

Pupil-Expanded Biocular Volumetric Display

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Abstract: A volumetric system is presented which displays a true volume image with realistic physical depth cues, such as focal accommodation, parallax, convergence, and biocular disparity. It operates by forming an image reflected off the windshield whose light rays, from the position of the driver are substantially indistinguishable from light rays that would appear to the viewer for an actual object. While the systems described in this reference were built and shown to work well, the optical systems were hampered by their size requirements. In this paper we will present a compact volumetric display which provides a large eye box and high image quality including correction of convergence errors induced by the windshield. The system compactness is achieved by the use of a pupil expander in the vertical direction which does not affect the convergence depth perception. The system size is such that it allows convenient mounting under the dashboard. A prototype of this system as well as prior larger prototypes is currently being tested by a number of major car companies.

Keywords: Display; Car; GPS; 3D; Volumetric; Pupil expander; compact; navigational.

Introduction

Three-dimensional (3-D) imaging has recognized value in a number of applications as diverse as medical imaging, visualization technologies, and navigational guidance systems. Advantaged over 2-D display methods and devices, 3-D imaging techniques help to improve how well image data can be represented to a viewer and provide useful characteristics that allow a measure of depth perception that can be particularly valuable in such applications.

A number of 3-D imaging methods are available for more closely representing objects as they appear in space. Stereoscopic imaging apparatus, for example, operate by forming separate images for the left and right eyes of a viewer. Typically, some type of a device, such as polarized glasses, is needed in order to separate the two

images and allow a measure of stereoscopic viewing. Auto-stereoscopic viewing apparatus can form a 3-D image without the need for a separation device, using virtual imaging methods for forming left and right eye pupils for the viewer at appropriate points in space. However, such devices must compensate for viewer movement out of the pupil space in order to successfully provide a suitable stereoscopic image.

While stereoscopic and auto-stereoscopic imaging apparatus provide the appearance of 3-D, however, the imaging methods that are used provide only a limited number of psychological depth cues. True depth perception is based on a complex interaction of the visual system and related brain processes that we use to recognize and locate positions in space. Stereoscopic and auto-stereoscopic systems simulate convergence which is an aspect of depth position, but fail to provide the visual cues for focal accommodation. Parallax, for example, is observable only over a limited viewing zone. The perspective of the stereoscopic pair is correct for only a small distance. Another cue, change of perspective with head motion, is lacking in stereoscopic systems. Overall, stereoscopic depth cues can tend to conflict with physical cues, leading to visual confusion and fatigue, as well as to misjudgment of distance, velocity, and shape. One such conflict is known in the art as the "convergence-accommodation discrepancy". For reasons such as these, stereoscopic techniques can be inappropriate for navigational guidance applications, such as for use in heads-up displays.

Unlike stereoscopic methods, volumetric display methods actually form a true volume image that provides realistic physical depth cues, such as focal accommodation, parallax, convergence, and biocular (not binocular) disparity. A volumetric display operates by forming an image whose light rays, from the position of the viewer, are substantially indistinguishable from light rays that would appear to the viewer for an actual object.

One useful application of volumetric imaging systems is for use in navigational guidance. For

example, Grabowski et al. [1] describe a navigational display system that forms an image of an overhead cable or other element for guiding the driver of a motor vehicle to a destination, much in the manner of following a cable. The volumetric imaging apparatus that is used forms a true volume image as a virtual image using the windshield or other surface that is disposed in front of the driver. In the volumetric imaging optical apparatus, a light source is rapidly scanned along a screen or diffusive element for forming the image of a "virtual cable". During each scan, the diffusive surface vibrates or uses some other method for rapidly changing the focus during a scan.

While the GPS display taught in Grabowski [1] provides the benefits of volumetric imaging for improved navigational guidance, however, implementation of such a system comes at a cost. The optical system shown on FIG. 1, needed to support volumetric imaging is hampered by its size requirements and by the complexity of its aspherical optical components. Lenses used are characterized by large diameters, resulting in high cost, placement constraints, and difficulty of mounting.

The system described in this paper has the following novel characteristics needed for commercially viable volumetric display for use in automotive and vehicular environments include the following:

- a) High image quality;
- b) Correction of convergence errors induced by the windshield;
- c) Compactness of the imaging optics, without noticeable impact on dashboard, windshield, or instrument panel design.
- d) Sizable eye-box and sufficiently large image area for comfortable viewing without eye-strain, with pupil sizing that accommodates the positioning of the driver, the vehicle dashboard, and the windshield.

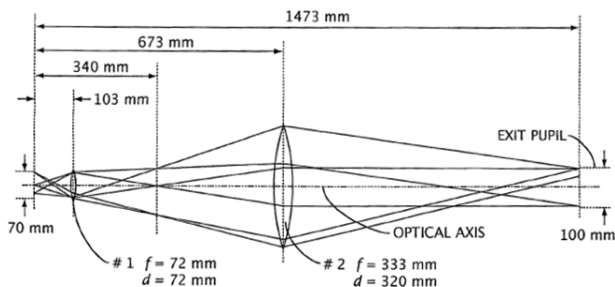


Figure 1. The optical layout of prior volumetric display [1] showing the moving image surface on the left and the large eye box on the right.

The optical design process of a compact pupil expanded volumetric display.

The volumetric system shown in FIG. 1 performed well in providing the driver with a true 3D display. A diffuser on the left was projected with the laser writer image as the diffuser was moving on a voice coil by a few mms in and out and its image relayed to the eye box through the optical system shown. The optics includes a first imager (the 103 mm lens) and a relay (the 333 mm lens) with a diameter of about 320 mm. To reduce the size of such a large relay, the lens in design per this paper was sliced along the horizontal direction. Thus it retains the convergence attribute over the horizontal field of view (FOV) albeit at a cost of the vertical aperture size and vertical FOV. Namely the input aperture at a distance of about 900 mm from the viewer is still large enough to accommodate both eyes (i.e. it is biocular). The sliced off vertical aperture and FOV would be later reconstructed by the usage of a pupil expander operating in the vertical direction.

The system thus sliced is now ready for folding in the vertical direction. We have chosen to perform the vertical folding of the system in an on axis fashion as shown on FIG. 2. Such on axis polarization means for folding provides for the most compact solution and for simpler and higher resolution optics as though it necessitates the use of polarization beam splitters (PBSs).

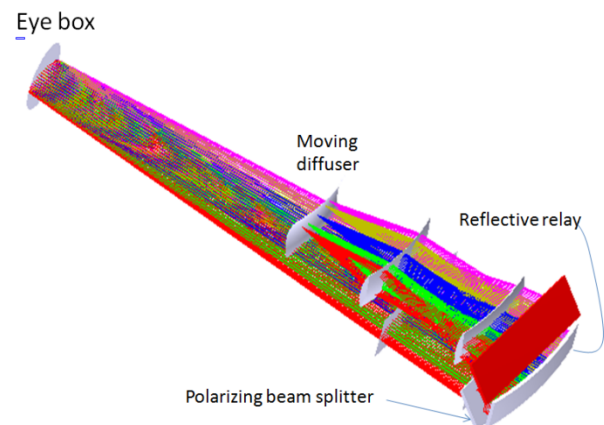


Figure 2 The optical layout of a vertically sliced and once folded system.

Fig. 2 shows the evolution of the system. The large refractive relay has been replaced with a slice of a concave mirror with a large dimension of about 140 mm in the horizontal direction and about 20 mm in the vertical direction. The rest of the optics is also sliced but still refractive. The PBS plate is shown which together with the quarter wave retarder (not shown) enables this polarization fold.

The polarization folding as shown is well known and is practiced in every CD player and in the Google Glass display. The PBS can be a MacNeille prism or a wire grid polarizer.

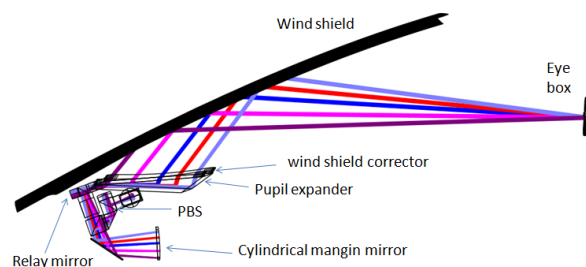


Figure 3. Cross section showing multiple polarization foldings, the pupil expander and the windshield corrector.

Fig. 3 shows a cross section in the vertical direction with the major system components from the driver eyes to the diffuser (hidden behind the PBS under the expander). The system includes two additional subsystems not shown on this figure. One is the subsystem which illuminates a DLP image generator (DLP7000 by Texas Instruments) and other is the projector system which projects this DLP onto the diffuser. The windshield corrector is just under the top of the dashboard (not shown). The FOV in the vertical direction is 9.6° and 12.8° in the horizontal direction. The Zemax CAD view of the system showing the horizontal and vertical fields is shown on Fig. 4.

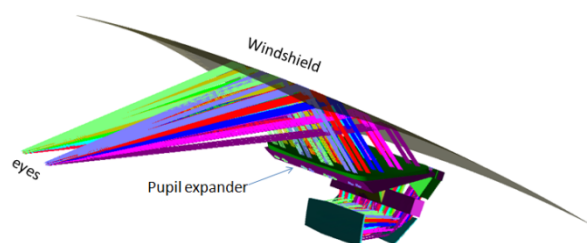


Figure 4. An isometric CAD view of the volumetric display

The Pupil Expander

The expander is a critical component of this volumetric display. Pupil expander generally replicates a small pupil and creates an effectively large pupil. The LUMUS [2,3] near to eye display has an element called LOE which is a pupil expander. In this application the LUMUS inventive LOE could not be easily used mostly due to the need for having the light coming out of the expander be directed at a slant angle towards the windshield. The LUMUS system emits the light perpendicularly to the

expander. Also the LUMUS LOE is guiding the light bouncing between its two parallel surfaces where as in the trapezoidal expander shown below, there is no guiding and thus the coatings of the multiplicity of its partial mirrors shown is simpler.

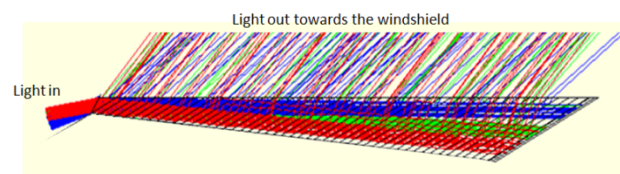


Figure 5. Vertical cross section of the trapezoidal pupil expander shows light coming in into a small aperture at different vertical angles (color coded). The exit pupil is large with light slanted towards the windshield.

The windshield corrector

The windshield is commonly an asymmetric surface with some significant cylindrical power in the horizontal direction. To preserve the convergence between the two eyes as light is reflected off the windshield a corrector is needed. The corrector is placed on top of the pupil expander and is designed for a specific windshield. The design process is done on Zemax using the ZEMAX powerful hybrid mode which allows the system to be analyzed as a sequential system with the non-sequential windshield (expressed as an STP file) is placed between the input and output ports within the sequential system. Thus the designer can use the biocular analysis or construct the equivalent of it in the sequential merit function. The design is aiming at to correct the windshield convergence error to less than one minute of an arc.

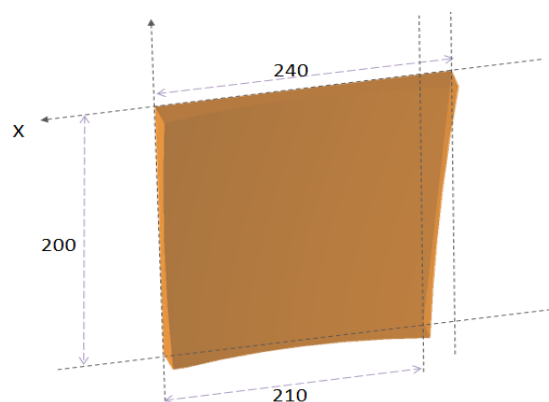


Figure 6. The windshield corrector is an XY polynomial surface on the top and flat at the bottom and made of PMMA. The dimensions shown are in mm. The maximum thickness is 16 mm.

The DLP projector

The projector subsystem projects the image generated on the DLP and projects it on the diffuser. The diffuser is constantly moving back and forth along the optical axis by about 2 mm. This displacement is then longitudinally magnified so that the depth of field as seen by the driver extends from about 5 m to infinity.

As the diffuser is moving, the projector images the appropriate image for the instantaneous depth. Obviously the aim is for the projector to make sure the image is focused on the diffuser as it moves. This is achieved by moving the barrel containing the diffuser and its objective which accepts substantially collimated light from the DLP.

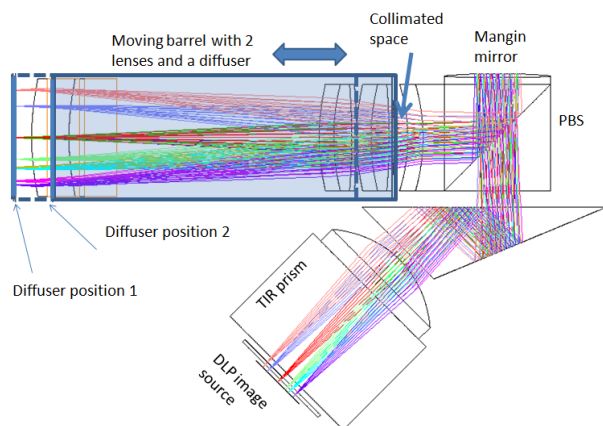


Figure 7. The projector system showing the moving barrel (exaggerated) with the diffuser and the objective lens pair. The input to the barrel is collimated. The 45° deviation prism is used for easier packaging.

The illumination system

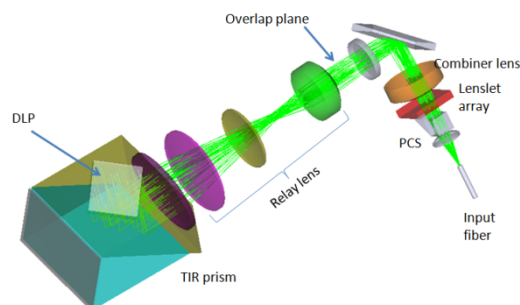


Figure 8. The illumination system is comprised of a fiber collimator followed by a Polarization Conversion System (PCS) and a lenslet uniformizer. At the overlap plane the illumination is in a shape of a uniformly illuminated rectangle which is then relayed to the DLP

This system uses an RGB laser as a source. The lasers are coupled to a fiber optic with 400 μ diameter and 0.22 NA. LED sources are also a possibility. Two prisms are used to do polarization conversion. Light reaching the DLP may be polarized all the way to the diffuser which does not disturb the polarization and then through the highly polarized optical system to the drivers eyes.

System assembly

The optical design has achieved the goals as outlined in the introduction. The whole system is shown on Fig. 9 from the input fiber to the driver eyes. It is highly compacted so as to fill within a relatively small volume provided under the dashboard. The size reference in Figure 9 is the pupil corrector which was shown on Figure 6. The system is now in the final stages of assembly and evaluation [4].

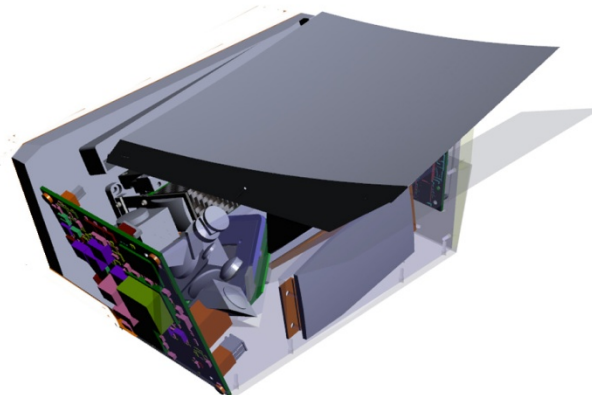


Figure 9. An electro-optical-mechanical CAD view of the system.

Acknowledgments

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