Rear-view virtual image displays

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Abstract: *Light Blue Optics' holographic laser projection technology can be utilised to create a virtual image display which, with a volume enclosing less than 700cc, exhibits a form-factor consistent with integration into a rear-view mirror. By combining the visual accommodation and concomitant reaction time benefits of a head-up display with the ability to present high resolution safety-critical information in a rear-view off-axis configuration with large eyebox, significant potential safety benefits can result.*

1 Introduction

In 2003, Najm et al. [1] determined that lane change and merge crash types accounted for 9% of all light vehicle crashes; a subsequent US Department of Transportation study found that this equated to some 630,000 collisions every year [2].

In an attempt to mitigate the lane change collision threat, a number of manufacturers have developed blind-spot warning (BSW) systems. Such systems typically employ ultrasonic, laser or radar sensing technologies to detect the presence of an object in the vicinity of the car and, since the relative speed of lane change/merge collisions is relatively low, the sensors tend to be short range. This restriction to warning of blind-spot occupancy limit the utility of such systems somewhat; other systems which exploit detection of the turn signal in order to reduce the probability of false alarm [3] are compromised by the surprisingly high average failure rate of turn signal usage prior to a lane change [2].

According to Mazzae et. al. [4], there are a number of desirable features that determine the ultimate utility of BSW systems. Of particular interest are those which provide a visual display located on or near the line of sight of the appropriate side-view mirror, as auditory stimuli would tend to interfere with those already reserved for the turn signal (for example.) Some commercially available systems, such as Iteris' AutoVue [5], already provide this functionality.

A 1997 study took this concept to its ultimate conclusion in suggesting that the integration of a visual display system into either rear-view mirror [6] would promote mirror check behaviour that could potentially reduce lane change accidents. However, as has previously been shown [7], the necessity to re-accommodate focus when transitioning between the outside world and instrumentation displays, and the amount of visual scanning required to absorb this information, imposes a significant time penalty on the driver's ability to recognise and act on such information. For these reasons, it seems that integrating a conventional display into a rear-view mirror would negate any potential BSW safety benefits.

To reconcile the conflicting requirements of presenting blind-spot information with accordingly minimal visual re-accommodation time, the authors propose the integration of a virtual image display into either the side or front rear-view mirror. Virtual images are typically presented at an apparent distance of greater than 2 m from the viewer's eyes, reducing the need to re-accommodate focus when transitioning between cluster imagery and the outside world. This presentation of imagery within the visual accommodation of the driver enables recognition and action upon information far more quickly than would be possible using the equivalent head-down configuration. The overall benefit time, which has been estimated at 777 ms (corresponding to a distance of 21.6 m whilst driving at a speed of 100 km/h) clearly indicates the safety benefits of projecting a virtual image within the visual field of the driver. Not only would this proposed scheme offer a significant benefit in reducing blind spot-related accidents, it also gives designers the opportunity to redundantly present blind spot warning visual data on both the head-up display (HUD) and rear-view mirrors, ensuring the driver has access to safety-critical information.

Until now, both the size [8] and inefficiency [9] of LED/TFT-based HUD solutions has precluded the use of such a solution. Light Blue Optics (LBO) has been developing laser-based virtual image displays that have the potential to be significantly smaller than current HUD designs and, additionally, are capable of displaying high brightness symbology at high resolution and in full-colour. In this paper, the authors present a virtual image display architecture consisting of LBO's holographic laser projector and a novel projection element which forms a full-colour virtual image in a package size and form-factor consistent with the integration of a virtual image display into a rear-view mirror.

2 Holographic Laser Projection Technology

LBO's holographic laser projection engine takes a unique approach to the formation of video images by exploiting the physical process of two-dimensional diffraction. A typical imaging projection system works by displaying the desired image F_{xy} on a microdisplay, which is usually sequentially illuminated by red, green and blue light to form colour. In this case, the microdisplay simply acts to selectively block (or amplitude modulate) the incident light; after passing through some magnification optics, the projected image F_{xy} appears. Conversely, holographic laser projection forms the image F_{xy} by illuminating a diffraction (or hologram) pattern h_{uv} by laser light of wavelength λ. If the hologram pattern is represented by a display element with pixel size Δ then the image F_{xy} formed in the focal plane of the lens is related to the pixellated hologram pattern h_{uv} by the discrete Fourier transform $F\,[\cdot]$, and is written as

$$F_{xy} = F\left[h_{uv}\right] \tag{1}$$

as shown in Figure 1 below.

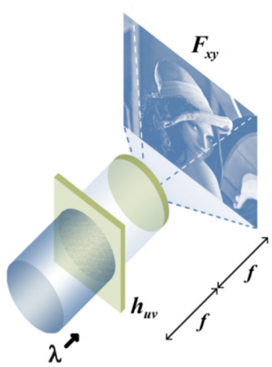


Figure 1 – The relationship between hologram h_{uv} and image F_{xy} present at the back focal plane of a lens of focal length f, illuminated by coherent monochromatic light of wavelength λ.

The crucial efficiency advantage of LBO's system occurs because the hologram h_{uv} is quantised to a set of phase only values φ_{uv}, where $h_{uv} = \exp j\varphi_{uv}$, so that the incident light is steered into the desired image pixels – without blocking – by the process of coherent interference, and the resultant instantaneous projected image appears as a direct consequence of Fourier optics. To achieve video-rate holographic display, a dynamically-addressable display element is required to display the hologram patterns; LBO's system uses a ferroelectric liquid crystal on silicon (LCOS) microdisplay.

To achieve high image quality, a fast microdisplay is used to display N holograms per video frame within the 40 ms temporal bandwidth of the eye, each of which produces an image F_{xy} exhibiting quantisation noise [10]. If the intensity of the i^{th} displayed image is $I_{xy} = \left|F_{xy}^{(i)}\right|^2$ then the time-averaged percept over N subframes is

$$V_{xy} = \frac{1}{N}\sum_{i=1}^{N}\left|F_{xy}^{(i)}\right|^2 \tag{2}$$

which is noise-free, as illustrated in Figure 2.

$$h_{uv} = \exp j\varphi_{uv} \qquad I_{xy} = \left|F_{xy}^{(i)}\right|^2 \qquad V_{xy} = \frac{1}{N}\sum_{i=1}^{N}\left|F_{xy}^{(i)}\right|^2$$

Figure 2 - The relationship between hologram h_{uv}, subframe F_{xy} and frame V_{xy} in LBO's holographic projection technology.

LBO has developed and patented proprietary algorithms for the purposes of calculating sets of N holograms h_{uv} from the desired image F_{xy} both efficiently and in real time, as first demonstrated in 2004 [11]. Crucially, such algorithms can be efficiently implemented in a custom silicon chip.

A practical realisation is shown in the schematic of Figure 3. A desired image is converted into sets of holograms by LBO's proprietary algorithms and displayed on a phase-modulating microdisplay which is time-sequentially illuminated by red, green and blue laser light. The subsequent diffraction patterns pass through a demagnification lens pair L_1 and L_2, which are chosen to provide a projection angle of 90°. Due to the nature of Fraunhofer diffraction, the image remains in focus at all distances from the lens L_2.

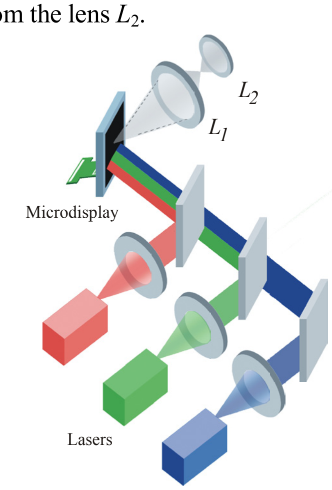


Figure 3 - A schematic diagram of LBO's holographic laser projection technology illustrating lasers, phase-modulating microdisplay and demagnification lens pair L_1, L_2.

3 Rear-view virtual image display using holographic laser projector

As has previously been shown, LBO's laser-based phase-modulating holographic projection display has a number of features and benefits that are uniquely suited for use as light engines in vehicular applications and particularly for virtual image displays [12].

Of principal concern in an automotive virtual image display is obtaining an acceptable image brightness level of 5,000 cd/m^2 (typically requiring an image source luminance of 25,000 cd/m^2) [13] when displaying sparse imagery. Due to the blocking nature of conventional HUDs employing amplitude modulating TFT panels, large arrays of LEDs [14, 15] must be employed as a backlight to provide the required image source luminance. The use of a phase-modulating projection technology, however, provides a highly power-efficient method of projection since, unlike such imaging displays, no light is blocked in the system. This property becomes especially advantageous when displaying symbology and night-vision imagery, which have average pixel intensities of less than 10% and 25% respectively [16], allowing brightness targets to be met using just three small laser sources. Furthermore, since laser sources can provide wide color gamut images due to their narrow spectral bandwidth, the Helmoltz-Kohlrausch effect [17] can further increase perceived brightness due to the psychophysical effects of highly saturated primaries.

For safety critical applications such as a virtual image displays in which blind spot information is to be presented, it is critical to maintain reliable operation despite potential pixel failures. Due to the diffractive nature of the technology, LBO's system does not exhibit a one-to-one correspondence between microdisplay pixels and projected image pixels, as imaging systems do. In fact, each pixel on the microdisplay contributes to every pixel in the image, so that faulty display element pixels do not correspond to 'dead' image pixels. This allows the realisation of a truly fault-tolerant display with built-in redundancy, since multiple microdisplay pixel failures can be tolerated without compromising the integrity of the displayed data.

Despite the commonalities in terms of light engine performance and functionality, the virtual image display requirements for a rear-view display as described previously differ markedly from a conventional HUD, principally because the image must be viewed off-axis. In common with HUDs, however, the eyebox must be large enough to allow free head movement by the driver and the light must be directed accurately in the direction of the driver to preserve the optical efficiency of the display.

The approximate geometry is shown in Figure 4, in which the eyebox (1) is located at approximately driver head-height and the virtual image (3) in this particular case appears to come from greater than two metres behind the position of the rear-view mirror (2). In this way, the driver is able to view the image without re-accommodating focus or becoming distracted. Realising such a geometry represents a challenging design task which cannot easily be satisfied by conventional HUD optical subsystems.

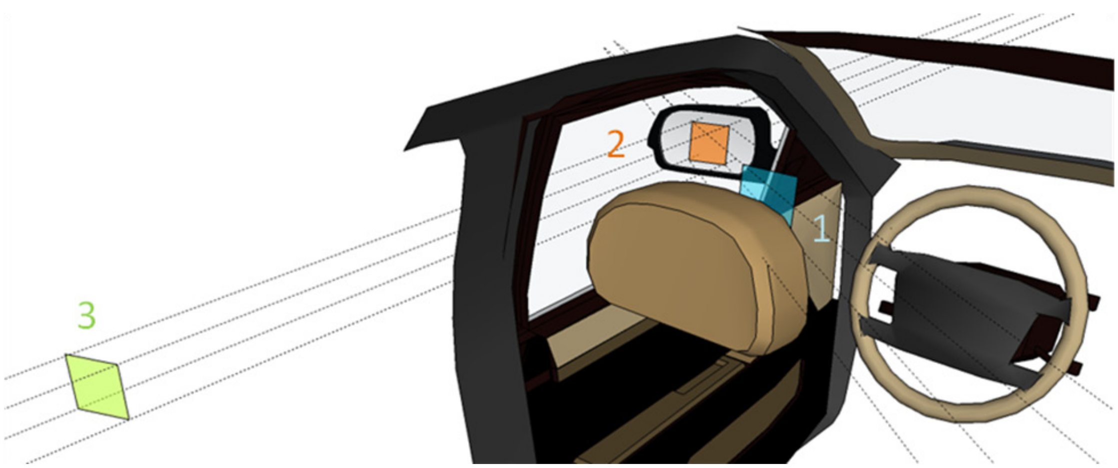
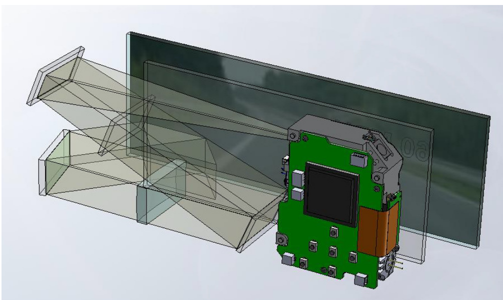
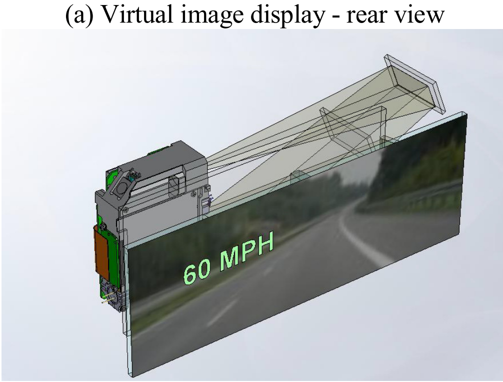


Figure 4 – Image viewing geometry for a rear-view virtual image display, showing the eye-box (1), rear-view mirror surface (2) and apparent virtual image position (3). The image display geometry allows the display of a virtual image within the visual accommodation of the driver whilst providing a large enough eyebox to allow realistic head movement.

The requirements were achieved in the context of a rear-view virtual image display by combining LBO's miniature light engine and a novel eyebox expansion optic, the last element of which forms the surface of the rear-view mirror. In such a configuration, LBO's projection engine is imaged onto the surface of a diffusing screen and the resultant image is transferred via some fold optics to the rear of the pupil expansion optic as shown in
Figure 5(a). Since the pupil expander is semi-transparent, the virtual image appears on the front surface as shown in Figure 5(b).



(a) Virtual image display - rear view



(b) Virtual image display - front view

Figure 5 – Front (a) and rear (b) views of the LBO projection engine, optical path (including diffusing screen and fold optics) and pupil expander.

The concept presented in Figure 5 confers several advantages. First, the total volume enclosed by this initial mechanical design, including the diffusing screen, fold optics, pupil expander, 30cc light engine and electronics (including hologram computation, video interface and laser drive circuitry) is less than 700 cc. As a result, the entire assembly is comfortably small enough to integrate into a rear-view mirror as shown in Figure 6, and with aggressive design optimisation a target volume of 500 cc should be achievable. In addition, the rear-projection configuration provides the off-axis virtual image formation of Figure 4 and presents a reduced sensitivity to solar loading compared to conventional HUDs since the imager cannot be directly exposed to external lighting. Finally, it should be noted that the rear-view virtual image display is invisible when not operating - which is desirable given the increasing attention of designers to the human-machine interface (HMI) [18] – and the off-axis viewing configuration minimises light pollution and hence the potential for distracting other drivers.

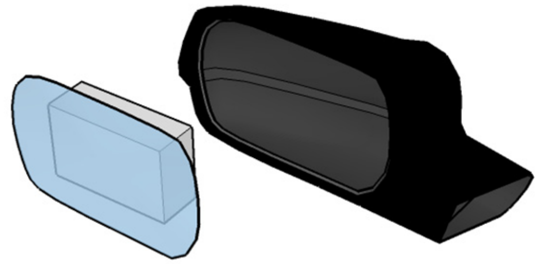


Figure 6 – Integration of LBO's virtual image display into a rear-view mirror. Note that the final surface of the pupil expansion optic is itself the rear-view mirror surface.

4 Initial performance evaluation

Some preliminary results for the virtual image display are presented in Table 1 below; the average pixel intensity in the virtual image was approximately 10%.

Parameter	**Value**
Total volume (cc)	< 700
Eyebox size (mm)	190 × 60
Field of view (deg)	8 × 3.5
Virtual image distance (m)	>2
Virtual image brightness (cd/m^2)	~6,000
Virtual image resolution	850 × 480

Table 1 – Specifications for prototype rear-view mirror virtual image display system.

An example image, captured in daylight, is shown in Figure 7 below; the high brightness and wide colour gamut due to the use of the LBO light engine are both evident.

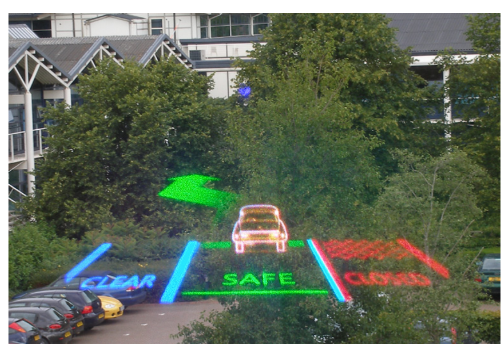


Figure 7 - Sample image demonstrating the performance of LBO's full-colour rear-view virtual image display.

5 Conclusion

The authors have demonstrated that LBO's holographic laser projection technology can be utilised to create a virtual image display in a form-factor consistent with integration into a rear-view mirror. In realising such a display, the visual accommodation and reaction time benefits of a HUD are combined with the ability to present high resolution safety-critical information in a rear-view off-axis configuration with a large eyebox.

The authors have demonstrated that significant potential safety benefits could result from reconciling the conflicting requirements of presenting blind-spot information with accordingly minimal visual re-accommodation time. Not only would this proposed scheme offer a significant benefit in reducing blind spot-related accidents, it also gives designers the opportunity to redundantly present blind spot warning visual data on HUDs and rear-view mirrors, ensuring the driver has access to safety-critical information.

6 References

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