# Exploring Wide Field-of-View VR Headsets

Andrew Wei
Paul G. Allen School of
Computer Science and Engineering
University of Washington
Seattle, WA, USA
nowei@cs.washington.edu

Daoyi Zhu
Paul G. Allen School of
Computer Science and Engineering
University of Washington
Seattle, WA, USA
daoyee@cs.washington.edu

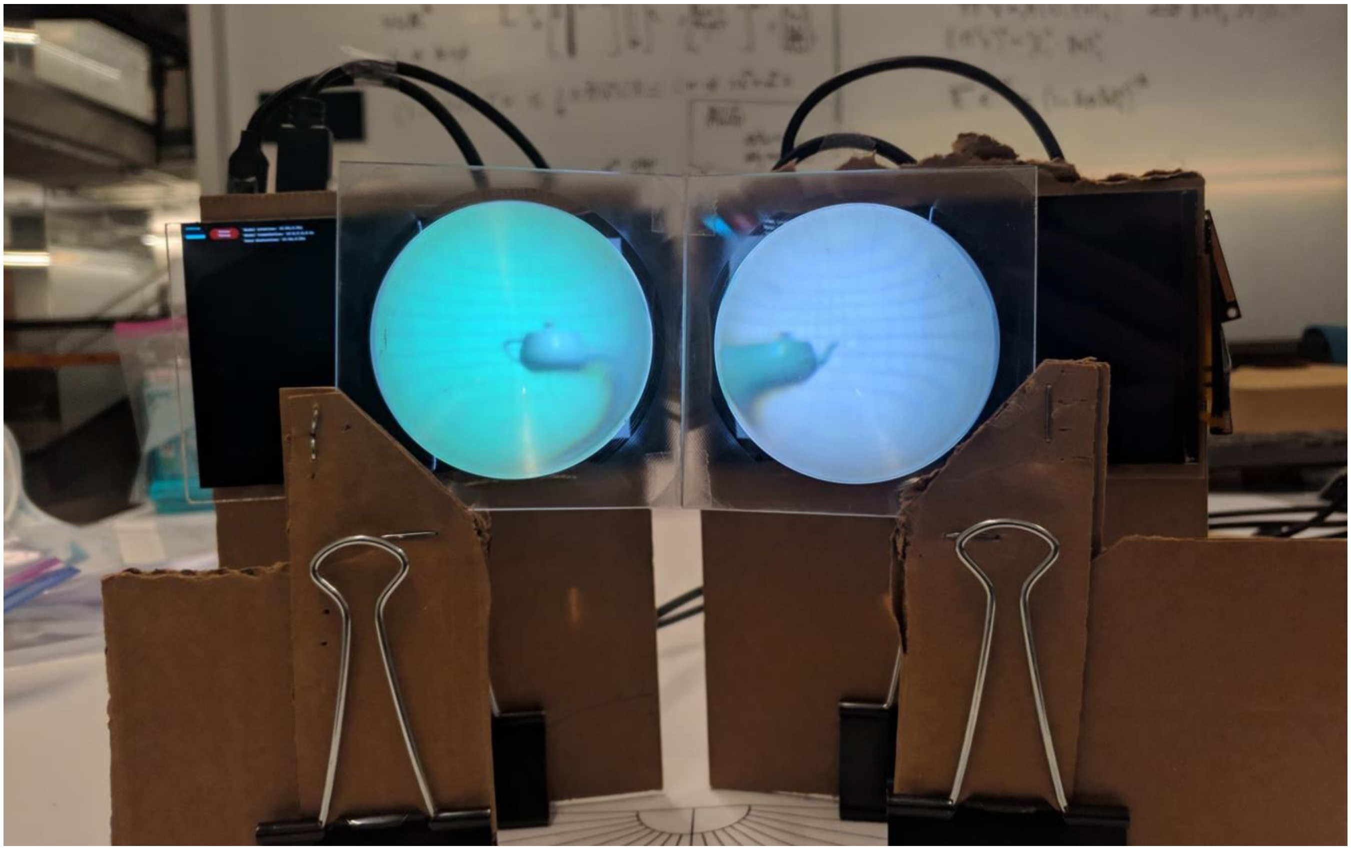


**Figure 1.** Fixed stand with 20° canting

## 1. INTRODUCTION

Every year, VR is getting better with the introduction of new algorithms, faster hardware, and better ideas of what VR should be. There are still many problems that prevent us from immersing ourselves in VR, like eye-strain, correct haptics, and a decreased field-of-view (FOV).

There are many companies building headsets, but we wanted to see what it would be like to design a wider FOV headset from scratch. In this project, we attempt to build a wide FOV headset.

### 1.1. Contributions

- Design and create model for HMD frame
- Create stands for testing out lenses and displays

## 2. RELATED WORK

Many of these companies achieve a wider field-of-view through company secrets or with patents so no one can legally copy them, so not much detail is known besides what they describe and what people have observed. How companies measure FOV is also inconsistent, which may have been a result of different marketing tactics.

StarVR, a commercial 210° FOV headset was first demoed during SIGGRAPH 2018. It was a project that spawned from InfinitEye, which was a French project that was the first to build a 210° FOV headset prototype in 2013. This is currently the widest FOV headset available commercially. StarVR uses custom Fresnel lenses and cants their displays to achieve this [1].

Rakkolain et. al made a 318° FOV headset using stacked, curved Fresnel lenses, and curved screens [2]. They mention that even though this was the largest FOV recorded that they know of, it exceeds the human field-of-view, so part of the headset wouldn't be useful. They made this as a proof of concept and tested it out by using three smartphones for the left, right, and center.

Samsung filed a patent for a 180° FOV headset using curved OLED displays, two Fresnel lens, and two wide angle strip lenses [3].

VRgineers, a group based in the Czech Republic, made XTAL, which is a 180° FOV headset which also uses OLED displays, but automatically moves the lens to adjust to the user's interpupillary distance. They use two displays, one for each eye, and custom aspherical non-Fresnel lenses [4].

Pimax made several 200° diagonal FOV headsets using two screens. The screens either use OLED or a customized low persistence liquid, which is a patented display technology. They use custom Fresnel lenses for each of the eyes [5].

Hashemian et. al made a 180° FOV headset using LEDs to approximate peripheral vision [6]. They use the observation that the far left and far right parts (peripherals) of our vision can generally have lower resolution than the center portion, so they can approximate the peripherals using spaced-out LEDs.

We are planning on using Fresnel lenses and LCDs to build a headset. While we doubt the headset we build will be able to reach a 180° FOV, we aim to provide a wider FOV than the headset designed in the course.

## 3. METHOD

If we have access to a 3D printer, we want to build a wide FOV headset using Fresnel lenses and two displays. At a minimum, we would set up a fixed lens-display system that would emulate how the headset would work. This section is organized as (1) how we achieve a wider FOV and (2) reasons and methods on the use of Fresnel lenses.

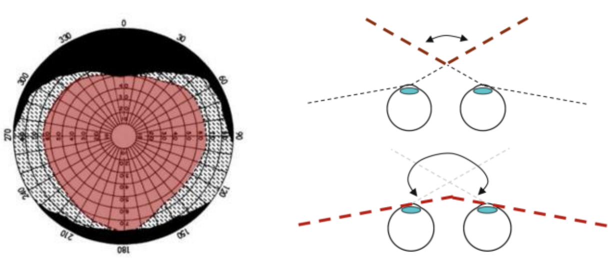


**Figure 2.** Human visual field
*Left*: Visual field for both eyes. Red and white region correspond to binocular visual field and monocular visual field respectively.
*Right*: Above image is horizontal binocular visual field; bottom is horizontal total visual field.

### 3.1. Eye-box

As we've mentioned before, there is no universal definition for FOV in terms of VR headsets. We're estimating our FOV using vertical and horizontal FOV in a manner similar to how visual field is calculated for the human vision system. Since horizontal FOV is more important when compared to vertical FOV in VR settings, we will focus more on the horizontal FOV.

As shown in [Figure 2], our FOV is equal to the angle of the visual field at the corresponding axis. The goal is to gain large total FOV while preserving enough binocular FOV for stereo fusion. If we keep the lenses parallel, it is possible to get a larger FOV by using larger lenses and displays. However, the flat design brings lots of optical design challenges, mostly related to distorted and low-resolution peripheral information [2]. We decide to cant the lens-display system to achieve a wider FOV.

To simplify the system for physical computation and headset design, we define an "eye-box" for each lens-display system and treat each of them individually. Briefly testing the relationship between inter-lens distance and interpupillary distance (IPD) gives that the inter-lens distance should be larger than the IPD in order to gain maximum sweet-spot area – implying that it is safe to put the eyes on the extended line orthogonal to the lens when eye-relief distance and canting angle are both relatively small. This can be seen in [Figure 6].

Therefore, given fixed eye-relief, lens-display distance, and canting angle; each "eye-box" has a fixed design where only the display can move on the plane parallel to the lens. By fixing the IPD, we can move the display to any position that maximizes the viewable area of the screen. The actual design will be discussed in the implementation section.

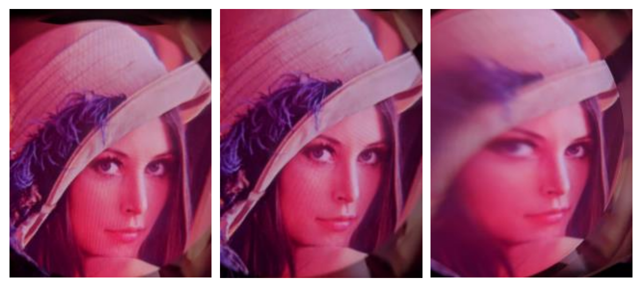


**Figure 3.** Seen through a $2.5" \times 2.5", f = 2.6"$ Fresnel lens. From left to right: lens-image angle $0°, 10°, 40°$.

There is one obvious problem that comes with this method. The canting angle will result in an angle between the focus plane and the actual display, giving an off-center blur.

The distortions are similar to the photos in [Figure 3], if we do not account for the difference between the lens center and the intersection of the lens plane and the eye-orthogonal ray. We note that the latter distortion is hard to measure and study without additional optical devices, but is negligible assuming a fixed relative eye-lens position.

Otherwise, the distortion is tightly related to the choice of lenses – larger lenses have larger sweet-spot area but suffer more from distortion with increased canting angle. We acknowledge the issue but also know it could be mostly solved with off-the-shelf lenses by limiting the canting angle. Most consumer products address this issue with custom Fresnel lenses, which are probably designed with non-uniform focal length [1].

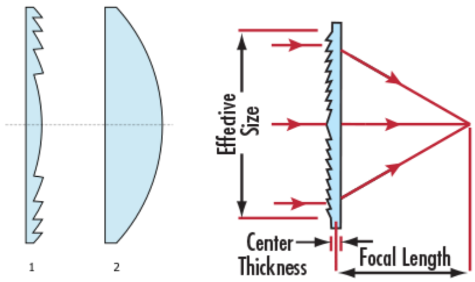



**Figure 4.** Left[1]: Cross sections of lenses 1. Fresnel Lens, 2. Equivalent convex lens. Right[2]: Cross-sectional views of Fresnel lens.

## 3.2. Fresnel Lens Image Correction

Fresnel lenses are lenses with circular, curved ridges cut in them that use less material to achieve similar optical properties (like focal length) to that of a larger convex lens [Figure 4]. As the granularity of the grooves increases, less material is used. Fresnel lenses used to be manufactured by etching glass, then by pouring glass into molds, and now they are made using plastic and injection-molding. Fresnel lenses have a reduced image quality when compared to conventional lenses, but their reduced thickness and weight makes them ideal in many head-mounted display technologies.

VR is flexible and a lot of care is put into the weight and feel of headsets to make them comfortable and realistically usable. Generally, it's fine to design something incredibly bulky and awkward, but there shouldn't be any expectation that anyone will use it. Fresnel lenses can be made to be thin, flexible, and relatively lightweight, which means that it won't impose many constraints on the system. Previously, we assumed all lenses are simple thin lenses. However, given the lens size required for a wider FOV, the thickness on refractive lenses would be non-negligible. Using a generally uniform and thinner lens gives us more confidence in being able to use the thin lens equation.

We use the decentering distortion[3] model to correct pincushion distortion across the image. In addition to that, Fresnel lenses experience more chromatic aberration compared to refractive lenses, and thus they are typically used as an optical collimator or concentrators instead of VR lenses. [7] The following subsection discusses methods for correcting chromatic aberrations.

### *3.2.1. Chromatic Aberrations for Fresnel Lenses*

There are multiple existing methods for correcting chromatic aberrations within an image. They are mostly done in a post-processing fashion.

The first method we look at is deconvolution [8, 9]. Aberration occur where there is a large intensity gap between RGB channels. Using gradients of one channel (suggested to be green since cameras typically calibrate on green channels), we can find all pixels in these transition regions. After identifying edges, we can remove chromatic aberration through limiting channel color difference in our transition regions.

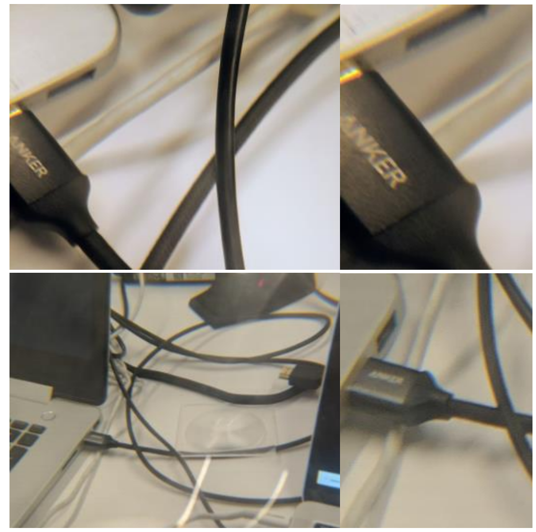


**Figure 5.** *Left*: normal. *Right*: enlarged.
Chromatic aberration on different Fresnel lenses. The above one (66mm focal length) has less aberration compared to another set of Fresnel lenses (300mm focal length) we have and the refractive lenses used in course.

This method is easy to follow and implement[4]. The kernels used for deconvolution are fully dependent on the image itself instead of the actual optical system. By doing calibration on sample images, we should be able to find kernels for a majority of cases.

If we consider Fresnel lenses as simple lenses with known point spreading functions (PSF), we should be able to approach this problem differently. There exists a deconvolution method that is designed more specifically for simple lenses [10]. Suppose a lens has blur kernel $B$, image $I$, the output image $I_{out}$ formed through the lens can be represented as $I_{out} = B \otimes I + N$ where $N$ is noise. Combining the method that sharing channel information by assuming edges in one channel should also be edges in another channel, we can perform deconvolution on $B, I$ and retrieve the image that would be undistorted though $B$. Previous work suggests that we can construct $B$ using calibrated PSF on each image tile [10]. It also provides methods for calibrating PSFs.

The lens we end up using does not have heavy chromatic aberration, as seen in [Figure 5]. Since we do not have the correct equipment or time to calibrate PSFs, we decide not to implement this, but leave this for future work.

## 4. IMPLEMENTATION DETAILS

The hardware we decided to use:

- 2x 3″×3″ Fresnel lenses from Edmund Optics with 66mm focal length
- 2x Topfoison 5.5″ 1920×1080 LCD

The type of lenses were chosen for the reasons specified earlier. The LCDs were used as a part of the course kit for the main

[1] Image Source: Wikipedia, https://en.wikipedia.org/wiki/Fresnel_lens
[2] Image Source: Edmund Optics, https://www.edmundoptics.com/knowledge-center/application-notes/optics/advantages-of-fresnel-lenses/
[3] https://en.wikipedia.org/wiki/Distortion_(optics)#Software_correction
[4] https://github.com/RayXie29/Chromatic_aberration_correction/blob/master/src/ColorAberrationCorrection.cpp

display. We are using two to have one for each lens. We use the 3D printer to create the frame for the headset.

We initially used math to give us a good ballpark of where things needed to be so that we can have a starting place when we tuned things. When testing out the Fresnel lenses, we realized that we didn't need to stack them to achieve a good lens-to-screen distance, so we ended up only using 2 Fresnel lenses. The following sections go through our design process.

## 4.1. FOV and Headset Layout

We define:

- effective focal length, $f = 66$mm;
- lens-to-display distance, $d_p = 65$mm;
- display width, $w = 121$mm;
- display height, $h = 64$mm;
- eye-relief, $d_{eye} = 18$mm; and
- interpupillary distance, $ipd = 70$mm.

We calculate vertical FOV, $fov_v$, and horizontal FOV, $fov_h$, assuming that the displays are parallel.[5]

- magnification $M = f - d_p$
- virtual image height and width $h' = Mh, w' = Mw$
- similar triangle give lens-image distance $d_v = \frac{1}{\frac{1}{f} - \frac{1}{d_p}}$
- $fov_h^{nasel} = \arctan\left(\frac{M\frac{ipd}{2}}{d_{eye}+d_v}\right)$
- $fov_h^{temporal} = \arctan\left(\frac{M\left(w' - \frac{ipd}{2}\right)}{d_{eye}+d_v}\right)$
- $fov_v = 2\arctan\left(\frac{M\frac{h'}{2}}{d_{eve}+d_v}\right)$

We get $fov_v = 55°, fov_h = 2fov_h^{temporal} = 104°$. Clearly this is less than our goal, so we add a cant of $10°$ to each eye-box, resulting in an additional $20°$ FOV, which gives us a horizontal FOV of $104° + 20° = 124°$.

With those calculations, we have a brief layout in [Figure 6].

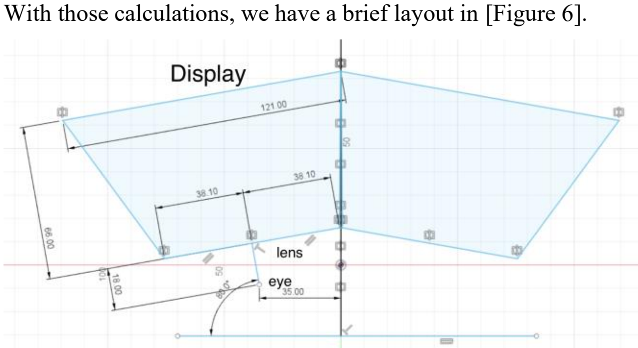
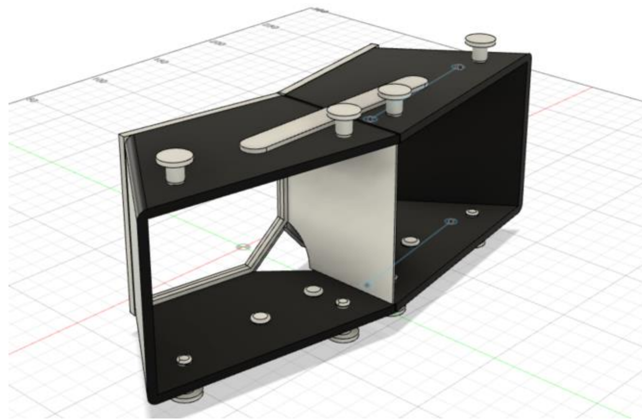



**Figure 6.** Headset measurement and layout.



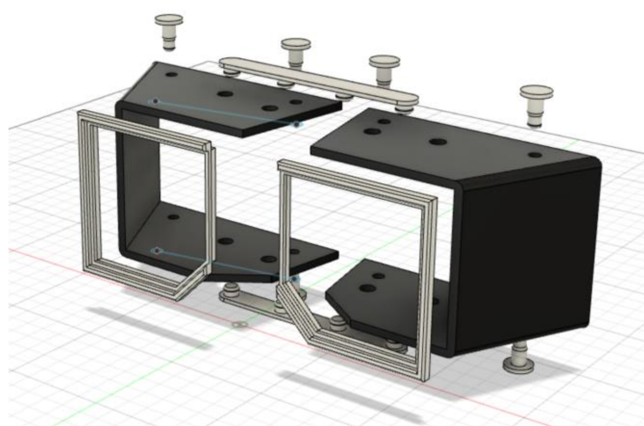


**Figure 7 (top), 8 (bottom).** Clips connect the left and right eye-boxes to save on filament in 3D printing. The LCDs are designed to be held using rubber bands through the pegs hanging on the top and bottom of the frame.

## 4.2. Building the Headset

For the best results, the headset is designed to be 3D-printed. Since we don't have 3D printing experience, we were aiming for a generally lightweight and reliable design. Our references are mainly Google cardboard[6] and other open-source VR kits. All models are done in Fusion 360[7].

Since we lost access to the 3D printer halfway through the printing process, we made a cardboard stand in [Figure1, 9].

In terms of software, we modified the course homework and render the left/right eye images on different monitors.

# 5. EVALUATION OF RESULTS

We originally finished 3D printing a model, but the model seemed to have shifted during the print, so the resulting structure came out uneven and the lens and displays wouldn't have lined up. Then the makerspace closed before we could pick up another attempt.

Although we did not manage to finish 3D printing our model correctly in time, we still managed to test the design using supplies we already have. The idea of having two separate eye-boxes and connecting them seems like it would hold based on

[5] The calculation details can be found in https://courses.cs.washington.edu/courses/cse490v/20wi/uwnetid/lecture9.pdf

[6] https://arvr.google.com/cardboard/

[7] https://www.autodesk.com/products/fusion-360

what we tested. We plan to take out our final 3D printed headset frame when the makerspace reopens in the future.

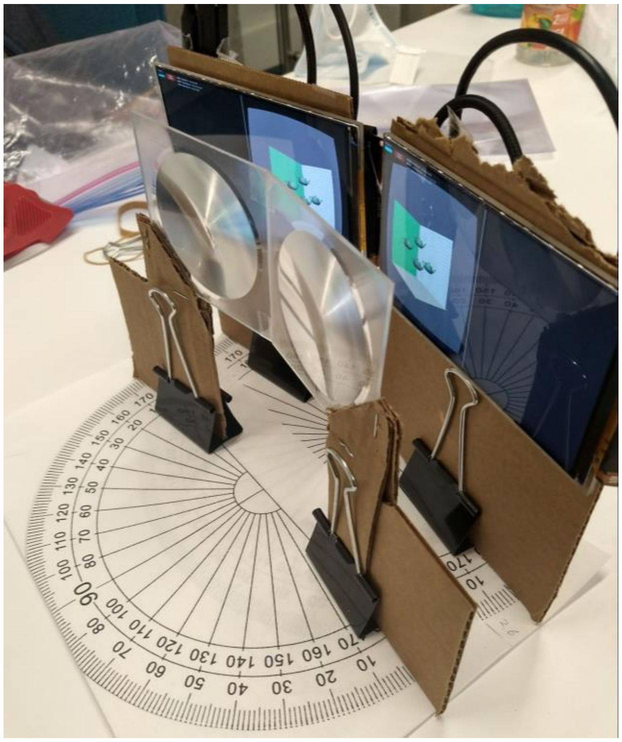


**Figure 9.** Cardboard stand. Eye-boxes are connected using joints between lenses. 2 protractors guarantee canting angle and lens-display distance.

The viewing experience is measured using the stands. The calculations we made initially made for a decent viewing experience. We exhibited some aberrations while we were testing out the stand setup, but this was generally negligible as seen in [Figure 5]. This can be additionally minimized if we had custom Fresnel lenses.

As a headset, the FOV would be around 120°, so our goal of creating a headset with a wider FOV than the course headset would've been achieved. We were also eventually able to merge the images in the binocular portion of the field-of-view by doing some light edits from the homework, so we were able to fuse the images between two separate 10° canted lens and display setups.

Note that the canting angle trades $fov_h^{nasal}$ for $fov_h^{temporal}$, which is $\frac{1}{2}fov_h$. A 10° canting gives $fov_h^{nasal}$ of 18° and a binocular FOV of 36°, which is approximately 1/3 of binocular human visual field. As a result, we do not experience very strong stereo fusion (although there is no "big nose" issue caused by the extremely constrained nasal FOV we initially expected).

We calculated that if we stacked two of the lenses we used, this would theoretically provide a significantly larger FOV (~160°); but the lenses would have to be so close to the display and eye that this seemed like an infeasible way to achieve a wider FOV. Even though a larger FOV is possible using the materials we have access to, most people probably wouldn't want an object being very close to touching their eyes; so this isn't a viable way to get a wider FOV and we would have to redesign the system to more comfortably achieve a better result. We suspect that if we had a larger lens, this issue would be solved.

From the observations we made using the stands, it seems that the lens and displays we chose and the dimensions we chose for offsets would lead to a viable first attempt at a custom wide FOV headset. The quality may not be as good as a commercial headset, but the FOV achieved by this would be slightly better than that of a normal commercial headset.

## 6. FUTURE WORK

It would not be difficult to finish printing the 3D model of the headset once the makerspace opens up again. Then it wouldn't take too much time to integrate everything to make it a functioning VR headset. This being said, we would like to correctly 3D print the headset, put everything together, and integrate an IMU and make it head-mountable with some sort of strap.

Additionally, it would be interesting to extend this project further to try out a system with a large curved Fresnel lens or wider lenses in general to see how far we can push the FOV and still maintain reasonable quality. We mentioned in the evaluation that it is possible to achieve a higher FOV at the cost of usability, but it would be more viable product-wise to see if we could extend the FOV to approach that of a modern wide FOV headset comfortably and without breaking the bank. Although if we were going to do this again, we would probably try prototyping this with cardboard and lenses rather than creating the model right away.

In terms of software, it would be interesting if we could create a visualizer for testing out displays and lens placements that allowed configurable types of lenses/parameters using some form of ray tracing. This would be an extension to the stands that we set up in that we could prototype designs before creating models and ordering materials, cutting down on the costs of ordering incorrect parts.

We would also like to tackle fixing chromatic aberrations in the future. This didn't seem to be a major problem in the current setup, as the distortion was fairly limited; but if we tried to extend the FOV, we would probably get larger, more visible aberrations. We have an idea of how to fix it, but this would take more time than we had.

## 7. CONCLUSION

There are still many problems with VR in general, but wider field-of-view headsets do exist and are commercially available. We attempted to build a wide field-of-view headset from scratch. We hit a roadblock with 3D printing the model for the frame, but the design was otherwise mostly fleshed out.

We have shown that it wouldn't be very difficult to build a wider field-of-view headset given the components and access to 3D printing, but it may prove to be more difficult to deal with the visual aberrations that arise from this method if extended to wider field-of-views and make it still look good. We believe a wider field-of-view will eventually be needed for VR to be a more immersive experience.

## ACKNOWLEDGMENTS

We would like to thank Doug and Ethan for providing guidance on the project and talking us through issues that came up in the process. We would also like to thank the John and David from the UW Reality Lab for their financial support.

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