Volumetric, dashboard-mounted augmented display

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ABSTRACT

The optical design of a compact volumetric display for drivers is presented. The system displays a true volume image with realistic physical depth cues, such as focal accommodation, parallax and convergence. A large eyebox is achieved with a pupil expander. The windshield is used as the augmented reality combiner. A freeform windshield corrector is placed at the dashboard.

Keywords: Freeform, volumetric, display, car, autostereoscopic, pupil expander, windshield, GPS, augmented, convergence, accommodation.

1. INTRODUCTION

Augmented Reality (AR) head up displays for drivers, commonly project a 2-D image on a virtual screen at "the end of the hood". A number of 3-D imaging methods both stereoscopic and autostereoscopic are available for more closely representing objects as they appear in space; however, they provide only a limited number of depth cues.

C. Grabowski and T. Zamojdo[1,2] invented a laser based system where a monochrome 3D virtual cable is vector-projected just above the road ahead for the driver to follow[2] without looking at his GPS monitor. This system was prototyped and mounted under a dashboard of a BMW sport utility vehicle and worked well. Because this is a volumetric display, there is no accommodation-vergence mismatch that is an issue with most 3D displays.

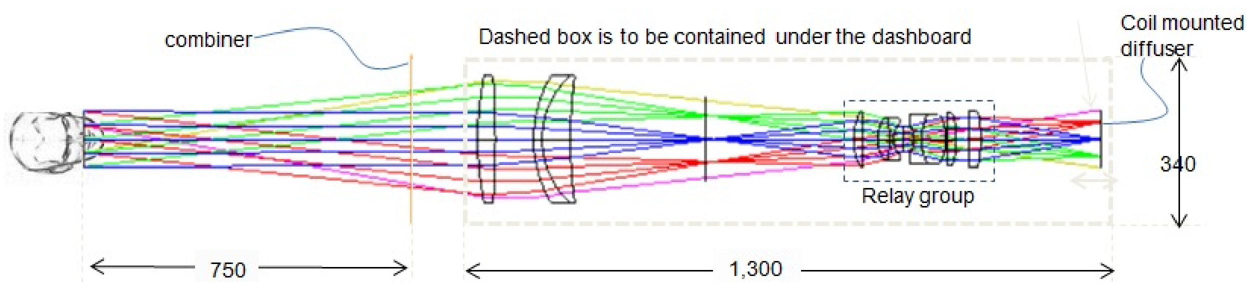

Fig. 1 The original Grabowski and Zamojdo volumetric, augmented, monochromatic vector display with a flat combiner

Auto manufacturers reviewed this system and pushed for a compact system that fits under the dashboard, with an xy rasterized display and for the windshield to be the AR combiner.

The Grabowski design[1,2,3] created the volumetric display by axially oscillating a diffuser, on which an image was generated for each of its axial positions. It is a biocular display with a large eye box at a large distance from the combiner that is placed over or at the dashboard. Since both eyes are within the eyebox, the convergence and accommodation are matched.

The Grabowski design was used as a starting point for the compact design that is the subject of this paper[5,6]. Fig. 2. Shows the overall view of the display system. Fig. 3 shows a closer view of the optics bellow the dashboard. The driver eyes can wander within a square eye box of about 100 mm in size. The field of view is 12.8^0 horizontally (**x** direction) by 9.6^0 vertically. The projector is contained within the "shoebox," that is the tight allocated volume under the dashboard.

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2. DESIGN STEPS

To compact the original system the following steps were taken:

1. The entrance pupil at the dashboard was sliced into a long aperture extending about 200 mm in the horizontal direction by 8 mm in the y-direction. For this slice the system is biocular, namely the two eyes could still fit into it, so that convergence will not be impacted for true volumetric perception.
2. A Pupil expander, consisting of a multiplicity of inclined slabs, is used to reconstruct the pupil in the vertical direction. The expander is also used to slant the output light from the projector towards the windshield.
3. The original large refractive elements were replaced with mangin mirrors.
4. Multiple polarization foldings, enabled by the small y-dimension of the pupil, were used to reduce total track. The foldings incorporate polarizing beam splitters and quarter-wave retarders.
5. The windshield is used as the augmented reality combiner.
6. A windshield corrector was placed at the dashboard to compensate for windshield induced convergence errors.
7. A compact, polarization-folded DLP system was used to generate the image on an oscillating diffuser that was then projected through the pupil expander and the windshield and towards the driver.

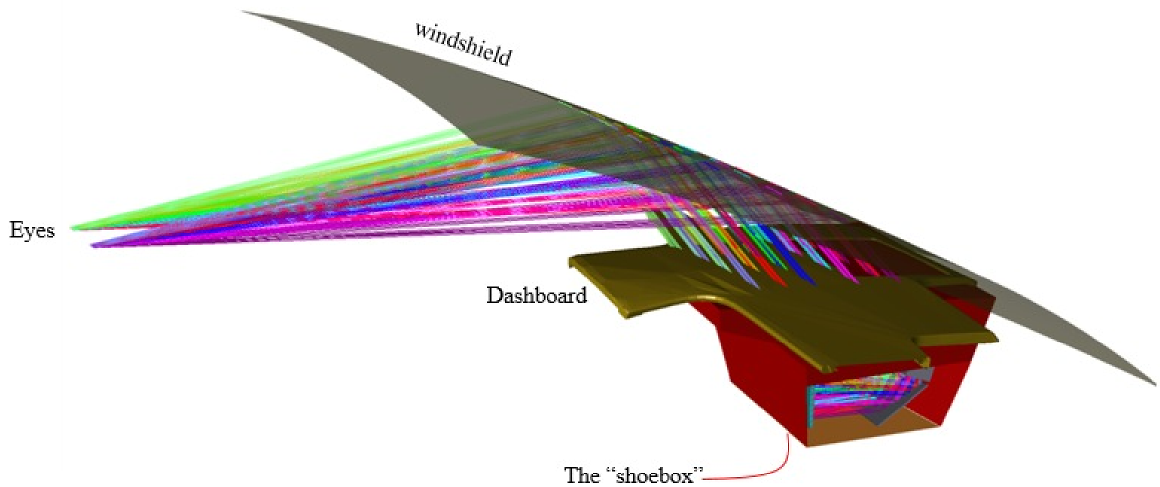

Fig. 2. Overall view of the volumetric projector.

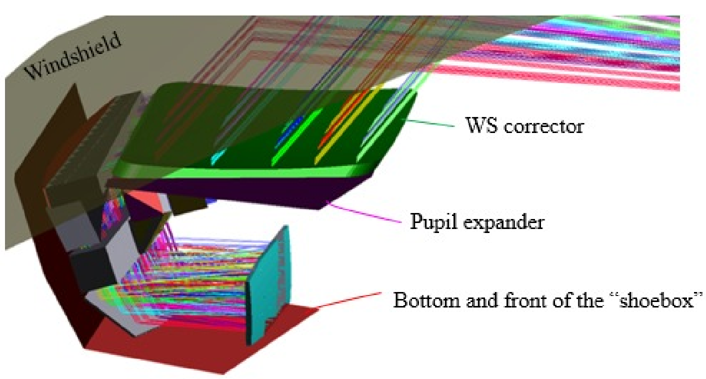

Fig. 3: Closer view of the pupil expander and the windshield corrector

3. OPTICAL CAD SETUP

Modeling of expanded pupil systems is a challenge. It can, of course, be done on a purely non-sequential model but then the optimization process may not be as effective or fast as compared with the sequential optimizations. For this project, the Zemax program was used in its three main modes: sequential, non-sequential and hybrid.

The optimization of the folded and sliced diffuser-to-eye system without the windshield, pupil expander and the pre-diffuser optics was done within the sequential mode, where fields were used for the x-direction only with the stop at the eyebox. The y-direction field was modeled using multi configurations with the 8-mm stop effectively at location of the pupil expander at the dashboard, about a meter away from the eyebox.

The pupil expander was modeled separately using the non-sequential mode, as was the illumination system used in the DLP projector (discussed later).

To put the total system together the Zemax hybrid mode was used with three non-sequential groups (with ports):

1. The windshield, the dashboard and the allocated "shoebox" under the dashboard supplied by the car companies and imported as STP files.
2. The pupil expander
3. The illumination optics of the DLP image generator.

4. CRITICAL COMPONENTS

4.1 The pupil expander

The pupil expander is shown in Fig. 3 positioned under the windshield corrector. It expands the pupil in the **y**-direction only. In the **x**-direction, the system is biocular and preserves the convergence angles of the volumetric image being projected. Fig. 4 shows the expander in more detail, using the Zemax non-sequential model. The entrance to the expander on the left is 240 mm by 8 mm. The narrowed dimension in the **y**-direction allows for multiple **y** foldings of the projector so it can be placed within the "shoebox."

The pupil expander, unlike for example the Amitai[4] expander, or the Microsoft HoloLens expander, is not a light guide or a waveguide. This is possible since the required Y-field is 9 degrees, and the 6.8 degrees wedge of glass shown can easily contain such a field. Forty-eight slabs of S-LAM2 glass are used, each coated on both sides. The reflectivity of each glass/cement/glass group is about 1%.

An important feature of the expander is that the output light needs to be slanted, since the positions of the driver, the windshield and the dashboard are all pre-determined.

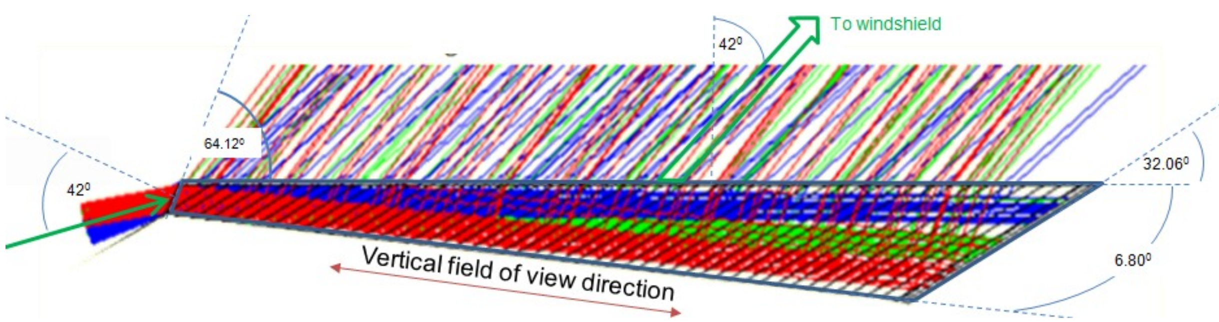

Fig. 4: Non-sequential cross-section of the pupil expander. Beams are color coded for three vertical field angles.

4.2 The windshield corrector.

Fig. 3 shows the windshield positioned just below and parallel to the dashboard. It is a PMMA element with a freeform top surface, an aspheric with 14 xy terms, and a plano bottom with maximum thickness of 15 mm. The corrector is designed for a particular windshield. Different vehicle models will each have its own corrector. The asymmetry of the windshield has a strong effect on the convergence angle. The two eyes look at two locations on the windshield with different reflective power. Initially there was a concern whether correction is even possible with an element that is not colocated with the windshield. However, despite the separation, the corrector does bring down the convergence error of the windshield to about 1' of an arc. In optimizing the corrector, the Zemax biocular operand (BIOC) is used in a setup consisting only of the corrector, the windshield, and an ideal projector in the hybrid mode with two-configurations setup for the two eyes. Making the 240 x 200 mm corrector prototype turned out to be a challenge, but one was eventually procured for less than $10,000.

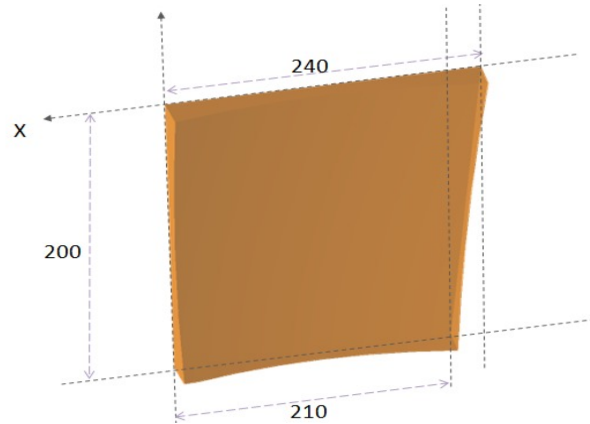

Fig. 5: The windshield corrector. Dimensions shown are in mm.

4.3 The diffuser to expander optics with multiple polarization folding.

Fig. 1 of the original Grabowski design uses refractive components. There are two groups of elements: one with large elements at the dashboard, and the other a smaller relay group. These groups are replaced in this new design by two mangin mirrors – primary and relay – as shown on Fig.6, and on another view on Fig.7. Polarization means – three polarizing beam splitters (PBS) and five retarders – are used to fold the light path three times on itself. In addition to shortening the total track, the polarization folding maintains the system symmetry about its optical axis for minimizing off-axis aberrations.

The light path on Fig. 6 and 7 is shown for the two eyes as follows (for a number of vertical field points and on-axis horizontally): A DLP projector, (not shown but placed inside the "shoebox") projects an image on the diffuser that moves back and forth along the axis by about 2 mms. An objective is placed following the diffuser. The diffuser is at a telecentric space on both the illumination and the objective sides. The S-polarized image light is reflected by the large right-angle prism shown behind the image diffuser into the PBS relay, and up to the relay mangin mirror. A retarder (not shown) sandwiched between the mangin mirror and the PBS changes the polarization, and the P-light goes though the Relay mangin into the y-fold prism.

A half-wave plate (not shown) changes the polarization to S polarization so the light is reflected by the Center PBS, towards the Cylinder Mirror, and back to the Center PBS. After a change of polarization, the P-light goes through the Center PBS and the Plano-toroidal lens. A half-wave plate again (not shown) rotates the P-light into S-light that is reflected by the Primary PBS into the Primary mangin mirror, changes polarization and goes through the wedge prism. The wedge prism is there to tilt the whole system by a few degrees about the vertical axis for a better fit in the assigned shoebox. At that point, the light enters the pupil at a slanted nominal angle of 42^0 off normal into the expander.

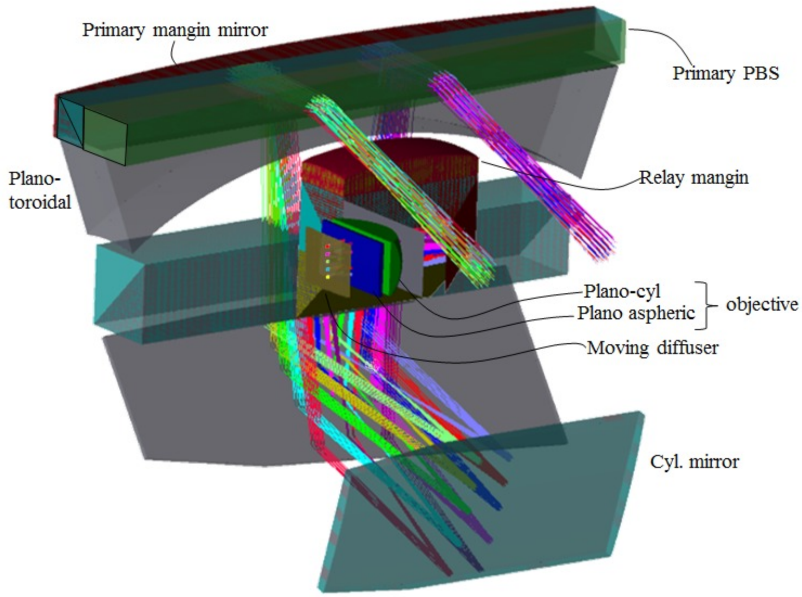

Fig. 6: Polarization folding

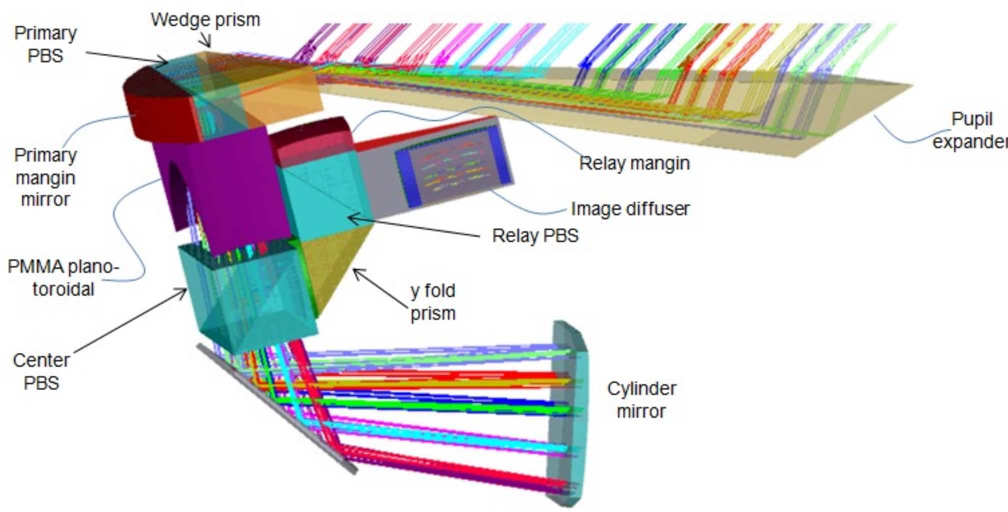

Fig. 7: polarization folding, another view.

4.4 The DLP image generator.

The image on the moving diffuser is generated by a DLP projector shown in Fig. 8.

The device used is an XGA DMD, .7" diagonal. For compactness, this system is also polarization-folded with a PBS shown and a retarder (not shown). The deviation prism is needed to squeeze the projector into the "shoebox". Since the diffuser must be moving, the challenge is to maintain the projected image at focus on the diffuser. This is done by moving the barrel containing the diffuser and two lenses, and having collimated space preceding the barrel as shown.

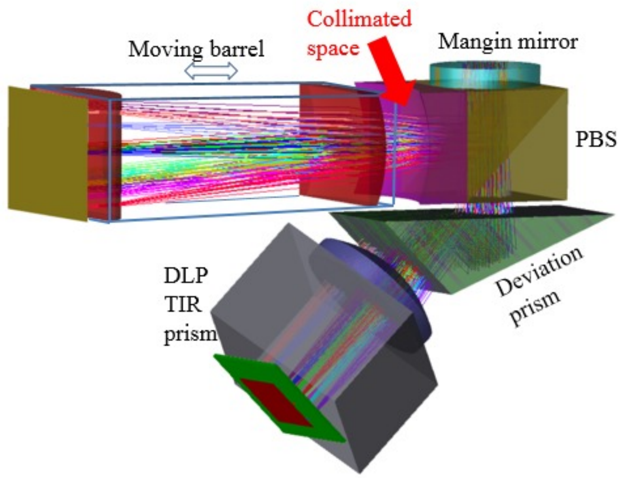

Fig. 8: The DLP projector subsystem for generating the image on the oscillating diffuser.

4.5 The DLP illumination system.

The DLP illumination system is shown on Fig. 9. The system uses a low-coherence RGB laser as a source. The lasers are coupled to a fiber optic, 400 μ in diameter and 0.22 NA. Two prisms are used to for polarization conversion. Polarization control is needed because the DLP projector in Fig. 8 is polarization-folded to reduce its size.

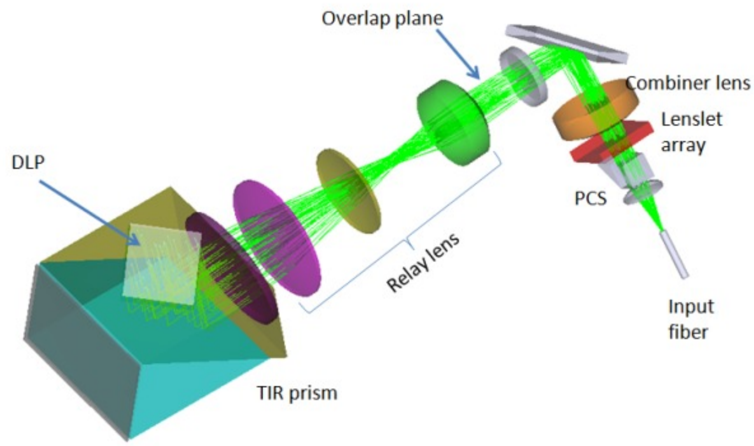

Fig. 9: The DLP illumination system comprised of a fiber collimator, a polarization conversion system (PCS) and a lenslet uniformizer.

5. PROTOYPE

A CAD view of the whole system design, including mechanics and electronics, is shown on Fig. 10 from the input fiber to windshield corrector. It is highly compacted to fill within a relatively small volume provided under the dashboard. The size reference in Fig. 10 is the pupil corrector that was shown in Fig. 5.

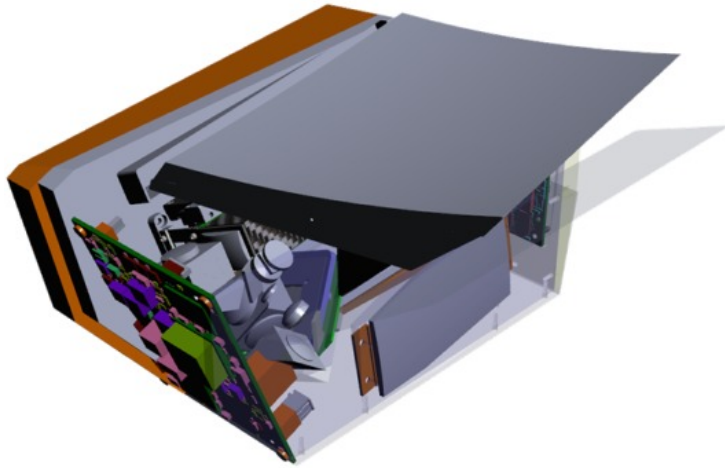

Fig. 10: An electro-optical-mechanical CAD view of the system.

6. PERFORMANCE

The design goals were achieved in terms of performance and fit into the "shoebox". A prototype was built at large expense; however, the performance predicted by the CAD models was not fully achieved at the time of delivery in terms of brightness and the presence of artifacts. The time pressure by the automobile company was such that some important breadboarding of the subsystems, and acceptance tests for the components may have been compromised.

ACKNOWLEDGMENTS

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