Full colour holographic laser projector HUD

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Abstract: *Light Blue Optics' holographic laser projection technology is uniquely suited as a light engine for automotive head-up display (HUD) applications, providing high brightness images with low speckle contrast and wide colour gamut whilst being robust and fault-tolerant. This paper describes the operation of the technology and its advantages, demonstrating – for the first time – the operation of a full-colour, laser-based automotive HUD which is capable of displaying both symbology and night vision virtual imagery. The ability of the projector to correct for distortion introduced by the windshield curvature is demonstrated, showing significant progress towards a 'one-size-fits-all' HUD.*

1 Introduction

Automotive head-up displays (HUDs) are used to extend the display of data from the instrument cluster to the windshield area by presenting a virtual image to the driver. Such virtual images are typically presented at an apparent distance of between 2m and 2.5m from the viewer's eyes, thereby reducing the need to re-accommodate focus when transitioning between cluster imagery and the outside world. This method of presenting data also reduces the amount of visual scanning necessary to view the instrumentation symbology, and potentially enables the display of imagery which is conformal with the outside world - as demonstrated by contact-analog HUDs [1], for example.

Virtual image displays offer numerous human-machine interface (HMI) advantages, notably in terms of driver safety, since the 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. A succinct demonstration of this advantage was provided by Kiefer and Gellatly [2, 3], who compared the response times of a driver when presented with information in both head-up and head-down configurations. This research resulted in the definition of a 'HUD benefit time window', illustrated in Figure 1, which starts when the eyes would have arrived at a conventional head-down display (HDD) speedometer and ends when the eyes would have returned to the road after reading the HDD.

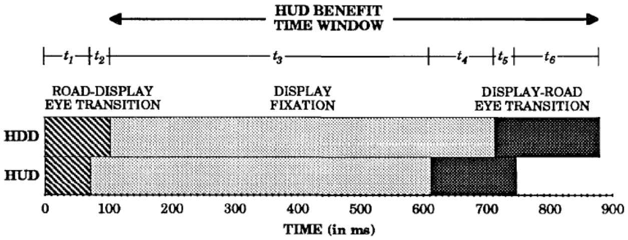


Figure 1 - The HUD benefit time window and the roadway-display transition time, display fixation time, and display-road transition time for HDD and HUD digital speedometer configurations (after Kiefer and Gellatly [2].)

The overall HUD benefit time of 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.

Light Blue Optics (LBO) has developed a novel laser-based HUD, which allows the display of full colour virtual images at a distance of 2.1m from the driver's eyes. The use of LBO's proprietary phase-modulating holographic projection technology as the light engine in the HUD provides several advantages since, unlike other commercially-available projection technologies, the projection engine exploits the physical process of two-dimensional diffraction to form video images.

The advantages of a HUD using LBO's projection technology as a light source have previously been discussed [4]. Principally, the use of laser light sources in LBO's projection system allows the formation of very saturated, extremely high brightness symbology and night-vision images with high efficiency and concomitantly low power consumption. The projected images have a high contrast, which is particularly important for automotive HUDs, and it has previously been shown [5] that laser speckle can be significantly suppressed in the projected image. Finally, the projection technology is robust and fault-tolerant [6], as required for safety-critical information displays.

In this paper the authors will demonstrate the operation of, and experimental results obtained from, LBO's full-colour laser HUD.

2 Holographic Laser Projection Technology

LBO's technology represents a revolutionary approach to the projection and display of information. Unlike other commercially-available projection technologies, LBO's projection engine exploits the physical process of two-dimensional diffraction to form video images.

A typical imaging projection system works by displaying a 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 $F\left[\cdot\right]$, and is written as

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

as shown in Figure 2 below.

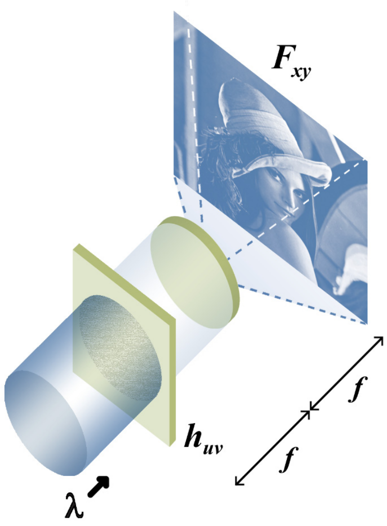


Figure 2 – The relationship between hologram h_{uv} and image F_{xy} present at the back focal plane of a lens of focal length f, when illuminated by coherent monochromatic light of wavelength λ.

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 custom-manufactured ferroelectric liquid crystal on silicon (LCOS) microdisplay manufactured by Displaytech, Inc.

To achieve high image quality a fast microdisplay is used to display N holograms per video frame within the 40ms temporal bandwidth of the eye, each of which produces an image F_{xy} exhibiting quantisation noise [5]. If the intensity of the i^{th} displayed image is $I = \left|F_{xy}^{(i)}\right|^2$ 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 3.

Hologram Video Subframe Video Frame

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

Figure 3 – The relationship between hologram h_{uv}, subframe F_{xy} and frame V_{xy} in LBO's holographic projection technology.

Uniquely, the key to holographic laser projection technology lies not in the optical design but in the algorithms used to calculate the hologram patterns h_{uv} from the desired image F_{xy}. LBO has developed and patented proprietary algorithms for the purposes of calculating N sets of holograms both efficiently and in real time, as first demonstrated in 2004 [7]. Crucially, such algorithms can be efficiently implemented in a custom silicon chip.

A practical realisation is rather simple and is shown in the schematic of Figure 4. 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 respectively. The subsequent diffraction pattern passes through a demagnification lens pair L_1 and L_2, which can be chosen to provide ultra-wide projection angles in excess of 100°. Due to the nature of Fraunhofer diffraction, the image remains in focus at all distances from the lens L_2.

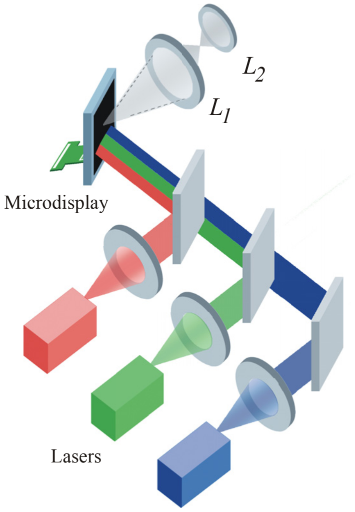


Figure 4 – A schematic diagram of LBO's holographic laser projection technology illustrating lasers, microdisplay and demagnification lens pair L_1, L_2.

3 Advantages of a holographic laser projector HUD

There are several exacting requirements imposed upon the light engine by automotive HUD applications. In addition to the high brightness and contrast ratios required for HUD imagery [8], the entire projection subsystem must be robust, fault-tolerant and optically efficient whilst maintaining wide operating and storage temperature ranges. To the authors' knowledge, only LBO's system is able to achieve these requirements whilst simultaneously providing efficient display of bright symbology and night vision imagery, with low speckle contrast. A number of these important advantages are described in more detail below.

3.1 Low speckle contrast

One of the advantages of LBO's technology is the ability to substantially reduce laser speckle, a phenomenon which makes the image 'sparkle' due to scattering of coherent light from an optically rough projection and subsequent interference at the retina. The ability to reduce speckle is important since, not only do users find the artefact very unpleasant, it also severely impacts the perceived image quality and effective resolution. Furthermore, the distracting nature of laser speckle is unacceptable in safety-critical applications such as automotive HUDs.

It is, however, possible to substantially reduce the speckle contrast by employing a combination of methods within the optical subsystem of a holographic laser projector [5]. This represents a significant advantage over laser-based scanned-beam systems, which exhibit unacceptably high speckle contrast ratios [9-11] that can only be reduced by the use of expensive custom projection screens [12].

3.2 High brightness and efficiency

It has previously been shown [13] that, due to the phase-modulating approach to image formation, a holographic projector can display significantly brighter sparse images - with far greater dynamic range - than imaging and scanned-beam systems. This is a huge advantage when displaying symbology and night-vision imagery, which have average pixel intensities of approximately 10% and 25% respectively. This allows brightness targets to be met using just three small laser sources, rather than the conventional large array of LEDs [14-16]. In addition, laser sources can provide images with extremely wide colour gamuts, due to their narrow spectral bandwidth. The Helmoltz-Kohlrausch effect can further increase perceived brightness due to the psychophysical effects of highly saturated primaries.

The use of laser sources and a phase-modulating hologram provides a highly power-efficient method of projection since, unlike imaging displays, no light is blocked in the system. In addition, the phase-modulating nature of the projector means that it is not necessary to continuously illuminate the microdisplay; the lasers are modulated in accordance with the frame brightness, thereby only utilising the power required to illuminate "on" pixels.

3.3 Robustness and fault tolerance

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.

3.4 Variable resolution

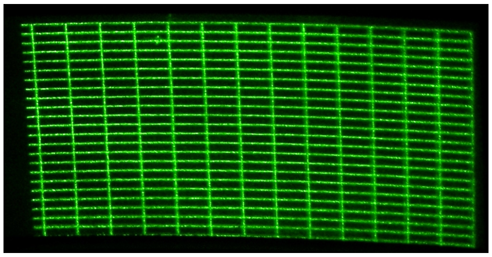
Since LBO's projection technology is based on diffraction, the resolution of the projected image is decoupled from that of the microdisplay. This is very different from an imaging system – in which field breakdown, diffractive effects and étendue matching considerations set the minimum pixel size of the display element [17] – and scanned-beam systems, where resolution is principally limited by the achievable laser modulation frequency.

In LBO's system, the resolution is largely controlled by the hologram computation and is fully variable up to a maximum of WVGA using a 7mm × 7mm active area microdisplay. This property is attractive for HUD applications, since the same device may be required to display both low resolution symbology and high resolution night-vision imagery.

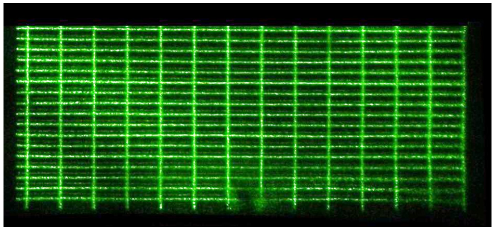
4 Holographic laser projector HUD results

An automotive HUD was constructed using LBO's holographic projector as the light engine and an additional optical subsystem to provide a virtual image capability. The HUD optics were designed to give a magnification factor of 4.5, producing a virtual image at 2.1m with a 5° × 2.5° field of view and corresponding eyebox dimensions of approximately 130mm × 70mm.

The curvature of the windshield introduced significant distortion into the virtual image, as shown in the captured image of Figure 5(a), which was measured and subsequently corrected for by the projector. Figure 5(b) demonstrates the efficacy of the distortion correction; the intensity variations are the result of a coating on the surface of the HUD glare trap that was incorrectly matched to the laser wavelength. The ability to correct for distortion clearly demonstrates the potential of the LBO projector to enable a "one-size-fits-all" HUD – that is, a HUD which can correct for changes in windshield geometries by software updates, rather than optical modification [18, 19]. This property has the potential to enable significant cost and time savings in HUD manufacture and installation.



(a) Grid pattern virtual image. The distortion is caused by the curvature of the windshield.



(b) Grid pattern virtual image, with distortion removed by appropriate correction performed by LBO's holographic projector.

Figure 5 – Correction of distortion caused by the windshield curvature (a), corrected by the holographic laser projector used as the light source (b).

Several test images were generated to demonstrate the capabilities of the holographic laser HUD. The first, a low resolution symbology-type image, demonstrates the highly saturated primaries typical of laser projection systems. The virtual image captured from the HUD is shown in Figure 6 below.

Figure 6 – Example symbology-type imagery formed using LBO's holographic laser HUD.

An interesting feature of the HUD symbology of Figure 6, which is particularly attractive for safety-critical applications, is the apparent lack of pixellation. This artefact has previously been found to be problematic in flat panel and scanned-beam displays [20], since it results in jagged edges which viewers find disturbing. This problem is substantially reduced in LBO's HUD due to the non-pixellated, diffractive nature of the light engine.

Figure 7 shows the same virtual image but captured in daylight, demonstrating the ability of LBO's projection technology to produce the high brightness symbology images required for daytime driving.

Figure 7 – Example symbology-type imagery formed using LBO's holographic laser HUD, captured in daylight.

The variable resolution capability of LBO's holographic projector also allows the display of high resolution night-vision imagery. A sample night-vision image captured from the HUD is reproduced in Figure 8; in this case, the resolution is WVGA.

Figure 8 – Example of night vision [21] virtual image at WVGA resolution formed using LBO's holographic laser HUD.

5 Conclusion

Light Blue Optics' technology represents a revolutionary approach to the projection and display of information, with attributes that are uniquely suited to vehicular displays applications. In particular, it has been shown that LBO's holographic laser projection technology is uniquely suited to automotive HUD applications, providing high brightness images with low speckle contrast using a projection technology that is robust and fault-tolerant.

A full-colour, laser-based HUD with the capability of displaying low resolution symbology and high resolution night-vision imagery was demonstrated. The ability to correct for distortion caused by the windshield curvature was shown, demonstrating significant progress towards a 'one-size-fits-all' HUD.

6 References

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