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A 360-degrees Holographic True 3D Display Unit Using a Fresnel Phase Plate

Levent Onural , Dept of EEE, Bilkent University, Ankara, Turkey

Abstract

Holographic true 3D displays attempt to duplicate the original light field with all its relevant physical features. To this end, spatial light modulators (SLM) are commonly used as display devices. Currently available SLMs do not satisfy the technical specifications to achieve a consumer quality true 3D display; one of the important drawbacks is the rather large pixel size, and this results in a low spatial resolution of the fringe pattern written on the SLM which in turn severely restricts the diffraction/viewing angle. A design that uses low spatial resolution, but still achieves a 360-degrees viewing angle, using a parabolic mirror was already reported. Here in this design, the parabolic mirror is replaced by a Fresnel phase plate which is mounted as a covering layer on top of the SLM.

Introduction

True 3D displays target physical duplication of the original time-varying light field [1-3]. Any receiver of light, for example, human eyes or a camera normally floats in a volume filling 3D light that is also time-varying, and does not really see the 3D environment, but actually sees only that light which enters its pupil. Therefore, if that light field which makes up the original scene is somehow duplicated in another possibly remote site, maybe at another time, and if a receiver now interacts with that duplicated light field, that receiver will see the same 3D environment as the original; since the light that enters the pupils is the same, its subsequent visual effects, including overall human visual system interpretation, will also be the same., Therefore, such a light field should be captured at the original site with all its relevant physical features, and a display device should replay it at the receiver site. Commonly used optical cameras capture only the focused intensity of the light field usually on a planar surface, and such a limited recording misses other relevant physical features of light that are needed for an identical replay. Stereoscopic recording or even multi-view recording of intensity is not sufficient, either. Here we use the term "light field" as the physical volume distribution of light wavefront at every point of space that propagates according to physical wave propagation priciples. We will distinguish it from the primarily computer science related "light-field" term which models the light as a collection of rays and assumes perfectly focused elementary image recording; ideal light-field recording may carry almost full 3D information about a scene , but still does not achieve exact duplication of physical light field. We will call any technique that achieves exact duplication of the physical time-varying light field as holographic video, and therefore, we use the term "holography" in a broader sense compared to those classical and rather restrictive holographic recording techniques which use a reference beam and record an intensity pattern of an interference pattern that carries the 3D information [3].

Here in this paper, we provide an optical design to achieve such a true holographic display device [24]. Another version of a true 3D holographic display was presented two years ago [4,5]. Now, the large size concave mirror of that design is replaced by a Fresnel phase plate [24]. Thus, a more compact design is achieved. A number of designs to achieve holographic video displays may be found in the literature [1-24].

A technique for holographic video is to modulate an incident light to generate a time-varying boundary pattern over a surface for a subsequent 3D light field which is generated by the modulated light as it travels away from that controlling boundary pattern. Ideally, both the amplitude and the phase pattern over the boundary surface are needed. However, usually only the amplitude, or the phase patterns are used in practice to avoid the device complexity when both are attempted; this will naturally cause a degradation in image quality, however. Such devices which holds such surface fringe patterns are called spatial light modulators (SLMs); amplitude only, phase only, or complex (both amplitude and phase) modulators are utilized in various designs. Most of those SLMs are pixelated arrays, and the modulation at each pixel is usually achieved electronically. Many holographic displays that utilize SLMs are reported [1-24]. However, none of those prototypes reached a consumer quality operation so far: neither the resolution, the size, nor the color quality is adequate. A primary reason for this shortcoming is the enormous number of pixels needed for a sufficient 3D image quality; furthermore, the pixel size must be close to the wavelength of light. An analysis of related requirements can be found in [2]. The need for large number of pixels is not due to information content of a 3D scene: even though a 3D image naturally carries more information compared to its 2D counterpart, the increase in the information is not prohibitively large. The small pixel size requirement is directly related to the subsequent angle of diffraction; the outgoing light from the SLM must have directional variation to carry the 3D information, and that directional variation includes larger angles to achieve higher quality 3D displays. Larger angles, when obtained by diffraction from the fringe patterns written on the SLMs, require small pixel sizes. This in turn, when combined with a decent size 3D image, requires prohibitively large arrays of small pixels, especially when the SLM surface is planar.

Both the design presented in [4,5] and the design presented in this paper [24] provide means of achieving larger diffraction angles, from planar SLMs with reasonable resolutions, using a geometry to couple the SLM arrays with either a concave mirror [4,5] or a Fresnel phase plate [24].

The Design

The aim of this presented design is to overcome the high resolution requirement while still achieving wide viewing angles. A way to achieve this goal is to have a curved SLM, or more practically, to place small planar patches of SLMs on a curved geometry, as in [6]. Another geometry, that incorporates a concave mirror is presented in [4,5]. Here in this design, a more compact display device is obtained by achieving the needed deflections via a Fresnel phase plate, instead of a concave (typically paraboloid) mirror. The basic structure of the display device is shown in Figure 1 for a transmissive SLM.

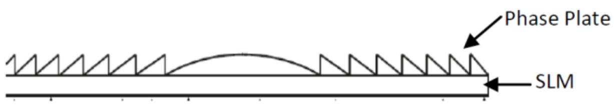

Figure 1. Basic structure [24].

Therefore the basic design principle is to essentially cover the entire exit surface of the SLM with a large size fixed Fresnel phase plate. The typical top view for a circularly symmetric geometry will then be a Fresnel phase grating as shown in Figure 2.

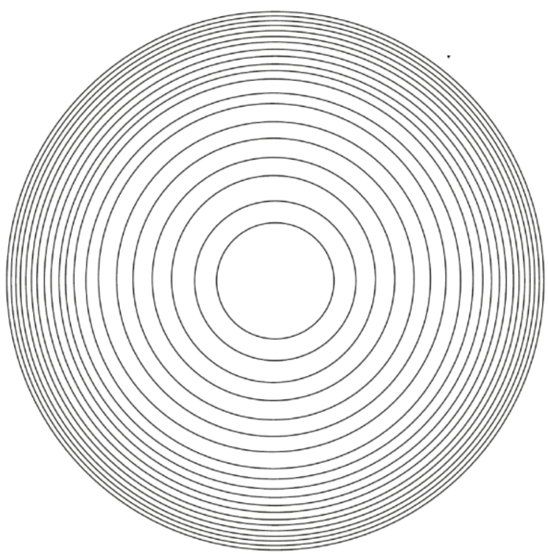

Figure 2. The top view [24].

In a typical operation, for the transmissive SLM case, the incident light will pass through the SLM first, and then pass through the Fresnel plate to converge and form the ghost-like true 3D image, as shown in Figure 3.

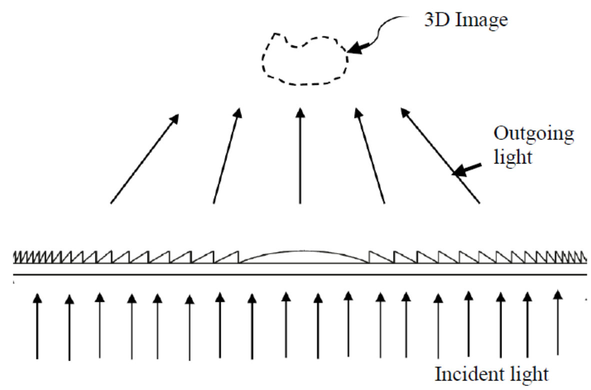

Figure 3. Operation [24].

It is possible to replace the transmissive SLM by a reflective type SLM; in that case the basic operation will be as shown in Figure 4.

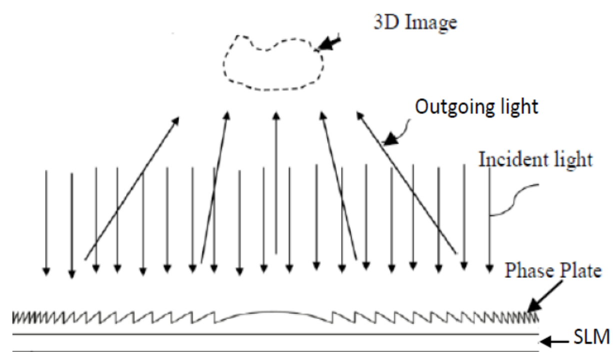

Figure 4. Reflective SLM case [24].

The SLMs intended for this design could have the resolutions of typical LCDs commonly used today, for example, as mobile phone displays. Since such commercially available display units still have quite large pixel sizes, the maximum achievable diffraction angles will also be small, as shown in Figure 5, and this will not be adequate for a good 3D image. However, the mounted Fresnel phase plate will then further diffract the light at different locations of the SLM, and thus, will introduce the needed larger angles. At the end, the collection of light beams from different locations of the SLM will have all of the needed large angle components, as well, in order to achieve the large viewing angle. Naturally, a large size SLM is needed for this true 3D holographic display operation; this could be achieved by tiling a plurality of commonly available SLMs underneath the Fresnel phase plate.

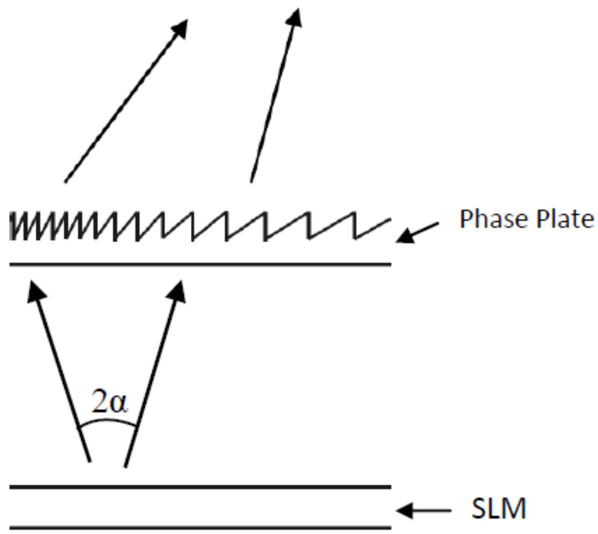

Figure 5. Rather low diffraction angles from the SLM gets a larger bend due to the phase plate [24].

It is possible to replace the order of the SLM layer and the phase plate layer, both for the reflective SLM case, and the transmissive SLM case.

In line with the practice of SLM based holographic video displays, it is possible to use phase-only or amplitude-only SLMs; however, a related distortion as a consequence of the lack of the amplitude or the phase is inevitable in such cases.

Color operation is achieved as in conventional display operations; for example, a time-sequential color operation is feasible. Fringe patterns that carry the holographic 3D image information and written on the SLMs could be generated to take care of both wavelength variations of the separate corresponding colors, as well as, any physical aberrations that might exist along the entire path of the light. A complicating problem is the fixed Fresnel phase plate during the possible color operation. However, this could also be handled properly by using an achromatic phase plate when time-sequential color illumination is used.

As a reciprocal device, a 3D true holographic camera is obtained when the paths of the light in the figures are reversed. In the camera case, the light propagating from a 3D object reaches the Fresnel phase plate which is directly mounted on a planar fringe capturing device.

Discussion

The design is presented to yield a 360-degrees lateral (azimuth) viewing angle. However, a large size SLM and a matching large size phase plate are needed to achieve a large vertical viewing angle. Furthermore, a large display (large SLM and large phase plate) is essential to get an acceptable size 3D image. The image quality will be better around the focal point of the phase plate; degradations will increase for larger images which extends well beyond the focal point. As also the case for the true 3D holographic display presented in [4,5], the expected quality of the resultant 3D image will get close to the quality of those 3D images obtained from the toy paraboloid mirror pair that relays a real image from the objects located around the focal point of one of them [4], provided that a full complex SLM with sufficient resolution is used. The design is not implemented or tested, at this time, yet.

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Author Biography

Levent Onural received his BS (1979) and MS (1981) in electrical engineering from Middle East Technical University, and his PhD degree in electrical and computer engineering from SUNY at Buffalo (1985). He has been teaching in the Department of Electrical and Electronics Engineering at Bilkent University since 1987; currently, he is a full professor. He had served Bilkent University as the Dean of Engineering between 2010-2016. Levent Onural is a fellow of IEEE.

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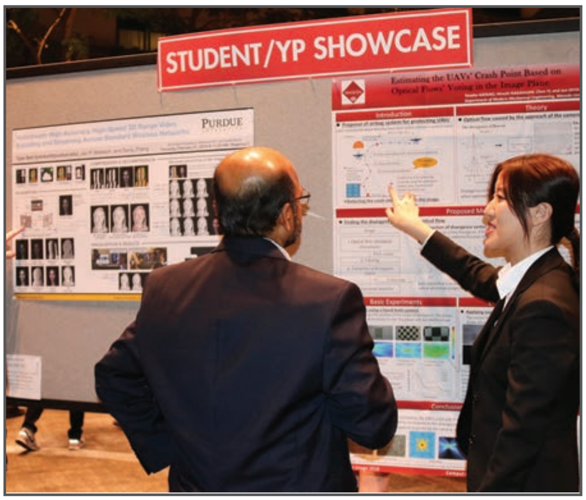

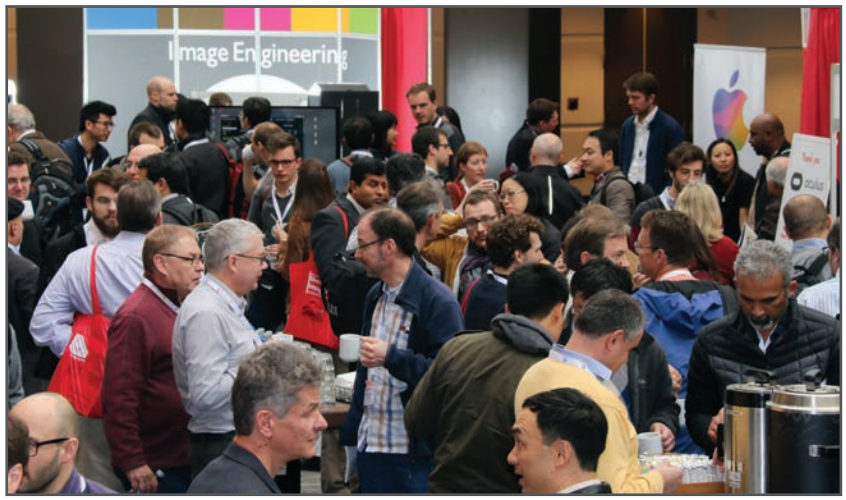

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