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Design and fabrication of multiple LED illuminated computer-generated holograms generating 3D effects for automotive applications

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ABSTRACT

Car manufacturers are strongly interested in optical systems producing the perception of an aerial 3D image. Such an effect can be obtained using surface relief computer-generated holograms (CGH). However, classical single light source illumination methods of holograms by a plane wave or spherical wave generally requires long optical path systems that are too bulky to easily fit in a car. In this article, we propose a method to design CGHs that are compatible with multi-LED illumination system while generating convincing 3D aerial images. We also demonstrate an experimental realization of a prototype of a holographic system through the fabrication of a hologram illuminated simultaneously by 6 separate LEDs.

Keywords: Surface relief holography, Multiple-sources holography, 3D floating image, Automotive applications

1. INTRODUCTION

Car manufacturers are currently showing more and more interest in optical systems producing the perception of an aerial (floating) 3D object. Applications inside vehicles include innovative Human-Machine Interfaces (HMI) for display and control systems, particularly when coupled with gesture recognition [1]. Outside the vehicle applications include upgrades of lighting and signalization systems to share driving information with other road users, such as a rear proximity alert, or to produce a “wow” effect through system styling [2]. For both applications, the automotive industry requires compact and low-cost mass producible systems.

Holography is one of the most effective ways to produce visually convincing high quality 3D images, as it provides a full set of consistent depth cues [3,4]. Compared to optically recorded holograms, surface relief Computer Generated Holograms (CGH) are one of the most suitable solutions for industrial applications, as such CGHs allow for fast and cost-effective mass production by nanoimprint replication [5,6]. Numerous algorithms have been developed for the calculation of synthetic holograms [3,7], but mainly focusing on the rendering of realistic 3D scenes, for images appearing behind the hologram and illuminated with a single light source. Synthetic surface relief holograms generating a convincing effect of a 3D floating in front of the hologram have been demonstrated [8] but using an alcove-shaped hologram which implies a bulky illumination system. Previous work [9] demonstrated synthetic holograms generating a 3D image compatible with a beam-shaping optics-free LED illumination but using a single light source. Illuminating a synthetic hologram with several distinct light sources usually contradicts the light source coherency condition and leads to the restitution of one object per light source [10]. However, the large images required for the targeted automotive applications require large holograms (>10 cm²) which implies high-volume illumination systems if only one LED is used. Single LED illumination of large holograms implies a bulky system.

In this article, a method to design a beam-shaping optics-free multiple-LED illuminated hologram generating a convincing floating 3D object effect is demonstrated, from the hologram calculation to the illumination system, their combination in a demonstrator and experimental results obtained with multiple-LED illuminated synthetic holograms.

2. HOLOGRAM CALCULATION

The algorithm, schematized in figure 1, is based on the angular multiplexing method described in [11], modified to generate higher efficiency phase only holograms instead of amplitude holograms, and to include only one image plane per object, with a very limited number of objects (here two) to reduce processing time.

In the hologram plane located at $z = z_h = 0$, the light field $o_n(x, y; z_h)$ from an object located at $z = z_{o,n}$ can be written, as defined by the angular spectrum theory [12]:

$$o_n(x, y; z_h) = \mathcal{F}^{-1} \left\{ \mathcal{F}[o(x, y; z_{o,n})](f_x, f_y) \times \exp \left(2\pi j(z_{o,n}) \sqrt{\lambda^{-2} - f_x^2 - f_y^2} \right) \right\} (x, y; z_h) \quad (1)$$

Where λ is the considered wavelength, (f_x, f_y) are the spatial frequency coordinates and (x, y) are the spatial coordinates (see figure 1). In the following developments, the propagation function, or angular spectrum method transfer function will be named $\mathcal{P}(z)$:

$$\mathcal{P}(z) = \exp \left(2\pi j(z) \sqrt{\lambda^{-2} - f_x^2 - f_y^2} \right) \quad (2)$$

For N objects in distinct planes, the light field observed in the hologram plane, $h(x, y; z_h)$, is the sum of the light fields of all of the objects propagated in the hologram plane:

$$h(x, y; z_h) = \mathcal{F}^{-1} \left\{ \sum_{n=1}^N \mathcal{F}[o_n(x, y; z_{o,n})](f_x, f_y) \times \mathcal{P}(z_{o,n}) \right\} \quad (3)$$

The 3D effect is obtained by an angular multiplexing of a set of different 2D views of a 3D object, as explained in [11]. For each object (i.e., image plane), the angular spectra of the different views are juxtaposed horizontally and vertically, as depicted in figure 1 right, before propagation. In this way the different views are coded onto different diffraction angles to give the perception of a 3D object at a given position in space, behind or in front of the hologram. Zero padding around the angular spectrum can be added to move higher diffraction orders out of the observer field of view.

The fabricated hologram codes the phase part of the light field in the hologram plane, i.e., $\arg [h(x, y; z_h)]$.

For convenience, figures 1 and 2 are drawn showing an object behind the hologram. However, the same algorithm can be applied for a hologram that produces the light field corresponding to an object floating on the observer side of the hologram. In this case, the propagation distance must be negative, i.e., $z_o < 0$, instead of positive for an object on the illumination side (i.e., behind the hologram).

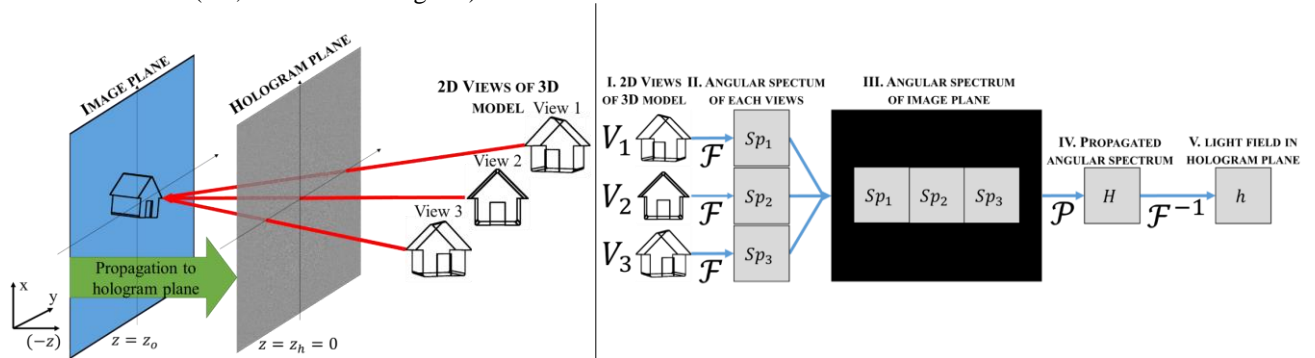


Figure 1. Algorithm principle: from the physical point of view (left) – from the processing point of view (right). A set of 2D views of the 3D object are numerically generated and then propagated from the image plane to the hologram plane using the angular spectrum method.

Hologram playback is depicted in figure 2. For proper image restitution, the hologram calculated above must be illuminated by a plane wave (which can be obtained using a laser and beam shaping optics).

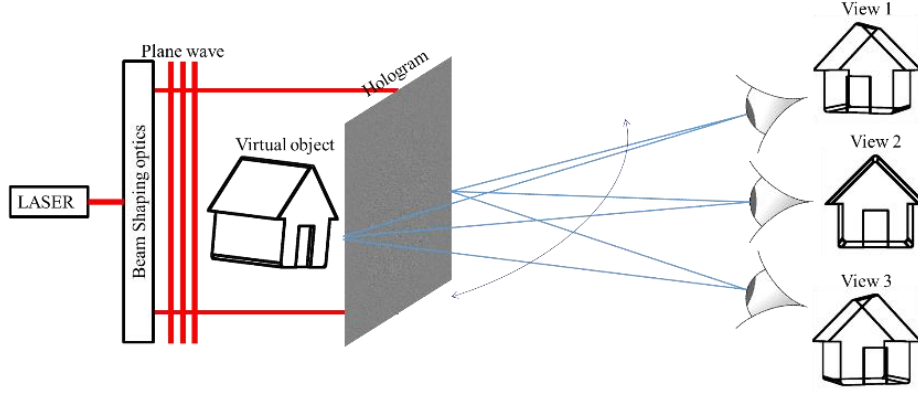


Figure 2. Principle of image restitution from a hologram generated by the algorithm described above, using a laser-based illumination system.

3. ADAPTATION TO MULTI-LED ILLUMINATION

To calculate a hologram adapted to illumination by other types of wavefronts, the hologram is given by:

$$h = o \times \bar{u} \quad (4)$$

Where $o(x, y; z_h)$ is the object wave and \bar{u} is the conjugate of the incident wave $u(x, y; z_h)$.

Monochromatic LEDs can be used as an illumination source for a hologram, as they can be approximated by a point source which verifies the spatial coherency condition. For an LED located at coordinate $(x_{LED}, y_{LED}, z_{LED})$, the light emitted can be approximated by a divergent spherical wave. In the hologram plane, the light field from the LED $u_{LED}(x, y, z_h)$ can therefore be written as:

$$u_{LED}(x, y, z_h) \propto \frac{1}{r} \exp[-jkr] \quad (5)$$

Where $r = \sqrt{(x - x_{LED})^2 + (y - y_{LED})^2 + (-z_{LED})^2}$ is the distance between the LED and the considered point on the hologram plane and $k = 2\pi/\lambda$.

As explained above, illuminating large holograms ($>10 \text{ cm}^2$) with a single LED leads to a bulky system, because the LED must be placed far from the hologram to illuminate it entirely and maintain diffraction angles to hologram fabrication technology limits. A potential solution is to illuminate the hologram with an array of LEDs (see figure 3). We use a commercial LED matrix to reduce the size of the illumination system. However, hologram illumination requires spatial coherency, which is a priori contradictory with illumination by multiple independent sources such as LEDs. Thus, to calculate a hologram illuminated by several independent light sources without beam shaping optics, only one light source is considered for each zone of the hologram during the calculation. Spatial coherency is then locally verified at each point of the hologram.

In the calculation, we assume that only the closest LED to each point of the hologram illuminates the point in question. Considering N LED located at distinct coordinates $(x_{LED,n}, y_{LED,n}, z_{LED,n})$, the wavefront reaching the hologram is then expressed:

$$u_{NLED}(x, y; z_h) = \frac{1}{r_n} \exp[-jkr_n] \quad (6)$$

Where $r_n = \sqrt{(x - x_{LED,n})^2 + (y - y_{LED,n})^2 + (-z_{LED,n})^2}$ with n being, for all points of the hologram, the closest LED to the considered $(x, y; z_h)$ point.

By inserting (3) and (6) in (4), the expression of a hologram illuminated by multiple LED is (7):

$$h(x, y; z_h) = \mathcal{F}^{-1} \left\{ \sum_{n=1}^N \mathcal{F}[o(x, y; z_{o,n})](f_x, f_y) \times \mathcal{P}(z_{o,n}) \right\} \times \frac{1}{r_n} \exp[-jkr_n] \quad (7)$$

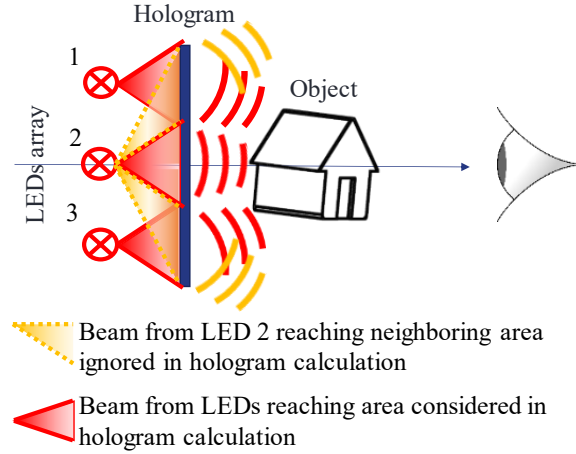


Figure 3. The hologram is illuminated by several LEDs. In the hologram calculation algorithm, only beams reaching the hologram from the closest LED are considered to generate the image.

Full hologram playback is obtained by aligning the LED matrix on the LEDs position defined during hologram calculation. The different zones of the hologram then all diffract the incoming light from their corresponding LED into the same single “image” at the same position, generating the perception of a floating 3D object.

However, each LED doesn’t only illuminate the zone of the hologram for which it has been designed but also illuminates the neighboring areas. This “incorrect” illumination reaches the hologram at an incorrect incident angle and leads to the generation of off axis parasitic images. These parasitic images are of lower intensity due to higher hologram diffraction angles and the LED divergence and are often only partially reproduced due to vignetting effects by the hologram window.

More importantly, the visibility of these parasitic images in the observer field of view can be avoided by zero-padding during the angular multiplexing process (figure 1). The zero-padding leads to an image free zone in the object field of visibility, i.e., a “dead” zone in the angular playback field. Thus, as presented in figure 4, the field of visibility of the parasitic images is completely separated from the field of visibility of the image properly generated by the hologram.

Although this limits the field of visibility of the holographic image, this is rarely a problem for our targeted applications as the object generated by the hologram is often observed by only one person: a seated driver inside the vehicle or an in-lane following vehicle for a rear proximity warning system. If required, the parasitic images can also be removed by adding barriers between the LEDs to stop the part of the LED’s beams diverging onto neighboring areas.

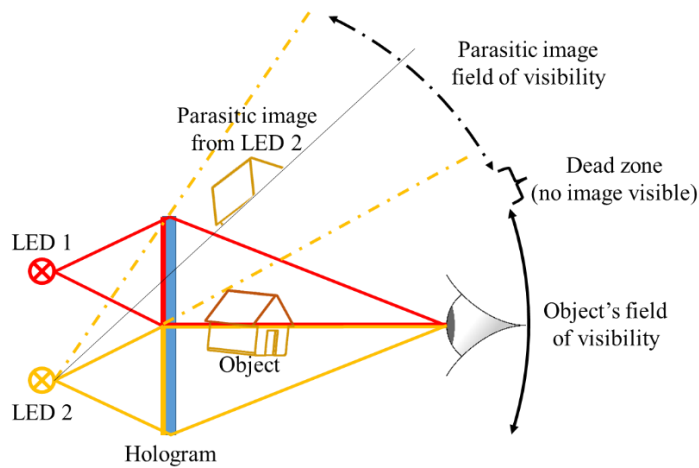


Figure 4. Principle of multi-LED hologram playback in the case of 2 LED illumination, with shown parasitic image out of object's field of visibility.

4. EXPERIMENTAL RESULTS

To experimentally confirm the hologram calculation process, we fabricated a hologram calculated using the algorithm described above using a homemade massively parallel direct-write photoplotter into a 1.6 μm thick layer of Shipley S1813 photoresist deposit on a 1.5 mm glass substrate [13]. The fabricated phase only hologram has 256 phase levels, $66\,666 \times 66\,666$ pixels with a pitch of 750 nm, giving a total size of 5×5 cm. The hologram produces an image floating 7.5 cm in front of the hologram and is designed to be illuminated using a 6-LED triangle shaped system placed 8 cm behind the hologram plane.

Hologram playback is presented in figure 5 with the camera focused on the floating image and in video 1. The circular spots are formed by the LEDs undiffracted zeroth-order light resulting from hologram fabrication limitations. As a comparison, illuminating a hologram of comparable size and characteristics with a single LED would have required the light source to be placed approximately 30 cm away from the hologram plane, resulting in a system of much greater volume that would have been incompatible with automotive volume constraints.

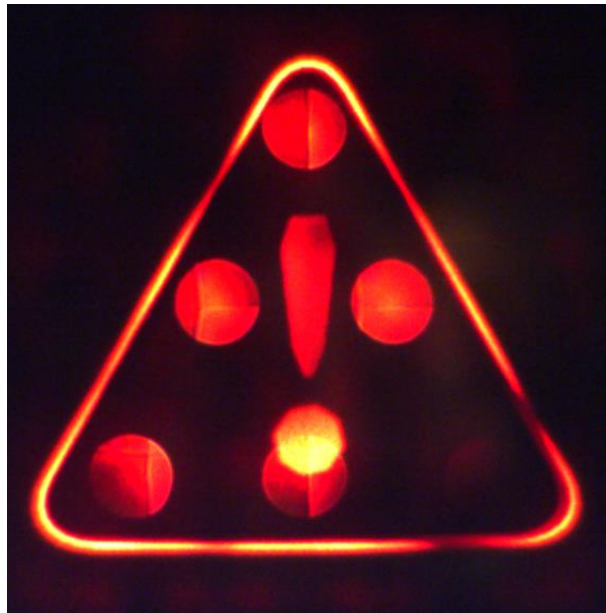


Figure 5. Camera capture from hologram playback, focused on the floating image.



Video 1. Hologram playback. <http://dx.doi.org/doi.number.goes.here>

To demonstrate that multiple LED illumination of holograms reduces the volume required for the illumination system, we fabricated a portable demonstrator, presented in figure 6. This demonstrator, which will be shown at the conference, uses a commercial 8×8 LEDs matrix [14] and is designed to illuminate holograms with multiple LEDs located 3 cm behind the hologram.

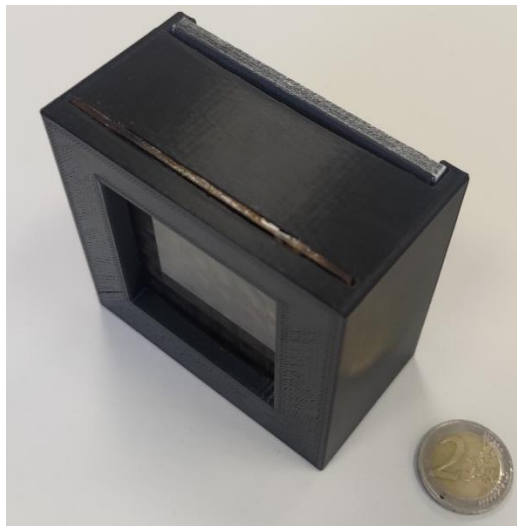


Figure 6. Multi-LED hologram illumination system demonstrator.

5. CONCLUSION

In this paper, we have proposed and demonstrated a method to calculate computer-generated holograms compatible with illumination by multiple sources, with no beam shaping optics, for automotive applications. We also presented an experimental confirmation of the technique through a hologram simultaneously illuminated by 6 LEDs generating an image floating in front of the hologram.

Our current research on multiple sources illuminated holograms centers on improving the brightness and compacity of the holographic system. Issues to overcome include the visibility of the parasitic images and the sensitivity of the hologram to the positioning error in the LED matrix, which result in a non-continuous image if the LEDs are not precisely placed.

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