Conjugate-optical retroreflector display system: Optical principles and perceptual issues

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Abstract — Conjugate-optical retroreflector (COR) display systems have the potential for providing inexpensive high-resolution imagery in a head–mounted display (HMD) configuration. There are several perceptual issues, however, that need to be addressed before a COR display system can be used effectively. One issue is the choice of projected-image location relative to the retroreflective screen, which is determined by the convergence angle between the binocular channels of the COR display. Another issue involves visual half-occlusions, which can occur when a portion of a stereoscopic image is visible to only one eye, as may occur in any HMD. If half occlusions are simulated in a COR display in a way that is inconsistent with natural viewing, undesirable perceptual effects may result. In the present paper, we first describe, the optical principles that underlie the COR display system. We then discuss the importance of binocular convergence and describe a COR display configuration that eliminates inconsistencies in the depth cues provided by displayed surface properties and half-occlusions.

Keywords — *Conjugate-retroreflector optics, head-mounted projector, half-occlusions, depth cues.*

1 Introduction

The visual display systems employed in high-fidelity full field-of-view flight simulators are often optically complex, large, and expensive.[1,2] However, a display system has recently been described,[3] that could provide highly detailed, wide-field imagery using relatively simple, light-weight, and inexpensive optical components. The system employs a head-mounted miniature display and projection optics to place an image at the plane of a retroreflecting screen located about 1–6 m from the user. In addition, separate conjugate-optical retroreflector (COR) displays can be used for each eye. A major advantage of this system over other projection systems is that imagery is visible only to a single observer and, thus, separate COR systems can be used to present simulated imagery from different viewpoints (*e.g.*, to individual pilots in multi-pilot aircraft.) Another advantage of the COR system is that the projected imagery is virtually undetectable to the user unless it is projected against a retroreflective screen. This means that the projected imagery will not be superimposed on instrument panels or other places it is not wanted.

As with any display device, there are potential problems associated with the use of COR systems.[4] These systems are very well suited to providing binocular imagery because the imagery is reflected separately to each eye. One design issue that arises, therefore, is where to place the projected image plane relative to the retroreflecting screen and, hence, relative to the observer. There are several unique characteristics of COR display components and imagery that suggest the most appropriate configuration. A second design issue arises when a binocular COR system is used to provide stereoscopic imagery. When a nearer object in a stereoscopic visual scene occludes a farther object, the degree of occlusion, as viewed by the two eyes, is different.[5,6] The degree of this so-called *half-occlusion* is determined by simple optical geometry. Binocular head-mounted displays (HMDs), including those using binocular COR projectors, may produce half-occlusions that are inconsistent with the optical geometry associated with natural viewing. These invalid half-occlusions may, in turn, produce perceptual effects that can reduce display efficacy or even invalidate the visual simulation.

Because COR systems are relatively uncommon, we begin by briefly describing the optical principles involved in these systems. We then discuss both binocular and stereoscopic COR systems and suggest configurations for providing appropriate cues for simulating both overall image distance and the relative distance of objects making up the image. Finally, we discuss the invalid half-occlusions that can be produced using conventional HMD configurations and the perceptual implications of these invalid cues for the design of COR systems.

2 Optical characteristics of COR systems

2.1 Retroreflecting screens

With an ordinary reflecting surface, such as a plane mirror, only the light rays directed perpendicularly (normal) to the surface are reflected back to the source parallel to the incoming rays; all other rays are reflected away from the

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source. However, if two ordinary reflecting surfaces are placed at right angles, the incoming rays will be reflected twice – once by each surface – such that all rays will exit parallel to the incoming rays. Such an arrangement is called a *retroreflector*. This optical geometry is easily extended to three-dimensional space by using three reflecting surfaces that are arranged at right angles, like the corners of a cube. Likewise, if numerous small, right-angle prisms are etched or otherwise formed on the surface of a glass or plastic substrate, the surface will reflect light back very nearly along its original path, thus producing a retroreflective surface. Embedding small plastic beads on a surface can also produce a retroreflector. Retroreflecting material is used routinely in traffic signs to increase the amount of light reflected directly back to a driver at night. Also, screens produced from retroreflective material are used to create background illusions in photography. This material is available in large flexible sheets that can easily be applied to curved surfaces.[7]

There are two important measurements in characterizing the properties of various types of retroreflective materials. The first measurement specifies how completely a beam of light impinging on the screen is reflected back along the same path. This measurement results in a *reflective efficiency* curve that shows the intensity of the reflected light as a function of the angle between the source and the detector. For typical retroreflecting materials, more than 90% of the light is reflected back within an observation angle of about ±1°.[7] The second measurement used to characterize retroreflective materials specifies how light intensity varies with the angle at which the light impinges on the screen. For this measurement, the source and detector are aligned, resulting in an *angular efficiency* curve, which describes the amount of light reflected, as a function of the *entrance angle* measured with respect to the normal to the screen. It is not unusual for peak angular efficiency to occur at entrance angles as large as 20° to 30°. The angular efficiency typically starts to decline when the entrance angle is greater than about 40°.

2.2 Conjugate planes of a simple optical system

Consider the simple optical system shown in Fig. 1(a). If the upper ray, shown emanating from the object, A, is parallel to the lens axis, that ray will pass through one focal point, F', after being refracted by the lens. Further, if the lower ray passes through the other focal point, F, that ray will exit the lens parallel to the lens axis after being refracted. The point of intersection of these two rays determines the location and size of the image, A'. Under these conditions, the object and its image are said to be located at *conjugate planes* about the lens. Furthermore, the object and its image are interchangeable in the sense that if the object were placed where its image is located, its new image would be where the object originally was (the word *conjugate* literally means interchangeable.) Finally, note that if the object is moved closer to the focal point on one side of the lens, then the image will move farther from the focal point on the other side of the lens and it will be magnified. The opposite is the case if the object is moved farther from the focal point. In either case, the location of the object and image points will have changed, but those points remain conjugate to each other.

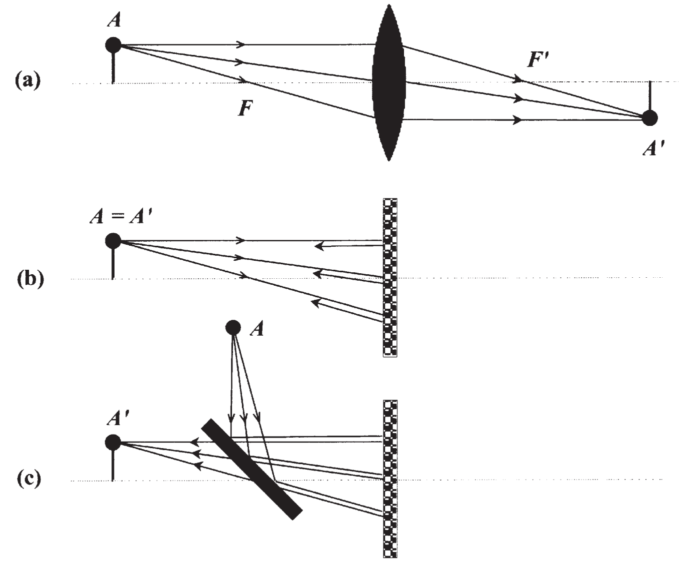

FIGURE 1 — Conjugate optical planes. (a) The definition of conjugate planes about a simple lens. The planes at which the objects *A* and *A'* are located are conjugate and hence optically interchangeable. (b) An optical system analogous to that in (a), but with the lens replaced by a retroreflecting surface, thus placing *A* and *A'* at essentially the same point in space. (c) A plate-glass beamsplitter is introduced to re-separate *A* and *A'*. This arrangement is the basis of the conjugate optical display system illustrated in Fig. 2.

Figure 1(b) illustrates an optical system analogous to that shown in Fig. 1(a), but in which a retroreflecting surface has replaced the lens. The result is that A' is now placed at essentially the same point in space as A. Further, if A is now moved closer to the retroreflecting surface, A' also moves closer, and so they remain at the same point in space. In Fig. 1(c), a plate-glass beamsplitter has been introduced to re-separate A and A'. The distances of A and A' from the screen are still equal, but now some of the rays are folded. This arrangement is the basis of a COR system.

2.3 COR system configurations

Using the principles described above, we can produce a very simple optical system that will provide a COR image (Fig. 2 is a schematic of such a system). An LCD microdisplay is the image source, and the retina of the eye is the detector. The optical portion of the COR system, consisting of the projection lens, the beamsplitter, the retroreflecting screen, and the optics of the observer's eye, is analogous to the simple lens of Fig. 1a. The COR display system of Fig. 2 places an image of the LCD at the observer's retina. In this configu-

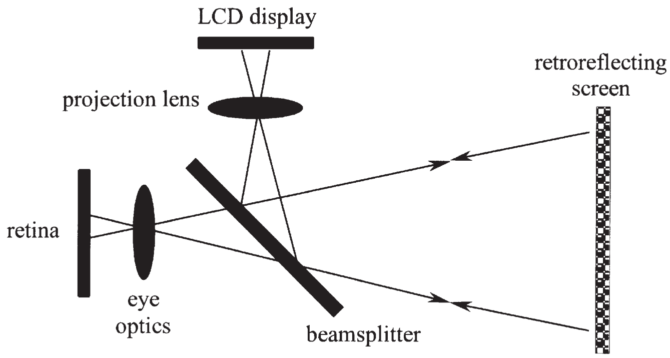

FIGURE 2 — Diagram of a simple, conjugate-optical display system. The objects *A* and *A′* of Fig. 1 are replaced by a microdisplay and its image at the retina of the eye, respectively. Ray displacement is exaggerated.

ration, the LCD and the retinal image are located at conjugate planes about the multicomponent optical system shown in Fig. 2.

A *monocular* COR display can be produced by optically centering a single-channel COR system on one eye. However, it is sometimes unnatural and visually taxing to view monocular imagery. Therefore, except in situations where monocular viewing is required, it is preferable to present imagery to both eyes. A simple way to do this with COR imagery is to optically center a single-channel COR system between the two eyes, which produces what is called a *cyclopean* configuration. This design takes advantage of the less than perfect reflective efficiency of the screen material as described earlier. For typical retroreflecting materials, each eye will receive at least 40% of the available luminance as long as the observation angle (see Section 2.1) is no greater than about 0.5°. Of course, the observation angle depends on both screen distance and interpupillary distance.

The cyclopean configuration described above has several disadvantages. First, it is not optically efficient because most of the light is directed to a point between the eyes and is therefore lost because the observation angle may be large relative to the width of the reflective efficiency function. Second, slight changes in the observation angle, as would result from slippage of an HMD on the head, could cause dramatic changes in the relative luminance levels to the two eyes. Moreover, if the slippage is lateral, such that the display moves closer to one eye than to the other, then the luminance change will be in opposite directions for the two eyes.

The disadvantages described above for the cyclopean configuration can be eliminated by implementing a *binocular* configuration that uses separate COR systems for each eye. Presenting separate images to each eye also allows the introduction of binocular and stereoscopic cues (see Section 3.0) that can often enhance realism and simulation efficacy. There are, however, also potential problems with binocular COR systems. One problem is that the imagery associated with one eye may be visible to the other eye. This crosstalk may result in the appearance of ghost images. The reflective efficiency of the retroreflective screens and the diameter of the projector lens will determine the amount of image crosstalk between the eyes. The amount and significance of crosstalk will vary with the type of imagery, the screen material, the screen distance, and the interpupillary distance. Therefore, this problem must be assessed for each system configuration.

3 Perceptual effects related to binocular COR systems

3.1 Vergence angle and the apparent depth of binocular imagery

One advantage of a binocular COR system is that the apparent distance of the image can be varied. If the system is configured such that the optical axes of the two channels are parallel, the COR imagery will appear to be located at effective optical infinity. This is the simplest configuration, but it results in the image appearing farther away than the retroreflecting screen if the screen is located less than about 3 m from the observer. The apparent location of the image plane can be brought closer to the observer by adjusting the angle between the optical axes of the two COR channels so that the axes converge. The observer's eyes must then be converged to the same angle to avoid double vision.

If the two channels of a binocular COR system are set such that their respective images converge on the retroreflecting screen, the projected image will appear to be located at the plane of the screen. If the angle between the optical axes of the COR channels is reduced, ocular vergence is reduced and the image will appear behind the screen. In that case, if the edges of the screen are visible, the perceptual effect is one of viewing imagery through a window or aperture. This is true even for very little convergence. At distances greater than about 2.5 m, the apparent separation between the screen "window" and the apparent image plane is small and probably of no practical importance.

3.2 Stereopsis and half-occlusions

As described above, the use of binocular imagery in a COR system can produce the visual impression of an image plane located in depth at some distance from the observer. In addition, the impression of depth of objects in the simulated scene, both relative to each other and relative to that image plane, can be produced by presenting slightly different views of the simulated imagery to each of the two eyes.[8] The slight difference between the views is called *binocular disparity* and the resulting perception of relative depth is called *stereopsis*. There are many visual cues to relative depth that are not related to stereopsis, but it is well established that stereopsis can significantly improve depth discrimination.[8] In addition, the impression of stereoscopic

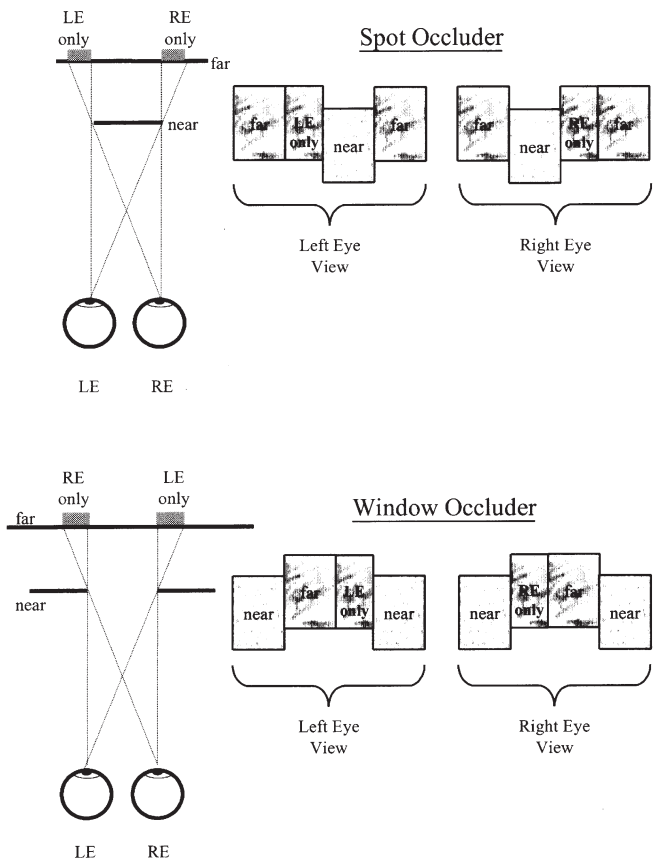

FIGURE 3 — Optical arrangement (left) and left- and right-eye views (right) corresponding to real-world viewing of either a spot occluder (top) or a window occluder (bottom). In both configurations, the half-occluded regions (small filled rectangles on diagrams at left) are part of the far plane. Although they are not visible in the optical arrangement diagrams, a speckled texture is located at the near plane and a marbled texture is located at the far plane. Optical arrangement diagrams after Shimojo and Nakayama (Ref. 9).

depth is perceptually compelling and can contribute significantly to the perceived realism of simulated images.

When a nearer surface occludes a farther surface, portions of the farther surface may not be visible to both eyes. These monocular regions arise because each eye has a slightly different view of the surfaces, and as a result, each sees the surfaces occluded to different extents. We refer to portions of a surface visible to only one eye as *half-occlusions*.[5,6] We call half-occlusions *ecologically valid* if they are consistent with natural, real-world viewing and we call them *ecologically invalid* if they are not. One consequence of ecologically invalid half-occlusions is that different images are presented to the two eyes, which may cause the individual images of the left and right eyes to be seen in temporal alternation. This condition is known as *binocular rivalry* and may result in an ambiguous perception of depth.

Examples of ecologically valid half-occlusions are shown in Fig. 3. Shown at the top of the figure are the left eye (LE) and right eye (RE) of an observer who is viewing two surfaces, one of which is larger and farther from the observer than the other. Because the smaller surface occludes a restricted portion of the larger surface, we refer to this configuration as a "spot occluder." As can be seen from the sighting lines drawn in the figure, two small portions (labeled "LE only" and "RE only") of the farther surface are each visible to only one of the two eyes, and are therefore half-occluded. Another ecologically valid occlusion configuration is shown in the bottom diagram in Fig. 3 and is referred to here as a "window occluder." As was the case for the spot occluder, there are two portions of the farther surface, which are each visible only to one eye.

As mentioned earlier, binocular disparity produced by the slightly different views of an object available to the two eyes can produce the perception of stereoscopic depth. Binocular disparity is not, however, required to produce stereoscopic depth. Liu *et al.*,[9] for instance, describe a pair of left- and right-eye images that contain no binocular disparity but which nevertheless give the impression of a white rectangle in front of a larger black rectangle. The image pair does, however, include half-occluded regions that correspond to what would be seen by an observer viewing a white surface that partially occludes a farther black surface. Also, Nakayama and Shimojo[6] demonstrated that adding a half-occluded region enhances the appearance of a step-change in depth produced by a stereoscopic image pair. Finally, Shimojo and Nakayama[5] found that a half-occluded region appears to be part of a far surface, but only if the half-occlusion is placed so as to be seen by the eye that would see it in a real-world scene. When the half-occluded region is placed so as to be seen by the other eye, no consistent impression of depth is produced. Thus, the results of all of these studies suggest that the impression of stereoscopic depth can be produced by half-occlusion cues but only when those cues are ecologically valid.[8,10]

The depth cues provided by half-occlusions are relevant in the present context because they can provide either ecologically valid or ecologically invalid information as to the relative depth of two objects or surfaces The window and spot occluders shown in Fig. 3 are ecologically valid configurations, but it is not obvious that the half-occluded regions in those cases will be correctly associated with the farther surface. It has been suggested[5] that a correct association is related to the fact that the spot occluder and the window occluder are naturally occurring configurations that the human visual system has evolved to interpret veridically.

3.3 Half-occlusions in COR systems

As described above, relative depth is a particularly salient cue used by the visual system to distinguish among the objects and surfaces in a visual scene. Another such cue is discontinuities in object and surface properties such as luminance, color, and texture. Under most natural viewing conditions, objects at different depths also have different surface properties, so the two cues are consistent. Under some viewing conditions, however, objects at different

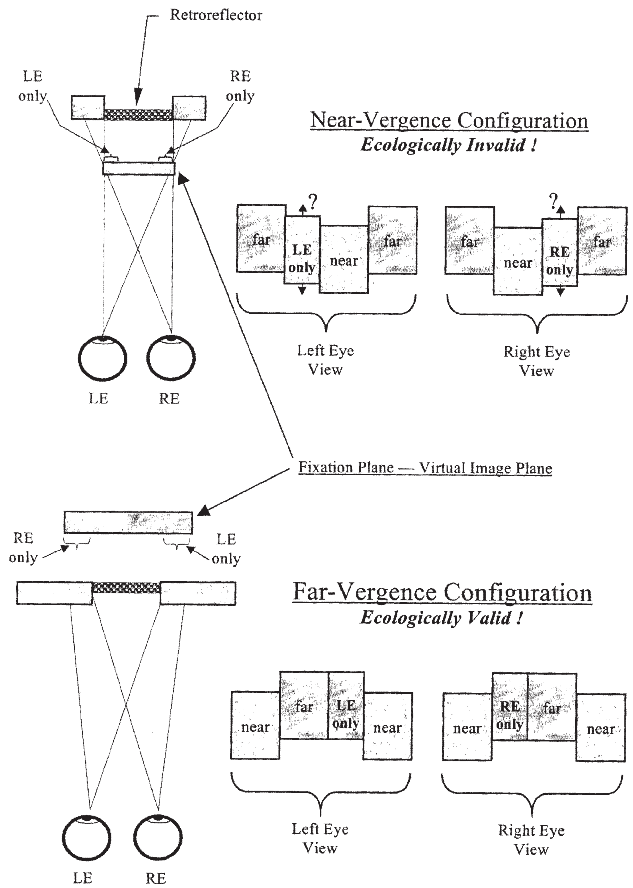

FIGURE 4 — Optical arrangement (left) and left- and right-eye views (right) corresponding to setting the vergence of the COR display channels so as to place displayed imagery either in front of (top) or behind (bottom) the retroreflecting screen. In the "near-vergence" configuration, the image regions labeled "LE only" and "RE only" have inconsistent half-occlusion and depth cues, making their perceived depth ambiguous (as indicated by the question marks). There is no such ambiguity in the "far-vergence" configuration.

depths have the same surface properties and, in that case, a *cue conflict* may result.

A cue conflict may be produced in a COR system when the retroreflecting screen is used to simulate a restricted aperture (such as a cockpit window) and the vergence angle of the two channels of a COR system is set so as to place the fixation plane nearer to the observer than the retroreflecting screen. Such a configuration is depicted in the upper diagram of Fig. 4. The textured regions visible to each eye of the observer as well as the relative apparent depth of those regions are shown in the right portion of the figure. The textures and relative location of each image region are the same for both eyes, so we will consider the left eye view only. Again, the observer is assumed to be fixated on the near plane where the image texture (speckled) appears after being projected onto the retroreflecting screen (see left portion of the figure). The far texture (marbled) is the background texture surrounding the retroreflecting screen. Thus, the left eye sees the far texture at the left, then a part of the near texture (speckled) not seen by the right eye, then a larger part of the near texture seen by both eyes, and finally the far texture again on the right. Note that the right eye does not see the "LE only", portion of the near texture because it does not reflect to that eye from the retroreflecting screen. A comparison with the upper right portion of Fig. 3 shows that three of the image regions (panels) are similar in both texture and depth to those seen in the spot occluder configuration. The only exception is the region labeled "LE only" which the observer could perceive either as part of the near plane, based on texture cues, or as part of the far plane, based on half-occlusion cues (recall that in ecologically valid configurations, half-occluded regions are part of the far plane; see Fig. 3). Thus, the near-vergence configuration shown in the upper portion of Fig. 4 places texture and half-occlusion cues in conflict, resulting in an ambiguous perception of depth.

The cue conflict described above can be avoided by setting the vergence angle of the COR display channels so as to place the displayed imagery, and hence the fixation plane, at or behind the retroreflecting screen. In many application, such as flight simulation, collimated imagery is preferred and would be obtained by placing the fixation plane behind the retroreflecting screen. This would result in a far-vergence configuration, an example of which is shown in the lower diagram of Fig. 4, where the half-occlusions are similar to those of a window occluder (compare with the texture panels in the lower portion of Fig. 3). An analysis of the image regions seen by each eye, similar to that done for the near-vergence condition, reveals that in this case the half-occlusions are part of the far plane and their texture matches that of the far plane. As a result, consistent depth cues are provided to the observer.

4 Summary

Most see-through HMDs are optically complex, whereas the COR display system is in many ways a simpler design. Also, most see-through HMD systems will overlay the simulated image on the instrument panel and elsewhere in the cockpit where the pilot might look. The COR system can significantly reduce this problem because the projected imagery is essentially invisible unless it is projected against a retroreflective screen. In addition, the COR display system has the advantage that its imagery is not visible to observers other than the user.

To avoid ecologically invalid half-occlusions, the convergence of the two channels of a binocular COR display system should be set so that the projected imagery appears farther from the user than the retroreflecting screen. An advantage of this configuration is that it can give the visual impression of looking through a window, which is particularly appropriate for flight-simulator applications. If it is not so placed, image half-occlusions can create uncomfortable and unrealistic viewing conditions.

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