Simple holographic projection in color

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Abstract: Extremely simplified image projection technique based on optical fibers and a single Spatial Light Modulator is presented. Images are formed by addressing the modulator with especially iterated Fourier holograms, precisely aligned on the projection screen using phase factors of lenses and gratings. Focusing is done electronically with no moving parts. Color operation is done by spatial side-by-side division of the area of the modulator. Experimental results are given, showing good image quality and excellent resistance to obstructions in the light path. Speckles are suppressed by micro-movements of the screen and by time-averaging of a number of holograms into the final image.

OCIS codes: (090.1705) Color holography; (090.1760) Computer holography; (090.2870) Holographic display; (090.5694) Real-time holography.

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1. Motivation

Image projectors have many unique advantages over flat-screen displays. Among them can be distinguished very large image, small device size, portability and seamless integration in households. On the other hand, projectors available off-the-shelf have serious drawbacks that prevent them from becoming popular in applications ranging from stand-alone home displays to small ultra-compact handheld devices mounted inside cellular phones (so called pico-projectors). They mostly use high power mercury-arc lamps, which generate radiant energy mostly in the infrared region, therefore contributing to extreme heat buildup, not mentioning the very low energetic efficiency. For this reason a special compact cooling duct is always installed, which causes a significant noise. The cooling itself must be very sophisticated in order to maintain low noise level and still be able to filter the incoming air. Otherwise, the lack of proper filtering will surely deposit particles of dust on the array of light intensity modulator and they will be directly imaged on the screen as dark spots.

The image contrast is limited due to light leaks on the polarizers and in the complicated light paths. Additionally this technique is energy-inefficient since most of the light is absorbed and turned into heat by LCD modulators. Apart from the problems with mechanical or motorized adjustment of the lens' focus, the limited depth of sharp imaging and non-uniformity of irradiance, the image has a poor color range, due to poorly monochromatic primaries. The solution lies in the laser light sources [1]. Recent advances in blue and green direct laser diodes [2] had led to 2W-class diodes in compact TO-9 cans and the speckle suppression by high-speed modulation, broadening the spectral lines of laser emission.

The second market for image projection is compact and ultra-energy-efficient pico-projection. Here designing the projectors to be more compact is always limited by the presence of a bulky lens, which requires much space due to its finite focal length and aperture. The image sharpness and homogeneity strongly depends on the size, quality and price of the used lens, which also contributes to the total cost of the projector. Additionally, the lower the aperture of the lens, the higher the blur due to a diffraction. The suppression of chromatic and geometrical aberrations, the zooming mechanism and free lateral shift of the image are the main problems, which are very challenging if the lens are assumed to be small and inexpensive. In order to overcome this issue, there can be distinguished the methods of a lensless projection, involving the micro-mechanical scanning of a laser beam over the surface of the screen, e.g. by Microvision corp [3]. On the other hand the image resolution is limited by the progress in micro-mechanical (MEMS) mirrors used as scanning elements [4]. The other problem is the requirement of lasers of a safety class 2, which affects the eye-safety in the case of a potential failure of the moving mirror [5]. The second class of laser projection is holographic [6,7], which provides a collective forming of each pixel of the image with all pixels of the light modulator. This gives a prefect resistance to local defects and obstructions like dead pixels and dust deposition. The image is created by the redirection of light into desired locations, which makes the method very energy efficient.

The final drawback of classic mainstream projectors lies in the problematic application of 3D stereoscopic viewing, mainly due to the lack of polarization control and a limited LCD response time (which prevents the optimal utilization of electronic shutter-glasses). One not-economic solution is the use of two projectors with perpendicular polarization directions and a metalized polarization-maintaining screen combined with polarized glasses.

2. Lensless projection method

In this section we outline the alternative method of a projection of two-dimensional images on a regular screen, without the use of a lens, as opposed to the classic imaging scheme. This technique takes advantage of a recent progress in the field of laser sources for laser projectors [8], but besides that it adds a new concept of tailoring (or redirecting) of the incoming light in a diffractive manner to form the projected image [6,7]. We use a phase-only Spatial Light

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Modulator (SLM) addressed with especially designed Fourier holograms of the color components of input image, placed side-by-side on its surface. The procedure is as follows. The input image in the form of a color bitmap is split into three bitmaps containing color components: red, green and blue. The red and green bitmap are then sized down in order to pre-compensate for the different diffraction angle in the first diffraction order for different wavelengths [9]. Each of those three bitmaps is then an input object for the calculation of a three diffuse-type Fourier hologram with Gerchberg-Saxton (GS) algorithm [10]. The technique begins with a random phase and involves multiple iterative Fourier transforms between the object plane and hologram plane with preservation of evolving phase and enforcement of amplitude of the desired input image. Here the number of iterations is variable between 3 and 10. The resultant phase patterns are then multiplied with phase factors of positive lens in order to cancel the divergence of the illuminating wavefronts and in order to include the optical power of the missing projection lens, thus assuring the reconstruction of the image at a fixed and known position on the projection screen. The focal lengths of the lenses in horizontal direction are 240, 184 and 141 mm for red, green and blue portion of the SLM, respectively. The focal lengths in vertical direction must be different as a result of the incidence of light from below the modulator, which changes the effective pixel pitch of the SLM in vertical direction. They were equal to: 242, 188 and 157 mm, respectively. The SLM is illuminated with closely positioned endings of three light fibers, which simplifies and miniaturizes the setup, as seen in Fig. 1.

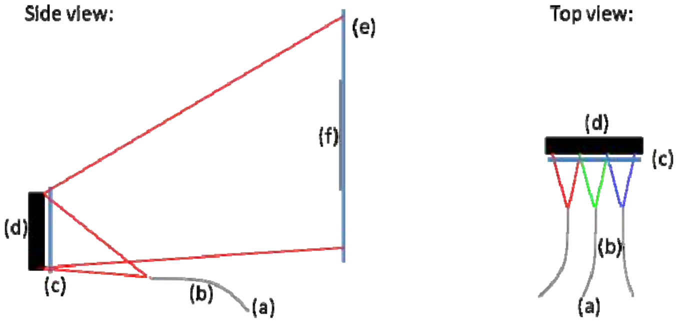

Fig. 1. Scheme of the experimental setup: a) fiber-coupled lasers; b) single-mode optical fibers; c) color filters; d) SLM; e) zero order light; f) projection screen.

Each of such point-like light sources illuminates its designated portion of the SLM. The distance between the fiber endings are equal to 1/3 of the longer side of the SLM, namely 5.1 mm. The fibers are located below the SLM and approximately 50 mm from its front surface. The elimination of a color crosstalk is done with plastic high quality color filters attached to appropriate portions of the surface of the SLM, as seen in Fig. 2. Three fiber-coupled laser sources (671 nm, 532 nm and 445 nm) are used in continuous work mode, without time-sequential switching, in order to avoid the color breakup and flicker effect. As the final step of the procedure, in order to precisely overlap the color component images on the screen we perform a fine positioning by adding phase factors of diffractive saw-tooth gratings of appropriate period and orientation to the holograms displayed on the SLM. In particular, the periods of the gratings were 17, 33 and 28 pixels (1 pixel = 8 µm), respectively.

The fill factor of the SLM is 87%, which causes at least 13% of the incident light to be reflected in a specular way, without being modulated in phase. This is also the result of time fluctuations of liquid crystal molecules in the SLM [11]. This contributes to the non-diffracted (or zero-order) light. Usually [12,13] this light causes obstructing spots or patterns, but the main improvement of this proposed method lies in the highly divergent illumination of the SLM from the fiber endings. This spreads the zero diffractive order on an area larger than the useful projected picture, thus its visibility is far less noticeable. In addition, due to the

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utilization of the central part of the Gaussian envelope of the laser beams, a highly uniform image brightness was achieved.

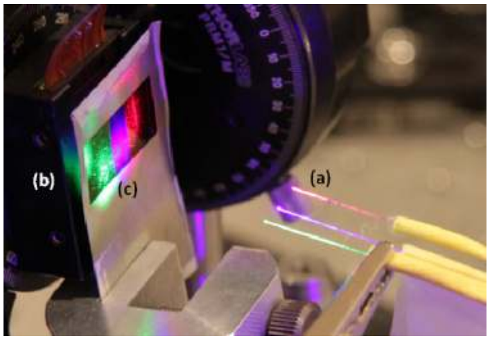

Fig. 2. Photograph of the projection head consisting of three fibers (a) and the SLM (b) with attached color filters (c).

The result is a sharp, color projection of the input bitmap on the projection screen, surrounded by faint patch of residual zero order light. The experimental results gathered in Fig. 3 and Fig. 4 (Media 1) show fine contrast, resolution and color reproduction. The size of the images was 10 cm by 10 cm at the distance of 1.5 m from the SLM plane.

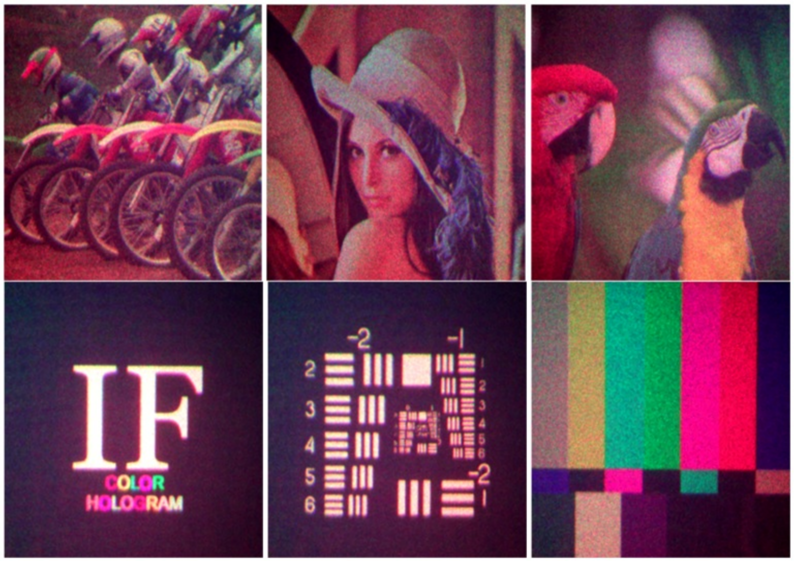

Fig. 3. Experimental results of holographic projection of test images.

The contrast is slightly lowered by the inevitable presence of the zero-order patch in the background, which is a consequence of a very simple and miniaturizable optical setup.

Fig. 4. (Media 1) Experimental projection showing the faint background non-diffracted light.

The images were captured using a Canon EOS 5D mk2 camera with a 300 mm objective. The screen was in motion during the exposures for the suppression of fine-grained speckles [12].

3. Current limitations

From the applicative point of view the main problem with the images projected in holographic methods are the visible speckles. We can distinguish two origins of this phenomenon. The first one is due to the phase-only modulation of the SLM, which requires iterative design of computer holograms yielding diffuser-like phase patterns resulting in speckled holographic reconstructions. The other comes from the reflection of a coherent laser light off a diffuse screen. The former can be addresses by the increased number of iterations during the design process, or by changing the iterative process to a more complex one (e.g. adaptive IFTA algorithm [14]). This obviously affects the computational effort, but can be done with parallel graphical processing, which is nowadays supported even by portable devices. The other way is to use time-sequential display of partial images with the same contents (signal), but different speckle distributions. We do this by calculating several holograms with different random initial phase distribution [12,13]. Provided that the phase modulator is fast enough (hundreds of frames per second, fps), this method gives an impressive real-time speckle suppression dependant on the square root of the number of time-integrated frames. In this work the results were acquired by 2 s exposures of the CCD camera while holograms with different speckle distributions were sequentially displayed on the SLM one after another. The second source of speckles can be eliminated with small fast lateral oscillations of the SLM (or the projection screen) with a small piezo-actuator. This shifts the image on the rough surface of the screen, which can average the fine-grained speckles. The combination of the mentioned methods was successfully tested [12,13]. Recent advances in high-speed modulation of direct laser diodes [2] provide serious speckle suppression with no moving parts.

Portable pico-projectors should have as high projection angle as possible, in order to ensure big image from close distances. The holographic method is strictly limited in this matter by the pixel pitch of the used phase modulator. We used a Holoeye Pluto, a phase-only LCoS (Liquid Crystal on Silicon) SLM having 1920 by 1080 pixels with a pixel pitch of 8μm. The pixel pitch determined the maximal diffraction angle according to Eq. (1):

$$\theta = \sin^{-1}\left(m\lambda / 2p\right) \tag{1}$$

where m is the diffractive order and p is the pixel pitch of the SLM. Obviously for $\lambda = 671$ nm this angle is 2.4°, which is unacceptable. Nevertheless it was enough for the needs of this proof-of-concept paper, based on currently available hardware. In the future, phase modulators with a pixel pitch of 1.2 μm and 500 nm will be available [15], increasing the projection angles to approx. 36°.

According to Eq. (1) in the 180° hemisphere around the projection screen there should be visible 47 diffractive orders. They are seen as a regular array of repeated projections, as seen in Fig. 5. Their presence is inevitable with any modulator consisting of discrete regularly-spaced pixels. This problem can be overcome with sub-wave modulators [15], which should produce only two visible first orders, one of which can be hidden by off-axis projection.

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Fig. 5. Higher diffraction orders visible on the projection screen.

3. 3D Stereoscopic mode

The successful welcome of stereoscopy in the display industry in recent years has not been that impressive in image projectors. The problem was the limited usefulness of shutter-glasses and a problematic control of polarization on regular projection screens disabling the use of polarizer glasses. The truly successful method of 3D projection is based on dichroic filtering. It uses slightly different primary colors in each channel (i.e. left and right eye) which combined with special low-cost passive glasses filtering out the unwanted colors, yield a very good three-dimensional viewing experience due to very low cross-talk of the stereo-channels.

The application of this concept in the proposed holographic technique is very straightforward. Instead of dividing the SLM into three parts (i.e. one for red, green and blue incoming laser beam) one can divide it into six regions [16] and attach color filters identical with those used in Dolby3D glasses directly to the SLM surface. Therefore in 3 parts of the SLM one should display holograms of the 3D scene dedicated for the left eye and in the other 3 parts – the scene for the left eye, as seen in Fig. 6. Obviously the used light sources must appropriately multiplied to cover the wavelengths matched with color filters.

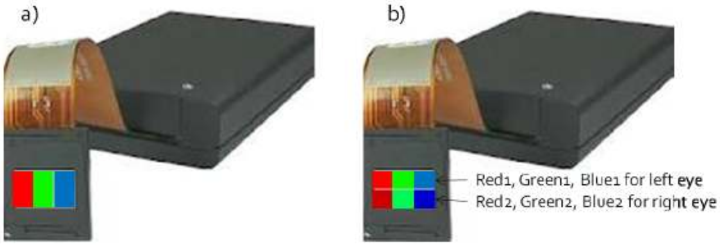

Fig. 6. The distribution of sub-holograms on the SLM in a) 2D mode; b) stereoscopic mode.

The inevitable loss of image resolution due to a smaller SLM area per hologram must be compensated by the increased pixel count in future phase modulators [15]. The main advantage of such an approach will be in the stable, non-flickering stereoscopic images with a great stereo-channel separation. Additionally, as the polarization encoding is not used, regular projection screens can be used, which greatly extends the versatility and lowers the price in comparison with metalized polarization-maintaining screens.

4. Summary

The proposed method can be treated as an alternative to current mainstream projection techniques, which overcomes most of their drawbacks. It can utilize commonly available and fast developing red, green and blue laser diodes, which provide the widest possible color gamut, internal speckle reduction and excellent energy efficiency at a relatively low cost. The use of optical fibers greatly simplifies the construction of the optical head. The use of lossless holographic light redirecting provides excellent efficiency, the controlled suppression of chromatic and geometrical aberrations, the focus adjustments without moving parts. The elimination of imaging lens greatly lowers the space requirements and makes the method suitable for small-scale devices. The technique is safe, as the light field is always strongly divergent, therefore is poses no threat to the naked eye, even from a close distance. Finally, the image quality is practically limited only by the available hardware. There are no fundamental obstacles to obtain high-resolution, stable, speckle-less, rich-colored images in 2D and 3D modes, provided that the SLM will have a high pixel count, small pixel pitch, high fill factor and high frame rate. The initial experiments have proved the feasibility of the concept and delivered high-quality images almost of TV-quality. The latest achievements in the field of sub-wave spatial light modulators and speckle-reduced laser diodes give hope for future improvements and implementations in the display industry.

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