The Future of Holographic Head-Up Display

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***Abstract*—The use of Holographic or Diffractive optics is on the rise, premium DSLR optics using this technology is an outstanding example of compact device. This technology applied to head-up display (HUD) is presented, using the windshield as a transparent holographic display, with the ability to present floating graphical object in a large field of view. Augmented Reality display will be possible, increasing considerably the User Experience and situational awareness. Additionally, the use of Holographic Optical Element reduces the size, weight and cost of the actual HUD box.**

Head-up displays (HUDs) are now popular on premium cars, but the first application was on an aircraft cockpit. The ability to superimpose graphic symbology on landscape, without any parallax issues and vergence—accommodation conflict—improves the situational awareness of the pilot, so that HUD was indeed the first device to bring Augmented Reality in cockpit.

This value became a must have for the automotive market, but is raising a lot of technical challenges. As volume available under the glareshield is limited, a compromise needs to be found for some functional parameters like Field of View (FOV), Eye Motion Box (EMB), and display luminance. But, by using classical optics, these compromises strongly limit the user experience. In this paper, we present a novel architecture using Holographic Optical Elements. This technology removes the need for complex optics, while offering a large FOV and a large eye-box, for a better user experience.

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BACKGROUND

HUDs have, for the last decades, kept the same global architecture (Figure 1):

The Picture Generator Unit (PGU): An intermediate image from the object to be displayed is generated by an imager. Historically, Cathode Ray Tube (CRT) was used as an imager, but has mostly been replaced by Liquid Cristal Display (LCD). Today, in order to get a maximum amount

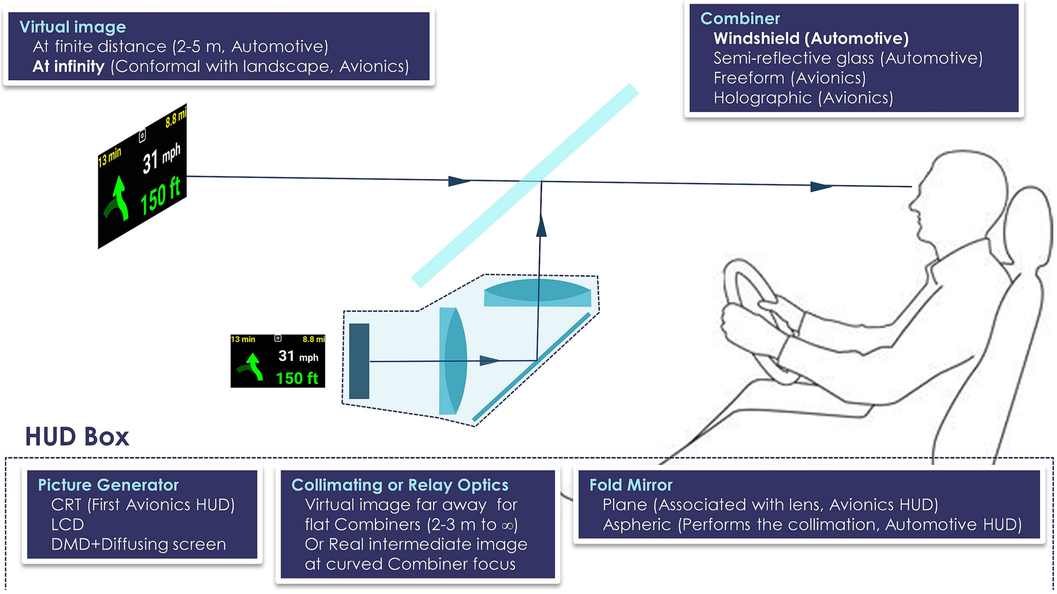

Figure 1. HUD architecture.

of luminance with a good efficiency, the current trend is to associate a Digital Micromirror Device (DMD) imager with a holographic diffuser.

The relay optics: The virtual image needs to be magnified (collimated) in order to present a virtual image at a finite distance (from 2–3 meter to infinite). The optical power is given by a set of refractive lenses, some with aspherical surfaces.

The fold mirror: In order to reduce the system length or comply with cockpit installation constraints, the optical path can be folded by at least one mirror. This mirror can be flat or with power to help with the collimation.

The combiner: The generated image is superimposed on the external landscape by a combiner, acting as a half-mirror (the reflective part is used for displaying the image). This function could be performed by the windshield (automotive), or with a dedicated combiner (free form optics with dielectric coating or holographic optical element). With such a combiner, the reflective function can be wavelength and/or angular selective, in order to reach a better efficiency.

HUD KEY PARAMETERS AND IMPACT

Three key parameters directly impact the HUD performances and its ability to perform augmented reality functions with a good user experience:

The FOV: A wide FOV is highly desirable for augmented reality to improve the immersion effect. With current architecture, the FOV is constrained by the volume available for the HUD box. In current automotive HUDs, with a strongly limited number or optically powered components, this limitation comes from the fact that the FOV is directly related to the size of the collimating optics and the fold mirror. The human eye can normally see a quite large FOV (60° above, 75° below, and up to 210° in horizontal if we consider both eyes).[1] However, not all of that can be apprehended by the visual system in the same manner. As depicted in Figure 2, what can really be perceived depends on the angle from the direction of gaze: vision becomes more limited when moving further from the fovea.

The EMB: The EMB can be defined as the volume of space from which the eyes can see the projected image (partially or entirely, depending on how it is defined). A wide EMB therefore

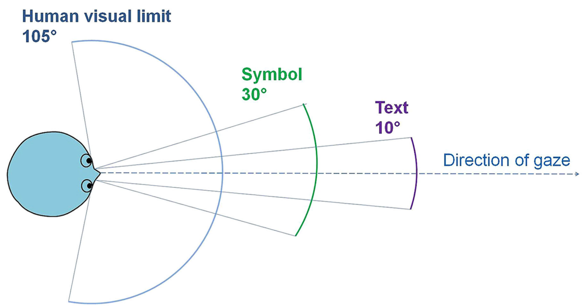

Figure 2. What can be perceived for a given FOV.

Table 1. HUD size and volume.

FOV	Width	Depth	High	Volume (liter)
7×4	200	125	200	5
14×6	325	175	250	14
35×20	600	400	350	84

contributes to the user experience. Also of interest is the notion of "geometric étendue": the étendue can be roughly described as the product of the EMB (surface) by the FOV (solid angle). The étendue provides a good measure of the intrinsic complexity of the optical system required to achieve simultaneously FOV and EMB.

According to the principle of conservation of the étendue, the value of the étendue in the pilot's space (FOV × EMB) is identical to the étendue in the imager space (surface of imager × the angle of aperture of the optical system). As the optical aperture is necessarily limited by geometry (strictly <90°), one way to increase the EMB for a given FOV is to work with a larger imager, or at least a larger intermediate image (large PGU).

The collimating distance: In order to display a virtual image superimposed on the external scene, the collimation distance shall match with the distance of objects of the scene, to avoid parallax error and accommodation-vergence conflicts.[2]

All these critical parameters have a strong impact on the HUD FOV. Increasing the vertical and/or the horizontal FOV will adversely affect the size of optical components, resulting in a large HUD box needed to host the large mirrors, as demonstrated on document.[3]

Depending of the HUD needs in term of FOV, EMB, and collimation distance, three categories of HUD are identified:

The legacy HUD: Displays only graphics symbols and parameters, avoiding the need of looking down the cockpit display system. For this application, the required FOV is not more than 7° × 4°, with a collimation distance about 2–3 m.

The Augmented Reality HUD (ARHUD): The goal is to display symbols superimposed on the real world as a synthetic vision of the road, directions to take, security distance from the front vehicle, warning on pedestrian crossing, etc. In this case, a FOV at least 14° × 6° is needed, with a collimation distance not less than 10 m.

The Full Windshield HUD (FWHUD): This is the ultimate HUD, giving the maximum usable EMB (500 mm and more), an FOV adapted to the human eye capability (>35° × 20°, see Figure 2, corresponding to the part of the human eye FOV where symbols can be assessed or recognized unambiguously) and a variable collimation distance between 2 m to infinite

If we consider that the most dimensioning parameter is the FOV, the relationship given by the document[4] could be used to estimate the impact on the HUD box size and volume (Table 1).

A FWHUD using an architecture based on classic optics is not achievable, regarding the huge volume needed to host the optical elements (84 liters).

DIRECT WINDSHIELD PROJECTION

For a better user experience, recent Automotive HUD uses the windshield as the last optical element. But the windshield needs to have specific properties to reflect images with an acceptable level of quality. In this case, the windshield is used as a partially reflective mirror, with a high transmission rate, meaning that the reflection rate is very poor (Typically, only 20% of the image luminance is reflected).

An intermediate approach is to integrate in the windshield the optical function of a concave mirror, as presented by Okumura *et al.*[5,6] This will result in larger field-of-view capability for the HUD within a constrained space envelope. The Fresnel reflector can be seen as an intermediate step toward a fully holographic combiner: the active pattern dimensions of the Fresnel component are sufficiently small to minimize see-through adverse effects, but sufficiently large to work only in classical Snell-Descartes reflection and not in diffraction mode.

HOLOGRAPHIC APPROACH

The use of Holographic components is not new: today, holographic diffusers are used in backlight systems, but also in projection systems, like the PGU, used to display the intermediate image on the HUD box.

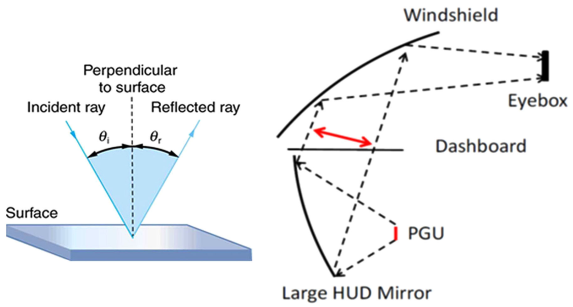

Figure 3. Snell-Descartes reflections laws lead to an large mirror.

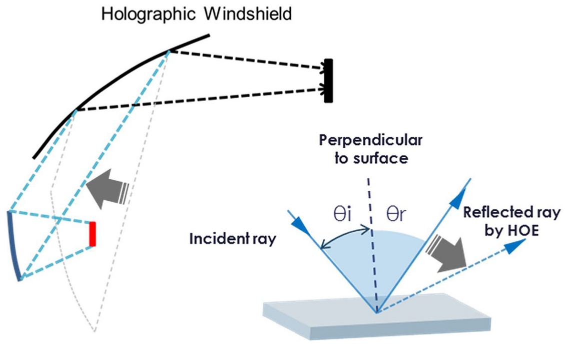

Figure 4. HUD mirror size reduced by using HOE first order of reflection.

In some existing aircraft HUDs, Holographic combiners are also used to reflect the light toward the eyebox. Such HUDs usually present a large off-axis of the combiner, resulting in a very large astigmatism, which can be partly corrected through the use of Holographic Optical Elements (HOEs).

But in these two cases, Holographic components represent only a part of the optical system, and not the whole system, as proposed in this paper.

Instead of using conventional refractive or reflective optics, Diffractive or HOEs could be used. By using one specific order of diffraction, it is possible to reflect light in a given direction, and/or add optical power.

One possible application is direct projection on windshield. With only one HOE, installation constraints are reduced, and only one small projector is required to display the HUD symbology. Wu *et al.*[7] presents such a system, using a small UV laser projector, and a windshield including a layer with transparent phosphor.

With the use of HOE, we take the benefit of the spectral selectivity of Bragg gratings, providing an efficient reflection when using a narrow bandwidth illumination source.

When the HUD illumination source match with the HOE reflection peak, most of the energy coming from the projector will be reflected towards the pilot, with limited loss in transmission.

One remaining issue is to achieve, when required, the "reflective-diffusive" function of the screen. This can again be done through the use of HOE.[8]

At each point on the screen, a specific optical function enables the incoming light to be spread over the required solid angle at a given wavelength. This function is performed by a surface grating computed and simulated by software (Computer Generated Hologram).

DISCUSSION

The image is formed on the windshield, near the driver's eyes. It raises several issues, particularly the mismatch between real world and images presented at short distance from the eyes (Vergence-Accomodation Conflict).[2]

Taking into account this limitation, such a system could still be used for displaying non conformal information, such as speed or vehicle parameters.

Today, ARHUD requires conformal image, and henceforth, collimated images as most of the external world is far away from the eye. This is performed with a HUD box as described in Figure 3, and needs very large mirror(s).

Again, in this case, HOE could solve this issue. The mirror sizes typically depend on ray's incidence that follows Snell-Descartes reflection laws.

But, with a HOE, it is possible to use a diffraction order that will not follow the Cartesian condition, and reflect the light at different incidences. Figure 4 shows a simple schematic example, showing an outstanding reduction of the mirror size.

This is a schematic principle; in fact, chromatic aberration occurs on such architecture, and a more complex optical system is needed to compensate this effect. But, the result remains the same; the HUD box size will be dramatically reduced.

In this example, the HOE is a Bragg grating and is only used as an angle deflector, but HOE

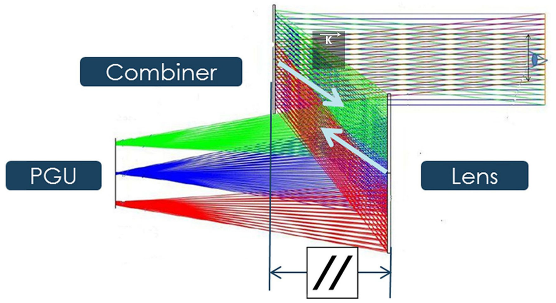

Figure 5. Z Architecture: Lens chromatic dispersion compensated by combiner, K vector sum = 0.

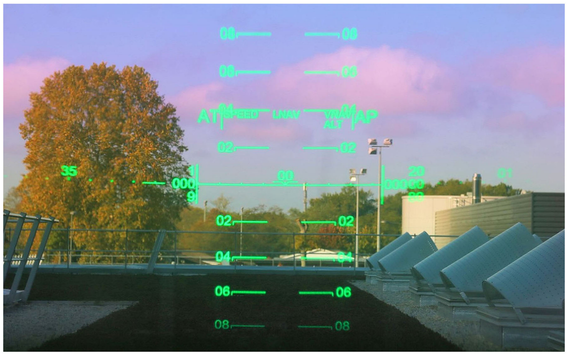

Figure 6. Image displayed by a holographic HUD using two HOEs working in reverse.[10]

can also perform other optical functions such as paraboloid mirror (lens), and then remove the need of aspheric mirrors.

By using two HOE in reverse mode, it is possible to compensate chromatic dispersions,[9] as represented in Figure 5.

Chromatic dispersion generated by HOE1 (lens) is strongly reduced by HOE2 (combiner). Grating vector K at HOE2, uniform on the whole surface of the component, is opposite to the grating vector at the center of HOE1. This compensation scheme can be generalized to more complex architectures, using more than two HOEs.

First experimentation results, which were measured on an experimental setup, are very promising, delivering a horizontal FOV as large as 20° with minor chromatic dispersion inside a wide eye box (200 mm $\times$ 200 mm) (Figure 6).

Measurements performed on this setup show a high level of luminance up to 13000 Cd/m^2, thanks to a very good efficiency of the HOE (85% of reflection rate between 535–540 nm), and a good photopic transmission rate (78%), all these results were presented by Coni *et al.*[10]

But, some issues remain: This prototype is monochrome, and even if it is possible to stack or multiplex several HOEs, the photopic transmission rate of the combiner will decrease, with an impact on the color perception of the external landscape.

Another issue is the volume of the HUD box. For example, to get a FOV of 35°H and 26°V, the volume required for these large HOEs will be about 35l.[10] The benefit is noticeable, regarding Table 1, but remains too large to fit on a car dashboard. A further issue is the possibility of ghost images in transmission when looking through the holographic combiner. Much progress has been made in the processing of the holograms to reduce the efficiency of such ghosts, but it is not easy to eliminate them all.

In fact, the main benefit regarding the volume of the HUD box is the use of flat holographic mirrors instead of paraboloid mirrors (working in Snell/Descartes reflection mode) as shown in Figure 4. In the prototype shown in image 2, the vertical FOV was measured at 13°, and the system height at 250 mm.

CONCLUSION

Today, the design of large FOV HUD, necessary for Augmented Reality applications, is limited by the poor reflective efficiency of the windshield, used as a combiner, and the necessary large size of the optical components.

The use of HOEs is the answer to these issues, and represents a serious candidate for performing augmented reality applications in car and aircraft cockpits, without using bulky AR helmets or headsets.

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