Design and Calibration of an Augmented Reality Haploscope

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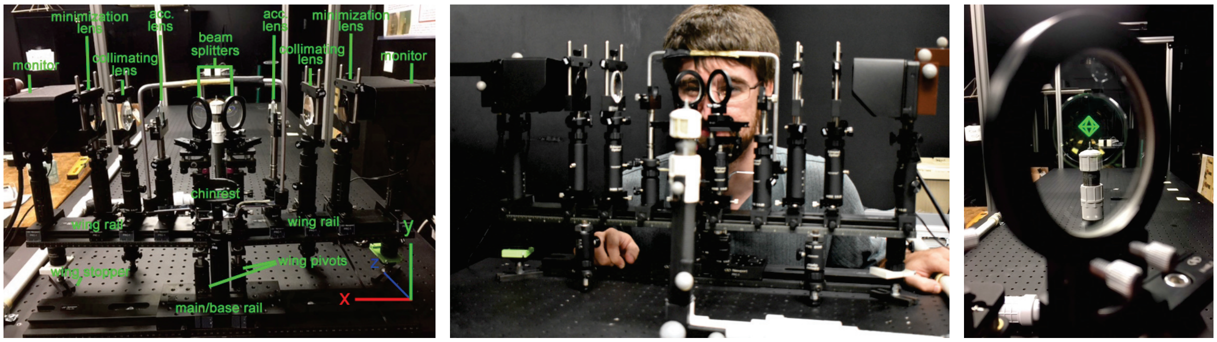

(a) (b) (c)

Figure 1: An Augmented Reality (AR) haploscope [5]: (a) front view, with main components labelled; (b) looking through the haploscope; (c) right-eye view of a virtual object, as seen through the optical system.

Abstract

Most augmented reality (AR) research is performed with commercially-available displays. However, these displays have unadjustable mechanical and optical properties, which limit the experimental questions that can be asked. In order to ask certain questions, it becomes necessary to build a custom display, using off-the-shelf optical components. In the field of visual perception, such devices are often developed, and are called haploscopes. In this paper, we describe the mechanical design of an AR haploscope, which can present virtual objects seen in augmented reality. In order to make accurate measurements, the haploscope must be carefully calibrated, but this calibration is quite difficult. Therefore, this abstract contributes a description of an AR haploscope, and outlines calibration procedures.

1 Introduction

Augmented reality (AR) has been an active field of research for the past 50 years [7], but recent advances and interest have dramatically accelerated developments in the field. This has resulted, lately, in an explosive increase in the development of virtual and augmented reality display devices, such as the Oculus Rift, Google Glass, Microsoft HoloLens, HTC Vive, and Meta 2, among others. These displays have inspired an increased tempo of AR research.

However, all current commercial displays have certain limitations, including a fixed focal distance, a limited field of view, a fixed optical design, and a limited luminance range, among others. Of course, as companies compromise between display performance, weight, and price, they make difficult design decisions and engineering tradeoffs. Unfortunately, these limitations also hinder the ability of our field to ask certain research questions, especially in the area of AR perception.

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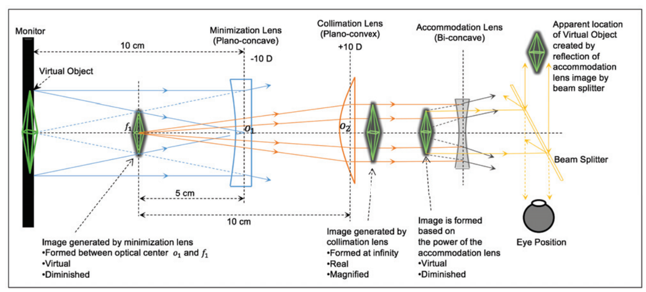

Figure 2: The design of the left eye optical system.

Therefore, our lab has developed a custom AR display (Figure 1), which we call an *AR Haploscope*, and which we assembled from off-the-shelf optical components. Our design is based on other haploscopes (e.g., [2, 9]), which have been widely used for research in the field of visual perception [8]. A *haploscope* is an optical system that produces tightly-controlled virtual images, typically with controlled accommodative demand, presented angle, brightness, divergence, and image choice [1, 3, 6]. Such a system is completely controllable; it can be adjusted for different inter-pupillary distances; it can be set up for a wide range of experiments; and configurations can be replicated.

However, the advantages of a haploscope come with the additional burden of calibration, and, through our own experience, we have discovered that the calibration of an AR haploscope is not at all a trivial task. There are many important factors to consider and compensate for, as well as many potential pitfalls. The difficulty is compounded by a lack of published research on haploscope calibration in our field. Therefore, this abstract contributes discussion on the design and calibration of an AR haploscope (Figure 1).

2 AR Haploscope Design

The components of our haploscope are labeled in Figure 1a, while the design of the left eye optical system is given in Figure 2. The goal of the optical system is to collimate the generated image, so that the image is located at optical infinity, or 0 diopters (D). At this

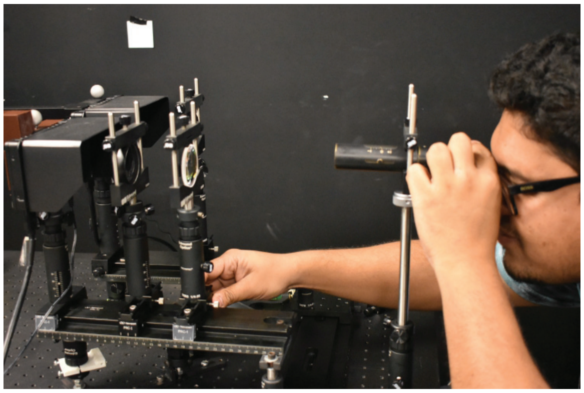

Figure 3: Adjusting the minimization and collimation lenses during calibration, using a dioptometer.

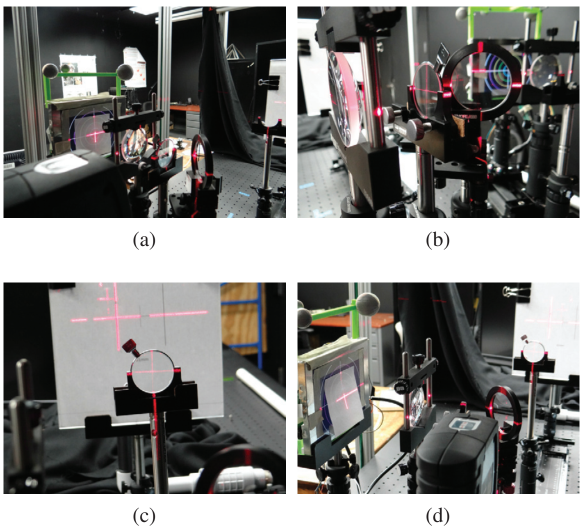

Figure 4: Calibration of the left eye optical system, using a gravity-balanced laser level: (a) monitor centering; (b) accommodation lens centering; (c) calibration target centering; and (d) optical combiner positioning.

point, the collimated image can either be left at optical infinity, or a negative power lens can reduce the focal distance. The image is first generated by a 1920×1080 pixel monitor. Then, the image is minified by a -10 D concave lens; without minification, only a small part of the monitor can be seen through the optical system. As shown in Figure 2, when this -10 D lens is placed 10 cm from the monitor, it creates a minified image at -5 cm. This minified image is then collimated by a $+10$ D convex lens, positioned 10 cm from the image. The collimated image is then passed through an accommodation lens. This comes from a standard optometric trial set; either a 0 D plain glass lens, which retains the collimation, or a negative power concave lens, which reduces the focal distance.

After generation, the images are reflected into the observers' eyes by 20% reflective optical combiners, mounted at 45° directly in front of each eye. Because these combiners are only partially reflective, observers see the real world beyond the display (Figure 1b), making this an AR haploscope. However, as discussed by Lee et al. [4], the combiners shift the view of the real world, which can lead to depth perception errors. This error is proportional to the thickness of the combiners. Very thin combiners are used—0.3 mm—which gives an approximate view shift error of 0.1 mm.

Observers must also verge appropriately to view the virtual object. During vergence, an observer's eyes rotate inward or outward until they can fixate the viewed object. For an object at distance d, the eyes rotate to the angle $\alpha = \arctan 2d/i$, where α is the angle of binocular convergence, and i is the inter-pupillary distance. Both the left and right optical systems are mounted on optical rails that rotate around pivot points (Figure 1a), which are positioned below the rotational centers of the observer's eyes (Figure 1b). This design allows the haploscope to match any angle of binocular convergence, without optical distortion.

3 AR Haploscope Calibration

With so many controllable variables, unsurprisingly, the haploscope can be exceptionally tricky to appropriately calibrate [5]. For a calibration scheme to be successful, it must carefully examine and root out potential error sources, such as chromatic aberration, dipvergence, spherical aberration, and other error sources, while correctly modeling important factors in human vision, such as convergence angle, focal demand, inter-pupillary distance, and binocular parallax. To accomplish these tasks, a systematic approach to calibration has been developed, incorporating each of these elements across six separate stages of calibration (Figures 3 and 4). Creating and implementing this calibration scheme has afforded an ability to ask research questions involving AR perception [1, 3, 6], which could not be asked using an off-the-shelf display.

Acknowledgments

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