White Paper

Overcoming Vergence Accommodation Conflict in Near Eye Display Systems

Mark Freeman, Ph.D., Director of Opto-Electronics and Photonics*, Innovega Inc.*
Jay Marsh, MSME, VP Engineering, Innovega Inc.

Executive Summary:

VR or AR display systems must present the synthetic world in three dimensions. The field of view should be large enough to create an immersive experience, on the order of 100° or larger. At the same time, the display should be capable of presenting a depth range that extends from infinitely far to less than an arm's length away. Most fixed focus display systems do not have the depth of field to present a clear focused image over this full range and additionally, due to the Vergence-Accommodation Conflict or VAC, viewing stereo 3D (S3D) content over this range can be quite uncomfortable. Currently, this is one of the biggest challenges for the headworn display industry. To address this problem, developers have taken a handful of different approaches. These include various methods to actively adjust the focus of the display using opto-mechanical or electro-optical means to change the optical path that relays the display to the eye. Alternatively, some developers are creating multiple display planes placed at a few distances within the depth range so that the display content can be moved between the multiple focus planes to span the depth range. We will briefly review some of these approaches below. They all add complexity and bulk to the optical system that must be worn on the head. Innovega is taking the unique path of downsizing the complexity and bulk of the headworn optical system by shifting important functionality to the iOptik® contact lens. The iOptik® lens provides an extended depth of field to the display content that spans the necessary depth range without the need for actively refocusing. This long depth of field mitigates the VAC by keeping the display in focus independent of the eye's accommodation state so that the accommodation distance can remain naturally matched to the vergence distance.

1. INTRODUCTION

The goal of Virtual and Augmented Reality systems (VR and AR) is to create synthetic worlds and present them to our senses so naturally as to make it impossible to distinguish between the real and the synthetic. This white paper focuses on one particularly challenging interface problem for the display portion of a head-worn VR or AR system, the vergence accommodation conflict (VAC).

In Section 2, we begin by looking at the optical considerations that define the problem, then briefly review some of the solution approaches that are being taken by developers. In Section 3, we will show that the use of eye-borne optics, as in Innovega's eMacula™ Eyewear Systems technology, offers a solution path that is simple and practical and mitigates the VAC with a unique accommodation-invariant display path.

2. OPTICAL CONSIDERATIONS

2.1 Depth of Field

Depth of field or DOF, as it pertains to a near-eye display or NED, is a measure of the depth over which the display content appears clear and focused to the user. It applies to the image field as observed by the user[1].

A diagram showing the optical system parameters that influence DOF is shown in Figure 1. Often the DOF far point is set at infinity by adjusting the focus position. Consequently, it's easier to speak of the DOF in diopters (units of optical power, the reciprocal of distance) than in distance units which would be infinite if the DOF far point is at infinity. As shown in the figure, DOF in diopters is independent of the focus position, is proportional to the allowed angular blur and inversely proportional to the aperture size. For the case of a NED viewed with the naked eye, the aperture is the eye pupil. For the case of the eMacula™ eyewear systems, the aperture is the diameter of the lenslet on the iOptik®contact lens.

To avoid the need to actively focus the display, it would be advantageous to have a DOF that spans the complete depth range of the VR or AR system, that is a depth range that extends from infinitely far to less than an arm's length away. What is this DOF in diopters? Infinitely far corresponds to 0D. A meter away corresponds to 1D (= 1/1meter =1Diopter). Similarly, 2D corresponds to 1/2 m, 3D corresponds to 1/3 m (13 inches), 4D to 1/4 m (10inches), etc. Therefore, the desired full depth range for VR or AR NEDs is 3 to 4 diopters.

$$\mathrm{DOF} = \frac{2\beta}{\mathrm{A}}(\textit{diopters})$$

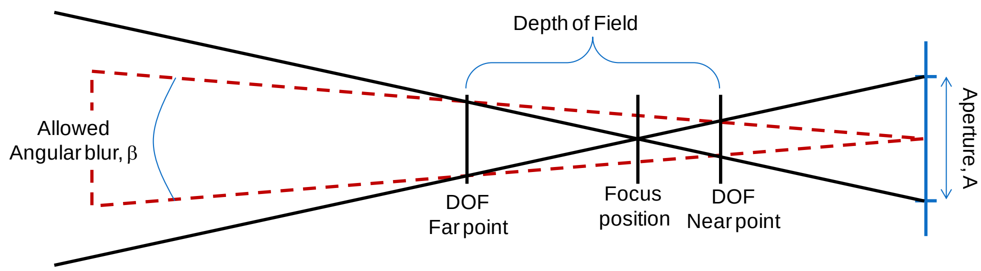

Figure 1: Diagram showing the optical system parameters that influence DOF

2.2 What is the vergence-accommodation conflict?

We see the world in three dimensions primarily by way of an unconscious triangulation in our brain using the slightly different perspectives of our two eyes. Our two eyes rotate towards each other (vergence) until we achieve binocular fusion (corresponding parts of the two images line up) and the two views merge into a single three-dimensional view. But we also sense the third dimension by the change in eye focus to make an object look sharp (accommodation) and by moving our eyes around the scene and noting how objects are occluded by other parts of the scene (parallax) as well as by the shading of the scene. If the ways of sensing 3D are consistent with each other, the depth cues 'feel' natural. But if the depth cues are not consistent across the various methods of sensing 3D, it can cause anything from mild discomfort to dizziness, headaches, and nausea.

1 - It is essentially the same concept as depth of focus, but in conjugate image space, that is, while depth of field applies to the observed image field, depth of focus applies to the positioning accuracy of the image source in front of the display optics needed to create a focused image at the nominal image position in the image field. The two are related by the longitudinal magnification of the display optics. In this paper we will restrict our attention to depth of field and refer to it by DOF.

The primary method for displaying 3D content is based on stereo vision. Two views of a scene with the proper offset perspectives (binocular disparity) are presented, one to each eye. The two eyes verge until binocular fusion is achieved and the 3D view appears. 3D depth is contained in the amount by which the perspective of various parts of the scene shift between the two views, that is, by the amount by which the eyes need to verge in order to fuse the two images. Close objects require strong vergence while distant objects may need no vergence. The effect is impressive and convincing, and can create scenes with a full range of visual depth. But after a while, it becomes uncomfortable. That's because the 3D effect is based solely on vergence. The left and right eye displays are fixed at an actual position in space, and the eyes must be focused (accommodated) to that distance to see them clearly. This gives rise to the Vergence-Accommodation Conflict or VAC. The 3D cues from vergence and accommodation are not consistent. The binocular content causes the eyes to verge according to the varying 3D position, while the fixed position of the displays forces the eyes to accommodate to the display distance. Figure 2 shows the difference in viewing paradigms between normal viewing of the real world (Fig. 2a), and the typical situation when viewing a virtual environment (VE) on a head-mounted display (HMD)(Fig. 2b).

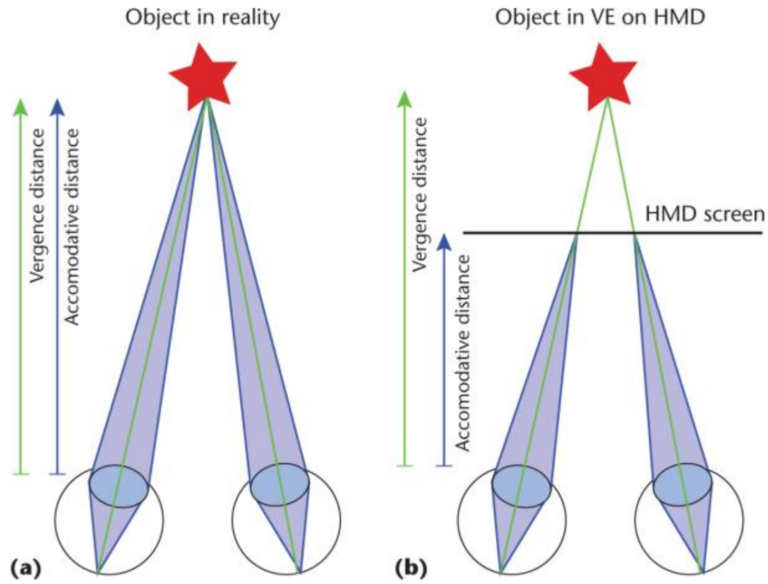

Figure 2: The origin of the VAC in head-mounted displays (HMD). (a) This shows the viewing paradigm that exists for real world objects. The vergence and accommodation distances are the same. (b) this show a typical viewing paradigm for a virtual environment, VE, viewed using a HMD. The vergence distance changes with the depth position of the virtual objects while the accommodation distance is fixed to the position of the HMD screen **(Carnegie & Rhee, 2015)**

In nature, the vergence and accommodation positions are always the same, so human vision has evolved with the two oculomotor adjustments neurally coupled. A change in vergence automatically stimulates a corresponding change in accommodation and vice-versa. (T. Shibata, 2011) Therefore, VAC is fighting against a hardwired human visual response; no wonder it's uncomfortable.

2.3 Zone of Comfort

The VAC pertains to all 3D displays based on stereo vision (S3D) and, as such, has been studied by numerous researchers over the years. Initially it was investigated in the context of dispensing spectacles, recognizing that certain combinations of prism and power could cause discomfort. An often-used rule-of-thumb is Percival's Zone of Comfort (Percival, 1892), which states that the comfortable zone is about one third of the range of vergence and accommodation differences over which it is possible to maintain binocular fusion and a sharp image. More recently, a study was performed by researchers at UC Berkeley that directly addressed comfort in S3D displays, (T. Shibata, 2011). The Zone of Comfort estimated by these researchers is shown below in Figure 3. Their results, which they state are consistent with Percival's, indicate that the Zone of Comfort is approximately ±0.5D difference in vergence and accommodation distances[2].

2 Diopters are units of optical power and, mathematically, are the reciprocal of distance in meters. So the positions correspond-

What does the Zone of Comfort say for a typical NED? Frequently, the nominal position for the display image is at infinity or 0.0 diopters. Then the nearest point that falls within the Zone of Comfort is at 0.5 diopter or 2 meters. Thus the desired depth range of ≥3 diopters for a VR or AR display is well outside of the Zone of Comfort. For this reason, VAC is a serious issue for NEDs. The following section will review some of the approaches that developers are taking to mitigate VAC and achieve the full depth range needed for VR/AR systems.

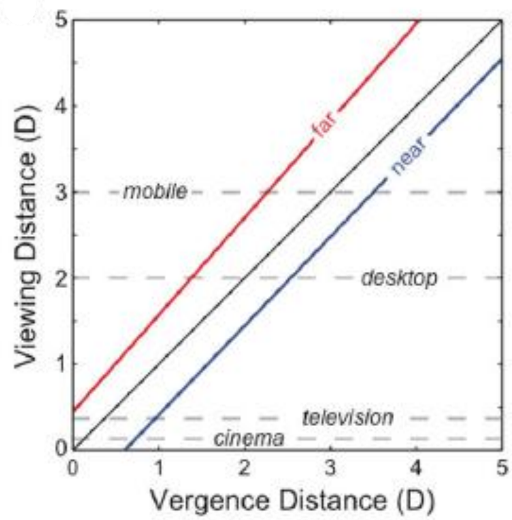

Figure 3: The region between the red and blue lines is the Zone of Comfort in diopters as determined by **(T. Shibata, 2011)**.The researchers estimated the difference between vergence and accommodation distances where most viewers will not experience discomfort based on human factors testing with 14 subjects between ages 20 and 34. Although there is some variation, the Zone of Comfort is roughly ±0.5D relative to where the vergence and accommodation distances are equal.

2.4 Brief survey of industry approaches to mitigate the VAC

Now, armed with a good understanding of the VAC, let us briefly survey the approaches that developers are trying in order to solve the problem. A more in-depth review of the technical details and tradeoffs can be found in (Hua, 2017).

The various approaches for solving the VAC in NEDs fall into a few categories: Dynamic Focus, Multiple focal plane, Focal Surface Displays, Light Field Displays and Maxwellian pupil(s).

2.4.1 Dynamic Focus or Varifocal systems

Dynamic Focus systems actively adjust the distance of the focus plane of the display by physically moving elements or by using a variable focus lens in the display optics train. In order to choose the distance to which the focus should be shifted, a VR system must also incorporate eye tracking to monitor the gaze direction of the user. In this way, the system always knows where the user is looking and can adjust to bring the currently viewed parts of the synthetic scene into focus. In AR, the system must monitor the gaze direction of both eyes to determine the vergence and/or must know the surrounding 3-D environment so that the focal plane distance can be properly adjusted. Dynamic focus systems do a good job of mitigating the VAC (George-Alex Koulieris, 2017) at the cost of adding the components and additional real estate and complexity necessary to dynamically reposition the focal plane.

2.4.2 Multifocal systems

In another approach, rather than actively moving the focus plane, some developers build systems with multiple fixed focal planes. Understanding that there is a zone of comfort associated with S3D content for each of the focal plane positions, the multiple focal planes are arranged to collectively span the full depth range of the system, while the content is apportioned amongst the fixed focal planes so that every depth is viewed comfortably. One drawback of this approach is the number of focal planes required. McKenzie et. al. estimated that the focal planes must be spaced by 0.6D in order to correctly stimulate

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ing to ±0.5D can be calculated as $\frac{1}{\left(\frac{1}{\text{nominal distance}} \pm 0.5\right)}$ *meters.*

accommodation (Kevin J. MacKenzie, 2012), necessitating the use of 5 focal planes to span the range of 3D. Although one can envision this implemented using multiple transparent display panels arranged one behind the other, each displaying the content for a particular focal plane, transparent displays don't currently have sufficient transparency to make this practical. Usually, the multiple focal planes are displayed time sequentially, using a single display panel that is sequentially switched between focal positions either using mechanical motion or variable lens technology. The added complexity in the optical path is similar to the dynamic focus systems just discussed. The speed of the display panel (and associated electronics and software) must also be sufficient to present multiple fields of full color images within a single system frame time so the eye will correctly merge the multiple data planes without experiencing flicker.

2.4.3 Focal Surface Display Systems

Focal Surface Displays (FSD) (Nathan Matsuda, 2017) are a third approach to deal with VAC, designed to reduce the number of fields that must be presented time-sequentially for multifocal displays. While they have some similarities to both of the preceding methods, rather than varying the focal position of the complete display plane, a phase-only spatial light modulator (SLM) is added to the optical path between the display panel and the eyepiece lens to act as a variable free-form lens. The phase SLM is configured using a depth map of the scene to add a local lensing effect to regions within the scene, thereby moving the focal positions presented to the user to the correct accommodation distances approximating the depth map. Researchers found that the FSD approach using a single display and phase SLM demonstrated good MTF performance for an approximately 2D depth range, but that limitations in the currently available SLM performance would necessitate the use of at least 2 time-multiplexed focal planes used in conjunction with the FSD approach. Therefore, hardware to support both the multifocal approach and the FSD approach would be required for this VAC solution.

2.4.4 Light Field Systems

Light field displays (LANMAN, 2013) (Maimone, 2014), also known as Integral Imaging displays, in theory create a field of light illuminating the eyes that exactly simulates the light coming from a natural scene. Using a ray optics representation, this equates to generating rays at all the proper angles for every position in a plane just in front of the eyes. As the eyes look around within the light field, one sees the 3-dimensional scene with natural vergence and accommodation as well as parallax. And in this theoretical ideal, there is no VAC. Practically, this is approximated by creating an array of partial views from slightly different perspectives of the scene that overlap at the eye. One serious drawback to this approach is resolution. Since the light field representation itself is highly redundant in that each point in the scene is present in many of the partial views, so the number of pixels in the *observed* display is just a small fraction of the *actual* number of pixels in the display panel (estimated at just 6% in (Maimone, 2014)). In this industry, where state-of-the-art microdisplays still fall short of providing enough pixels to produce an image with 20/20 acuity (1 arcmin pixels) over 100 degree FOV, a technology that wastes pixels is a serious drawback.

2.4.5 Maxwellian View Systems

A Maxwellian view system creates a small entrance pupil at the location of the eye pupil. The small entrance pupil gives the display system an extended DOF as discussed above in Section 2.1. The basic optical layout of a NED with a Maxwellian pupil is shown in Figure 4. The essence of the system is that a point light source, S, is imaged onto the eye pupil using the condenser and eyepiece lenses. This creates an effectively small eye entrance pupil, smaller than the actual eye pupil. The SLM (spatial light modulator, in this case modulating intensity) which carries the display content is located between the condenser and eyepiece lenses, and imaged onto the retina by the eyepiece lens. Effectively, the DOF of the display is governed by the size of the Maxwellian pupil, the smaller the pupil, the longer the DOF. The difficulty with these Maxwellian systems is that, only a small amount of eye motion is supported by the display architecture shown in Figure 4. Developers have taken a couple of paths to support full eye motion. One approach steers the position of the Maxwellian pupil to follow eye motion in response to an eye tracking signal. Alternatively, some developers have created an array of point sources giving rise to a corresponding array of Maxwellian pupils at the eye, such that a new Maxwellian pupil from the array enters the eye pupil just as a different one is blocked by the eye pupil due to eye rotation. Both approaches add non-trivial complexity to the eyewear system.

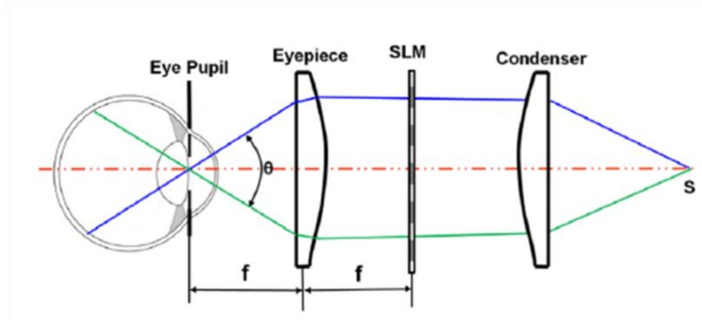


Figure 4: The optical layout of a Maxwellian view display. (Hua, 2017)

Furthermore, as will be shown in the next section, since the Maxwellian pupil is not physically limited at the eye, the light entering the eye carries the display information from the SLM as a diffraction field around the ideal Maxwellian pupil, (akin to the Fourier transform of the SLM display). This diffracted light pattern also carries information about the location of the SLM, cancelling out some of the DOF extension that comes from the small entrance pupil.

3. THE EMACULA™ EYE-BORNE OPTICS APPROACH

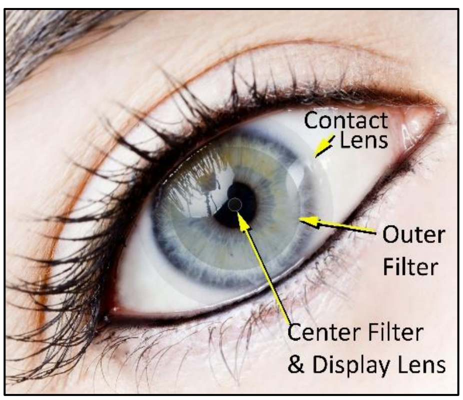
The eMacula™ Eyewear System consists of an iOptik® custom contact lens or intra-ocular lens along with headworn eyewear that houses the display image source and associated optoelectronics. The use of eMacula™ eye-borne optics in a NED system has a number of distinct advantages. First, it mitigates or eliminates the VAC by creating a small physical pupil for display light centered on the eye pupil. Since it is built into the eye-borne optics, the small lenslet pupil moves with the eye and there are no limitations on eye motion. This gives a display with an extended DOF that spans the 3D-4D depth range of a VR or AR system. This is discussed further in the sections that follow.

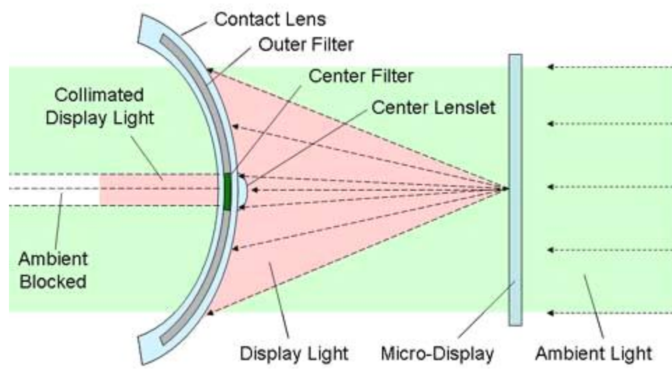
They eMacula™ eye-borne optics approach also simplifies the optics that must be included in a headworn system by enabling the user to directly view the microdisplay panel or its image projected onto a screen in the spectacle plane. This removes the need for bulky relay lenses or waveguide relays that must present the unadorned eye with a large eyebox where each and every pixel's information fills the complete eyebox and enters the eye with the proper angle corresponding to that pixel's position. Furthermore, the iOptik® contact lens is not tied to any specific FOV. The same iOptik® could be used with multiple eyewear display systems, for example one for immersive VR with a large FOV, one for large FOV

AR used for training or computer-guided assembly, and one for glance-able AR with a small FOV leaving a clear path in the user's forward view.

3.1 The iOptik® Contact Lens and IOL design

The key principles of the iOptik® custom contact lens used in the eMacula™ Eyewear System are presented in Figure 5. A person wearing a simulated iOptik lens is shown in Figure 5a. The details of the optical elements comprising the iOptik® are shown in Figure 5b. Fundamentally, the iOptik® adds a high-power lenslet onto the center of the contact lens. The lenslet has a diameter of about 1 mm, sits just over the center of the user's eye pupil, and adds an optical path that is focused very near to the eye. In terms of optical refraction, the rest of the contact lens contains the user's normal distance vision prescription or no optical power if no correction is needed. The path through the lenslet is used to directly view a microdisplay that is built into the NED eyewear, while the area around it, that is the annulus between the lenslet in the center and the boundary of the eye pupil, is used to view the natural world. In order to maximize contrast and minimize crosstalk between the two optical paths, the iOptik® also contains complementary filters, one in the display path that passes display light and blocks light from the natural scene, and a complementary filter in the outer region that blocks the display light and passes light from the natural scene. Currently the complementary filters are realized using crossed polarizers. The two optical paths are shown in Figure 5b, the pink path representing the display light and the green path representing the ambient natural light. Alternatively, the same functions that are built into the iOptik® contact lens can also be built into an intra-ocular lens (IOL).





a) **b)**

Figure 5: The main principles of the iOptik® contact lens. (a) the iOptik® contact lens is a gas permeable soft lens worn just like any standard contact lens. (b) The primary optical function added to the iOptik® contact is a high power lenslet in the center that allows one to directly view a microdisplay that is built into the NED eyewear. The 1 mm diameter lenslet is centered directly in front of the eye pupil. The remaining area of the contact lens around the lenslet is used for viewing the natural world. Filters are included in the iOptik® to separate the display light path from the natural ambient light path. Content viewed through the two separate paths is superimposed on the retina.

3.2 Overcoming VAC with eMacula™ Eye-Borne Optics

By using a small 1mm diameter lenslet as a physical entrance pupil into the eye for display light, the eMacula™ Eyewear System creates a display with a large DOF. This is a game changer in terms of the VAC.

The human eye pupil diameter varies over the range of 2-8mm depending on ambient brightness, age, and other factors. (Watson, 2012). For sake of comparison, let's use a nominal eye pupil diameter of 4 mm. Since DOF is inversely proportional to aperture size (see Figure 1), this indicates an increase in the DOF by a factor of 4 for the eMacula™ system compared to any of the other major NED systems (which all use the full eye pupil).

Another way to look at it is its impact on the Zone of Comfort. What was originally ± 0.5D also expands by the same factor to approximately ± 2.0D or a total span of about 4D.

Furthermore, the lenslet size in the iOptik® contact lens is fixed and unchanging, while the eye pupil size changes moment-by-moment depending on the brightness of the ambient setting or of the display. So the DOF of the eye and any of the major NED systems is short and changing while the DOF in the eMacula™ Eyewear is long and unchanging.

What about diffraction? Typically, shrinking the aperture of an optical system causes an increase in the size of the point spread function due to diffraction. That is true for diffraction-limited optics, but the human eye behaves somewhat differently. The center region of the human eye lens is known to have the best optical quality and make the sharpest image. By using just the central region for imaging the display light, Innovega produces the best quality image on the retina.

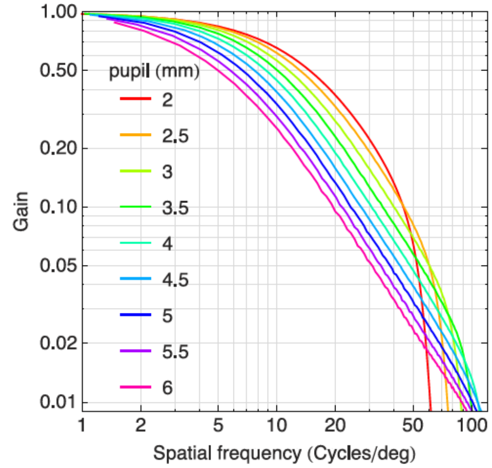


Figure 6: Mean radial MTFs for pupil diameters from 2 to 6 mm based on data collected for 200 eyes. **(Watson, 2013)**. Contrary to what one would expect from basic diffraction theory, the MTF becomes worse as the pupil gets larger.

The actual MTF of the human eye as a function of pupil size, computed from wavefront aberrations for 200 normal corrected healthy eyes is shown in Figure 6. As the pupil enlarges, the diffraction limited optical transfer function does expand, but the amount of wavefront aberration also increases, so the MTF in fact gets worse as the eye pupil expands. Counter-intuitively, the best optical quality for the human eye generally occurs at smaller pupil sizes.

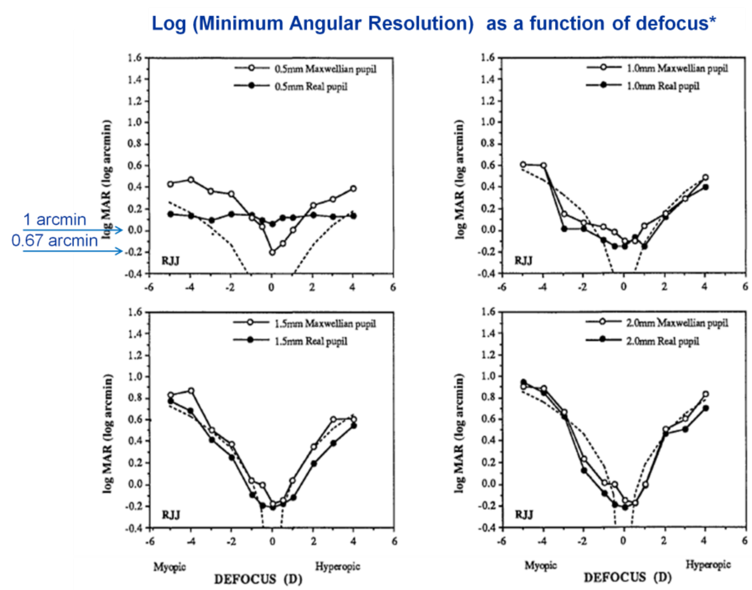


Figure 7: LogMAR as a function of defocus for various pupil sizes. These graphs compare the change of logMAR as a function of defocus for both real and Maxwellian pupils from 0.5mm to 2.0 mm in diameter. (R.A Jacobs, 1 July 1992) The dashed lines show the predicted results based on geometrical optics.

The smallest pupil size in Figure 6 is 2 mm. Is it possible to still get good acuity with pupils smaller than 2 mm? In Figure 7, the authors measured the Minimum Angular Resolution (MAR) as a function of defocus for very small pupils. Recall: MAR for 20/20 vision is 1 arcmin. The small aperture in the iOptik® contact lens is represented by the "real pupil" in the graphs. A few things are apparent from the graphs. First, the logMAR is relatively constant for the 0.5mm and 1.0mm real pupils over a range of defocus. This corresponds to the extended depth of field for the small pupil. Second, notice that, for a 1mm real pupil, the region of nearly constant logMAR covers about 4D. Third, for the 1.0mm pupil, the acuity is 20/20 or better over the extended depth of field. Fourth, the smallest Maxwellian pupils at 0.5mm and 1.0mm do not show the same extended DOF as do the real pupils.

Greater DOF resulting from the smaller aperture at the eye means that the display content remains in focus even as the eye verges and accommodates to the perceived S3D depth content. In other words, the display is accommodation-invariant over its DOF.

In recent work, a team of researchers at Stanford University built a bench-top S3D accommodation-invariant display to test whether an S3D display, which provided only vergence/disparity depth cues, would be tracked by the accommodation of the test subjects (Robert Konrad, 2017). The accommodation-invariant display was implemented by using a focus-variable lens to continuously scan the display position from 0D to 5D based on a 60 Hz triangle wave. An autorefractor was used to measure the accommodation of test subjects as they watched the display. The results showed that the accommodation of the observers was stimulated to follow the vergence cues in the disparity-only S3D content.

To summarize, the eMacula™ eyewear system, using a real pupil implemented in the iOptik® contact lens creates an extended DOF for display content, resulting in an accommodation-invariant display. It has been shown that a S3D NED will stimulate the user to accommodate naturally to a distance similar to, and tracking, the vergence distance. Therefore, this display system is expected to reduce or eliminate discomfort resulting from the VAC. Further testing with human subjects is needed to validate this expectation.

3.3 Demonstrating the long depth of field

3.3.1 The test apparatus and setup

When creating a camera system to simulate the human eye wearing a eMacula™ eyewear system display, there are constraints imposed by the human interface. For example, the distance between the contact lens and the camera focus lens should not change, nor should there be any rotational adjustments between the contact lens and the display system because the polarizing filters in the lens must remain aligned with the display. As a result of these constraints, a camera system was built with all adjustments anchored to the system around the primary camera focus objective.

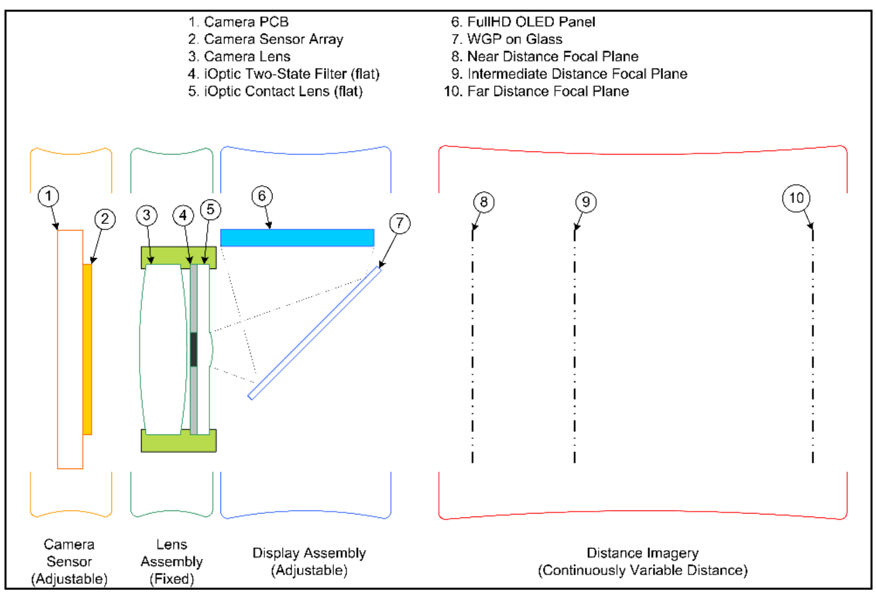


Figure 8: eMacula™ eyewear display camera simulation system

The display simulation camera system is shown in Figure 8. The lens assembly, consisting of the imaging lens, the polarization filters and the test contact lens, is fixed in place. The camera sensor is translated relative to the lens to adjust the focus of the distance images (simulating accommodation). The Display Assembly, consisting of a flat panel OLED microdisplay and a wire grid polarizer (WGP) serving as a combiner to superimpose the display and distance vision paths, is moved relative to the lens assembly the bring the display into focus. Then the display focus is locked in place. Objects were placed at near, intermediate, and far locations to observe one-by-one using the focus (accommodation) adjustment on the camera sensor. In the accompanying video, it is demonstrated that, as accommodation is adjusted to bring each distance object sequentially into focus, the display content remains continuously sharp.

For this system, an 18 MP camera from IDS is used with a Sunex F2.6 lens with a 5mm focal length resulting in a FOV of about 53 degrees when capturing at 3840x2160 resolution. Since the system is being used to observe DOF as constrained by the fixed pupil in the contact lens, the camera lens was chosen for its high resolving power to create the sharpest image on the camera (~0.7 arcmin per pixel).

The contact lens was fabricated as a flat disk with an integrated 1 mm lenslet that provides near focus for display vision and no optical power in the outer part of the contact. The display system is located on a 6 degree-of-freedom mount to allow for precision adjustments to 3 axes of tilt and 3 axes of translation. The display for this test was a 1920x1080 OLED panel that is reflected off of the WGP to relay the display content to the eye, polarizing the display light in the process. This same WGP, serving as a polarizing combiner, transmits only the orthogonal polarization of the distance light. The polarization directions of the contact lens filters in the lens assembly have been set up to be aligned with the polarization directions dictated by the WGP combiner.

3.3.2 Video link and description

The test apparatus was placed in a position that allowed an unobstructed view over a 70 foot distance with objects of high contrast located at specific distances. The far object at 0.047D (69 ft.) was selected as the postal mail boxes because of their defined lines and bright coloring. An intermediate object at 1.09D (3 ft.) was created by using the silhouette of a standard 1/4-20 threaded camera mount found in a tripod. The sharp lines of the fastener threads make for excellent acuity confirmation. The near object 3.28D (1 ft.) was selected as a business card with high contrast lettering. The card allowed for only a small portion of the distance vision in the camera's FOV to be occupied during the entire test. Having all three objects continuously in the camera FOV helps demonstrate that no "behind the scenes" adjustments were made. Automatic gain control was used to adapt to the scene brightness as it fluctuated with cloud coverage, so scene intensity adjustments are visible in the video.

The video content selected was from a pre-recorded Spritz® demonstration video that was played on a Windows OS laptop connected to the eyewear display system through HDMI. The OLED panel display brightness was set to approximately 300 nits and the eyewear position was adjusted until a suitable alignment with the camera system was established to provide good acuity over the range of test distance. The video was recorded at 3840x2160 resolution and then down converted to 1920x1080 for portability and ease of streaming over the internet.

The video can be found at the following static link:

Demonstrating 3 Diopter DOF with iOptik and eMacula Systems

The video provides compelling evidence that an exceptionally long depth of field is possible with the iOptik® contact lens used on conjunction with a NED system. The total depth of field demonstrated in the video is 3.23D (3.28D – 0.047D).

4. CONCLUSION

Most fixed focus display systems do not have the depth of field to present a clear focused image over the full depth range required by VR and AR systems. Additionally, due to the Vergence-Accommodation Conflict or VAC, viewing stereo 3D (S3D) content over this range can be quite uncomfortable. Currently, this is one of the biggest challenges for the headworn display industry. To address this problem, developers have taken a handful of different approaches. One thing they have in common, they all add complexity and bulk to the optical system that must be worn on the head. Innovega is taking the unique path of downsizing the complexity and bulk of the headworn optical system by shifting important functionality to the iOptik® contact lens. With the eMacula™ eyewear system, greater depth of field resulting from the small fixed lenslet aperture at the eye means that the display content remains in focus even as the eye verges and accommodates to the perceived S3D depth content. This long depth of field mitigates the VAC by keeping the display in focus independent of the eye's accommodation state so that the accommodation distance can remain naturally matched to the vergence distance.

5. REFERENCES

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