Design of a compact optical see-through head-worn display with mutual occlusion capability

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ABSTRACT

We present the first-order design details and preliminary lens design and performance analysis of a compact optical system that can achieve mutual occlusions. Mutual occlusion is the ability of real objects to occlude virtual objects and virtual objects to occlude real objects. Mutual occlusion is a desirable attribute for a certain class of augmented reality applications where as it can provide a critical cue to depth. Compactness is achieved through the use of polarization optics. First order layout of the system is similar to that of a Keplerian telescope operating at finite conjugates. Additionally, we require the image to lie on the plane of the object with unit magnification. An implementation of the system is designed where the same lens is used as the objective and the eyepiece. The system is capable of having very close to zero distortion.

Keywords: Head-worn display, head-mounted display, augmented reality, wearable display

INTRODUCTION

Augmented reality provides the capability of adding or subtracting information from the real world. Augmented reality displays can be grouped into two general categories: optical and video see-through. A thorough comparison between the two categories is provided in [1]. Many scientists prefer video see-through simply because it is relatively easier to implement occlusions on a pixel-by-pixel basis. However, video see-through displays have several drawbacks such as lag time due to processing and reduced resolution of the real-world scene due to sampling of the cameras. Therefore, it is desirable to use optical see-through displays if they can provide occlusion capability. The main goal of this paper is to describe the design of an occlusion capable head-worn display. A compact optical occlusion capable display layout has been proposed in [2], for the case of infinite conjugates. However, several applications that would make use of such an occlusion display would require operation at finite conjugates. Therefore, in this paper, we will present the finite conjugate extension to the original design.

SYSTEM DESCRIPTION

We shall briefly summarize the principles of operation of the design described in [2]. The objective lens images the scene onto a spatial light modulator. The spatial light modulator allows for pixelated control of the illumination from the scene as collected by the objective lens. An x-cube prism combines the modulated output from the scene with the output of the microdisplay. An eyepiece places the combined output back to the object distance, which is at infinity for the design discussed in [2].

If the image lies at the same plane as the object, the system is a called a Bravais system [3]. In addition to the Bravais constraint, our system has the additional requirement that the objective should form a real intermediary image. The design for the case of infinite conjugates is shown in Fig. 1.

In the case of finite conjugates, the objective lens will image the scene beyond its focal point. In order to create a virtual image, the intermediary image will need to reside inside the focal length of the eyepiece. We also desire that the virtual image created by the eyepiece coincides with the object. The final image should have unit magnification. The problem as specified here is an instance of the two component design problem. In our system, a meaningful object distance is about two times larger than an average arm's length at 2 meters. The separation between the two lenses is constrained by the size of the x-cube prism. We also demand a telecentric system in the intermediary image space. Telecentricity is required mainly for efficient modulation on the liquid crystal based modulator as well as to reduce vignetting.

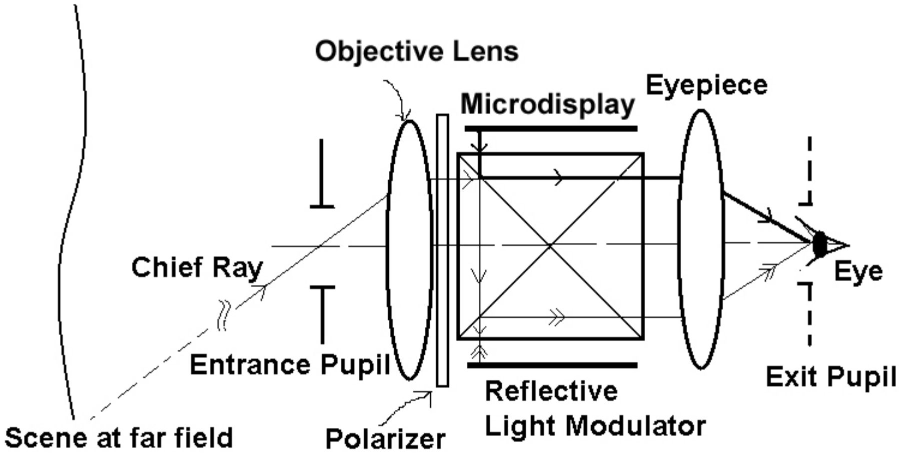

Fig. 1. Optical Layout of the System

TWO COMPONENT DESIGN PROBLEM FOR A TELECENTRIC SYSTEM

The focal length of the first lens shown in Fig. 2. can be calculated if the object and image distances are known. A meaningful object distance for our system is 2m. The image distance depends on the size of the x-cube prism and can be estimated. The separation between the two lenses depends on the minimum size of the x-cube. The size of the x-cube prism depends on the f/number, the separation distance between the x-cube prism and the image plane, the height of the marginal ray for the edge field (taking distortion into account), and the refractive index of the cube. Due to telecentricity constraint in the intermediary space, ideally, the height of the chief ray at the exit face of the x-cube would be equivalent to the size of the detector. We can estimate the angle α' (shown in Fig. 3) by applying the Lagrange invariant at a pupil plane and using the invariant at the modulator plane to solve for the angle α'. For large object distances, the angle α' for on-axis and maximum field angle will be approximately equal. Applying the Lagrange invariant at the pupil plane yields

$$H = -\theta_{1/2} \cdot EPD/2, \tag{1}$$

where EPD represents the entrance pupil diameter and $\theta_{1/2}$ represents half of the field of view (FOV).

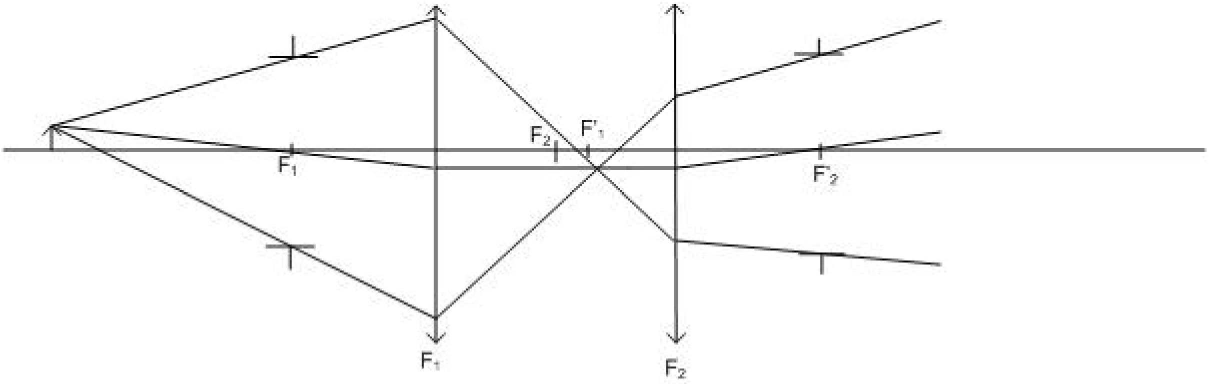

Fig. 2. Geometry of a unit magnification Bravais system with a real intermediary image

At the intermediary image plane where the LCOS modulator is located, the Lagrange invariant yields

$$H = u' \cdot h_{l\cos}, \tag{2}$$

where u' is the marginal ray angle for the edge field at the LCOS plane and h_{lcos} is the half of the diagonal length of the modulator.

Based on this marginal angle, we can estimate the x-cube length as in equation (3), using the geometry shown in Fig. 3.

$$t = \frac{d_2 \cdot \tan(\alpha') + h_{LCOS}}{\frac{1}{2} - \tan(\theta_1)} \tag{3}$$

d_2 is the distance between the exit face of the x-cube polarizing prism and the plane of the reflective spatial light modulator, α' is defined as $\frac{1}{2 \cdot F^{\#}{}_{working}}$, h_{lcos} is the height of the marginal ray for the edge field, θ_1 is the marginal ray angle for the edge field inside the x-cube polarizing prism.

Using the Lagrange invariant, α' in the intermediary image plane can be calculated since we know the diagonal height of the lcos in that plane.

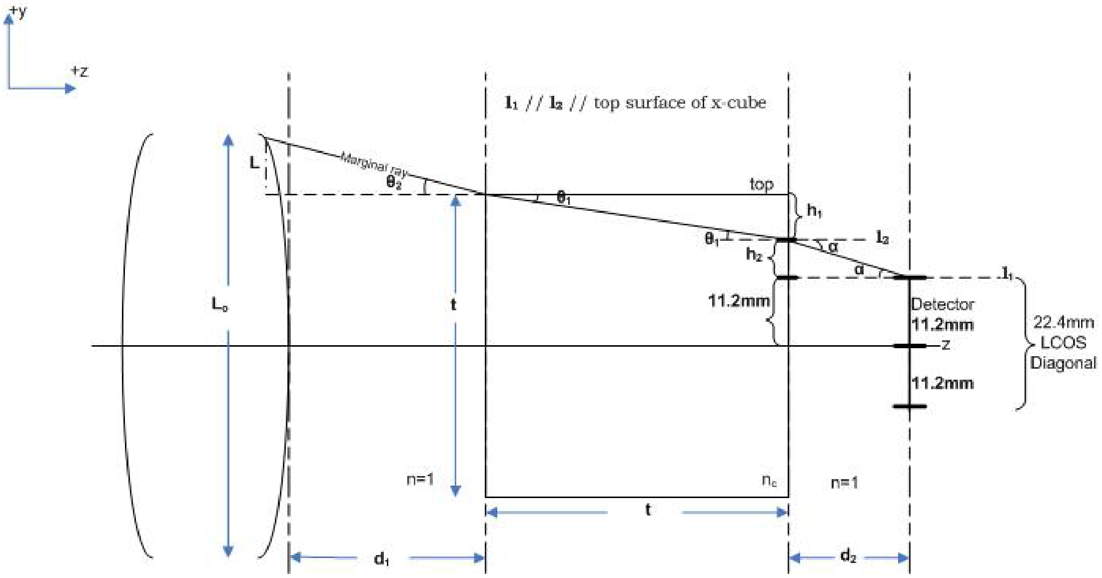

Fig. 3. Geometry for the x-cube minimum size estimation

DESIGN OF A UNIT MAGNIFICATION BRAVAIS SYSTEM WITH A REAL INTERMEDIARY IMAGE

In this section, we shall discuss the details of computing the focal lengths for the objective and eyepiece lenses. The parameters that can be set in this design are the field of view and the entrance pupil diameter. We start with a design choice of a 40 degree full field angle and a 9mm exit pupil diameter. Based on equation (1), (2) and (3), we calculate the

Lagrange invariant to be $\frac{\pi}{2}$, α' to be 0.14025, and the thickness of the x-cube to be ~28mm. Assuming a refractive index of 1.7 for the glass used in the x-cube prism, the reduced thickness is calculated to be ~19mm.

In the case of infinite conjugates, the effective focal length is equal to the eye relief distance. In a thick lens, the eye relief distance imposes the bounds on the back focal length, such that the back focal length can not be less than 17mm or greater than 30mm. The F/# of the system which determines the minimum size of the x-cube prism imposes a second constraint. In order to allow for 3mm airspaces, 1.5mm on each side of the x-cube prism, a minimum number for the back focal length would be 22mm for this system. However, it would be advantageous to consider increasing the back focal length, simply to keep the system to reasonable angles of incidences to achieve good image quality. Increasing the back focal length also gives us the opportunity to have more airspaces before and after the cube for manufacturing tolerances. An upper limit on the back focal length is imposed by the maximum acceptable eyerelief distance. Therefore, assuming that the principal planes reside within the objective lens, we set the back focal length of the objective to be 30mm, resulting in an f/3.3 system. In our current implementation the principal planes lie within the lenses, therefore, we were able to achieve a 23 mm eye relief as measured from the edge of the first surface while maintaining telecentricity and the 30mm back focal length constraints. Our discussion so far has been built upon the infinite conjugate case and the statements remain correct in the case of finite conjugates due to the fact that the object is at 2m which is relatively far compared to the focal length, yielding a system behavior similar to the infinite conjugate case.

Finally, we check whether the telecentric system makes use of the maximum height on the optical modulator, by multiplying the field of view with the computed focal length, which yields an 11mm height on the modulator. In our specific case, the light modulator has a height of 11.2mm, therefore, a maximum height for the chief ray at the edge field angle of 11mm is acceptable.

Due to +1 angular magnification at the pupils, we can conclude that the chief ray emerges from the system undeviated. We would expect no distortion and lateral color for a strict implementation of the telecentricity condition. Also, the sine condition is satistified, if the system can be designed free of spherical aberration, we would expect the system to have no coma as well. Wetherell discusses the Gaussian analysis of afocal lenses, in the case of both finite and infinite conjugates in greater depth [5].

LENS DESIGN

In a recent study, we compared the use of doublets versus diffractive optical elements on aspheric substrates in correcting chromatic aberrations and quantified the impact of eyerelief on the design performance. Our study has shown that the diffractive optical element based system can support an eyerelief of up to 80% of its effective focal length. We have also seen that the diffractive optical element based systems yield better correction of both lateral color and astigmatism, the latter being a main limiting aberration of large field of view eyepiece designs. Guided by these results, our starting point can be considered as a system resembling an Erfle eyepiece where one doublet is replaced with a singlet and the second doublet is replaced with a diffractive optical element. The optical layout of the objective lens is shown in Fig. 4a. The minimum feature size for the DOE is measured to be 11.5 µm which can be considered feasible to fabricate. The performance of the lens, measured with the modulation transfer function, is shown in Fig. 4b. The modulation transfer function makes the astigmatic nature of the system apparent.

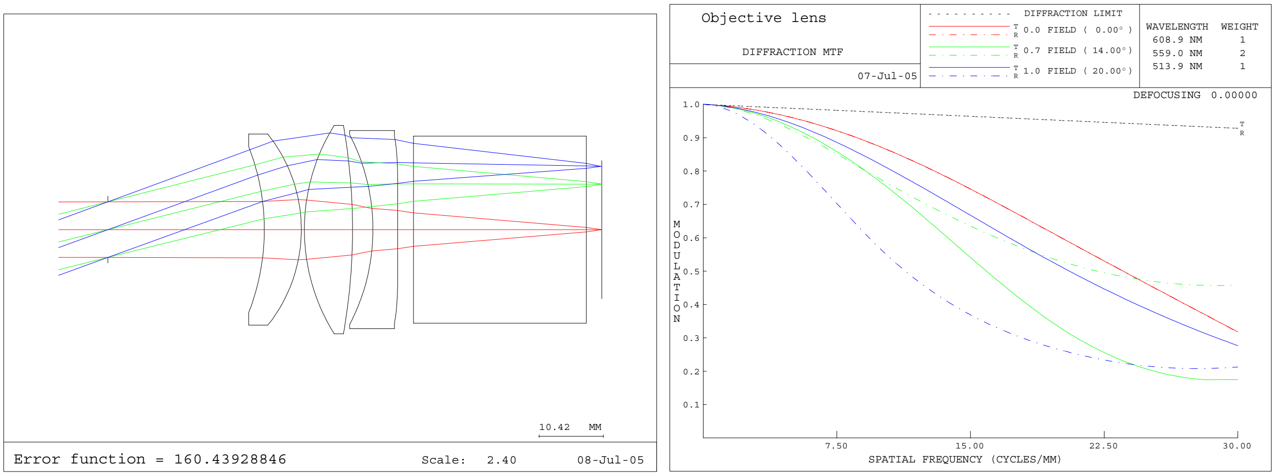

Fig. 4. (a) Optical Layout of the Objective Lens (b) Performance of the Objective Lens

The system composed of the objective lens and the eyepiece is shown in Fig. 5. Currently, the system is modeled in transmission, therefore, the ray trace indicates a negative magnification. The performance of the combined system is measured to have an average 6 arcmins of RMS spot size across the fields.

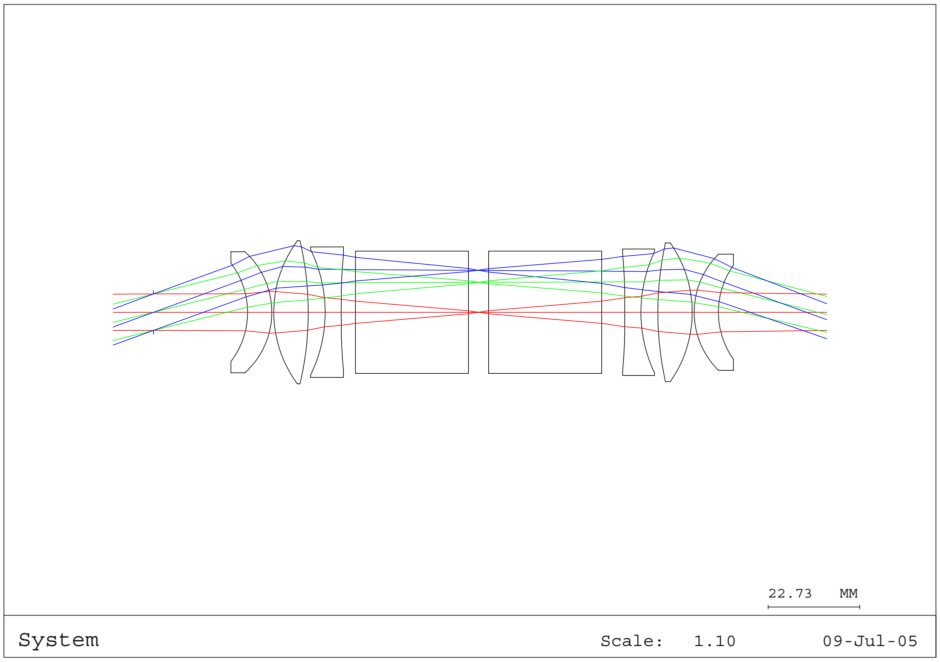

Fig. 5. Optical Layout of the Combined System

We achieved our goal of close to zero distortion in the combined system as shown in Fig. 6. In the current implementation the eyepiece is a flipped about the y-axis version of the objective. Optimizing the eyepiece can further minimize the average RMS spot size.

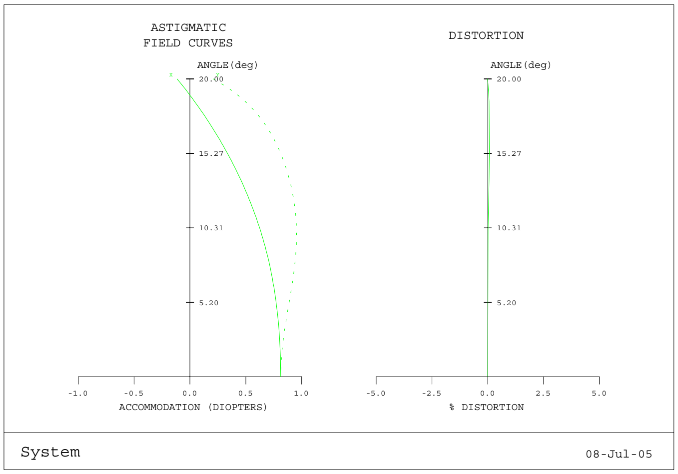

Fig. 6. Field curves for the combined objective and the eyepiece system

CONCLUSION AND FUTURE WORK

A compact system capable of mutual occlusions has been presented. The first-order layout is similar to that of a Keplerian telescope operating at finite conjugates. The system is an instance of a Bravais system forming a real image and having a telecentric intermediary image space. We have shown that the objective lens can be used as the eyepiece lens. The combined objective and eyepiece system is able to achieve close to zero distortion. The image quality of the combined system is measured to be 6 arcmins RMS spot size. In the current system, the eyepiece is exactly the same as the objective except that the distance between the cube and the eyepiece is adjusted in order to achieve the correct first order properties. We intend to further optimize the system performance by optimizing the eyepiece. The design details presented in this paper are focused on the virtual objects occluding the real objects and we do not address the real objects occluding the virtual objects which is the topic of a future study.

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