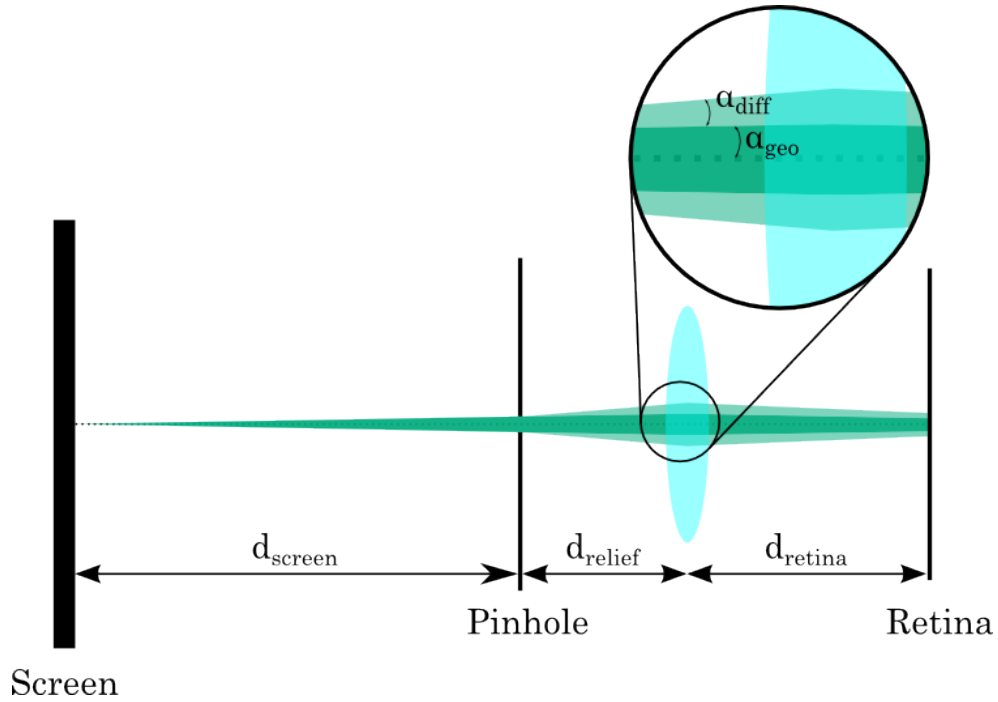


Figure 3.5: Sketch showing what happens to the image of a point source on the retina when a pinhole is placed in front of the eye-lens taking into account both geometrical and diffraction optics.

3.2.2 Pinhole Separation Design

The design of the pinhole array (i.e., determining the location of the pinholes) is crucial to perceive a seamless retinal image free of artifacts. Two conditions must be satisfied. (i) Full Retinal Coverage: the retina must be fully addressed, i.e., there should not remain any dark areas (i.e., areas that do not receive any light from the display) on the retina, (ii) Single Vision: there should not be any pixel on the display with an image at more than one point on the retina, so that multiple vision is avoided.

In other words, each display pixel must at most be visible through only one pinhole. These two conditions guarantee that the mapping from the display to the retina is an on-to function.

Figure 3.6 shows the visual effects of different pinhole array designs. It is assumed throughout the figure that pinholes have point apertures. The conceptual sketches in the left column figures are made only for three pinholes, while the experimental results in the right column are obtained using seven pinholes packed on a hexagonal grid. In left column figures, the rays that pass through the leftmost, middle and rightmost pinholes are shown in red, green and blue color, respectively. Note that only the rays that enter through the eye pupil and reach the retina are shown. Other rays emitted by the display but stopped either on the pinhole or on the eye pupil plane are hidden. The details of the experiment in which right column images are taken are explained in Section 3.3.

In Figure 3.6a, pinholes are placed too close, resulting in the violation of the Single Vision condition. As shown in the figure, for some display pixels, two different rays emerging from that pixel (dark green and red rays) pass through two distinct pinholes and land on different points of the retina. As a result, multiple vision occurs, and the retinal image will inevitably be corrupted. Figure 3.6b shows an experimental illustration of the retinal image formed by a pinhole array with so small separation. Note the many replications of the text Reminders visible in Figure 3.6b.

Figure 3.6c shows a case where the pinhole separation is increased too much, resulting in the violation of the Full Retinal Coverage condition and formation of some non-addressed dark retinal regions. Figure 3.6d illustrates a retinal image where the dark regions are indicated within red circles. Obviously, this case is also unacceptable.

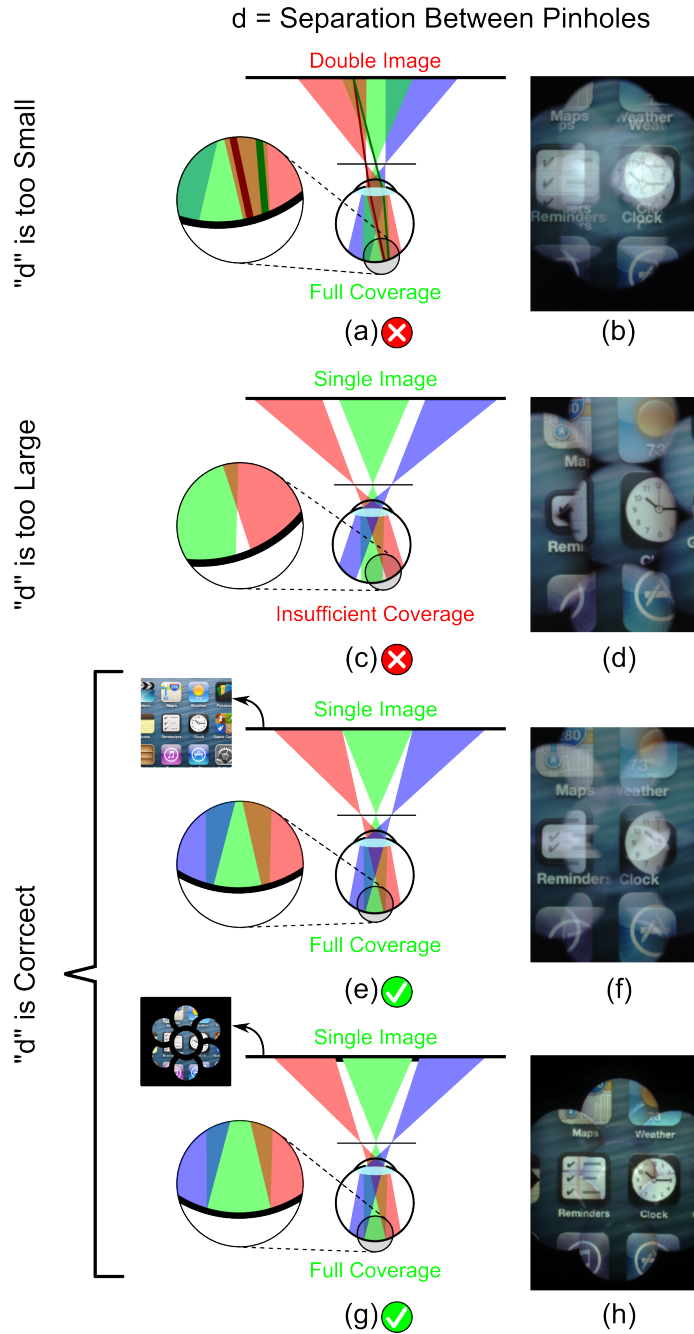


Figure 3.6: Effect of pinhole array design on the resulting retinal image. (a) Too small pinhole separation. Some display pixels are seen via multiple pinholes, and illuminate different retinal points. (b) As a result, double or multiple vision occurs. (c) Too large pinhole separation. Some portions of the retina do not receive any light from the display. (d) Resulting retinal image that suffers from dark regions. (e) The pinhole array design is correct: single vision and full retinal coverage are achieved. However, the desired image is directly placed on the display without pre-processing. (f) Resulting retinal image that suffers from overlap artifacts. (g) The same pinhole array as in e, but with processed content including the darkened pixels. (h) The seamless artifact free retinal image. " d " is a function of eye-relief distance, pinhole-screen distance, and pupil size.

Figure 3.6e shows a correct choice for pinhole separation that meets both the Single Vision and the Full Retinal Coverage criteria. However, the retinal image in Figure 3.6f, which is obtained by directly placing the desired image on the display, is still degraded by artifacts due to the overlap between the retinal sub-images delivered through each pinhole. Note that this overlap is observed despite the fact that the sub-images are seamlessly tiled on the display. The easiest way to understand the formation of this overlap artifact is to consider the pinholes as point sources, and to recognize that the defocused images formed by the pinholes do overlap on the retina.

Finally, Figure 3.6g shows a system that uses the pinhole configuration in Figure 3.6e, but this time the content on the display is such that some pixels are intentionally darkened to avoid the retinal overlap between sub-images of pinholes. As a result, the artifact free seamless image in Figure 3.6h is obtained. The next section details the computation of the display content used in that final case. In closure, we note that given the display-to-eye and eye relief distances, and an expected eye pupil size and location along with an expected focal length of the eye lens, the pinhole array can be designed via simple ray trace simulations conducted in an optics design software such as Zemax.

3.2.3 Content Creation Procedure

In this sub-section, we explain the content creation procedure that will lead to a seamless artifact-free retinal image in our system. Note that such an image is in principle guaranteed to be achieved if a pinhole array configuration which satisfies both the Full Retinal Coverage and Single Vision conditions discussed in Section 3.2.2 is designed, which we assume to be the case. We further assume that the retina can be modelled as a pixelated sensor array. The size of a retinal pixel is taken to be equal to the size of the geometric image of a display pixel. Under these assumptions, Figure 3.7 summarizes the steps of the content creation procedure.

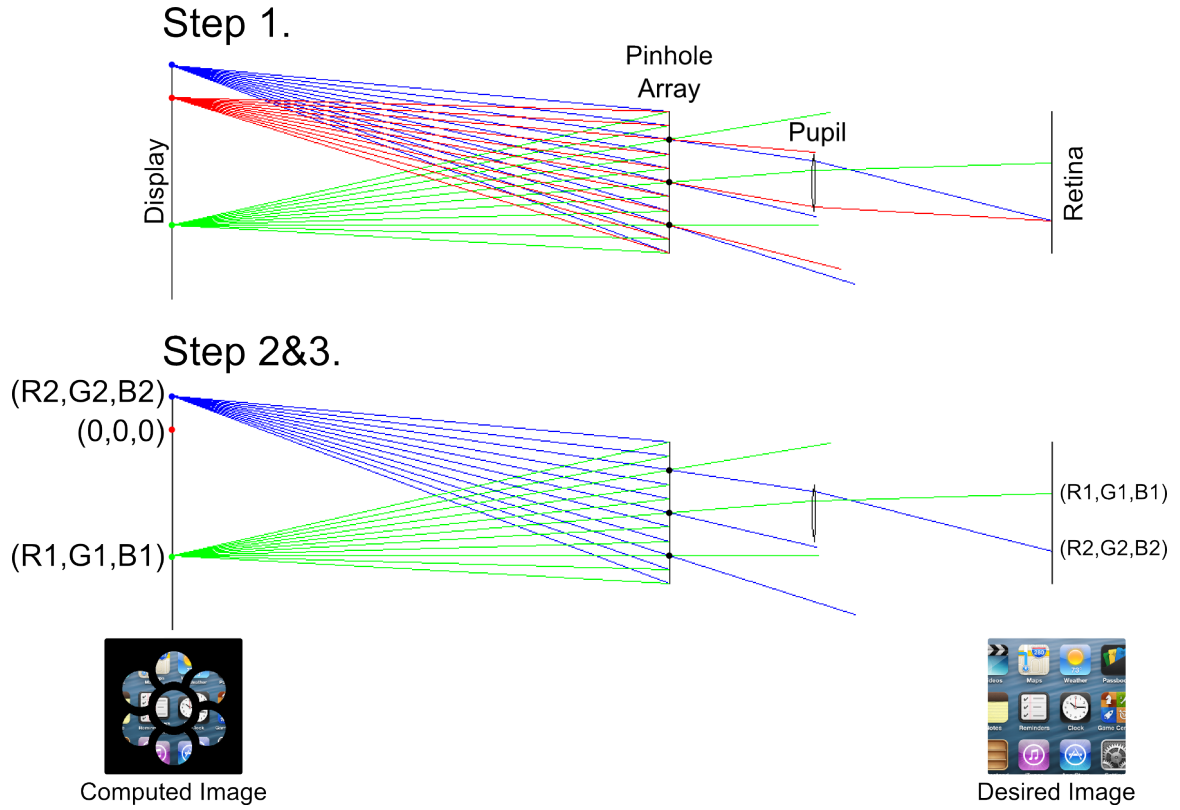


Figure 3.7: Content creations procedure in three steps. Step 1: "Display Pixel-to-Retinal Pixel Mapping". Rays are traced from each display pixel to the retina through pinholes and eye. The retinal pixel that each display pixel hits is determined. The design of pinhole array guarantees that each retinal pixel is addressed, and each display pixel hits only one retinal pixel. However, some retinal pixels might be hit by more than one display pixels. Step 2: "Overlap Elimination". For a retinal pixel hit by more than one display pixels, only one of the display pixels is kept alive, and the other pixels are darkened. In this way, retinal pixels are mapped to a sub-set of display pixels in a one-to-one manner. Step 3: "RGB Assigning". The desired retinal image is mapped to the display content according to the mapping obtained in step 2. The darkened pixels have zero RGB values.

The procedure consists of three steps. The first step is named "Display Pixel-to-Retinal Pixel Mapping". Here we find the retinal pixel where each display pixel is imaged on, using a ray trace simulation. A ray is shot from each display pixel towards the only pinhole through which that display pixel is visible, and passed into the eye and propagated to the retina to identify the retinal pixel that is hit. In this way, a look-up table is prepared, where for each display pixel a retinal pixel is linked.

Note that some retinal pixels appear more than once in the table, since some overlap between the sub-images of different pinholes is initially expected. Then starts the second step of the procedure, which is called "Overlap Elimination". In this step, the look-up table in the first step is processed and a second look-up table is prepared which stores the display pixel or pixels linked with each retinal pixel. To avoid the overlap artifact, the retinal pixels addressed by more than one display pixels are identified. For such retinal pixels, only one of the display pixels is kept, and the other display pixels are eliminated from the table. The last step is called "RGB Assigning". In this step, a desired seamless retinal image is mapped to the display pixels based on the look-up table obtained in the second step. Those display pixels that are eliminated from the look-up table remain dark, i.e., they are assigned zero RGB values. We note that the availability of multiple options for the darkened pixels in Step 2 implies that a desired retinal image can in theory be generated by a multitude of different display images. Finally, we note that the first two steps of the procedure need to be executed only once. Once the look-up table in step 2 is computed, it can be stored in system memory, and then only the third step of the procedure, which has an insignificant computational cost, needs to be executed in real-time operation. More details on the ray tracing procedure, the MATLAB code used, is shown in Section 5.1.

3.3 Experimental Results & Discussion

In order to prove the concept of our proposed HWD solution, we designed a test setup with a configuration similar to that in Figure 3.4. Instead of the eye, we used a PointGrey FL3-U332S2C-CS camera in front of which a ThorLabs MVL8M23 F1.4/8mm camera lens is attached. The diameter of the entrance aperture of the camera is set to 3 mm to mimic the eye pupil. The display is 35 mm away from the pinhole array and the pinhole array is 10 mm away from the camera lens. The camera lens is focused to a distance of 250 mm. As the display, we used an iPod touch 4th generation with 960×640 pixels and a pixel size of 78 μm . An array of hexagonally packed pinholes is drilled on a 0.5 mm thick copper sheet using a PCB

machine. Drilled pinholes have a diameter of 0.4 mm and a center-to-center separation of 3.4 mm . The array has a total of seven pinholes. The pinhole array satisfies the conditions described in Section 3.2.2, and the content is computed according to procedure described in Section 3.2.3.

Figure 3.8 shows the obtained experimental results. In all five cases, the goal is to reconstruct the desired retinal image in Figure 3.4. In each case however, a different content is uploaded to the display, where the contents differ by their selection of darkened display pixels. For each sub-figure, the content loaded on the display is shown on the left, while the resulting experimental camera image is shown on the right. The camera images indicate that in all cases, a focused image is formed on the CCD plane despite the fact that the camera lens is focused at a distance much beyond the display, proving that the pinhole array successfully relays the near to eye display to the retina. Moreover, in all cases, the captured images are seamless and almost free of overlap artifacts; verifying the premise of the proposed content creation procedure.

In theory, all of the five contents in Figure 3.8 should generate the same retinal image perfectly, i.e., free of any overlap artifacts. However, careful examination of the camera images reveals that some degree of overlap artifacts is present at the boundaries between sub-images of different pinholes. These artifacts are caused by small misalignments between system components and the inability of the display to represent fine image borders due to its large pixel size. Actually, the content on the display determines the location of sub-image boundaries on the retina and hence the location of overlap artifacts. Since the contents on Figures 3.8a, 3.8b, 3.8c and 3.8d all have well defined boundaries due to a systematic darkening of overlapping display pixels in some definite order; the overlap artifacts in the corresponding camera images have well recognizable patterns as well. An interesting case is the content in Figure 3.8e, in which the darkened display pixels are randomly chosen. As a result, the sub-image boundaries are not well defined but are diffuse (however, the zoomed in inset shows that different sub-images still merge into a complete image, verifying that even in this random case the information in the desired retinal image is preserved and

completely mapped to the display). The diffuse nature of the sub-image boundaries also lead to diffuse overlap artifacts which are less recognizable. In a video application, randomizing the darkened display pixels from frame to frame might further reduce the level of recognition of the overlap artifacts by benefiting from temporal averaging.

The diagonal FoV of the display prototype is 45 degrees. It is notable that despite such a relatively large FoV, all of the images are almost aberration-free, which is an important advantage of using pinhole relays. Actually, the FoV of the prototype is kept only at 45 degrees due to the fact that the camera CCD array size is not large enough to image a greater FoV. When the HWD is used with actual human eyes, much larger FoVs can be provided by simply adding more pinholes to the array.

One fundamental drawback of the proposed HWD is its poor light efficiency, since most of the display light is lost at the pinhole plane. Another fundamental drawback is the somewhat poor resolution. Assuming that the display has a sufficient resolution, the resolution of the overall system is mainly determined by the size of pinhole apertures. From a geometric optics perspective, the smaller the pinholes, the better the resolution. However, too small apertures lead to increased diffraction spread which enlarges the retinal spot size. Therefore, there is a lower limit on the pinhole size below which resolution starts to worsen. In our prototype, we experimentally found the optimum pinhole diameter to be 0.4 *mm*. The resulting resolution is about 4 cycles per degree; which is not high but we believe is acceptable for a low-cost HWD.

The prototype we demonstrate works for a single pupil position with an exit pupil diameter of 3 *mm*. Though, it cannot cover the entire movement range of a human eye, its exit pupil can be enlarged to a certain degree by placing periodic gratings on the pinhole plane. A more sophisticated solution is to implement the pinhole array via fast binary LCDs and update the pinhole array based on the feedback obtained from eye tracking devices. Besides extending the exit pupil, such a solution can also provide a means for handling small misalignments within the system. However, such a solution increases system complexity and may not be preferable since one of the main advantage of the proposed system over other alternatives is its hardware simplicity.

Therefore, an opto-mechanical design that will provide a first time user the opportunity to perform manual display calibration using some adjustment knobs along with some test images might be a better solution.

A dynamically configurable pinhole array is also needed if the pupil size of the user is expected to vary during operation. In particular, when the eye pupil size changes, the pinhole array design and the computed content for the previous pupil size will fail to deliver a seamless retinal image and artifacts will start to form. Thus, the new pupil size requires the design of a new pinhole array the computation of a new content. A further complication may arise due to the fact that for large pupil sizes around $7 - 8\text{ mm}$, a pinhole array that satisfies the conditions in Section 3.2.2 may not be possible to design for reasonable eye-relief distances. Hence, the best strategy might be to avoid varying pupil sizes and keeping the pupil size at minimum, perhaps by periodically flashing a short duration intense light pulse towards the eye of the user.

As a final remark, the proposed system can be extended into an AR system by using a transparent OLED display with specific spectral characteristics, and by placing the pinhole array on a transparent plate coated with appropriate color filters such that the OLED light can only pass through the pinholes. However, the poor light efficiency may limit the usability of such a display especially in outdoor conditions. Therefore, VR or indoor AR applications may be a better target. The proposed system can also be used as a simple visual aid. With the optimized design of the pinholes and the content, total number of resolvable pixels approach to the total number of pixels on the display screen. Such a display essentially magnifies the display images about 5 times and makes it possible to read text comfortably even for people with severe eye aberrations.

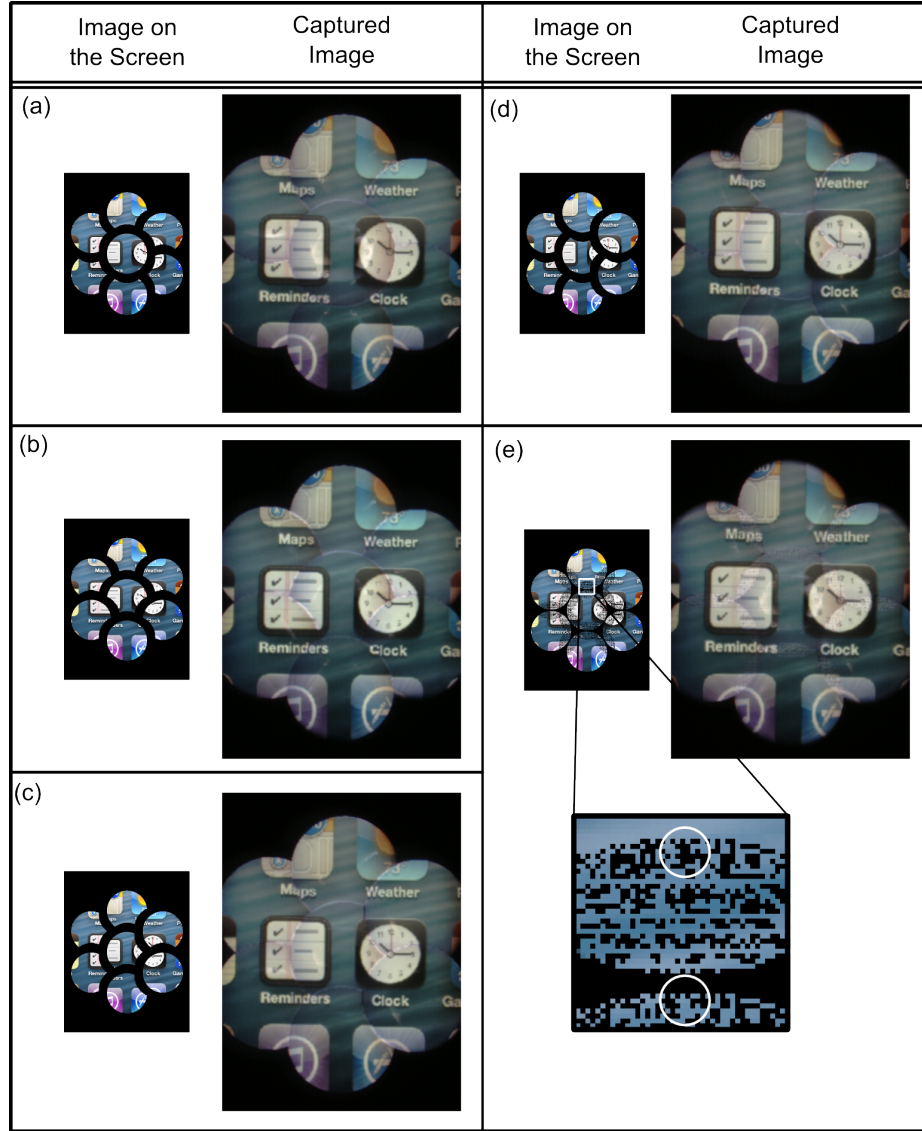


Figure 3.8: Experimental results obtained with the HWD prototype. In all five cases, the goal is to reproduce the desired image shown in Figure 2. In each sub-figure, leftmost image shows the display content, while rightmost image shows the recorded camera image. Diagonal FoV of camera images is 45 degrees, and resolution is about 4 cycles per degree. (a)-(d) Four different contents obtained by a systematic selection of darkened display pixels in a definite order. The well-defined borders of the segments in display contents lead to minor but recognizable overlap artifacts (due to misalignments within the experimental setup) on the camera images along boundaries. (e) Another content obtained by a random selection of darkened pixels. The diffuse segment boundaries result in less recognizable overlap artifacts. The zoomed in inset verifies that despite the random decisions made in the computation, the display content still preserves all the information of the desired image (notice that the patterns in the diffuse boundaries actually complete each other into a seamless image).

3.4 Publication Record

Out of this part of the research, 1 journal paper has been submitted.

1. Amir Hossein Ghanbari Niaki, Erdem Ulusoy, and Hakan Urey. "Pinhole Array Based Head Worn Display with Artifact-Free Image Relay " Optics Express –, no. – (2015): ...-.... ([Link](#))

Chapter 4

CONCLUSIONS

As a conclusion for the first half of the research, a novel SS3D technique has been introduced which provides quite convenient solutions to the A/C conflict and lack of natural blur problems of conventional stereoscopic displays. The most important advantage of this technique is that it can be used with minor modifications over the existing stereoscopic systems. The particular eyeglasses design uses two pinholes with color filters on each side only requiring a regular polarizer or shutter based stereoscopic display to separate left and right views, providing easy adaptation to existing 3DTV and cinema systems. Though selecting this case for our demonstrations, it is also possible to come up with convenient SS3D system designs that deliver higher number of parallax images for each eye. For instance, three parallax images can be provided per eye by using RGB color filters instead of red and cyan color filters. This strategy again can function using a conventional stereoscopic display. In another strategy, one can use a polarization multiplexing stereoscopic display in synchronism with an SS3D glass equipped with electronic shutters and two sets of RGB color filters on each side (giving six pinholes per eye) where the two sets are covered with complementary polarizers. In this manner, six parallax images can be delivered per eye at the cost of halved frame rate of the display, and so on. In addition, having vertical slits instead of pinholes degrade the ability to trigger correct accommodation. On the contrary, our technique is much easier to implement and demonstrate than the similar existing techniques. Moreover, when supplemented with appropriate tracking and content update modules, our technique is also much easier to be implemented as a multi-view system. Obviously, the main drawback of our technique is some loss in the brightness and some decrease in natural spatial resolution limit of the eye due to the usage of

pinholes. However, we believe that these losses are within tolerable limits and the benefits of SS3D technique far outweigh them.

In the second half, we introduce a pinhole array based VR HWD concept. Since the HWD is lensless, it has the potential to provide a wide FoV with minimal aberrations while keeping the form factor comfortable. The proposed content creation procedure ensures that a seamless content is delivered to the retina and overlap artifacts are eliminated to provide the highest image quality possible. Since only the third step of the procedure needs to be executed in real time, the system has low computational cost. Since the system can function with any suitable size full color display, unlike some other methods there is no need for time-sequential color multiplexing to generate a full RGB image. The proposed technique can further be integrated with Super Multi-View (SMV) [24] and Super Stereoscopic 3D (SS3D) [35] techniques for more natural and realistic 3D experience. One fundamental drawback of the proposed HWD is its poor light efficiency, since most of the display light is lost at the pinhole plane. Another fundamental drawback is the somewhat poor resolution. Assuming that the display has a sufficient resolution, the resolution of the overall system is mainly determined by the size of pinhole apertures. From a geometric optics perspective, the smaller the pinholes, the better the resolution. However, too small apertures lead to increased diffraction spread which enlarges the retinal spot size. Therefore, there is a lower limit on the pinhole size below which resolution starts to worsen. In our prototype, we experimentally found the optimum pinhole diameter to be 0.4 mm . The resulting resolution is about 4 cycles per degree; which is not high but we believe is acceptable for a low-cost HWD. The prototype we demonstrate works for a single pupil position with an exit pupil diameter of 3 mm . Though it cannot cover the entire movement range of a human eye, its exit pupil can be enlarged by placing periodic gratings on the pinhole plane. A more sophisticated solution is to implement the pinhole array via fast binary LCDs and update the pinhole array based on the feedback obtained from eye tracking devices. Besides extending the exit pupil, such a solution can also provide a means for handling small misalignments within the system. However, such a

solution increases system complexity and may not be preferable since one of the main advantage of the proposed system over other alternatives is its hardware simplicity. Therefore, an opto-mechanical design that will provide a first time user the opportunity to perform manual display calibration using some adjustment knobs along with some test images might be a better solution. As a final remark, the proposed system can be extended into an AR system by using a transparent OLED display with specific spectral characteristics, and by placing the pinhole array on a transparent plate coated with appropriate color filters such that the OLED light can only pass through the pinholes. However, the poor light efficiency may limit the usability of such a display especially in outdoor conditions. Therefore, VR or indoor AR applications may be a better target.

Chapter 5

APPENDIX

5.1 Appendix A: Content Creation Code for the Pinhole Array Near-to-Eye Display

```
close all
clear all
clc

img = imread('./ipod.png');
imgg = flipdim(flipdim(flipdim(img,1),2),1);
[H,W,RGB] = size(imgg); % x direction (W) and y direction (H)
final_image = uint8(zeros(H,W,3));

%% design parameters (all in mm)
screen_pixel = 0.078; % device pixel size
d_screen      = 35;    % distance between object and pinhole
d_separation  = 2.4;    % distance between central and the first
                        % neighbor pinholes
d_relief      = 10;     % distance between pinholes and eye
% d_pinhole    = 0.4;    % pinhole diameter
pupil         = 3;      % diameter of the pupil

%% parameters of the eye (mm)
d_retina = 17; % distance between eye lens and
               % retina
focus    = 250; % focus distance
```

```

f_eye      = 1/((1/focus)+(1/d_retina));    % focal length of eye lens
detector_pixel = (d_retina/(d_relief+d_screen))*screen_pixel;

%% intermediate paremeters
screen_height = H*screen_pixel;            % height of the object
screen_width  = W*screen_pixel;            % width of the object

% z coordinates of each plane
z_screen = 0;
z_pinhole = d_screen;
z_eye = d_screen + d_relief;
z_retina = d_screen + d_relief + d_retina;

% x,y coordinates of the incident ray
x = linspace(-screen_width/2,screen_width/2,W);
y = linspace(screen_height/2,-screen_height/2,H);
[x_screen,y_screen] = meshgrid(x,y);

% x,y coordinates of the retial detector
x = linspace(-W*detector_pixel/2,W*detector_pixel/2,W);
y = linspace(H*detector_pixel/2,-H*detector_pixel/2,H);
[x_detector,y_detector] = meshgrid(x,y);

% defining the image on the screen
x = zeros(1,W);
y = zeros(1,H);
[x_screen_image,y_screen_image] = meshgrid(x,y);

% defining the image on the retina
x = zeros(1,W);
y = zeros(1,H);
[x_retina_image,y_retina_image] = meshgrid(x,y);

retina_char = zeros(H,W);
display_char = zeros(H,W,2);

```

```

x_retina_char = zeros(H,W,3);
y_retina_char = zeros(H,W,3);
[h,w,Z] = size(x_retina_char);

%% creating pinhole array
hex_rad = d_separation;
theta = 0:60:300;
x_pinhole = [0,hex_rad*cosd(theta)];
y_pinhole = [0,hex_rad*sind(theta)];
char = zeros(H,W,2);

%% main part of the code
for p = 1:size(x_pinhole,2)
    for h = 1:H          % width
        for w = 1:W      % height
            j = 1;
            % checking that the ray passes through which pinhole
            x_eye = (((z_eye-z_pinhole)/(z_pinhole-z_screen))*(x_pinhole
                (1,p)-x_screen(h,w))) + x_pinhole(1,p);
            y_eye = (((z_eye-z_pinhole)/(z_pinhole-z_screen))*(y_pinhole
                (1,p)-y_screen(h,w))) + y_pinhole(1,p);
            if sqrt(x_eye^2+y_eye^2) <= pupil/2
                x_screen_image(h,w) = x_screen(h,w);
                y_screen_image(h,w) = y_screen(h,w);
                % the hitting angle
                hit_ang_x = atand((x_eye-x_pinhole(1,p))/(z_eye-
                    z_pinhole));
                hit_ang_y = atand((y_eye-y_pinhole(1,p))/(z_eye-
                    z_pinhole));
                % angle after deflection
                new_ang_x = asind(sind(hit_ang_x)-sind(atand(x_eye/f_eye
                    )));
                new_ang_y = asind(sind(hit_ang_y)-sind(atand(y_eye/f_eye
                    )));
            end
        end
    end
end

```

```
% point hitting the retina
x_retina = x_eye + (z_retina-z_eye)*tand(new_ang_x);
y_retina = y_eye + (z_retina-z_eye)*tand(new_ang_y);
% assigning values for the retinal image
x_retina_image(h,w) = x_retina;
y_retina_image(h,w) = y_retina;
% index number of the ray hitting on the retina
x_retina_index = ceil(x_retina/detector_pixel)+(W/2);
y_retina_index = ceil(y_retina/detector_pixel)+(H/2);
% corssing out the similar points
if x_retina_char(y_retina_index,x_retina_index,1) == 0
    && y_retina_char(y_retina_index,x_retina_index,1) ==
        0
        x_retina_char(y_retina_index,x_retina_index,1) = w;
        y_retina_char(y_retina_index,x_retina_index,1) = h;
else
    while (x_retina_char(y_retina_index,x_retina_index,j
        ) ≠ 0) && (j < Z)
        j = j+1;
        if x_retina_char(y_retina_index,x_retina_index,j
            ) == 0 && y_retina_char(y_retina_index,
                x_retina_index,j) == 0
                x_retina_char(y_retina_index,x_retina_index,
                    j) = w;
                y_retina_char(y_retina_index,x_retina_index,
                    j) = h;
                break
            end
        end
    end
end
end
end
end
```

```
%% assigning RGB values from the retina to the corresponding screen
pixels
for h = 1:H
    for w = 1:W
        count = 0;
        if x_retina_char(h,w,1) ~= 0
            for i = 1:Z
                if x_retina_char(h,w,i) ~= 0
                    count = count+1;
                end
            end
            count;
            random_index = randi(count,1);
            final_image(y_retina_char(h,w,random_index),x_retina_char(h,
                w,random_index),1) = imgg(h,w,1);
            final_image(y_retina_char(h,w,random_index),x_retina_char(h,
                w,random_index),2) = imgg(h,w,2);
            final_image(y_retina_char(h,w,random_index),x_retina_char(h,
                w,random_index),3) = imgg(h,w,3);
        end
    end
end

figure;
imshow(final_image)
```

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