Artistic Control of Defocus in Computer-Generated Holography

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1 Introduction

Lens characteristics such as bokeh make up an important part of the feel of an image. Many lenses are designed to produce pleasing effects, and many lens imperfections are emulated in CGI renders or added in post-production. Naturally, with our eye being a lens, we as viewers of the world experience lens effects such as bokeh; where in out-of-focus areas, points of light assume the image of the limiting aperture – our iris. Current AR/VR/MR displays are unable to offer this as a crucial visual element, as they are merely stereoscopic 2D displays; but with Computer-Generated Holography (CGH), where we employ a phase modulating Spatial Light Modulator (SLM) to construct holographic wavefronts [2], we can provide a field of light as a simulated real world view, where the viewer can focus on content within their vision as they would in reality – without Vergence Accommodation Conflict, with real focusable depth and with full natural 3D. So bokeh is again an important consideration in forming the final image for the viewer.

In this work we propose a novel method for artistic control of bokeh and depth of field in computer-generated holography, entirely in software with very low processing requirement. In a typical optical system, a physical limiting aperture would be required to provide a given defocus shape/f-stop, but in CGH as we are operating in the frequency domain, we can simply mask the resulting hologram to produce the desired bokeh and lens speed; provided the eyebox of the hologram is smaller than that of the eye of the viewer or smaller than the lens aperture of a camera viewing the hologram. Without intervention, in this scenario the defocus of holograms in a square eyebox will also assume a square shape, see Figure 1(b), but with our method we can control the aperture shape, depth of field and chromatic aberration of the defocus. All of which can be animated over frames and applied to pre-generated holograms or masked in real-time; both are visible on a holographic laser projector by eye.

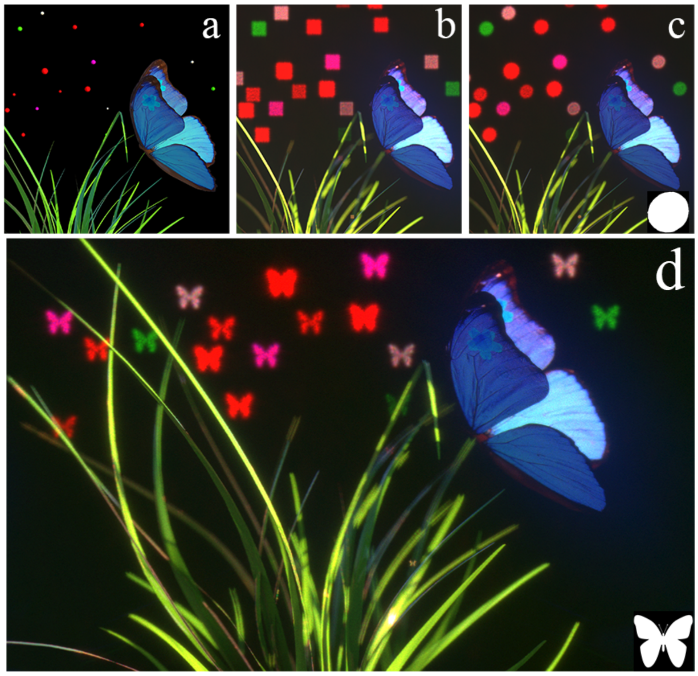

Figure 1: (a) Rendered RGBZ (from an EXR format file) image with butterfly at 12cm from camera, and coloured dots between 40m and 100m. (b) Resulting hologram replay of source with no masking applied, square defocus is visible matching eyebox aperture shape. (c) Dilated pupil shape hologram replay (simulated at 2mm diameter). (d) Butterfly mask replay. (Note) All holographic replays are simulated with eyebox size of 2.048mm square, at 2048x2048 input resolution (1μm pixel pitch), and have equal input energies.

2 Approach

We start with RGBZ data in Figure 1(a). We then generate a hologram of the given pixel data using VividQ's 'Core' package. Here we then have an output image in Fourier space (where the image is decomposed into its constituent frequencies) which can be shown on an SLM. In Figure 1(b) we see a simulated replay with the square shape of our unmasked hologram, matching the eyebox shape. We can now digitally apply our mask by removing the pixels outside of the given desired shape area, and must do this for each colour channel. Each channel can also have independent masks applied to provide chromatic aberration effects. Typically masks such as this are used to provide filters such as a lowpass, to remove frequencies within the image. Indeed as a side effect of this masking we lose spatial resolution in the resulting image where our aperture is smaller.

In order to provide the most natural defocus and to replicate eye characteristics, we opted to use accurate human-acquired iris aperture shapes from example data [1] by rendering an orthographic view of the iris geometry to mattes. We can then use the resulting mask to match the defocus shape of a given eye, with a result almost indistinguishable from real world eye defocus. The resulting hologram replay for a dilated pupil is given in Figure 1(c). In MR applications these masks can be applied per eye view, despite pupil dilation being linked, pupil shape will vary. Masks of course can get more creative, as in Figure 1(d), the input can also be animated or morphed as desired. The resulting holograms can be projected as is, and still focus at the correct depths with sharp results; only the defocused areas inherit the effects as intended.

3 Future Work

In future we should be able to measure pupil dilation using IR cameras and match pupil size, therefore approximating to the nearest captured dilation size as per [1] and apply the associated aperture shape to the holographic projection. Additionally, we can also ensure that our emulated aperture is always smaller than the viewer's pupil aperture, so that a given artistic bokeh or chosen f-stop can always be visible, even as eyebox size increases with advances in SLM resolution.

[1] Pascal Bérard, Derek Bradley, Maurizio Nitti, Thabo Beeler, and Markus H Gross. High-quality capture of eyes. *ACM Trans. Graph.*, 33(6):223–1, 2014.

[2] T Widjanarko, M El Guendy, A O Spiess, D M Sullivan, T J Durrant, O A Tastemur, A J Newman, D F Milne, and A Kaczorowski. Clearing key barriers to mass adoption of augmented reality with computer-generated holography. In *Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR)*, volume 11310, page 113100B. International Society for Optics and Photonics, 2020.