VR HEADSETS: ENGINEERING THE GATEWAY TO VIRTUAL SPACE

by

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ABSTRACT

Virtual reality (VR) headsets are increasingly becoming more prominent in entertainment, medical practice, manufacturing, defense, customer satisfaction, and much more. These headsets possess a distinct history and a promising future. VR headsets represent one wing of the head mounted display (HMD) category alongside augmented reality (AR) headsets. This report provides an overview of the evolution of VR headsets, the challenges HMDs pose to the human visual system (HVS), followed by an examination of various display, mechanical and optical systems used in VR headsets. After presenting the history of VR headsets, this report discusses the fundamentals of experiencing virtual space by first discussing the HVS, specifically how the eye perceives depth. This is followed by a discussion of current headset setbacks, such as motion sickness and user fatigue. Furthermore, this report will review the innovations of VR lens systems and optical display technologies. This review follows the discussion of performance, display, and lens parameters, providing the background required to discuss the layout for display and lens architectures. Additionally, this report will discuss the advantages and disadvantages of non-emissive displays, self-emissive displays, optical materials, the Fresnel lens architecture, and the pancake lens architecture within VR headsets. Subsequently, an optomechanical discussion of lens mounting and focusing techniques will occur. This will be followed by the analysis of a multi-pass lens system for VR headsets by way of the optomechanical design process. This consists of defining performance specifications and system constraints followed by a review of the lens design and mechanical system design process. This approach will combine all the previously discussed topics into a concise procedure representing the nature of VR headset design and analysis.

Keywords: Virtual reality, head mounted display, pancake lens, optical displays, Fresnel lens

1. INTRODUCTION

1.1 Terminology

Over the past century, experiencing a virtual world has evolved from science fiction to scientific reality. Ever since American author, Stanly G. Weinbaum wrote the 1935 short story titled *Pygmalion's Spectacles*, VR has exponentially gained public interest. Fascinatingly, the term "virtual reality" was not coined until the late 1980's. Regardless, Weinbaum's creation stars an inventor who created goggles allowing for an immersive movie-like experience.

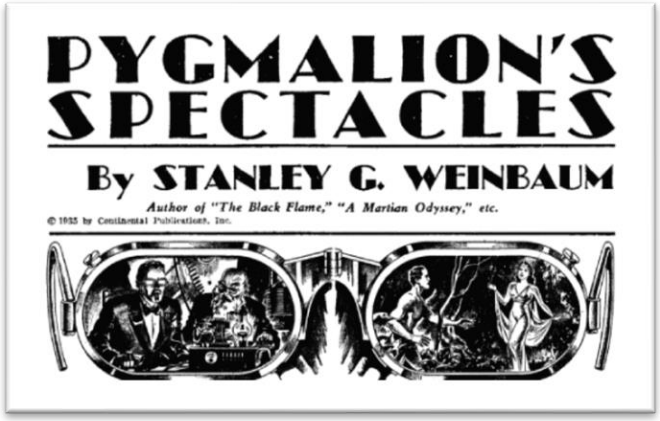


Figure 1. *Pygmalion's Spectacles* written by Stanly G. Weinbaum [1].

Fast forward to today, we are able to enjoy just that. VR headsets have a dynamic history, with increased innovation in military defense, medical practice, manufacturing, and most prominently video games. A close relative to VR headsets are AR headsets, which incorporate virtual overlays with our view of a physical environment. Both types of systems are included under the umbrella of HMD, which may also be referred to as helmet mounted displays. Some HMDs can further be defined as helmet mounted sights (HMS), which typically remain in military applications. The basic components of an HMD include the mechanical housing, the optical lens assembly and, of course, the optical display. Next, I will discuss the history of HMDs and their evolution. However, most of this report will mainly concentrate on VR headsets.

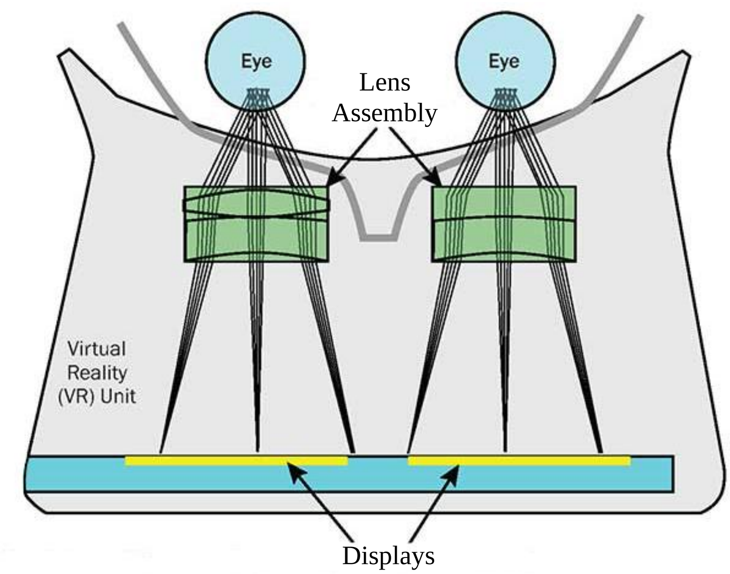


Figure 2. Modern virtual reality ray trace layout [2].

1.2 History of Head Mounted Displays and Sights

As mentioned previously, much of the innovation in HMDs has taken place in the military sphere. As such, it is necessary to briefly discuss this progression. The first instance of an HMD to be patented was in 1916 with Albert B. Pratt's head mounted targeting and firing system. This weapon could be activated as the wearer blows air through a tube causing the mechanism to fire rounds from the helmet [3]. This HMD may have resembled Galileo Galilei's helmet sighting system designed in 1618 to observe the four largest moons of Jupiter, now called the Galilean satellites, however, drawings of his design were never made [4]. Similar to Pratt's HMD, in 1973 innovations for military targeting systems were developed by Honeywell for the US Navy called the VTAS (Visual Target Acquisition System) [5].

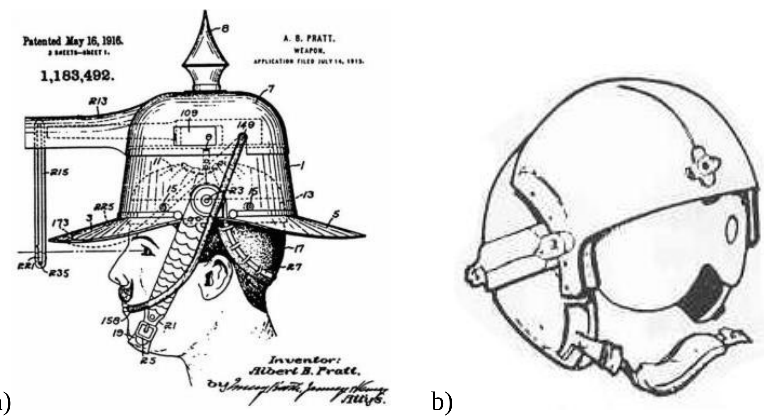


Figure 3. a) Albert B. Pratt's 1916 head mounted targeting and firing system [3].
b) Honeywell's 1973 Visual Target Acquisition System (VTAS) used by US Navy [5].

A comparable version of the VTAS was completed in 1985 attached to a Soviet fighter aircraft. This HMS was for off-axis missile targeting [6]. The American response to this came in the form of the Agile Eye, an HMD developed by Rockwell Collins, utilizing reflections to enable F-15 fighter pilots with the ability to track aircrafts directly behind them [7]. Rockwell Collins then came together with three other companies in 1994 to develop the Joint Helmet Mounted Cueing System (JHMCS) [8]. This HMS was then adapted to many US aircrafts. This system is now the precursor to modern military HMS applications. The development of HMS for military functions seemingly created an inadvertent pathway to the improvement of HMDs for other functions including entertainment and medical practices, just to name a few.

1.3 History of VR Headsets

1.3.1 Early Adaptations

As this report is centralized towards VR headsets, this vein of HMD history must first be described. What makes these applications unique to the ones previously mentioned is their overall goal. Simply put, VR headsets aim to create simulated existence. This oxymoron is further defined in Webster's dictionary as, "an artificial environment which is experienced through sensory stimuli (as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment. [9]" This differentiates VR headsets from other HMDs by effectively eliminating outside lighting influences. Though immersion in the form of a VR headset would not be invented until 1960, other mediums would be foundational in creating what we now call a virtual world. The first agent of this would be the panoramic painting. Offering perspectives of up to 360 degrees, panoramic paintings of the nineteenth century aimed to engage their viewers into an alternate world. It would not have been until 1838 that Charles Wheatstone understood that viewing two similar two-dimensional images focused to the same point would cause the brain to process three dimensions. Titled the Stereoscope, this device utilized angled mirrors to view different images in either of the viewer's eyes [10]. Slightly less than a century later, in 1929, Edward Link would create the first flight simulation system to prepare pilots for combat in World War II. Although the system did not utilize a visual display, this would be the first instance, where a "virtual world" could be manipulated by a user. In this case, it would be done with motors connected with the cockpit instruments to simulate the sensation of flying [11]. All these systems would create the groundwork for the first VR headset which came in the form of the Telesphere Mask in 1960. Although it produced a noninteractive medium, the user would be able to view three-dimensional stereoscopic images with a field of view of around 40 degrees. The Telesphere Mask would incorporate a cathode-ray tube display which at times would be accompanied with stereo sound [12].

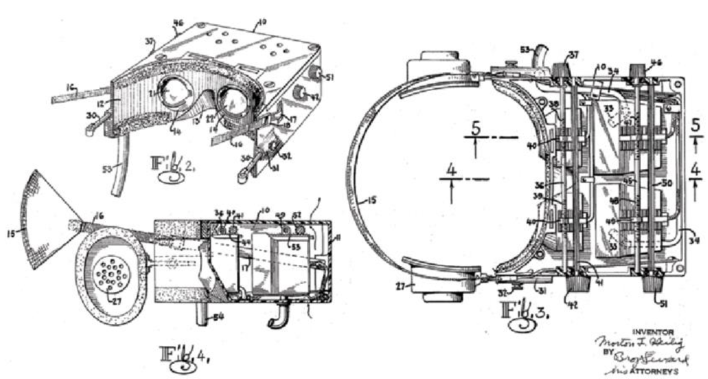


Figure 4. Morton Heilig's 1960 Telesphere Mask [12].

A similar display system would accompany the Headsight system created just a year later by two engineers from the Philco Corporation engineers. This was the first headset to apply motion tracking, making it the first headset to create telepresence, or the sensation of being elsewhere. This was accomplished with a camera positioned in another room from the user [13]. Telepresence in the form of computer-generated images came in 1968 from Harvard professor Ivan Sutherland with his VR/AR HMD titled Sword of Damocles [14]. Just three years prior, Sutherland defined the "Ultimate Display" as, "a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked. [15]" The Sword of Damocles would fulfil his vision to a degree, but it still would be considered primitive to the devices we have access to today. For one, the system was too heavy to be laid on a person's head, requiring it to be fastened to the ceiling. This, however, is where the system's name was contrived. Those familiar with the ancient parable will recall that to simulate the torment and constant fear of assassination, the tyrannical king Dionysius allowed Damocles to experience the pleasures of a king, including feasting at his table, however a sword would dangle above Damocles by a single horsehair. Understanding that with many riches came an equivalent number of enemies, Damocles soon asked to return to his normal day-to-day life, never again wishing to be so fortunate as he once thought [16].

1.3.2 VR Headsets of the 1990's

Nearly two decades would pass before the term virtual reality would originate. Within this time frame, avionic HMDs would increase in popularity. The term virtual reality then emerged as Jaron Lanier, founder of the visual programming lab (VPL), created the EyePhone VR headset [17]. This familiar name would predate Apple's iPhone by twenty years. Nevertheless, VPL would become the first company to make VR headsets available to the public. This system also included what was called a "Dataglove" which allowed viewers one additional step into the immersion of VR space [18]. The promise of VR to bring the future of entertainment and innovation came to a peak in the 1990's when the VR industry erupted. Large VR gaming systems began populating malls and arcades, and although archaic to today's standards, the public's enthusiasm sparked [17]. In 1993 SEGA released the SEGA VR headset for its Genesis console. Which included LCD displays, head tracking and stereo sound [17]. Nintendo eventually responded in 1995 with the Virtual Boy VR-32 which marketed itself as the first fully portable VR headset [17].

a) b)

Figure 5. a) SEGA VR (1993)[19] b) Nintendo Virtual Boy VR-32 (1995)[20]

Despite growing interest in VR systems, both gaming headsets would eventually fail commercially. One theory is the systems were too expensive to properly tap the market, however, disappointment with computer graphics, and software are likely to blame. Entertainment was not the only field that saw an increase in VR use during this time, VR technology allowed therapists to treat patients with PTSD. One such system was created by Georgia Tech and Emory University in 1997, which used VR to treat war veterans [21].

1.3.3 Modern Era of VR Headsets

Although films like The Matrix assisted in bringing ideas such as simulated reality into pop culture, enthusiasm towards VR stalled for about a decade after the turn of the century. This drought mainly affected the public's perception as during this time, innovation in the field was taking place, aiming to not repeat the shortcomings of the 90's VR consumer headsets. In 2010, one such innovator created a VR headset kit that would eventually lead him to create the Oculus Rift. His name was Palmer Lucky and after working with John Carmack, computer programmer and video game developer, he launched a Kickstarter that regenerated the VR community into the modern era of HMDs [22].

a) b)

Figure 6. a) Oculus' 2012 Development Kit 1 (DK1) [23] b) Oculus Rift (2016) Consumer Version 1 (CV1) [24].

After raising 2.5 million dollars, and obtaining interest from many potential investors, Facebook, now known as Meta, purchased Lucky's company in 2014. From then on, nearly every tech giant had developed and continued to improve their VR products [22].

2. EYE OPTICS

2.1 Eye Anatomy

Before diving too much further into the functions and properties of virtual reality headsets, we first need to describe, in simple terms, how the eye will capture light from the headset to stimulate our brains into perceiving an immersive, yet virtual world. Starting from the back side of the eye, the sense of vision is created at the retina, a photosensitive surface tasked with converting light into neurological signals, which are then sent to the brain. The retina is composed of two photoreceptors, cones and rods. Rods make up nearly 95 percent of the retina's photoreceptors and are responsible for capturing light in dark conditions [25]. Conversely, approximately 6.4 million cones are responsible for daytime and lit conditions. Although cones make up a fraction of the photoreceptors present, they are greatly concentrated at the fovea [25].

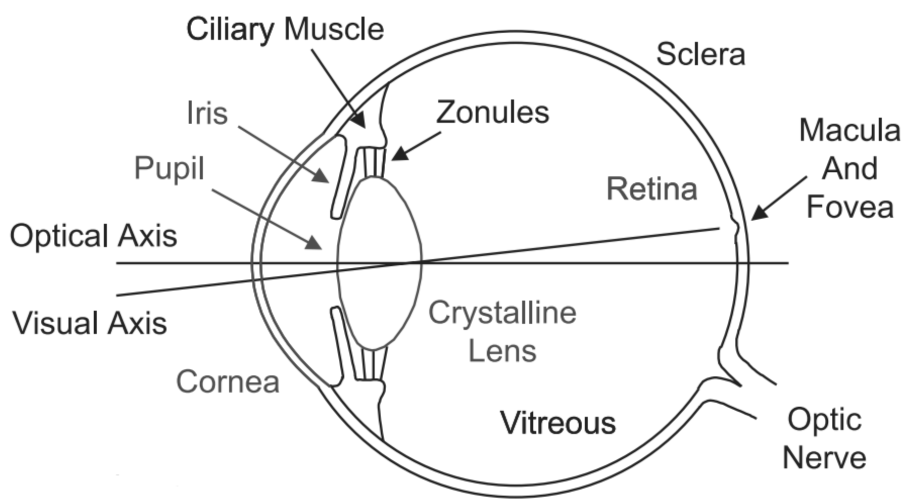


Figure 7. Right eye horizonal cross-section [26].

The fovea is the high-resolution central portion of the retina and on average covers a diameter of 1.5 millimeters. Before the light can be received by the retinal photosensors, it must travel through the vitreous fluid, located between the crystalline lens of the eye and the retina. The vitreous fluid has viscosity around three times that of water with a refractive index of around 1.336. Consisting of a third of the optical power of the eye, the crystalline lens can adjust focus to near or far objects. This is possible by the ciliary muscle, which either pushes down on the crystalline lens causing it to accommodate the viewing of near objects or creates tension with the lens allowing for distance objects to be viewed. Continuing closer to the front surface of the eye, the iris acts as the eye's aperture stop. The liquid between the crystalline lens and the eye's cornea is called the aqueous humor, a less viscous liquid than that of the vitreous humor and is measured to have a refractive index of around 1.377 [26]. Finally, the cornea is responsible for the remaining two thirds of optical power in the eye. Some additional members of the eye are the sclera and optic nerve. The sclera is the white of the human eye which protects the inner working of the eye. The optic nerve acts as the pathway from optic nerves to travel to the brain, carrying the information captured by the retinal photosensors. This pathway is also responsible for our eye's blind spot, which is located about 15 degrees temporally [25]. Thankfully, our brain "fills in the blanks" and in most daily situations is completely unnoticeable.

2.2 Optical Properties of the Eye

In order to weigh in on what features are necessary to implement into a successful and immersive VR headset, we must first describe the optical properties and limitations of the human eye. Although it is easy to think of these eye limitations as negative restraints on what a HMD can provide, these properties often allow for creative solutions to provide the perception of depth, time, motion and much more. The first optical property of the eye is its field of view (FOV). Each eye has an FOV of approximately 160 degrees [25]. A pair of eyes can achieve a FOV of approximately 200 degrees, where the central 120 degrees can be described as the binocular field as both eyes can see within this range. This leaves an additional 40 degrees of what is called monocular vision on each side of the human head. Amazingly, this also means that each eye can see 10 degrees behind our heads when looking straight ahead. However, to properly mimic reality, VR headsets must also consider the additional 50 degrees of view angle humans can achieve when rotating their eyes completely in one direction or the other [25]. Like any optical system, optical aberrations arise, the human eye is no different. The following aberrations are present in the eye and are important to be aware of while creating any visual optic; they are spherical aberration, chromatic aberration, and astigmatism. Another important property of the human eye that is extremely relevant to the design of VR headsets is visual acuity. Visual acuity is defined as the ability to distinguish small resolvable high-contrast details. There are many different types of visual acuity including separable acuity (closely spaced details), perceptible or detection acuity (single lines or points), vernier acuity (small lateral displacements) and stereo acuity (depth difference determination) [25]. Visual acuity varies from person to person, but regardless of who you are, visual acuity is greatest at the fovea, as the density of cones is highest on the retina. Visual acuity can also be defined in terms of spatial frequency, or the ability to separate sine wave patterns in an object. Spatial frequency can also be related to contrast modulation making visual acuity heavily dependent on the contrast of an object. This relationship between contrast modulation and spatial frequency is defined in the contrast sensitivity function (CSF). Each observer will have a different CSF and performance with varying target sizes or luminance levels will decrease with age. Essential to display design, the temporal resolution of the eye simply defines the minimum time it takes for the human eye to recognize two separate flashes. Ideally, the speed of integration will be minimal to improve temporal resolution. On average rods and cones period of integration is 100 milliseconds and 15 milliseconds, respectfully [25]. Finally, critical flicker frequency or CFF is the last optical parameter of the human eye necessary to account for in VR headset design and manufacturing. CFF is defined as the frequency at which an observer no longer detects a flickering light, instead observing a constant source. This again varies person to person, but for moving objects, like the ones encountered in virtual space, the CFF for the human eye is near 16 hertz. Additionally, CFF varies with modulation, luminance, the retina location, and age of the observer.

2.3 HMD Health Effects

Now that we have discussed the properties of the human eye, we can now discuss common health effects that can be caused when using HMDs, specifically VR headsets. One of the most prominent complaints of HMD use is motion sickness. Motion sickness refers to adverse symptoms and readily available observable signs that are associated with exposure to real and/or apparent motion. We can further break up this effect into two cases, visually induced motion sickness and physically induced motion sickness. The first being caused by scene motion presented in a VR headset. Visual motion can occur when a virtual scene's movement does not match that of the user's physical motion. This difference is felt more with motion acceleration as the otolith organs, the biological version of an accelerometer located near our ear drums, do not detect a difference when velocity remains constant [22]. Motion sickness can also be caused by vection, "the illusory self-motion in the absence of physical self-motion through space and thus, is inherently an experience that occurs under sensory conflict conditions [22]." This occurs often as some VR headset applications will provide virtual motion or travel, while requiring the user to stay stationary. Perhaps the second most common health concern when experiencing virtual reality, and one headset designers must take into consideration is eye strain. Scientists have attributed much of eye strain in VR headsets due to the following realities, the accommodation-vergence conflict and binocular-occlusion conflict. In the real world, our eyes easily adjust to near and distant objects, matching the accommodative distance and vergence distance, as we focus to a point [22]. However, inside a VR headset, these two distances are not equivalent resulting in this conflict, due to the stereo viewing nature of HMDs. Similarly, binocular-occlusion conflict occurs when reality and virtual space clash. In this case, screen overlays, that do not provide natural depth will cause the user to have this conflict and can result in eye strain [22]. Flicker is another HMD factor that at times can cause adverse health effects. Flickering in VR headsets should occur at high rates much greater than that of the CFF discussed in the previous section. Additionally, flicker can become a trade-off in HMD design, with parameters like FOV. Another aspect of HMDs that are directly related to the user's health is simply headset weight. Excessive weight added to the user's head for a long period of time may cause problems. Similarly, headsets with misaligned center of gravity (COG) to that of the head's COG will cause additional fatigue. If a headset is placed on a user with an unaligned COG, the user will experience strain from the neck or other areas, attempting to hold their head to the appropriate height. These are just some of the health effects that need to be at the forefront of any VR headset design, to ensure the user with the most comfortable, safe, and enjoyable experience.

3. THEORY

When considering the design and creation of an HMD, more specifically a VR display, there are several specifications that need to be defined. However, before discussing each system parameter that goes into the construction of a VR display, we must first consider the definitions of these optical properties, both in general optical systems and of course VR headsets. The parameters needed to effectively define VR headsets are as follows, display parameters, eyepiece parameters, and performance parameters.

3.1 Display Parameters

The purpose of an optical display is to obtain and convey information in a way most useful to a viewer [25]. The general process of a display starts with the image source, where the graphics generator and capturing device feed data to the display processor. From here information is sent to the display environment where the electronic display and hard-copy display work in tandem to send light to the viewer [25]. This process can be seen below in the display imaging chain. The most important parameters regarding the display of a virtual reality display include display resolution, pixel density, and refresh rate.

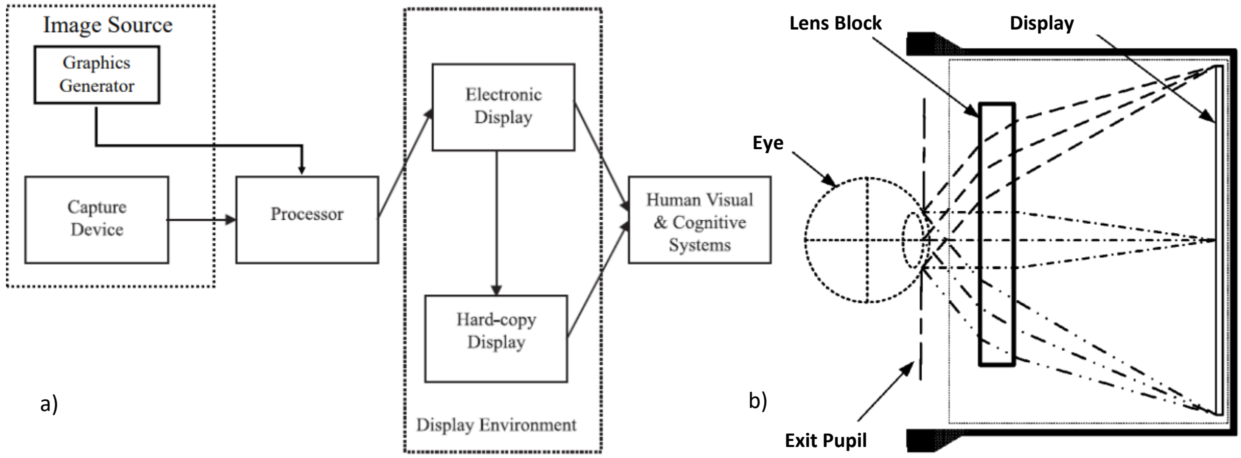


Figure 8. a) Display imaging chain. [25] b) Cross-section of VR headset layout [27].

3.1.1 Resolution

Resolution is defined broadly as the smallest resolvable detail in an image. In optical systems, many types of resolution can be relevant. For instance, optical systems have angular resolution, detector resolution, and limiting resolution. Additionally, the HVS previously discussed has temporal resolution and resolution acuity. With many terms sharing resolution in their title, it is easy to get their definitions confused with each other. For HMDs, angular resolution can be the most useful of the resolution terms. Angular resolution, often called pixel subtense or instantaneous field of view (IFOV), is measured in arcminutes per pixel [26]. It is defined as the ability to distinguish small details of an object. Angular resolution is directly related to the Rayleigh criterion, which defines the smallest separation between two Airy disk patterns at a distance where two distinct points are still resolvable. An Airy disk can be defined as the ideal diffraction-limited spot size, which can be visualized as a point spread function (PSF) in the figure below.

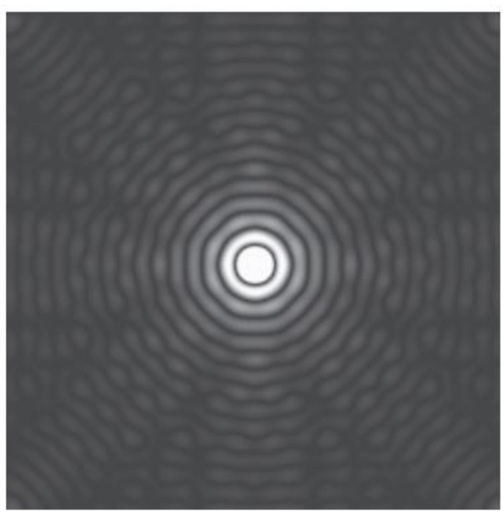


Figure 9. The point-spread function of an ideal, diffraction-limited optical system [28].

An ideal optical system is called diffraction-limited because its sole limitations are effects of diffraction through the system apertures. This means that wavefront error is approximately zero, and all other refinements in fabrication or assembly no longer require improvement. However, it should be noted that for HMDs and other visual systems, the addition of the HVS makes achieving the requirements for a diffraction-limited system near impossible. Furthermore, the PSF can be described as the focal spot, an image of an object positioned at infinity, from a single point of light distributed at the image plane. The PSF is useful to determine performance and imaging quality of a system [28]. The Airy disk is shown in the figure above as the most central core surrounded by diffraction rings [26]. The Airy disk diameter can be calculated with the following equation:

$$D_{Airy} = 2.44\lambda\, F/\#\ [\mu m]$$

Similarly, the Rayleigh resolution criterion defines that when two objects are considered resolved when the diffraction pattern peak of the first object falls on the first minimum (first dark ring) of the second object [29]. This can be seen in the figure below and following equation.

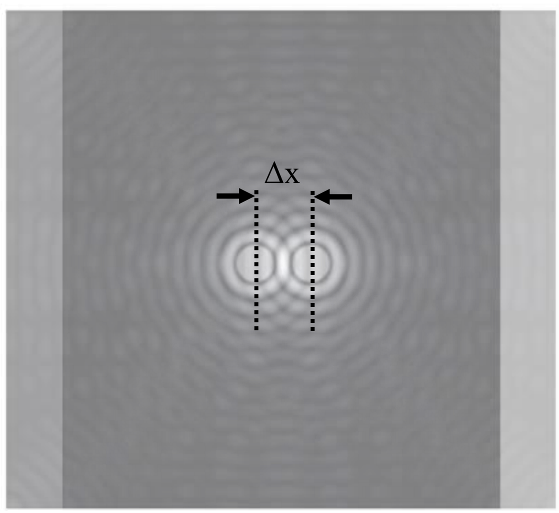


Figure 10. Two adjacent Airy patterns describing the Rayleigh resolution criterion [28].

$$Resolution = \Delta x = 1.22\lambda\, F/\#\ [\mu m]$$

From here we can define angular resolution or instantaneous field of view (IFOV) by dividing be the image distance [26]:

$$Angular\ Resolution = IFOV = \frac{1.22\lambda}{D_{EP}} \left[\frac{arcmin}{pixel}\right].$$

Another definition of resolution for displays which is recognizable to most people defines the total number of pixels in which make up a display. For example, the Meta Quest 2 has a pixel resolution of 3664×1920 pixels. This term most often determines the length by height of the display in terms of pixels. As seen in the equation above, angular resolution is related to the entrance pupil diameter, f-number, and numerical aperture.

3.1.2 Pixels Density

Pixel density simply defines the number of pixels in a specific area of a display. This term is often characterized in units of pixels per inch (PPI). Pixel density can further be defined as the ratio between display size and resolution [25]. A similar specification is that of pixel pitch which is often measured in millimeters, defining the distance between the center of one pixel to its adjacent pixel. These parameters, although simple to define, allow for consumers to compare headset specifications.

3.1.3 Refresh Rate

The rate of a display can be defined as the number of times per second that the display hardware scans out a full image [22]. This value is inversely proportional to the resolution specification discussed previously as the more pixels addressable, the lower the refresh rate will be. As mentioned earlier, the CFF of the HVS is about 16 Hz. As such, when designing virtual reality headsets, achieving a refresh rate much higher than 16 Hz is a necessity to ensure the most immersive experience for the user. Typically, headset displays will have refresh rates in the range of 60 to 120 Hz [22]. Higher refresh rates reduce latency, judder, and flicker [22]. Refresh rate is limited by the display processor's frame rate and pixel switching time. Frame rate is a system factor that depends on the application's scene complexity and software optimizations [22]. Pixel switching time is the time required for all the pixels of a display to be updated, which itself is governed by maximum switching voltage [30].

3.2 Eyepiece Parameters

There are countless ways to project light from a display to the user's eye in a head mounted display. In a later section common design forms will be discussed in great deal. However, before discussing these configurations, it is essential to define common parameters within these lens systems.

3.2.1 Field of View

Arguably the most crucial parameter to define a virtual reality headset is its field of view (FOV). FOV can be described as the maximum angular size of an object or display seen from the entrance pupil of the optical system. Defined as the ratio of the object size and image size, this parameter directly affects the immersion capability of a VR headset, as a small field of view would limit the engagement of the user with the virtual space projected [26].

3.2.2 Focal Length

One of the rudimentary optical specifications, defining focal length is essential to the design process of projecting systems like HMDs. Defined as the distance between system principal planes and focal points, an optical system will have both a front and back focal length [26]. However, the effective focal length of a lens system containing one or more lenses is far more crucial to define when discussing VR headsets. This is because this term will determine the distance between the lens system and the display as well as the user's eye. Thus, to obtain a small profile system, smaller focal lengths may need to be necessary, however as optical power is inversely proportional, this may result in a more aberrated system. Hence, the balancing act of an effective, low aberrated and reasonably sized eyepiece inside a virtual reality display begins.

3.2.3 Stop and Pupils

Pupils are simply images of the system's stop, where the image from the object plane is defined as the entrance pupil and the image from the image plane is the exit pupil of the system [26]. In addition to determining the entrance and exit pupil, the size of the aperture stop of a lens system controls a variety of essential parameters. The stop controls the level of vignetting and in turn the FOV, the aberration characteristics found within the system and the diffraction performance of the system. As such the stop is a critical parameter for the optics inside of a virtual reality headset. The exit pupil of the optical system will ideally align with that of the entrance pupil of the user's eye. Because of this the pupil of the eye will act as the system's stop.

3.3 Performance Parameters

With any complex optical system, characterizing performance parameters is imperative to identifying the success or failure of a designed or fabricated system. HMDs are no exception to this. Some of the many performance parameters that aid in this identification are efficiency, aberrations, and contrast.

3.3.1 Efficiency

Optical efficiency in projection systems can broadly be described as the ratio between light emitted from the display to that of the light which reaches the exit pupil of the system. For virtual reality headsets, this exit pupil is the front of the user's eye. Furthermore, we can characterize optical efficiency as the product of these three individual terms for optical efficiency, the efficiency of the display, the efficiency of the lens system and the coupling efficiency between them. This is a meaningful specification for headsets as high efficiency will require less light to be projected from the display, thus having a direct relationship with battery life and operating time. Étendue is a crucial term to discuss regarding the efficiency of an optical system, as it describes the flux propagation characteristics of an optical system [31]. This geometrical term is conserved through a lossless system and decreases as loss is introduced. These losses could include vignetting, aberrations and scattering to name a few [31]. For HMDs, étendue tends to decrease as not all the light projected through the headset optics will enter the user's eye pupil, resulting in a loss as some light will be projected onto the user's iris and sclera.

3.3.2 Aberrations

Aberrations in an optical system are defined as any deviation from perfect. Thus, there are many different types of aberrations, including distortion, defocus, astigmatism, spherical aberration, chromatic aberration, coma, field curvature and tilt, just to name a few. These aberrations can be modeled in different orders to properly represent a system. In virtual reality headsets, the most common metrics of aberration performance are chromatic aberration and distortion. One difference between these two types of aberration is chromatic aberration blurs an image while distortion warps an image. Furthermore, chromatic aberration occurs in systems with many wavelengths which will result in a variation of focal lengths, causing blur.

3.3.3 Contrast

Contrast is the measurement of relative modulation between two luminance values. Thus, for displays, contrast is expressed as a ratio. This is why many consumer displays, such as televisions or phones will state contrast as 1000:1. However, this ratio can be exaggerated by manufactures by the way each luminance is measured. Thankfully, there are even more accurate representations, mainly, the contrast sensitivity function (CSF). Contrast sensitivity is calculated as the inverse of modulation in the form of spatial frequency [26]. The modulation transfer function (MTF) is a measurement of the effectiveness of a lens system to convey contrast from an object to an image [26], in our case from a display to the user's eye. MTF is measured in cycles per millimeter and requires both frequency information and modulation.

4. DISPLAY TYPES

To fully understand the intricacies of VR headsets we must discuss displays. There are numerous types of displays used for projection displays. However, the most common display types used in virtual reality headsets are liquid crystal displays (LCD), liquid crystal on silicon displays (LCoS), organic light emitting diode displays (OLED), and micro light emitting diode displays (μLED).

4.1 Non-Emissive Displays

4.1.1 LCD

LCD displays are non-emissive displays which are composed of multiple layers of various optical materials. They act as either passive or active-matrix forms. Passive-matrix LCDs are composed of a grid of Indium Tin Oxide conductors in which an intersection controls a single pixel of the display. The active-matrix LCD has many layers and is structured as follows: The first layer in the LCD structure is a linear polarizing film, aligning the source light's orientation of oscillation into one direction. After this, the light will pass through a thin glass substrate, then through a transparent electrode, often made from Indium Tin Oxide [32]. The light then encounters a thin polyimide layer which aligns the liquid crystals, which is followed by the liquid crystal layer. The light then passes through a set of color filters, ending with the polarizer, which is oriented ninety degrees from the original fast axis orientation of the initial polarizer.

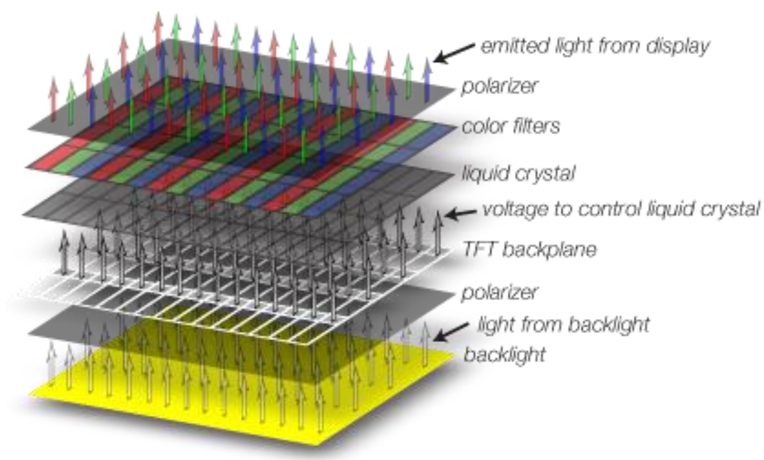


Figure 11. Cross-section of LCD backlit display [33].

There are a number of modes in which LCD displays can act. For active-matrix LCDs, there are many modes, including twisted and super twisted nematic (TN), in-plane mode (IPS), multi-vertically aligned (MVA), fringe field switching (FFS), and ferro-electric mode (FEM) [34]. In VR headsets, it is common for the mode of choice to be IPS and FFS as they allow for large viewing angle [25]. However, modes such as TN and MVA have quicker response times. Additionally, TN modes have the highest transmittance compared to other modes, making them great approaches for laptops and smart watches, where MVA modes often are used for televisions, due to the larger viewing angle compared to the TN mode.

4.1.2 LCOS

LCoS displays act similarly to that of an LCD display, but with a few key differences. The first difference is that instead of the liquid crystals being positioned between two glass plates in the LCD case, in LCoS displays, the liquid crystals are positioned between one glass plate and a silicon microchip. This microchip is responsible for controlling each pixel from a pixel grid. The advantages of LCoS displays include a large fill factor, higher resolution, and faster switching capabilities than LCD displays [32]. The LCoS structure is as follows: From the silicon microchip which controls the liquid crystals, there is a reflective layer responsible for reflecting the light necessary to create the proper image. Next, the liquid crystal layer, responsible for allowing how much light reaches the reflective layer. Additionally, there is the alignment layer of the structure, followed by the electrode, necessary to creating a completed circuit with the microchip. Finally, all these delicate and thin layers are covered with a single glass layer previously mentioned. A setback that LCoS displays face occurs when voltage controlling a single pixel, effects that of adjacent pixels causing a fringing field effect (FFE). This effect increases as the pixel pitch decreases past that of the cell gap size [35]. However, the large contrast ratio, high brightness capabilities, light efficiency, and image quality, make LCoS displays a viable display option for many projection systems.

4.2 Self-Emissive Displays

4.2.1 OLED

OLED displays are comprised of extremely thin layers, utilizing an organic semiconductor to emit light through the fundamentals of electroluminescence. Electroluminescence is a phenomenon caused by the energy release of electrons as photons, which are excited through a process called recombination. Recombination occurs after the electrons and electron holes are separated by doping, forming a p-n junction. The layers of an OLED include the electron-injection layer, electron-transporting layer, emitting layer, hole-transporting layer, and hole-injection layer [34]. The electron-injection layer and hole-injection layer are responsible for conducting electrons, while blocking holes. The electron-transporting layer and hole-transporting layer takes the carrier to the emitting layer. Finally, the emitting layer emits light and is made from materials with high quantum efficiency and mobility [36]. The total system allows for applied voltage to cause the transportation of electrons and holes from the cathode and anode to the emissive layer, recombining and causing the emission of light. The advantages of an OLED display include fast response times, wide color gamut, thin profile enabling flexible displays, true black color state, and low power consumption [34].

4.2.2 MicroLED

MicroLED displays, often notated as μLED, are self-emissive displays made up of LEDs less than fifty microns in size. μLEDs consume nearly half of the energy needed to project light with an LCD. Compared to the other display types mentioned above, μLEDs are generally new to the field. In 2012, μLEDs were introduced to the public as Sony launched a 55” display with μLED’s original name, crystal light-emitting diode (CLED) [37]. In addition to the low energy consumption, μLEDs have a higher luminous efficiency and brightness compared to LCDs and OLED displays. Because μLEDs are self-emissive, the structure is simpler than that of the LCD or LCOS displays. MicroLEDs are layered between transparent substrates and include color filters and in some cases, funnel tube arrays to improve the light efficiency of the display [38]. A figure of this upgraded structure can be seen below.

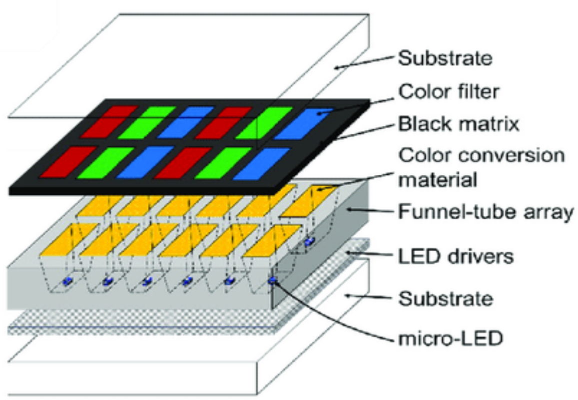


Figure 12. MicroLED cross-section with funnel-tube array [38].

The compact structure of the small LEDs provides higher resolution than the previously mentioned displays. Interestingly, this compact nature is also one of the μLEDs largest setbacks as manufacturing, transferring and correctly aligning millions of μLEDs is a huge technological obstacle [37].

5. OPTICAL DESIGN FORMS

There are two lens architectures that are most common in current VR headsets. These are the Fresnel lens architecture and pancake lens architecture. Before describing these schemes, I will first outline prevalent optical materials used to create the architecture systems previously mentioned. After doing such, I will discuss common mounting practices and focusing techniques for VR headsets.

5.1 Optical Materials

5.1.1 PMMA

Two categories of materials crucial to the development of virtual reality displays are lens materials and optical film materials. HMDs once relied solely on glass lenses to project light to the user. Plastic lenses entered the public eye midway through the twentieth century as a comparable glass alternative. This initially exclusively affected the eyeglass industry. However, glass lenses used for HMDs were eventually replaced by plastic lenses sometime during the 1990s. In one case, this change came about when the US Air Force challenged Rockwell Collins to reduce the weight and improve the center of gravity of their fighter pilot HMD. This change resulted in a weight reduction of 50% and although optical performance was a concern at first, the effects of early plastic adaptations in HMDs proved to be a success [39]. From then on, glass lenses in HMD optics were rare. Today, plastic and acrylic lenses as polymethyl-methacrylate (PMMA) are beneficial substitutes to glass, as they not only are far lighter than typical glass lenses, they also are safer to use. Additionally, PMMA is scratch resistant and mechanically stable [40].where regular glass lenses are prone to scratches if not properly protected. In addition to this, glass lenses are more likely to crack or shatter, which could leave remnants inside optical systems, or worse, harm users of said optical system. The process in which PMMA is created is called polymerization [41]. The molecular formula for methyl methacrylate is $C_5H_8O_2$ and when in its liquid state, can be molded into many different forms including sheets, resins, and lenses. Other advantages of plastic optics include low density, ease of shaping both optical and mechanical surfaces and features, resistance to shock, and low costs in large quantities [42]. However, the use of plastic optics does come with some setbacks including low abrasion resistance, low temperature coefficient of refractive index, and coefficient of thermal expansion much larger than those of glass, low softening temperature, difficulty in coating, high cost of molding and tooling, hygroscopic tendency, possible birefringence due to stresses from the molding process, and surface and internal scattering greater than those of glass [42]. Injection molded lenses, particularly plastic lenses, will exhibit stress birefringence. Birefringence occurs when a material's refractive index differs by polarization or direction of propagation. Moreover, stress birefringence is defined as spatially varying birefringence resulting from forces within the lens that compress or stretch the material's atoms, causing birefringence [43]. This causes a localized change in refractive index of the material that creates an optical path difference (OPD) between two orthogonal polarized components of the radiation transmitted through the stressed region

[44]. The relationship between this OPD and applied stress (σ) can be expressed by a materials stress optic coefficient (C) and material thickness (t) in the following equation [44]:

$$OPD = C\sigma t = \Delta n C$$

Below is a plot between the localized change in refractive index versus the stress optic coefficient when 15 MPa of stress is applied to a material.

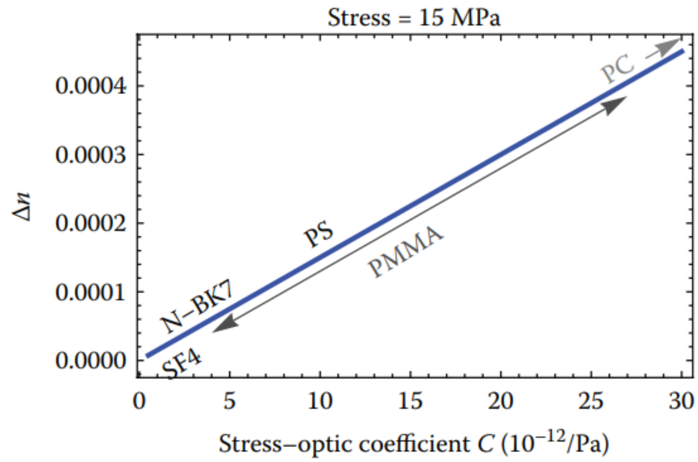


Figure 13. Change of refractive index as a function of material stress-optic coefficient C for 15 MPa applied stress [43].

Here we can see that glass materials such as N-BK7 and SF4 have stress optic coefficients of less than 5 whereas polymers such as PMMA, polystyrene (PS), and polycarbonate (PC) have larger stress optic coefficients which will vary with temperature [43].

5.1.2 Thin Film Materials

Thin films are much more prevalent in optical systems than most people may think. Most of these films are used to limit reflection in purely refractive systems. In contrast, films can also be used to boost reflection, when placed over metals and other mirrored surfaces. For both cases, films also provide an element of protection to the optic they are placed upon. Thin films can be categorized into four different interfaces. The first is called a homogeneous interface, simply meaning the properties across the film are constant. Contrastingly, the properties of an inhomogeneous interface will change based on the thickness of the applied film. Next, an isotropic interface has consistent indices of refraction in every direction, unlike an anisotropic interface, where the refractive indices depend on the polarization state of the film [43]. Thin films are characterized by their Fresnel reflection and transmission amplitude coefficients, based on the s and p eigenpolarizations. The pancake lens architecture utilizes quarter-wave plates and polarization beam splitting films.

The role of a quarter wave plate is to introduce a phase delay of a quarter of a wavelength of light. This ability converts linearly polarized light into circularly polarized light and vice versa. This is only possible when the waveplate's fast axis is oriented 45 degrees from that of the linear polarization's fast axis. Polarizing beam splitting films ideally split light into s and p polarizations, reflecting the s component and transmitting the p components. However, films of this nature have a limited range of angle of incidence, as well as wavelength to which they are effective [43].

5.2 Fresnel Lens Architecture

Originally invented for lighthouse optics, Fresnel lenses have been an intricate piece to the innovations in optical design for two centuries. Named after the physicist Augustin-Jean Fresnel, the Fresnel lens capitalized on optical refraction [45]. With a side profile resembling a symmetric sawtooth pattern, the lens acts as a group of prisms which allow for the collimation of light at a desired angle. In the case of a light house, this would collimate the light into a massive beam. This design has maintained demand throughout its lifetime as it saves both material and space, which in turn, allows for a cheaper and narrower lens. Below is a graphic of a Fresnel lens that may be used for a VR headset. Where the prism-like behavior of the lens is shown with dynamic draft [46].

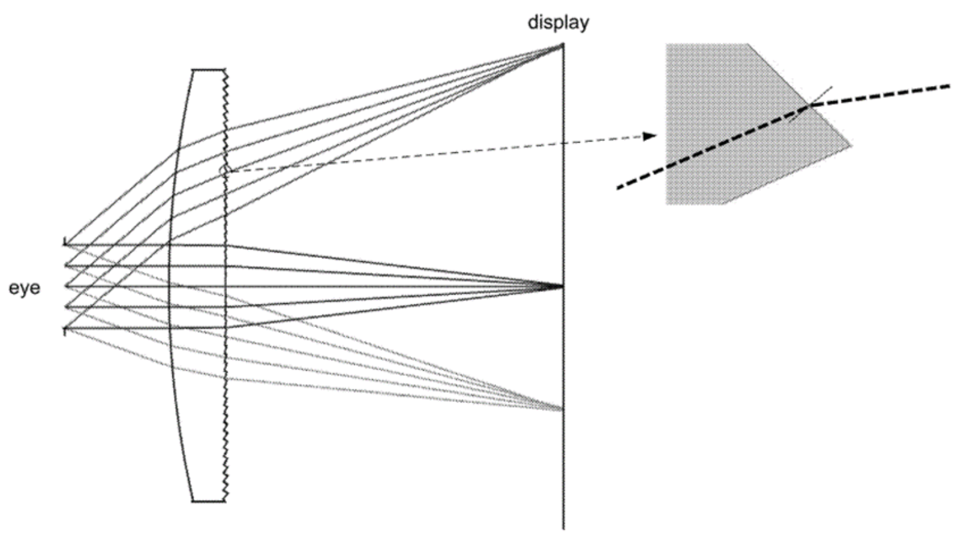


Figure 14. Cross-sectional view of a Fresnel lens with dynamic draft from 2018 Oculus patent [46].

This is a popular choice of optic for HMDs as saving space within the optical housing is essential in creating an effective, comfortable, and light system for its user. Because the refraction of an element depends on its refractive index, and varies with wavelength, Fresnel lenses can produce some levels of chromatic aberration (CA). Although this CA is less than that of a traditional diffractive optical element, it still is possible to reduce this effect by adding a broadband diffractive lens. This combination is effectively called a hybrid Fresnel lens, where the CA of the pair counteract each other, ideally leading to achromatic behavior [47]. The refraction angle of a Fresnel lens can be determined via Snell's law as [26]:

$$\theta_1 = \sin^{-1}\left(\frac{1}{n}\sin\theta_2\right).$$

Other advantages of Fresnel lenses in virtual reality headsets include high efficiency and uniform refraction for large angles. Disadvantages of Fresnel lenses include geometric shadowing problems and transmission loss due to the grooved structure, resolution limitations due to the flat prismatic-type surface approximations and reduced contrast due to the vertical surfaces and groove peak [48]. These limitations for massed produced Fresnel lenses lead to expected performance not to be diffraction limited. Two possible Fresnel lens designs included a grooves-out and grooves-in design. A grooves-out design directs the facets towards the side of the collimated beam, also called the infinite conjugate or the long conjugate, and a grooves-in design orients the facets towards the focal point, also called the short conjugate [49]. These two configurations can be compared by their fractional transmission efficiency over various f-numbers which can be calculated based on surface reflections and draft losses. Below is a plot of these values.

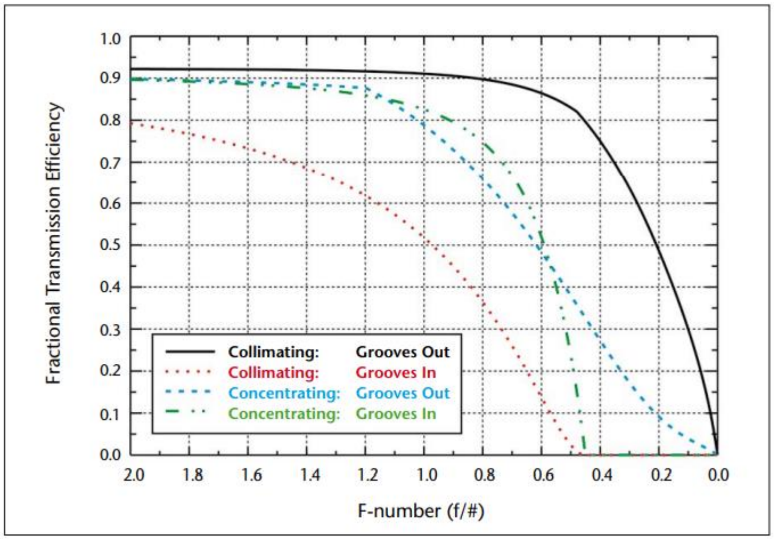


Figure 15. Idealized efficiency values of Fresnel lenses in various configurations [49].

From this chart we can see that a system's f-number can limit transmission for Fresnel lens configurations. Finally, Fresnel lens grooves that can be visible in display applications such as HMDs pose issues for users.

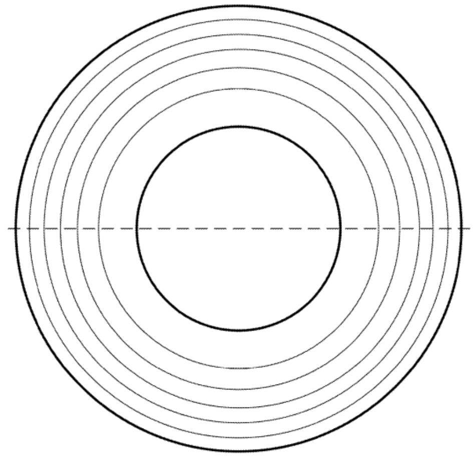


Figure 16. Fresnel structures arranged on a flat surface [46].

Despite certain limitations, Fresnel lenses still present practical applications to VR headsets.

5.3 Pancake Lens Architecture

For a VR headset to be successful it must succeed in mimicking reality; this however comes with certain limitations. One major constraint being the overall weight of the headset, mainly coming from the lenses themselves, used to provide the headset's immersive and large FOV. Another important consideration involves the overall distance between the entrance pupil of the user's eyes and the headset display system. Decreasing this distance will not only result in less weight, but a more comfortable and relaxed COG for the user's head. Both these concerns can be mitigated with the use of pancake lenses in VR headsets, allowing for longer focal lengths in smaller packages, as well as creating a more comfortable user experience for longer periods of time. Pancake lenses utilize an optical folding technique which allows for a larger optical path length (OPL) while maintaining a smaller physical system size. In VR headsets, the use of pancake lenses can reduce the physical distance between user eye and display to be a third of the needed OPL. The structure is as follows: from the headset display, light is linearly polarized by an initial polarizer. Next, the phase of the light is delayed by a quarter wavelength after traveling through a quarter-wave plate oriented 45° from the transmission axis of the initial polarizer. Next, the light passes through a 50/50 mirrored surface, where the remaining transmitted light returns to a linear polarization state after traveling through a second quarter waveplate oriented an additional 90° from the first quarter waveplate. Finally, this linear state is again reflected by a polarized beam splitting film, which transmits the perpendicular linear state. Then after a second pass through the system, the reflected portion of the 50/50 mirrored surface will return light to the originally propagated direction until it transmits through the polarized beam splitting film to the eye.

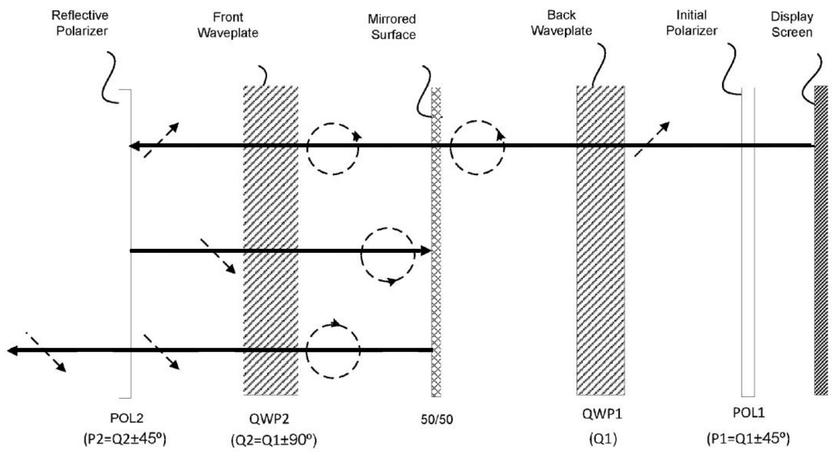


Figure 17. Pancake lens architecture phase alteration from 2018 Oculus patent [50].

As the light travels through the pancake lens system, the phase of the light will change from linearly polarized (+0°) to right circularly polarized, back to linearly polarized (+0°), to left circularly polarized, to linearly polarized (+90°). One setback when using polarized based reflection optics in virtual reality headsets is that as the OPL is reflected and folded twice though the system, the total transmission is cut in half at two separate interfaces resulting in a total transmission of 25% through the optics, in the best case. The relation to lens configuration can be seen below.

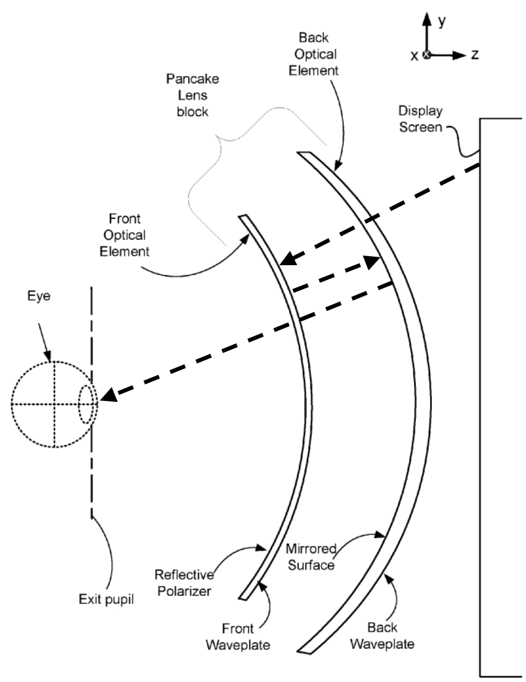


Figure 18. Cross-sectional view of a pancake lens from 2018 Oculus patent [50].

The one surface that contributes a 50% decrease in transmission occurs at the beam splitting mirror surface as the light travels in either direction, resulting in a total transmission of 25% at best. Additionally, the two interfaces in which light is reflected occur first at the last surface of lens two which is coated with a polarized beam splitting coating that allows one direction of linear polarized light to transmit while reflecting the other. In this case, the p-polarized light is reflected, and the s-polarized light is transmitted. The second surface that reflects light in our system is at the beam splitter where the remaining 50% of light is lost via transmission and does not reach the user's eye.

5.4 Element Mounting

Before discussing the intricacies of tolerancing a pancake lens system, we must first discuss the many ways to mount optical systems to mechanical housings. There are two categories of mounting techniques: retaining mounts and bonding mounts. Bonding mounts, due to the typically long curing time, allow for more time to adjust and center a lens inside of a cell. Because of this, bonding often takes place during or immediately after the centering process. Bonding does introduce other drawbacks including bond shrinking, due to temperature changes, loss of contact, the inability to disassemble the structure, if necessary, laborious manufacturing processes, and outgassing during temperature change or curing process, which may damage optical surfaces [51]. Retaining rings are another common mounting technique. These rings utilize axial preload to keep a lens in place, by forcing a lens to sit onto a shoulder [51]. When multiple lenses are included in a design, spacers can be utilized to maintain a consistent distance between elements. The retaining technique has some disadvantages, including lens movement induced when tightening the rings and temperature changes able to effect lens preload. Preload is the necessary force required for a retaining ring or shoulder to maintain contact with a lens or optical surface. Therefore, the preload force must be larger than the total external force along the direction of potential separation [51].

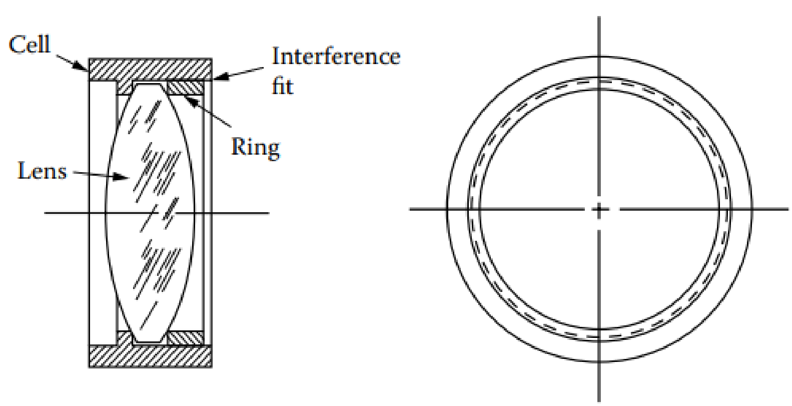


Figure 19. Retaining ring lens mounting technique [52].

Like retaining rings, snap rings fit into mechanical slots machined near the lens surface. The ring itself has a gap to allow for compression when assembling to slide into the groove. A cross section of the layout and ring can be seen below. Note that creating constant contact between the lens and snap ring can be difficult as the groove dimensions and position is one additional factor that can be a source of error, usually when large temperature changes take effect.

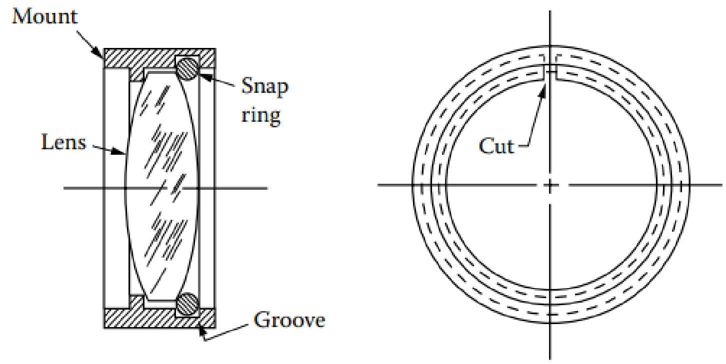


Figure 20. Snap ring lens mounting technique [52].

In addition to retaining and snap rings, preload can be applied using either one or a combination of the following methods. First, preload can occur as a result of gravitational force, which although constant and predictable, is not controllable by the designer.

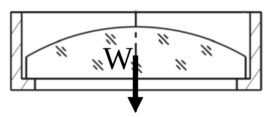


Figure 21. Gravitational preload upon a lens [52].

Next, preload can be applied by vacuum. This method requires that the mounted surface is properly sealed. Additionally, this method exclusively applied preload force as a pulling motion. Conversely the method in which preload is applied by pushing is that of fluid pressure, this also requires proper sealing of elements, ensuring that the fluid is properly controlled and does not negatively affect other elements inside the optical system. Sealing is often achieved by either the use of O-rings or cured elastomer, both which can be seen in the figure below.

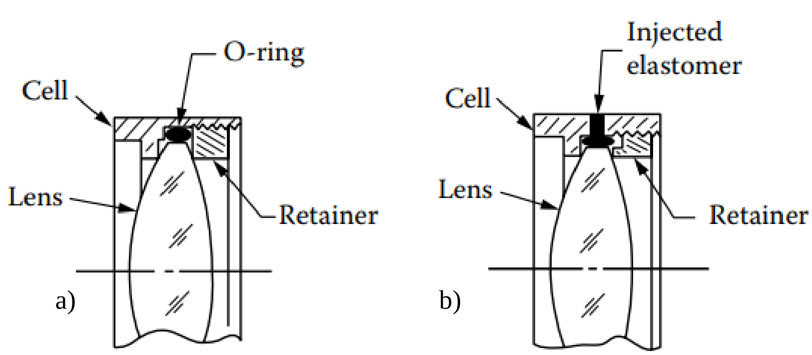


Figure 22. a) O-ring sealing technique. b) Elastomer sealing technique [52].

Other methods of applying preload are magnetic and electrostatic forces, both of which are usable in vacuum and are extremely complex to control [51].

5.5 Focusing Mechanism

Many VR headsets have lens focusing mechanisms to assist in keeping the user's eye at the point of optimal comfort. This is possible through what is called a varifocal element as it varies the focal length of the lens system. There are many different avenues of achieving linear motion of lens elements. In this section I will discuss a handful of these possibilities. The focusing apparatus is typically responsible for the linear translation of one lens element. In the following examples, I will assume a two-element lens system, like that of the pancake lens architecture previously discussed. Some ways that make this possible are motorized actuators, gear drives, and vacuum pressure [53]. In the case of a motorized translation, a motor could be attached to one side of a lens as additional guide shafts ensure that the linear movement does not add unwanted lens tilt [53].

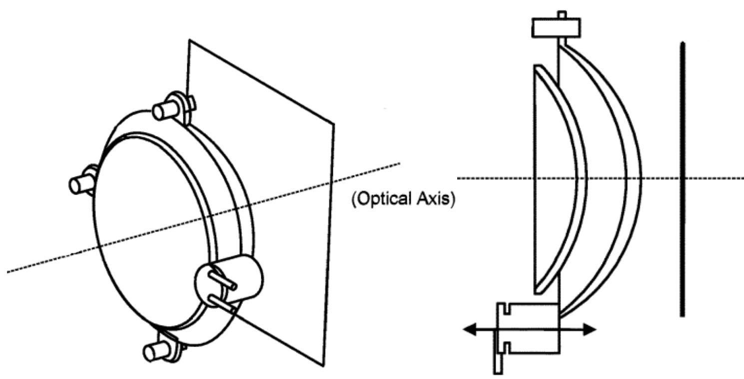


Figure 23. Motorized focusing technique utilizing guide shafts and motor [53].

One possible motor that could be used for this linear shift is a voice coil motor. Voice coil motors are simple electric motors consisting of a magnetic housing and coil. When a voltage is applied, the motor will translate forward. Conversely, the reverse polarity will cause the motor to move back. Another motor that could be used is a piezoelectric motor, which is controlled by sending electrical signals that result in a mechanical motion [53]. Linear motion caused by gear motion is made possible with many threaded elements. First, one of the lenses will have an edge collar which meets a worm gear with a shaft perpendicular to the optical axis of the lens system. The rotation of this worm gear will result in the translation of the collared lens, assuming all other degrees of freedom are accounted for with guide shafts [53].

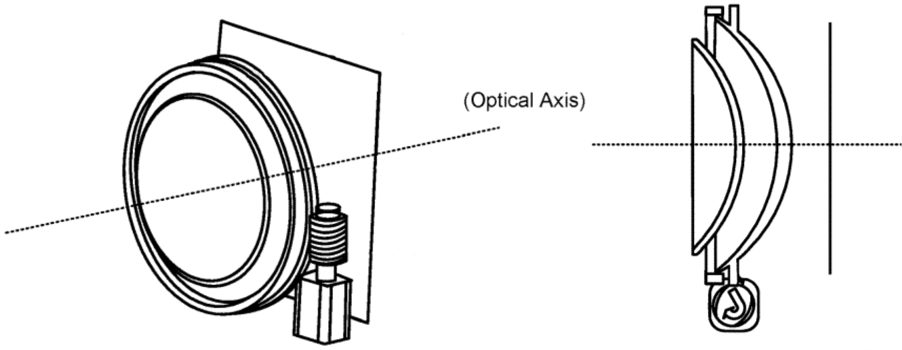


Figure 24. Gear focusing technique with lens collar [53].

Another possible focusing solution for VR headsets would be the use of liquid crystal lenses. Focusing by means of liquid lenses is achieved by a process called electrowetting. Electrowetting is the application of electric fields to manipulate the wetting properties, and therefore shape and curvature, of a liquid [54]. The liquid lens cell contains two immiscible liquids: a non-conductive oil and a water solution separated by an interface. Applying a voltage at the interface between the two liquids changes the curvature of the lens within tens of milliseconds. Applying more voltage increases the overall curvature and optical power of the liquid lens [54].

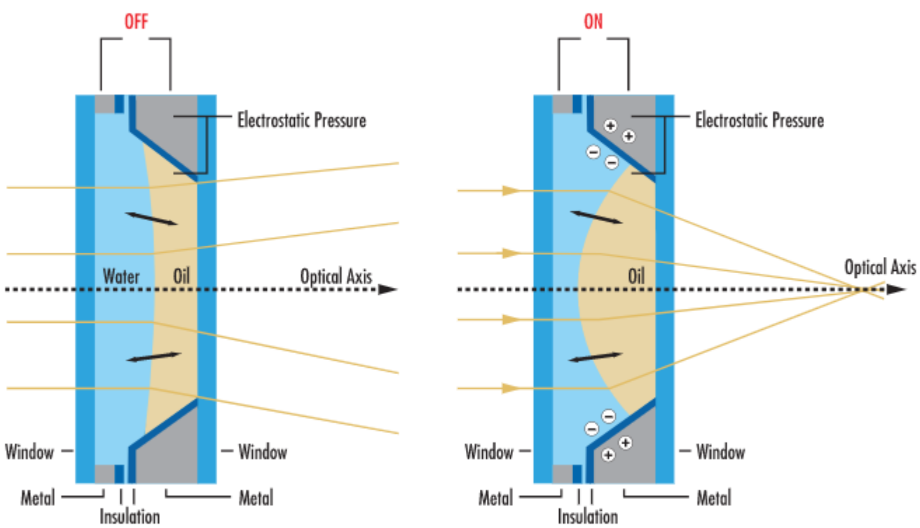


Figure 25. Diagram illustrating the working principle of the Corning Varioptic Liquid Lens [54].

Liquid lenses would allow a variation of focus distances that could better match the human visual system, furthering the immersive nature of VR headsets [54]. The final example of a possible focusing mechanism inside VR headsets is that of vacuum pressure actuation. Utilizing an air-tight chamber, seen in the figures below, a vacuum port can be accessed by a pump that can create positive and negative pressure [53].

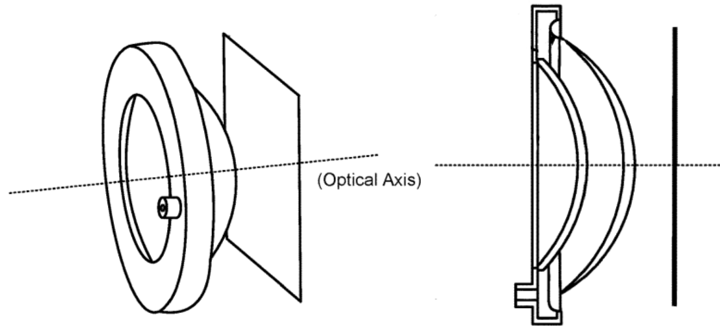


Figure 26. Vacuum pressure focusing technique with vacuum port [53].

Because one edge of the chamber is made up of a flexible material, possibly rubber, attached to one of the lenses, the pressure induced by the pump to the chamber can manipulate the adjustable lens along the optical axis [53].

6. ANALYSIS OF MULTI-PASS SYSTEM

The multi-pass nature of the pancake lens system architecture within a VR headset requires an in-depth design development process focused on additional reflections within the lens system. The pancake lens system is able to achieve this multi-pass behavior through manipulation of the geometrical phase of light as it passes through the system. This section will describe the optomechanical design process for a pancake lens and accompanying mechanical mounting system within a VR headset.

6.1 The Optomechanical Design Process

Optomechanics is a field of mechanics that addresses the specific design challenges associated with optical systems [55]. The abbreviated steps for the optimization of an optical lens system and mechanical mounting design are as follows. First a designer will define lens specifications, followed by a first order layout of the system [56]. From here, within lens design software, the designer may replace ideal lenses with real lenses and materials. This is followed by system optimization, using a merit function, to correct from the discrepancies caused by the realistic lens materials. This optimization includes minimizing aberration presence. Once optimized, the lens system undergoes tolerancing. As no optical system can perfectly be manufactured or assembled, the tolerancing process is necessary to simulate these imperfections allowing the designer to analyze the system's design to ensure that performance requirements can still be met. In addition to the design and optimization of a lens system, the designer must also model an optomechanical mounting system to accommodate the lens system's function. This mechanical model must undergo similar steps to that of the lens system. The opto-mechanical design process begins with requirement definition, conceptualization, performance specifications and design constraints followed by a preliminary design, constructed in computer-aided design (CAD) software [44]. Similar to the lens design process, the optomechanical design must be optimized and undergo tolerancing. In junction with the optimization process of both the lens system and mounting apparatus, finite element analysis (FEA). FEA is a process of detailed analysis utilizing CAD software. Common uses include structural, thermal, and frequency analysis of complex geometries [51]. The results of these processes are organized and expressed in an error budget, where the overall performance goals can be quantified and achieved.

6.2 System Performance Specifications

Performance specifications set forth the definition of what the end item must do and how well it must work to be judged acceptable [44]. In addition to the performance specifications, certain constraints must be defined for the system, these often include physical limitations, such as size, weight, configuration, and environment. For a pancake lens system for a VR headset as the one previously discussed, certain specifications need to be made. Because we are interested in the pancake lens configuration, a possible specification of the design could be to design the lens system and lens tube for one arm of the VR headset. This tube may then be duplicated and configured with a display system to create a complete VR headset system like the one shown below.

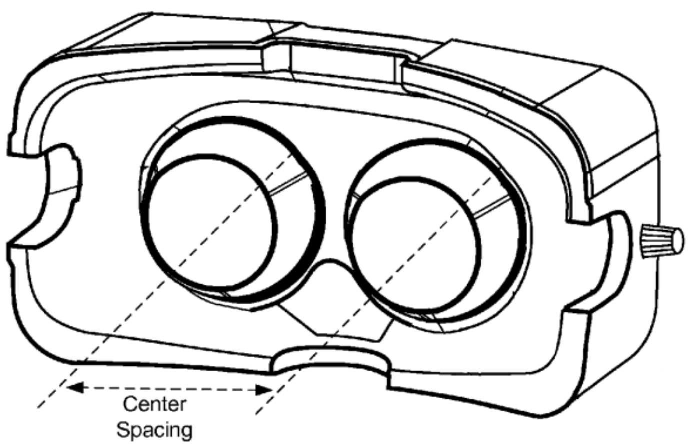


Figure 27. Simple VR headset drawing displaying binocular behavior [57].

Any number of constraints may aid in the design specification of this design, some possible constraint definitions can be seen below.

Table 1. General Design Features Typically Included in Specifications and Constraint Definitions [44].

• Performance requirements such as resolution, WFE, or numerical aperture
• Focal length, magnification, and object-to-image track length
• Angular or linear field of view
• Entrance and exit pupil sizes and locations
• Spectral transmission requirements
• Image orientation
• Sensor characteristics such as dimensions, element size and spacing
• Size, shape, and weight limitations
• Survival and operating environmental conditions
• Thermal stability requirements
• Emergency or overload conditions
• Center of gravity (COG) location and lifting provisions

For the case of a pancake lens system for a VR headset, important constraints may include COG location, angular field of view, performance requirement of wavefront error (WFE), magnification and weight, just to name a few. However, a very important specification for a pancake lens system would be to describe its multi-pass nature and require the design to do just that. As discussed previously this would include the polarization phase specification throughout the system as well as the components required to achieve this. Below is an example of a drawing that would be included in the system specifications for a pancake lens system.

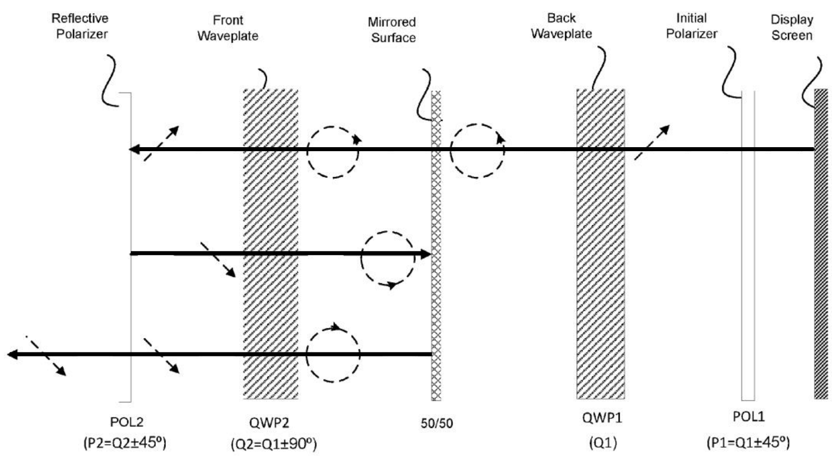


Figure 28. Pancake lens architecture phase alteration from 2018 Oculus patent [50].

Once these specifications have been documented, first order lens design will commence to continue the design process.

6.3 Lens Design

6.3.1 Preliminary Design

At the earliest stage of preliminary design, the optics may be represented as thin lenses or mirrors that possess focal lengths, apertures, and axial separations, but have no specific radii, thicknesses, or material types [44]. This preliminary phase may include a combination of first-order equations and lens design software. There are a variety of lens design computer programs. Some of them are CODE V, OpTaliX, OpticStudio's Zemax, Oslo, and Synopsys [56]. An example of a preliminary lens design for a pancake lens system architecture may be seen below.

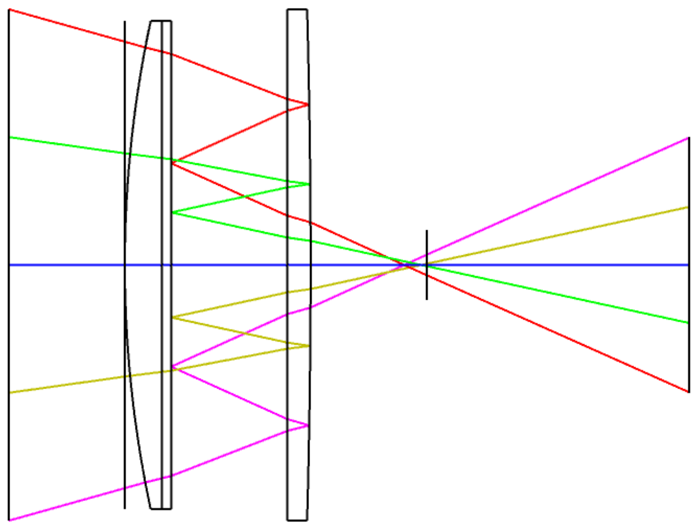
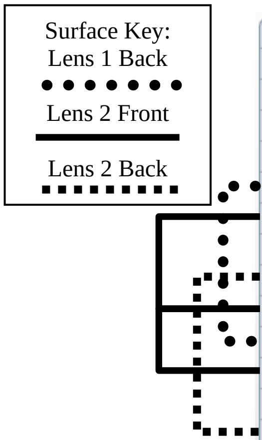


Figure 29. Preliminary design of a pancake lens system in Zemax.

This design defines the quarter wave plates, 50/50 mirrored surfaces, and reflective polarized surface defined in the system specifications. However, all radii, thickness values and aperture values are variable. The lens material used for the model was PMMA, whose properties were discussed earlier. The sequential nature of this Zemax configuration required the definition of light path surface by surface. This means that there are multiple surfaces in the Zemax lens data for individual physical surfaces. To be more specific, this multi-pass system required two surfaces to be defined for the back surface of lens one, three surfaces for the front surface of lens two and two surfaces for the back of lens two. These physical surfaces and their Zemax representation can be seen in the figure below. Note the jones matrix elements represent quarter waveplates and the split coating represent the same 50/50 reflection coating described earlier.



	Surface Type		Comment	Radius	Thickness	Material	Coating
0	OBJECT	Standard		Infinity	10.000		
1		Jones Matrix			0.000		
2	(aper)	Standard		100.000	4.000	PMMA	
3	(aper)	Standard		Infinity	0.000		
4		Standard		Infinity	10.000 V		SPLIT
5		Jones Matrix			0.000		
6	(aper)	Standard		Infinity	2.000	PMMA	
7	(aper)	Standard		-800.000 V	-2.000 P	MIRROR	
8	(aper)	Jones Matrix			-10.000 P		
9	(aper)	Standard		Infinity	10.000 P	MIRROR	SPLIT
10		Jones Matrix			0.000		
11	(aper)	Standard		Infinity P	2.000 P	PMMA	
12	(aper)	Standard		-800.000 P	10.000 V		
13	STOP (aper)	Paraxial			22.600		
14	IMAGE	Standard		Infinity	-		

Figure 30. Zemax lens data for preliminary pancake lens design.

The figure above shows the duplication of physical surfaces with those defined in Zemax. To ensure that the optical surfaces above represented the same point in space as their counterparts, I utilized pickups throughout, notated by P, in the thickness and radius columns. Now that the preliminary design is complete, optimization can take place to improve the system's optical performance.

6.3.2 Optimization

In order for a lens to be evaluated or improved, a merit function must be constructed. The merit function conveys specifications of the lens system and serves as the input for the lens design optimization algorithm [56]. The Zemax software includes a merit function wizard which aids in compiling this merit function by allowing the designer to choose the image quality metric and type. For the pancake lens system, it is appropriate to select RMS wavefront as the type and image quality metric. After ensuring all the necessary surfaces are included, the merit function wizard can be run, which provides a list of operands used to optimize the lens system. Possible optimization algorithms are damped least squares (DLS), simulating annealing, genetic algorithms, simplex method, and orthogonal descent. Perhaps the most used and proven is the DLS algorithm. In DLS, derivatives of the merit function, as a function of the optimization variables, are computed, and changes of the constructional parameters are determined that may decrease the error function [56]. This is the algorithm used to locally optimize the pancake lens system, which can be seen below.

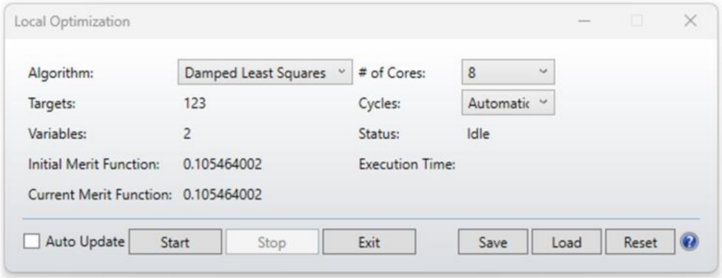


Figure 31. Optimization window from Zemax, showing the DLS algorithm.

This optimization technique resulted in the following updated system, which can be seen in the figure below.

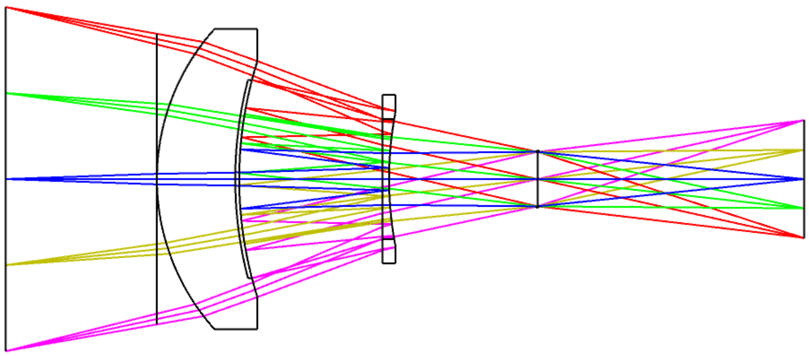


Figure 32. Optimized pancake lens system from Zemax.

Immediately we can see that the radii of curvature have dramatically changed along with the aperture sizes of each surface, which follow the shape of the focusing light which will eventually save lens material during manufacturing. Additional optimizing techniques for improving a lens system can be found in the table below.

Table 2. Techniques for modifying and improving a lens [56].

• Scaling a lens.
• Shifting the stop aperture.
• Bending a lens element.
• Allowing light vignetting.
• Making one or more surfaces aspheric.
• Increasing the index of refraction of the lens elements.
• Selecting different lens materials.
• Adding a field flattener lens.
• Including diffractive optical elements, or gradient index materials.
• Reducing the RMS of the marginal ray angle of incidence in the lens surfaces.

Optimization is a tedious task, once a modification takes place the designer will reoptimize with the optimization function. By observing the merit function increasing or decreasing it can be determined if the modification improved or worsened the design. Once an expectable design is found, system tolerancing can take place.

6.3.3 Tolerancing

Tolerancing is the act of estimating the allowable error in a set of geometry and material properties that will result in the system meeting its performance requirements [51]. The goal of the lens tolerancing process is to provide tolerances to each of the constructional parameters of the lens system [56]. Analysis techniques for tolerancing a lens system include forward tolerancing analysis, inverse tolerancing analysis, and Monte Carlo analysis. Forward tolerancing analysis uses perturbations to calculate performance, inverse tolerancing analysis uses a desired performance to calculate allowable perturbations. Finally, Monte Carlo analysis simulates the constructional parameters of a lens randomly chosen from ranges defined by the nominal parameter values and their error probability distribution [56]. This process can be automated in Zemax, once the tolerancing data editor is completed. The tolerance data editor is used to define, modify, and review the optical system's tolerance values. These tolerance values can be adjusted in the form of operand which represent various system parameters. A list of various operands can be seen below.

Table 3. Summary of some tolerance operands [58].

• TRAD	Tolerance on surface radius of curvature in lens units
• TCUR	Tolerance on surface curvature in inverse lens units
• TFRN	Tolerance on surface radius of curvature in fringes
• TTHI	Tolerance on thickness or position in lens units
• TSDI	Tolerance on clear semi-diameter or semi-diameter in lens units
• TSDR	Tolerance on Standard surface radial decenter in lens units
• TSDX	Tolerance on Standard surface x-decenter in lens units
• TSDY	Tolerance on Standard surface y-decenter in lens units
• TSTX	Tolerance on Standard surface tilt x in degrees
• TSTY	Tolerance on Standard surface tilt y in degrees
• TIND	Tolerance on index of refraction of surface

Tolerance operands can either be created manually or by use of the tolerance wizard. The tolerance wizard allows the designer to select presets of various vendors and grades. Additionally, adjustments of tolerance values can take place for chosen tolerancing parameters including radius, thickness, decenter, index, and tilt. A figure representing the tolerancing wizard can be seen below.

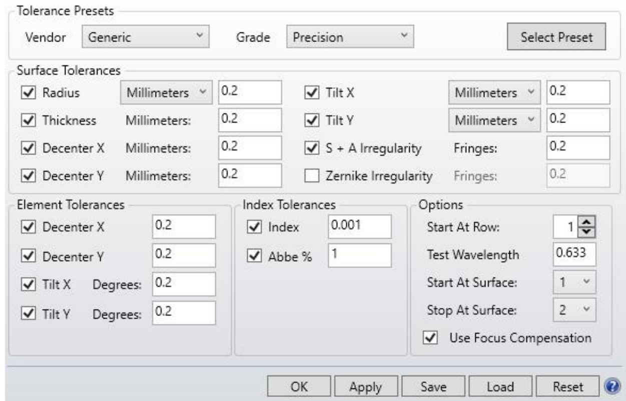


Figure 33. Tolerance wizard from Zemax.

For a multi-pass system as the pancake lens, it is important to understand that Zemax maintains solves such as pickups throughout the tolerancing process [58]. Additionally, tolerancing criterion as thickness between surfaces only requires the surfaces of one single pass through the system, instead of a total of three criterion to represent the multi-pass nature of the lens. After selecting and fine-tuning the tolerance operands for the system, the Monte Carlo tolerance tool can be executed. The tolerancing tool requires input for tolerancing mode, criterion, and number of Monte Carlo runs. For a system like the pancake multi-pass lens, an appropriate number of runs may be around 200 trials. A rule of thumb is to execute a number of trials in the order of the square of the number of parameters under error [56]. Once run, the Zemax tolerancing tool will output tolerancing results which summarize each Monte Carlo analysis by tolerance parameter, tolerance value, criterion, and performance change. A concise outline on the success of the tolerancing can be found at the end of the tolerance summary tab, where every Monte Carlo run is considered and the performance due to the chosen tolerancing errors can be found. An example of this portion of the tolerancing results can be seen below.

```
Number of traceable Monte Carlo files generated: 200

Nominal              0.12961007
Best       0.12413572      Trial      109
Worst      0.14181986      Trial      110
Mean       0.13047647
Std Dev    0.00284128

Compensator Statistics:
Change in back focus:
Minimum          :      -0.624804
Maximum          :       0.617534
Mean             :       0.019461
Standard Deviation :               0.233697

90% >      0.13383409
80% >      0.13264355
50% >      0.13017528
20% >      0.12830146
10% >      0.12702634
```

Figure 34. Tolerance summary from Zemax.

The tolerancing process, similar to the optimization process, requires many iterations until the system meets the requirements originally defined for the system. Once a system has been properly optimized and toleranced, the design of a mechanical mounting system may commence.

6.4 Mechanical Design

6.4.1 Preliminary Design

The preliminary design of a mechanical mounting system begins by importing the lens configuration optimized and tolerance in the previous section into CAD software. Here the designer can make inferences on how to accurately mount the designed lens system while maintaining the defined system requirements. Throughout this process, it is still possible for the designer to make changes to the lens system, given that proper re-optimization and re-tolerancing take place. For the pancake lens system, a potential mounting technique may include the mounting of the two individual lenses into cells, which are spaced apart by a spacer and mounted into a lens tube via retaining ring. A visual of this possible design can be seen below.

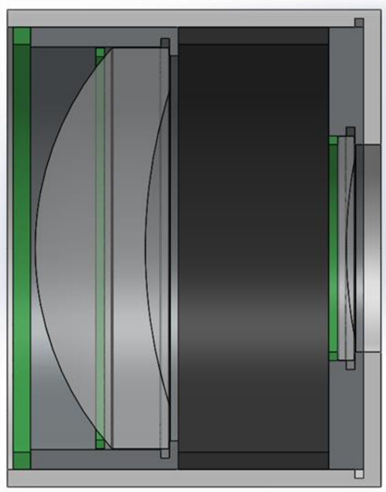


Figure 35. Cross-section of possible mounting solution for the pancake lens system in SolidWorks.

One reason this design would be desirable is that it maintains the distance between the elements by use of a spacer, which could be defined as a separate material if further analysis deemed it necessary. Additionally, this design requires less material for the lens cell, making it possible to choose a slightly more expensive material with better performance metrics if required. The use of retaining rings would require first-order analysis of preload to ensure the elements do not slip. Additionally, analysis of the stress induced on a lens by a retaining ring would be required to make proper material choices for each mounting element. It is likely that many iterations of the design take place, each aimed to account for discrepancies found in the previous design using first-order analysis. It is during this first-order calculation process that a small list of potential materials is tested, to determine which material parameters have the greatest impression on system performance. A few common material parameters necessary to consider in an optomechanical design can be seen below.

Table 4. List of possible material parameter considerations.

• Elastic modulus, E
• Poisson's ratio, ν
• Density, ρ
• CTE, α
• Thermal conductivity, k_{th}
• Yield strength, S_Y
• Temperature coefficient of refractive index dn/dT
• Weibull characteristic strength, σ_0
• Weibull modulus, m

Once first-order calculations are completed and materials for the mechanical elements have been decided upon, finite element analysis can be used to validate these calculations and provide further inspection into the design ensuring that all system requirements are met.

6.4.2 Finite Element Analysis

Finite element analysis (FEA) is useful to visualize and calculate parameters such as deformation and stress, but most of all it is a great way to validate first order calculations. The process of FEA includes building the structure/geometry, defining the materials of each subsystem, defining constraints, connections, external loads, and creation of a mesh. Then the simulations can be run, followed by post processing and data evaluation. The final design of a system is guided by the FEA, although it may be necessary to iterate between the parametric first-order analysis and the FEA to achieve an optimal design. Skipping first-order analysis and going directly to FEA is often unproductive in that it can take a long time to converge to a design solution using just FEA [44]. FEA takes place in CAD software. Since the construction of the mechanical mounting system for the pancake lens system took place in SolidWorks, the FEA process will be described within the same CAD software. Some common FEA simulations include thermal simulations, frequency simulations, and static simulations. For each simulation, target parts must be selected, connections between parts and fixtures must be defined. Additionally loads must be added to the design at the correct surfaces and a well-defined mesh must be created. These steps can be seen within the SolidWorks simulation tab as shown in the figure below.

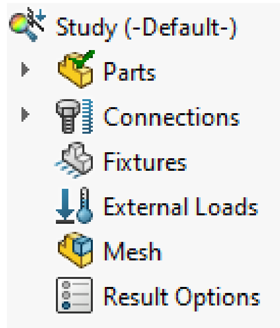


Figure 36. SolidWorks study simulation tab [59].

The loads for two types of simulation previously mentioned can be seen in the table below.

Table 5. External loads for two simulation types [59].

Static Loads	Thermal Loads
Force...	Temperature...
Torque...	Convection...
Pressure...	Heat Flux...
Gravity...	Heat Power...
Centrifugal...	Radiation...
Bearing Load...	
Temperature...	

Often the choice for what simulations are necessary to run for the designed system can be found by comparing the list of loads seen above with the defined system requirements. However, if the requirement does not have a related load, first-order calculations may help determine the effects of the unrepresented load. For example, simulating lens element tilt would require first-order analysis to determine the forces and moments on the lens surface. Results for this example and others include stress or strain maps throughout the designed system and lateral displacement of a surface to name a few. In the case of the pancake lens system, it may be necessary to determine the effects of temperature fluctuation throughout the system and analyze the axial displacement of the partially reflecting surfaces, as these contribute to the multi-pass nature of the system. In essence, the choice of simulations to run FEA is at the judgment of the designer who is responsible for properly evaluating the system to meet design requirements. These decisions should be motivated by the type of system being tested, the environment in which it will operate, and the circumstances that would deem the system to fail. The evaluation process of optomechanical design is anything but linear. Making design changes at one junction will affect how to inspect the system at another. Because of this, it is important for the designer to organize these variables and requirements in one space to protect key details from going unnoticed. The next section will summarize the usefulness of an error budget in making iterative adjustment to a system at any point in the design process.

6.4.3 Error Budget

The error budget is a tool created at the very beginning of the design process and is updated throughout. The error budget accounts for all necessary errors produced during development including all tolerancing, fabrication, assembly, and environmental errors. This budget is also a critical component in deeming a design successful, which is the reason this is the last section discussing the optomechanical process. The components of the error budget include the error source, the error sensitivity, the error magnitude, and the influence on performance. An example of error budget in the case of the pancake lens multi-pass system can be seen below.

Table 6. Error budget for pancake multi-pass optical system.

Error source	Sensitivity		Error magnitude		Wavefront Error	
	Value	Units	Value	Units	Value	Units
Fabrication	*0.0004*	-	***200***	**µm**	**0.084**	**µm**
Assembly	*0.0004*	-	***200***	**µm**	**0.089**	**µm**
Mirror	-				**0.104**	**µm**
Fabrication	*0.0022*	-	*20*	*µm*	*0.044*	*µm*
Assembly	*0.0022*	-	*20*	*µm*	*0.044*	*µm*
Thermal Soak	*0.0030*	*µm/K*	*5*	*K*	*0.015*	*µm*
RSS total					**0.277**	**µm**
Requirement					**0.317**	**µm**
Margin					**0.154**	**µm**

As seen above, allocations for both fabrication and assembly errors were allocated for the system. Because of the multi-pass nature of the system, the partially mirrored surfaces would require looser tolerances than the other refracting surfaces. Because of this, separate categories for fabrication and assembly errors are added for the sensitive surfaces. In addition to this, wavefront errors on the mirrored surface due to a 5° C change are listed. Sensitivity values can either be determined in first-order analysis or by analyzing tolerancing data from Zemax. In the former case, mechanical formulas allow for the designer to relate a change in perturbation with a change in performance. Similarly, sensitivity values can be found using Zemax tolerancing results by dividing the change in merit function or performance by the tolerancing value or perturbation. This ratio allows the designer to allocate errors in the error budget accordingly. Finally, FEA can relate perturbations to changes in performance by dissecting the resulting data from given loads. For example, in the pancake lens system, a load of 5° C could be applied to a partially mirrored surface and the effects would then be simulated. The results could be in the form of displacement data in the lens surface, which through further data processing would be related to the performance criteria of wavefront error. In conclusion, the error budget provides a useful visualization of crucial system errors and once these errors are mitigated and all systems requirements are met, the error budget will confirm that the system designed has been completed.

7. CONCLUSION

VR headsets have experienced an abundance of advancements from their origins of combat centered head mounted sights and displays. Although VR headsets only represent one of two arms of the HMD family, their ability to transport a user to an immersive and strictly virtual space remains exclusive to these types of headsets. Over the past century, this virtual space has become increasingly accessible to the public. The groundwork in experiencing this virtual world through VR headsets began with understanding the HVS. How the eye perceives depth is critical to VR headset's success, and recognizing the setbacks of current headsets, such as motion sickness and fatigue, is the first step to pushing HMDs further into the future. This future of VR headsets will develop alongside VR lens innovation and optical display technology. As such, the discussion of performance, display, and lens parameters, within VR headsets, was needed. These parameters provide the background required to discuss the layout for display architecture. Such discussion revealed that although self-emissive displays are dynamic and powerful displays, non-emissive displays are an affordable and efficient option for VR headsets. An additional design decision includes optical material choice, which is crucial to the performance and manufacturing success of VR headsets. Moreover, this report discussed how Fresnel lenses provide cost efficient and practical solutions to VR headsets. In the same manner, this report discussed Pancake optics, which implemented polarization components for a creative and effective multi-pass VR system. These architectures would be considered useless if not properly mounted, thus discussion of mounting techniques took place as correctly mounting optical systems proved just as essential of a process as designing them. Additionally, various focusing techniques were analyzed, allowing for lens adjustment and user comfort to be improved. Finally, the optomechanical process was discussed as it incorporated previously mentioned concepts into a concise design procedure. This process included defining performance specifications and system constraints which were required to determine the success of a system's design. This was followed by the lens design process, which required preliminary groundwork followed by the optimization and proper tolerancing of the lens system to ensure the ability to manufacture. Similarly, the design of a mechanical system aimed to contain VR headset optics required thorough material, external load, and survivability analysis. This optomechanical process not only provided a clear method of designing VR headset optics, it also tied together the parameters, elements and theory that represent the essence of VR headset design and analysis. This report presented the fundamental knowledge required to pioneer the next chapter of VR headsets. If the exponential growth and innovation of the past century is a hint to the future of VR headsets, the day where system flaws and setbacks are all but eliminated is just around the corner.

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