14.4: Novel Human-Machine Interface (HMI) Design Enabled by Holographic Laser Projection

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Abstract
Despite the current proliferation of in-car flat panel displays, designers continue to investigate alternatives to flat and rectangular thin-film transistor (TFT) panels - principally to obtain differentiation by freedom of design using, for example, free-form shapes, round displays, flexible displays or mechanical 3D solutions. A perfect demonstration was provided at the 2008 Paris Motor Show by the BMW Mini Center Globe, a novel instrument cluster design which combines lighting, a circular flat panel and a holographic laser projector provided by Light Blue Optics (LBO) to redefine the state of the art in human-machine interface (HMI).

In this paper, the authors will show how the incorporation of LBO’s holographic laser projection technology can allow the construction of a unique display technology like the Mini Center Globe, and how such a combination of technologies represents a significant advance in the current state of the art in automotive displays.

1. Introduction
In the last decade, thin-film transistor (TFT) panels have reigned supreme in automotive applications and a continued increase in volume sales of automotive TFT panels is expected in the next few years. The proliferation of such displays is driven both by the increased desire for more communication and entertainment functions and by the steep, and continued, price erosion in flat-panel display technologies. Indeed, the extent to which these twin market forces have influenced the human-machine interface (HMI) is aptly demonstrated by the availability of automotive-qualified TFT displays with diagonals in excess of 40” [1].

Despite the popularity of flat panel displays they are fundamentally limited as a design element since, by definition, they are flat, regular and opaque. This conflicts with the desire of the automotive industry for HMI differentiation by freedom of design using, for example, free-form shapes, round displays, flexible displays or mechanical 3D solutions. For this reason, an increasing number of car manufacturers are discussing and exploring free-programmable cluster concepts [2] employing large displays and hybrid solutions.

A perfect example of such a hybrid solution was provided by the BMW Mini Crossover concept car demonstrated at the 2008 Paris Motor Show. The instrument cluster design, termed the Mini Center Globe and shown in Figure 1, presented a completely revolutionary approach to transforming displays to real 3D components by combining TFT, laser projection and lighting technologies into a complete solution. It is the first time that a multi-disciplinary approach, combining the common development of display makers, lighting companies and laser projector manufacturers, has been employed in realising an automotive display.

Figure 1 - Artist’s rendition of the BMW Mini Center Globe instrument cluster, incorporating circular TFT, laser projection and lighting technologies.

In this paper, the authors will show how the incorporation of Light Blue Optics’ holographic laser projection technology provides unique features which can revolutionise the HMI, creating a new class of automotive display technologies and further increasing the in-car display density.

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 the desired image $F_{uv}$ 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 $F_{uv}$ appears. Conversely, holographic laser projection forms the image $F_{uv}$ by illuminating a diffraction (or hologram) pattern $h_{uv}$ by laser light of wavelength $\lambda$. If the hologram pattern is represented by a display element with pixel size $\Delta$ then the image $F_{uv}$ formed in the focal plane of the lens is related to the pixelated hologram pattern $h_{uv}$ by the discrete Fourier transform $F$ [ ], and is written as
as shown in Figure 2 below.

The crucial efficiency advantage of LBO’s system occurs because the hologram $h_{uv}$ is quantised to a set of phase only values $\phi_{uv}$, where $h_{uv} = \exp{j\phi_{uv}}$, 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 [3]. If the intensity of the $i^{th}$ displayed image is $I_{xy} = |F_{xy}^{(i)}|^2$, then the time-averaged percept over $N$ subframes is

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

which is noise-free, as illustrated in Figure 3.

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 sets of $N$ holograms both efficiently and in real time, as first demonstrated in 2004 [4]. 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 3 - The relationship between hologram $h_{uv}$, subframe $F_{xy}$ and frame $V_{xy}$ in LBO’s holographic projection technology.
**Long depth of field** - The combination of the diffractive nature of LBO’s technology and the use of laser light sources ensures that the projected image is always in focus, regardless of projection distance or projection surface geometry. This property, coupled with the ability to correct for distortion in the projected image [6], allows the projection of images of arbitrary non-plane geometries - thereby allowing the realisation of curved displays which cannot be achieved with current flat panel display technologies.

**Aberration correction** - Due to the diffractive nature of LBO’s technology, which by definition exerts accurate control over the optical wavefront, it is possible to correct for aberrations caused by the projector optics by appropriate modification of the hologram patterns. It is therefore possible to construct a projector using simple, cost effective optical elements and correct for any resultant aberration in software; in the same way, the optical subsystem can be designed with a far wider range of tolerances than would ordinarily be possible. Not only does this allow cost effective assembly, but it provides a degree of insensitivity to process tolerances which is crucially important when integrating optical subsystems into, for example, automotive instrument clusters. A demonstration of this powerful capability is provided in Figure 5 below. The laser spot shape of Figure 5(a), after propagation through the projector optics, demonstrates that significant aberration is present. As a result, the quality of the projected images (b) and (c) is severely impacted. Appropriate correction for the optical aberrations, however, results in a laser spot that is almost diffraction limited (d), leading to recovery of the image fidelity in (e) and (f).

![Figure 5](image.png)

**Wide throw angle** - The small field sizes incident upon the demagnification output optic of LBO’s diffractive projection system allows for the realisation of ultra-wide throw angles (>100 degrees). It is simply not possible to achieve such projection angles with scanned-beam or imaging systems. Imaging systems encounter both distortion and aberration due to challenging optical requirements at large field angles whilst in the case of scanned-beam systems, unacceptable pincushion distortion would result due to the fundamental MEMS action. This typically limits imaging and scanned-beam systems to projection angles of approximately 45° though, even then, some scanned-beam systems exhibit residual distortion. The wide-throw capability of LBO’s projector allows the construction of a very thin rear-projection display, which is particularly important for instrument cluster applications. The ability to provide a throw angle in excess of 100 degrees, coupled with the small opto-mechanical assembly size of ~25cc, allows LBO’s technology to overcome the fundamentally incompatible requirements of projecting a large image from a projector mounted in a shallow console.

**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.

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 [3]. This represents a significant advantage over laser-based scanned-beam systems, which exhibit unacceptably high speckle contrast ratios [7, 8, 9] that can only be reduced by the use of expensive custom projection screens [10].

**High brightness, wide colour gamut and high efficiency** - It has previously been shown [11] 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 video, which have average pixel intensities of approximately 10% and 25% respectively. This allows brightness targets to be met using just three small laser sources. In addition, laser sources can provide images with extremely wide colour gamuts, due to their narrow spectral bandwidth. The Helmholtz-Kohlrausch [12] 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. The correspondingly low laser modulation frequency also allows efficient digital modulation schemes to be used for each colour, in contrast to the high frequency, low efficiency, approach employed by scanned-beam systems.

**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.

4. **Novel projection geometries enabled by holographic laser projection**

One of the advantages of the LBO technology is the ability to realise novel projection geometries which, as previously discussed, is one of the key requirements for next-generation automotive instrument clusters. By combining the wide depth of field, wide throw angle, distortion correction and aberration correction capabilities of the projector it is possible to realise some truly unique projection geometries. Due to the phase-modulating nature of the light engine, the luminous flux of the projector remains unchanged despite the geometry correction. This is contrast to conventional imaging systems which will always block light due to the unused (cropped) pixels.

Figure 6 gives a succinct demonstration of these capabilities. In (a), LBO’s projection technology is demonstrated in wide-angle (90°), front-projection mode; the image diagonal is 13.5” and the horizontal distance from the projector aperture to the screen is approximately 6”. Using the same projector optics, however, it is possible to project in a table-down mode; by appropriate pre-distortion, shown in (b), the table down operation of (c) is obtained. The image has a diagonal of 9” and the vertical distance of the projector from the surface is approximately 3.5”.

![Figure 6](image-url)

**Figure 6** - The LBO projection technology can demonstrate truly novel projection geometries. Both front (a) and table-down projection geometries (c) can be achieved using the same projection optics.

The ability of LBO’s projection technology to form images with arbitrary geometry was also used in the BMW Mini Center Globe. As shown in Figure 7, virtually any non-plane projection geometry (b) can be achieved and, regardless of the configuration of the projection surface, the focus is maintained at all points of the output image as shown in (c).
14.4 / E. Buckley

Figure 7 - Projection onto arbitrary non-plane surfaces using LBO’s projection technology. Images (a) are appropriately processed to account for the projection geometry (b); the captured images at the output of the projector (c) demonstrate that, in all cases, the images are in focus.

The construction of the BMW Mini Center Globe is shown in Figure 8 below; the LBO projector is configured to project on the outside and inside of the spherical surface, above the round TFT display. The horizontally rotating hemisphere is therefore effectively used as a projection screen to enable the use of the third dimension. The image size can be varied by changing the distance between the projector and the spherical projection screen, without the need to refocus, allowing a greater degree of freedom to present driver and front-passerenger oriented information simultaneously. Using this arrangement, for example, the passenger can watch a movie or use web services whilst the driver receives all necessary navigation and other driving-related information from the same HMI display. Although dual-view TFT displays [13] have addressed similar use cases, they have the previously stated disadvantage of being limited to flat, rectangular form-factors.

5. Conclusion
The authors have demonstrated that current HMI limitations imposed by flat panel displays can be overcome by combining several novel display technologies. In particular, the advantages provided by LBO’s holographic laser projector allow the construction and integration of a curved instrument cluster display. By transforming displays to real 3D components, the BMW Mini Center Globe has redefined the state of the art in human-machine interaction and created a new class of automotive display.

6. References
Figure 9 – A photograph of the Mini Globe display concept in operation, showing images produced by LBO’s laser projector.