Vision Correcting Display M.Eng Capstone Report

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Visual Computing and Computer Graphics (VCCG)

VISION CORRECTING DISPLAY

JIA ZENG

This **Masters Project Paper** fulfills the Master of Engineering degree requirement.

Approved by:

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Vision Correcting Display

Master of Engineering Capstone Final Report

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with Vivek Claver, Sijia Teng

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Table of Contents

Abstract

This is the report of the Master of Engineering (M.Eng) program's capstone project - Vision Correcting Display led by Professor Brian Barsky. The goal of the project is to develop vision correcting displays, which would enable people with visual aberrations to see a sharp and clear image on a display without requiring the use of corrective eyewear. The project team consists of both graduate and undergraduate students; this report will mostly cover the work done by Sijia (Scarlett) Teng, Jia (Sophie) Zeng, and Vivek Claver from the M.Eng program. Chapter 1 includes three individual technical contribution reports, in which Vivek focuses on the pinhole mask and the projection algorithm, while Scarlett and Sophie focuses on the parallax barrier and eye-tracking algorithm of the project. Chapter 2 is a team-written report to demonstrate our team's ability to apply Engineering Leadership Series concepts, tools, and insights. It will discuss project management, social and industry context, and industry analysis in details.

CHAPTER 1

Technical Contributions

1.1 Introduction to the Project and the Project Team

Our capstone project is to design a vision correcting display that enables people with vision aberrations (far-sighted, near-sighted, astigmatism, etc) to see a digital display in sharp focus without the need for glasses or contacts. We approach the problem by dividing the whole project into several sub-problems. In order to generate pre-filtered image and result in sharp focus in viewers' eyes, we try to use multi-layer screens and a pinhole mask. To help people with different aberration in each eye, we try to solve the problem with parallax barriers. We also want to track the angle and the position of the viewers in order to adjust the image for best results. Our team decided to approach the problem with the eye-tracking technique.

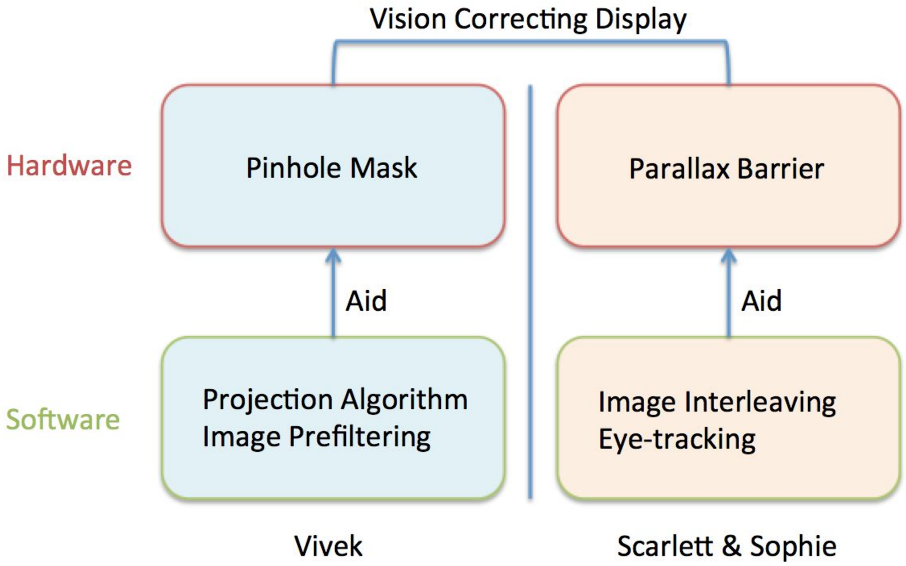


Figure 1 (Joint with Teng)

The project team is led by Professor Brian Barsky who provides technical advice to us. Our work is mainly based on his previous research as well as the research from his former Ph.D students Fu-chung Huang, Zehao Wu. The current team (2016-17) is combined with master of Engineering students (MEng) in EECS (Vivek Claver, Sijia (Scarlett) Teng, and I), Master of Science students in EECS, and some undergraduate students. Figure 1 shows the work structure among the MEng Students. Vivek focuses his work on the projection algorithm and image prefiltering of the pinhole mask while Scarlett and I are working together to solve the binocular vision problem with parallax barriers.

This paper is a part of group effort to discuss technical contributions made by the MEng students. I will discuss my work to solve the binocular vision problem with a focus on the physical setup of the parallax barrier. My partner Scarlett will focus on the image interleaving part of the project, which can be referred from her individual technical contribution paper (Chapter 1) in our final capstone report.

1.2 Binocular Vision Problem

The goal for my work on the parallax barrier is to solve the binocular vision problem. For people who have different vision in two eyes, we aim to enable both eyes to see equally focused image. Therefore, we use a parallax barrier, which has many vertical black stripes to block part of the images such that it can display two different images to each of the eye. The main idea is adapted from the technology used for bare-eye 3D, which is also discussed, by Perlin, Paxia, and Kollin(2000). As they described in the paper, parallax barrier is a method “in which a fine vertical grating or lenticular lens array is placed in front of a display screen” (Perlin, Paxia, &

Kollin, 2000, p. 1). As shown in figure 2, we first generate two images for left and right eye according to the prescription based on measurement of aberrations (typically by a licensed eyecare practitioner such as an optometrist or ophthalmologist) . Then we interlace two images together, where the width of the image stripes is calculated based on the barrier width and the distance between the barrier and the screen. The parallax barrier enables the display user's right eye to see only the corrected right eye image and the left eye to see only the left eye image, as illustrated in figure 2. When each eye sees a different image, the human visual system will combine information from the two sources and the user perceives the interleaved image as one sharp image. By this means, we can accommodate people who have different vision aberrations.

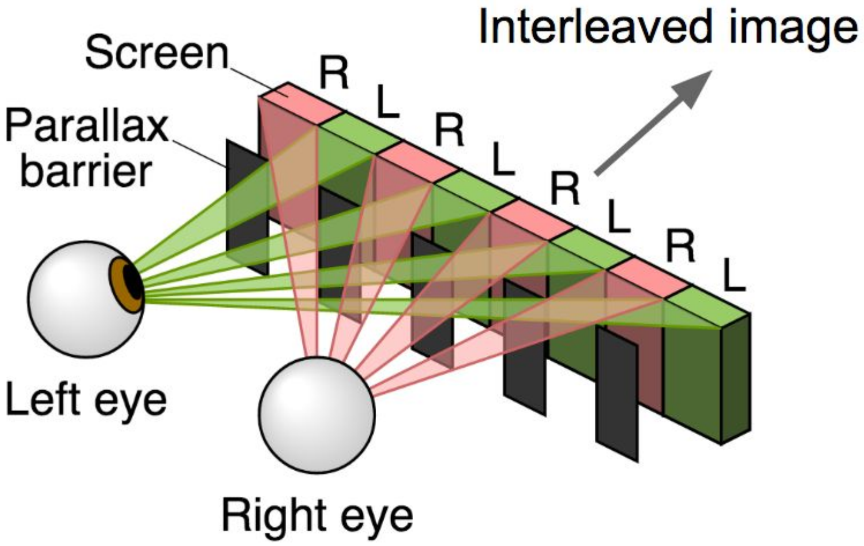


Figure 2: Demonstration of the parallax barrier, which enables people's two eyes to see two different images and perceive as one whole image by the brain (image from Wikimedia Commons).

1.3 Software Simulation of the Parallax Barrier

We first approached the overall problem by experimenting with different configurations of a parallax barrier. The ideal experimental setup would be any monitor to display and switch between the different pre-filtered images,, and a see-through LCD screen on which we can program the slits as a high-temporal frequency switchable barrier, and a high-temporal frequency monitor that would alternate display of the suitable half-images, and ideally the eye-tracking technique is enabled and combined with the parallax barrier (Perline, Paxia, & Kolin, 2000). Since a see-through LCD screen is very expensive, the first approach we took was to simulate the results with software.

A successful software simulation should enable people to perceive two different images for each eye in two phases without noticing the appearance of the black strips. In phase 1, a person should perceive half of the left-eye image with left eye through the clear strips (the parts that are not blocked by the black strips), and see the half of the right-eye image with right eye through the clear strips. In phase 2, the black stripes flip the position so that a person should see the other half of the left eye image with left eye, and see the other half of the right eye image with right eye.

Unfortunately we did not get an ideal result because the barriers were very visible no matter how we adjust . We tried to simulate the result of the parallax barrier with the base code written by Professor Barsky's research group. In order to create the effect of parallax barrier, we firstly wanted to generate two images for both left and right eyes, and interlace the two images together. Then we aimed to generate black strips as the barriers to block one eye's image at a time and switch between both eyes. If we were successful, when we switch the barriers fast enough (>60 Hz), human eyes will not notice the existence of the barriers (Dodgson, 2005, p.32). However, the software simulation did not make the existence of the barriers less visible, because it is hard for a computer to simulate how the binocular mechanisms of the human visual system actually combines monocular information to create percepts. Moreover, the software also incorporates the effect of the pinhole mask; therefore it is hard to adjust for error correcting since we did not know which technique was causing the blurring and black strips.

1.4 Time-multiplexing Barrier

Due to the difficulty in software simulation, we shifted our focus (so to speak!) to experiments with a physical setup to explore the effects of a parallax barrier; from these we gained useful insights but also experienced limitations with the setup. Following the instruction we found on a forum, we tried to create a DIY autostereoscopic LCD monitor with a transparent film of printed black barriers (Cybereality, 2008). We used our MatLab code from the previous experiment to interleave the two-eye images again. Then we actually printed out a transparent film of thin black stripes with the corresponding width and place the sheet in front of our computer screen to simulate the effect of a parallax barrier. The distance of barrier-to-screen and the distance of barrier-to-eye is calculated in Appendix A of Teng's paper. The result is shown as Figure 3 below, the black strips block about half of the interlaced image and result in one combined image effect. Although, the results seem decent, it was hard for us to simulate the high-temporal switching effects of the actual barriers as mentioned in Section 1.2.

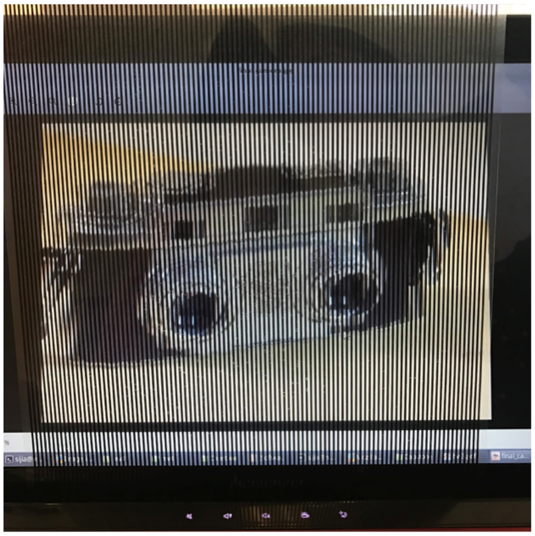


Figure 3: Thin barriers on a transparent film, the displayed image is interleaved with MatLab (joint with Teng).

Due to the limitations of a static physical setup with an unmoving ‘picket fence’ fixed in the same visual location for each eye, we then decided to simulate the time multiplexing parallax barrier result with a video or a GIF image with a layer of black strips on top of the interlaced images. We started with one eye because we realized from previous experiments that it is hard for a computer to simulate two eye results generated by the human brain. Then we generated two different images where the barrier blocks the complementary strips, and display the two images alternatively in high frequency. If we were successful, when we look at the image with only the left eye, we should not see the black barriers anymore. We tried with many different frame rates to switch the barrier, however, the results were not too much different (Figure 4). After some research, we realized that the LCD screen that general laptop uses has a limitation of 60Hz refresh rate meaning no matter how fast we generate the images, the display is always going to display the images at a frame rate of 60Hz or lower (Ghazi, 2012, p. 8). By the time of this report is written, we discovered that we could have tried with a gray barrier so as to reduce the perceived flicker from the luminance transient from the screen’s average luminance to the dark black. For future research, we recommend to experiment with gray barriers.

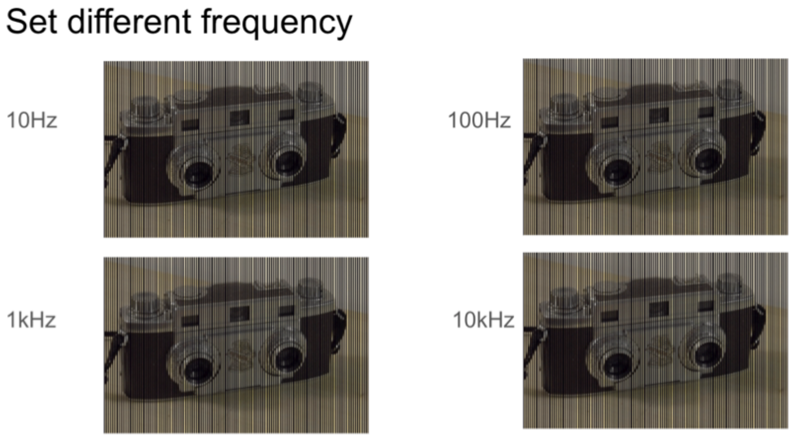


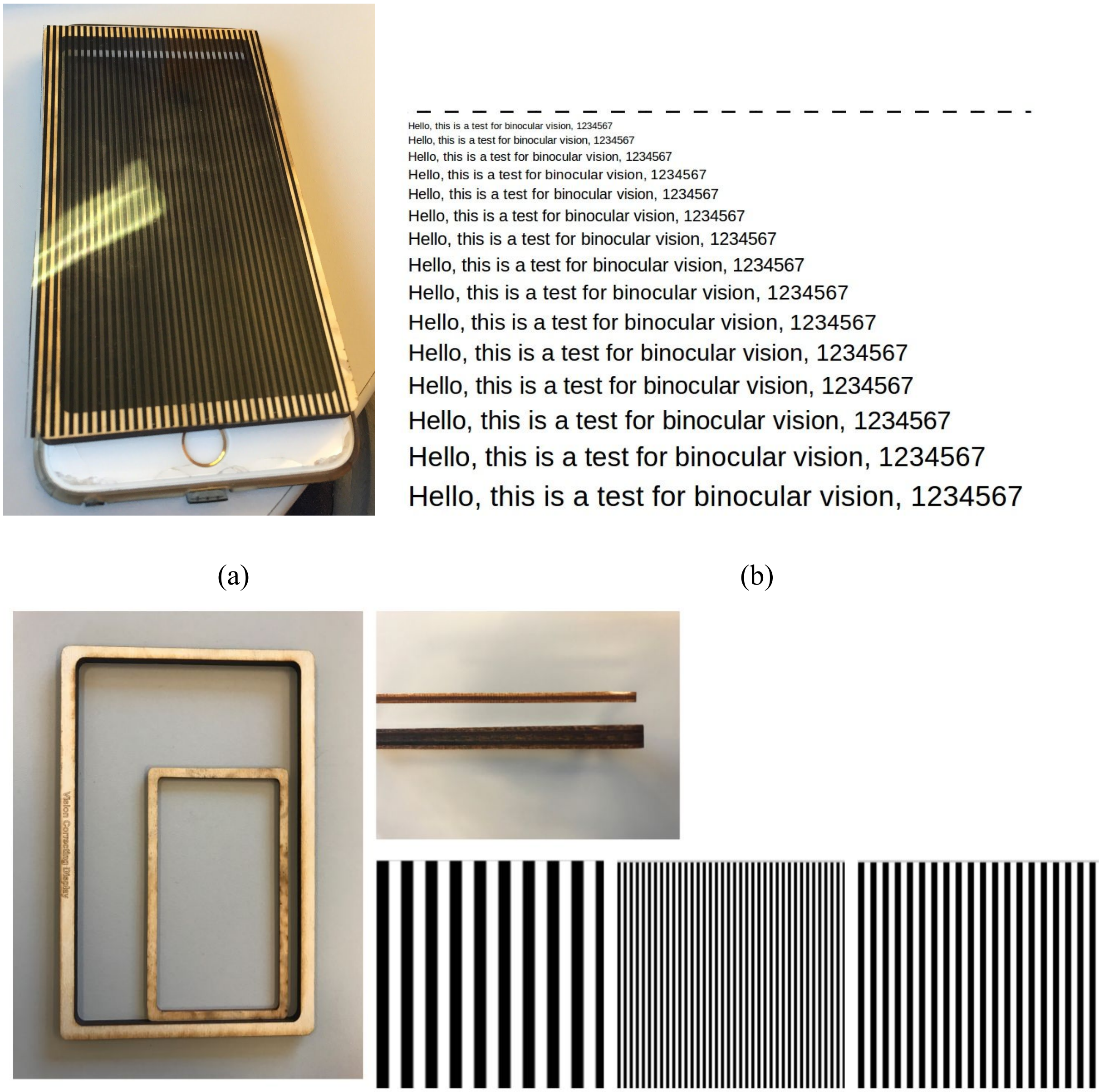
Figure 4: Results with different frame rate does not seem different (joint with Teng).

The limitation of the physical display’s refresh rate causes two main problems for our project. Firstly, the simulation cannot be proved by the monitors and screens we have. Secondly, if specially equipped monitors can prove it, it is not feasible for us to implement the same technique on the devices that the users will use (a cellphone display or a general home monitor).

1.5 Static Parallax Barrier

1.5.1 Build the Prototype

Because of the hardware limitation of the time-multiplexing barrier, we changed our research direction to static parallax barrier. Instead of shifting barriers or images, we keep both the image and the parallax barrier static. When the barrier is thin enough, we should be able to view the image binocularly, at the appropriate viewing distance, and synthesize the whole image from the two half-images, without noticing the barriers too much. We made a prototype again for the static barrier as shown in figure 5, the prototype consist of a wood frame to keep the distance between the barrier and the display consistent, and a transparent film with black stripes. We also created a testing image with some test and a line of black dashes on top.



(a) (b)

(c)

Figure 5: (a) The physical prototype, the barrier is placed on top of the frame (joint with Teng). (b) The testing image, we adjusted the width of the dashes and the image size accordingly.

(c) We created several different frames with different thickness and different sizes for both iPhone 6 Plus and laptop displays. We also printed many barriers with different width for testing.

We conducted experiments on different barrier width and different methods for interleaving the images, which Scarlett discussed in her technical contribution paper. The measure of sucess is that when the image is generated and the barrier width is calculated correctly, one should see only the black dashes with one eye, and not see any of the dashes with the opposite eye.

1.5.2 Calculating the Barrier Width

E : the distance between the center of two eyes

G: the distance between the barrier and the display (thickness of the frame)

D: the distance between the midpoint of the two eyes and the display

B: the width of each black strip of the parallax barrier

I: the width of each strip of the interleaved image

According to the properties of similar triangles shown in figure 6, we derive the formula:

$$B = E * G / D$$

$$I = E * G / (D - G)$$

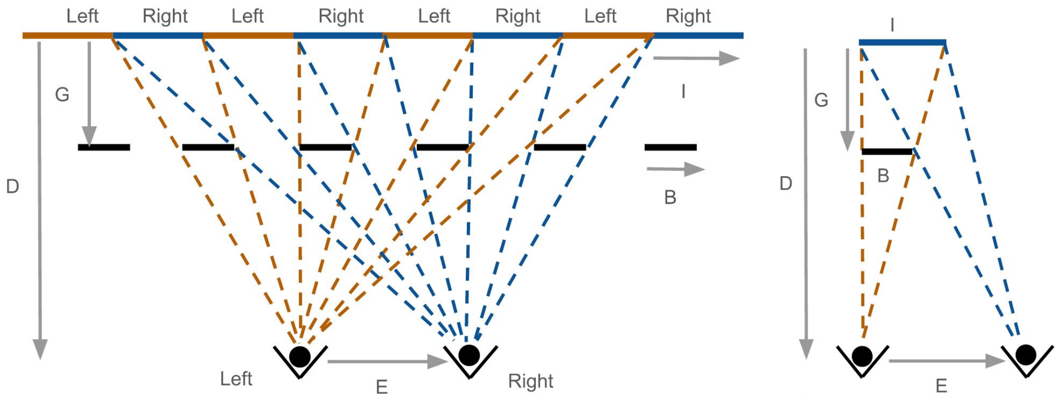


Figure 6: The triangles formed by the image strip, the barrier strip, and the eye are similar since the image plane is parallel to the barrier plane (joint with Teng).

1.5.3 Experiments

We created the barriers with Adobe Photoshop and printed with a printer that has an output resolution of 1200dpi or more. In order to create the barrier, we followed the instruction from Cybereality(2008) and calculated the width of the stripes by converting pixel per barrier to inch. We used a laser cutter to create the frames. Once we had all the parts ready, we put the frame on the display and put the barrier on top of the frame. We measured the distance between the eyes and the screen, and as the observer, I held my head still at the designed-for distance calculated based on the barrier width and image width with the formula in Section 1.5.2. Then we tried to move the barrier left and right to align the barrier with the image strips. An ideal result is that with one eye sees all the black dashes, that is the dashes form a straight line, and the other eye sees none of the black dashes. The initial results were not ideal because it appeared to have the dash-line for both eyes. A perfect result would be a straight line for one eye and no dashes at all for the other eye.

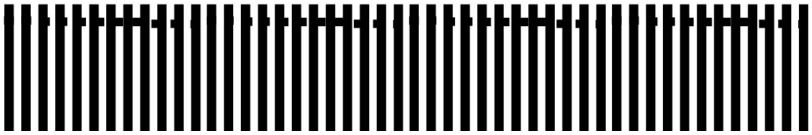


Figure 7: the initial result has cut-off dash-line (joint with Teng)

1.5.3.1 Hypothesis 1: The viewing angle caused the "cut-off" effects

We discussed the "cut-off" problem during our weekly meeting, and Dr. Grosof who attends our meetings regularly suggested that the viewing angle might be the cause. We tested the hypothesis by trying with different viewing angles with the same image. We had a soft ruler from the display to the center of the two eyes in order to make sure that the distance between the eyes and the display to stay the same. Then I shifted my heads up, down, left and right to see if there is any change in the results. However, we were unsuccessful because the "cut-off" effect stayed the same no matter of the viewing angle. Then we also proved the hypothesis wrong mathematically. According to figure 6 mentioned earlier, when the distance between the eyes and the screen stay the same, the ratio of the part we can see and the part the barrier blocks stays the same.

1.5.3.2 Hypothesis 2: The experimental errors caused the cut-off effects

Experimental errors include the printer error, the calculation rounding error, and the viewing distance error. We first made sure that the printer prints the process barrier in 100% scale instead of scale to fit. We used rulers to check that the printer's actual pitch is equal to what was calculated. We also ruled out that the viewing distance error was the cause with a fixed-length string with one end attach to the forehead of the viewer and the other end attach to the center of the screen. Although the viewing distance was not more accurate than about <?>because our heads cannot be perfectly still, the results still did not change much when we moved forward and backward within a range of about <?> viewing distances. Another possible error is the accumulated error due to the rounding in calculation of the image barrier width. When creating the barriers, we need to convert the width of the barrier from inch to pixel, which include rounding. There might be only a small difference between the actual width and the expected width of the barrier strips, however, when many stripes were added together, there might be some accumulated errors (i.e. errors that extend across multiple stripes) that cause the cut-off effect. The calculation flowchart is demonstrated in figure 8. Therefore, we tried with a method called period compensation discussed by Scarlett when creating the barriers. We found out that using period compensation instead of rounding, we got much better results.

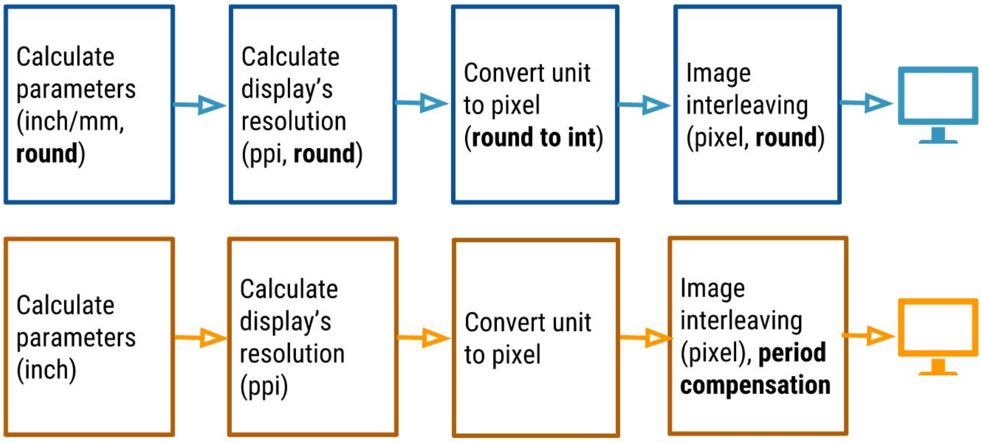
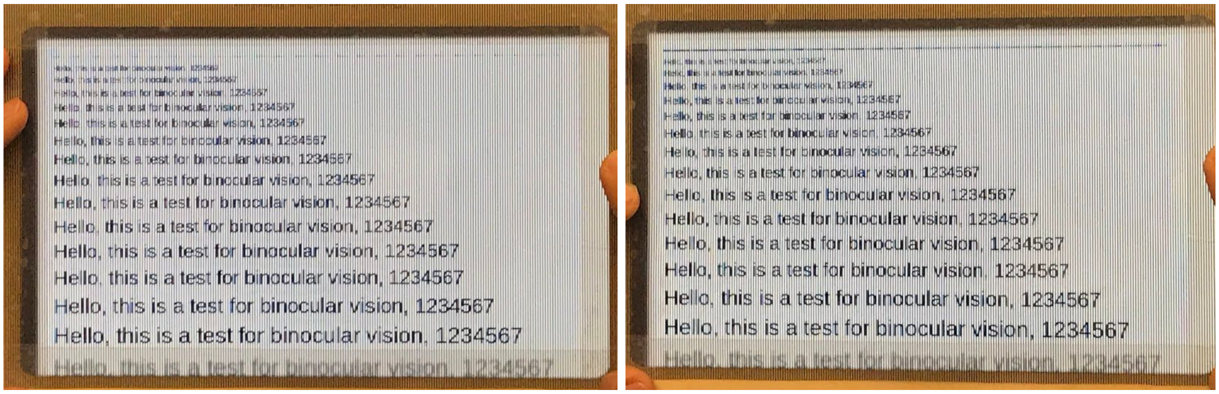


Figure 8: The calculation flow chart, the top is the rounding method that caused accumulative errors, the bottom describes the approach of period compensation (joint with Teng).

1.5.3.3 The Results

We finally got much better results after adopting the period compensation method. Figure 8 shows the results with barrier that has 1/64 inch strips and a frame with 1/8 inch frame. Although the barrier is not thin enough, the text below is still legible. The results still have some problems; first the dashes are not displayed perfectly; second there were also puzzling chromatic effects we do not understand.



(a) left eye view

(b) right eye view

Figure 8: the experiment result with 1/64 inch barrier and ⅛ inch frame (joint with Teng)

1.6 Eye-tracking for Vision Correcting Display

After getting improved results from the parallax barrier, we shifted our focus to the eye-tracking algorithm. The eye-tracking algorithm is essential to the project because we want to use the distance between the viewer and the screen in order to dynamically adjust the barrier width *B* and the image width *I* (introduced in section 1.5) so as to accommodate different viewing distances in real-world situations of practical interest. It is also important for the pinhole mask in the future since the algorithm needs to be computed differently with different viewing distance and position. Scarlett and I currently focused the eye-tracking algorithm only on the parallax barrier in order to simplify the problem. In this report, I will focus on the eye-distance detection while Scarlett will discuss our work in eye detection in greater detail.

1.6.1 Eye-tracking Specifications and Limitations

The vision correcting display will be used on a mobile device and it needs to be able to track the distance between the viewer (center of the eyes) and the display. We decided as a matter of design specification that it should accommodate moving or tilting viewers, work across a range of common lighting conditions, and should use only a common visible-light camera. Since the parallax barrier currently only works when the viewing plane (the line between the viewing eyes) is parallel to the screen according to the derivation of the barrier width and image width mentioned in Teng's appendix A, the eye-tracking algorithm should also take this limitation into consideration. The targeted users will not wear eyewear such as glasses or contact for the purpose of vision correcting display, therefore, we do not need to take the reflection from the glasses or contacts into consideration.

1.6.2 Eye Center Localization by Means of Gradients

Our research on the eye-tracking algorithm is built upon the former student Wenjing Ke's research, which is based on the image gradient algorithm to detect eye center by Timm and Barth (2011). Timm and Barth proposed an accurate eye center localization method that detects face region first, and then compute a rough eye region, then find the center of the eyes by image gradient. Detailed explanations on the eye detection algorithm can be found in Scarlett's report.

1.6.3 Distance Detection from Eyes to the Display

According to Section *1.5.2* and Figure 9, the barrier width B and the image width I is calculated by the formula: $B = E * G / D; I = E * G / (D - G)$. The distance between two eyes E and the distance between the screen and the barrier G are known as input values. We use eye-detection algorithm to measure and to compute the eye-display distance D in order to compute the barrier width B and the image width I.

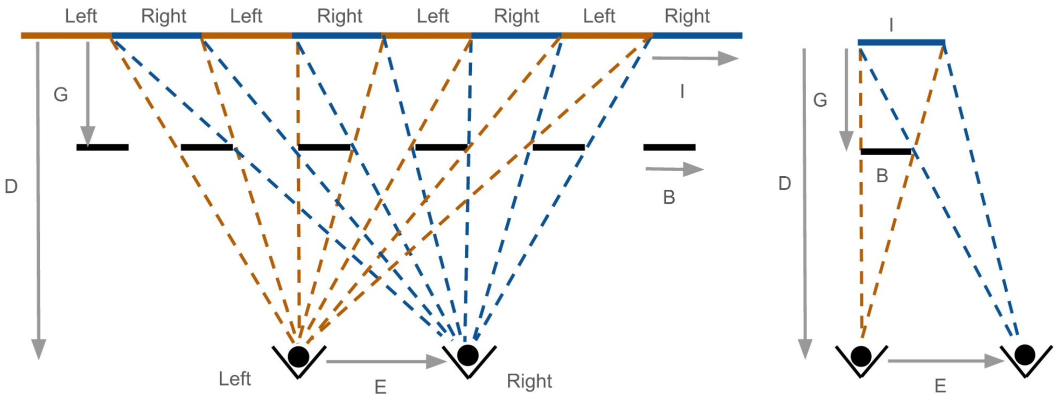


Figure 9: Using similar triangles, $B = E * G / D; I = E * G / (D - G)$ (joint with Teng)

The pixel distance of the two eye centers in the captured image calculates the distance between eyes and the display by the camera (mounted into the display). We need to measure the eye-screen distance $D_{eye-screen0}$, and the eye center distance (pupil distance) D_{pupil0} at distance $D_{eye-screen0}$ as reference values. We have the relationship between reference values and any other captured pupil distances at difference eye-screen distance: $D_{pupil0} / D_{pupil1} = D_{eye-screen0} /$

$D_{eye-screen1}$. Once the reference values are measured and recorded, we can compute any other eye-screen distance $D_{eye-screen}$ by the captured pupil distance D_{pupil} from the camera: $D_{eye-screen} = D_{eye-screen0} \times D_{pupil0} / D_{pupil}$. In order to get more accurate results, we calibrated the reference values with 10 pairs of pupil distance D_{pupil0} and eye-screen distance $D_{eye-screen0}$.

1.6.4 Experiments of the Distance Detection

We kept the viewer's face parallel to the computer display, and adjust the distance between the two eyes and the camera. Then we compared the measured results (expected value) with computed results (experimental / detected value). We experimented with 10 different distances measured in centimeters (cm). The results are as below:

Expected	30	39.5	47	50	55.5	60	61	67	75	92
Detected	31.00	39.99	47.14	50.40	55.77	59.79	60.99	66.64	75.33	91.3

The resulted relative error is 0.49%. According to previously mentioned formulas for barrier width *B* and image width *I*, we can compute the change or error in *B* and *I*:

$$B' / B = D / D', I' / I = (D - G) / (D' - G).$$

The relative error of the barrier width is $e_B = 1 - 1 / e_D \sim= e_D = 0.49\%$. The experimental result of the distance detection is relatively good. However, we still need to design a measure of success quantitatively to evaluate how much accuracy we need for the purpose of the vision correcting display.

It's been brought to our attention that we need to correct the changes in the vergence of the two pupils. Currently, our distance detection algorithm assumes that the distance between two pupils stay the same at any viewing distance in order to calculate the reference values as mentioned in Section 1.6.3. However, in real-world, human eyes rotate towards each other when viewing a closer distance. Our algorithm underestimates the eye-camera distance if our reference position is closer to the screen, and vice versa (see proves in Teng's Appendix B).

1.7 Future Work

Although the result from part 5 was not perfect, it still proved that the parallax barrier can work to show two different images for each of the two eye. In the future, we should use more accurate methods for printing the barriers and create a more stable prototype instead of the handmade one we had. We should also try to solve the RGB effects to get better result. Dr. Grosof suggests that that chromatic fringes near high-contrast luminance targets are often the result of the eyes' own (lateral and transverse) chromatic aberrations. These are aberrations that the lab's aberration -correction display technology does not at present rectify; however, using barriers that are the average of local luminance and chrominance may be expected to reduce fringes arising from those aberrations because the local contrast at the edges of the barrier will be reduced.

Moreover, for the eye-tracking algorithm, Dr. Grosof suggested that we need to find a way to incorporate the vergence of the pupils at different viewing distance to eliminate error in reference values. Human pupils converge when looking at closer distance and diverge when moving further from the viewing object.

By the time of this report , we had already started the process of combining the parallax barrier with the eye-tracking algorithm in order to adjust the image based on the distance between the eyes and the display. We received a relatively good result for the eye detection experiments; however, in the future we need to determine a quantitative measurement for the accuracy of the detection.

Finally, moving forward from the parallax barrier and eye-distance detection, we want to combine the parallax barrier with the pinhole mask in order to build the vision correcting display.

Chapter 2

Engineering Leadership

2.1 Introduction

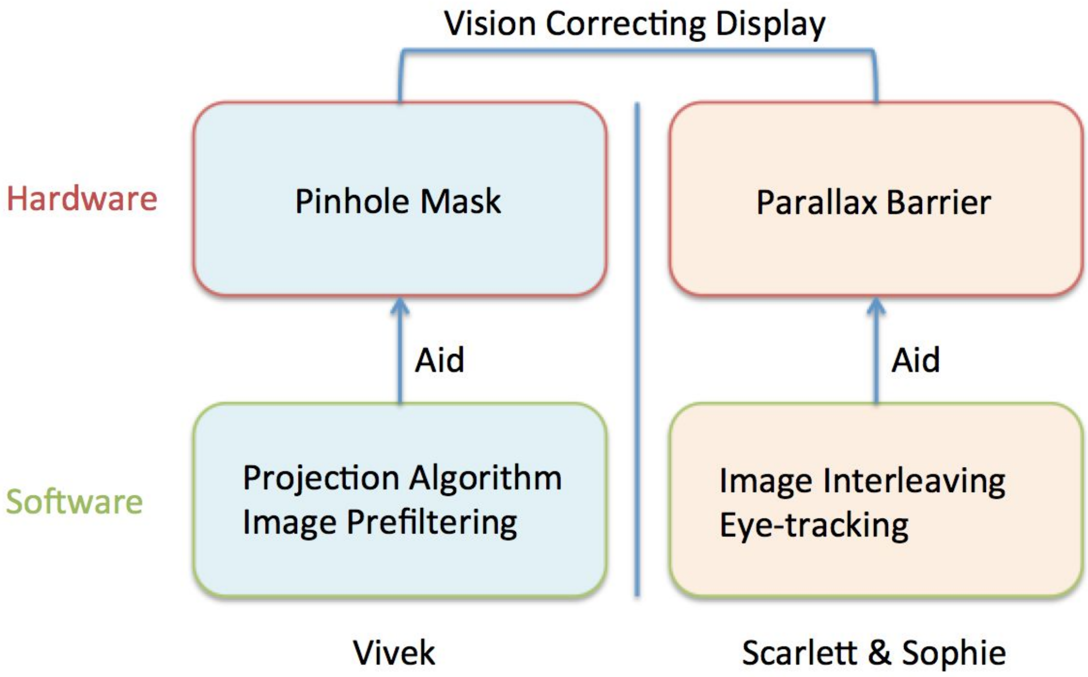
The second part of the report is to focus on the engineering leadership abilities we learned from M.Eng leadership classes and how we adapted throughout the project. We also want to provide context of the project in details. We have identified three key dimensions of the engineering analysis: our project management strategy, the social context of our research, and industry analysis of the potential market for our research.

2.2 Project Management

Our a long term research project is currently at a research stage. Our group is lead by Prof. Brian Barsky of the Visual Computing Lab, and consists of Prof. Barsky, vision science professional David Grosof, grauduate and undergraduate students from UC Berkeley. There are also other student researchers working remotely. Our group also has close collaborative ties with the MIT Media Lab.

Our current research address two major problems based on previous researches. The first problem is how to improve the performance of the display. This involves the optimization of the algorithms used to calculate the way to project the image, which can be divided into the two tasks: first, establishing the projection relationship between the display and the eye; second, the prefiltering of the image once this relationship is established. It also involves the design of better hardware to project the prefiltered image.

The second problem is the binocular vision problem, which determines how to accommodate people with two different sets of aberrations in their left and right eyes. Both problems have a combination of software and hardware considerations. The division of the workload among us three MEng students is the following: Sophie and Scarlett are working on the binocular vision problem together, while Vivek is working on the optimization of the display algorithms.



Based on the organization of our group and the time limitations, it is not reasonable to use the waterfall model where one team needs to wait until the other finishes. So we instead use the agile model of project management (Lotz, 2013), which is better for parallel tasking between the two different teams. Besides, since the agile model is more tailored towards software development, yet our project also contains many hardware implementation and experiments, we adopted a flexible project management model that extends the agile model (Smith & Oltmann, 2010). Specifically, we implement our project management method in the following ways:

1. Self-organizing small teams.

Due to the diverse nature of the subproblems of our research, we have divided our research group into several small teams. Each team has several meetings every week. The meetings are for choosing weekly goals, dividing work between each member of the team, synthesizing work that has been accomplished by individual members, and write status reports.

2. Combination of software and hardware research.

Since hardware costs more than software, we do software simulations before hardware implementations. For example, we simulate the results of using different kinds time-multiplexing barriers and pinhole masks before implementing them on expensive devices. Techniques from software development management can therefore be applied to the construction of the simulations. For the hardware experiments that require spending time all together, we improve effectiveness and efficiency by making full preparations beforehand, with the preparation in a multi-functional group being that everyone takes charge of one area: materials by someone with mechanical experience, process design by physics and vision experts, etc.

3. Information exchanging and work synthesis among the research group.

Every week we hold a meeting with the whole research group where each team gives a status report. The goals of these meetings are to find problems in the compatibility of the different results, absorb ideas from different perspectives, and inform everyone in the group as well as the remote researchers about the overall achieved progress. The meetings are presided by

Prof. Barsky and David Grosof, who with their knowledge on the subject give feedback about the work achieved and suggestions about the venues in which to pursue research.

2.3 Social and Industry Context

In order to understand the scope of our project fully, it is important to address the social context of our project, which is the context of the prevalence of visual aberrations among the general population. According to Huang and Barsky (2014), "global surveys estimate that 153 million people worldwide are visually impaired due to uncorrected refractive errors" (p. 15). They further addressed that "246 million people have low vision (below 20/60), 43% of which is due to simple uncorrected refractive errors (such as myopia, hyperopia, or astigmatism)" (Huang & Barksy, 2014, p.15). The targeted user is anyone whose eyes' refractive errors cannot be simply corrected with eyewear.

According to our research, there is no existing product that addresses the same problems as our project. To date, there are mainly three ways to correct aberrations of the eye: eye glasses, contact lens, and refractive surgery. Market research reports reveal that the demand for glasses and contact lens has greatly increased, "as the US population ages and the number of people with vision related health complications increases" (Glasses & Contact Lens Manufacturing in the US: Market Research Report, 2016, p5). If our research leads to a product coming to market, it will take up a portion of the market share of the current glasses and contact lens industry for it improves upon the weakness of glasses and contact lenses to correct high order aberrations.

2.4 Industry Analysis

Having analyzed the social and industrial dimension of our project, we can now perform an industry analysis of our potential market and identify potential competitors. The bargaining power of our customers would be low, as for our targeted users, who possess high order aberrations, there currently exists no product that can correct their vision perfectly without resorting to surgery. The threat of a substitute product is low for a similar reason. However if we want to broaden our target market to all people suffering from ocular aberrations, however mild they might be, then the bargaining power and the threat of substitute become very strong since there are cheaper and more applicable devices such as glasses and contact lense that can solve the vision problems efficiently. The current industry structure also makes the threat of new entrants very low, since Prof. Brian Barsky has conducted research in this domain for a long time in the academic world and is its most prominent representative. It will take a lot of time and effort for a new competitor to catch up and enter the field of vision correcting displays. The material required to manufacture the displays can be found from a lot of different suppliers, and the physical design of the display is not technologically complex, therefore there is not much bargaining power from the suppliers or manufacturers. Moreover, since the product would be new and would not exist in the market before our introducing it, there would be no immediate rivalry from existing competition. All of these facts lead to the following conclusion: if our research leads to our bringing a product to market, it will be important to maintain our technological uniqueness, and it would be more efficient to target specifically users who suffer from high order aberrations.

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