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Perceptually guided Computer-Generated Holography

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ABSTRACT

Computer-Generated Holography (CGH) promises to deliver genuine, high-quality visuals at any depth. We argue that combining CGH and perceptually guided graphics can soon lead to practical holographic display systems that deliver perceptually realistic images. We propose a new CGH method called metameric varifocal holograms. Our CGH method generates images only at a user's focus plane while displayed images are statistically correct and indistinguishable from actual targets across peripheral vision (metamers). Thus, a user observing our holograms is set to perceive a high quality visual at their gaze location. At the same time, the integrity of the image follows a statistically correct trend in the remaining peripheral parts. We demonstrate our differentiable CGH optimization pipeline on modern GPUs, and we support our findings with a display prototype. Our method will pave the way towards realistic visuals free from classical CGH problems, such as speckle noise or poor visual quality.

Keywords: Computer-Generated Holography, Foveated Rendering, Perceptual Graphics, Varifocal, Gaze-Contingent, Differentiable Optimization, Metamerization

1. INTRODUCTION

Enhancing display technology to enable perceptually three-dimensional images has attracted much attention from relevant scientific communities as displays are essential for future Human-Computer Interaction.[1] As an emerging trend, Computer-Generated Holography (CGH) promises to improve visuals in the next generation displays[2] while enabling novel applications and experiences.[3–5] Unlike conventional displays, pixelated images are not sent to holographic displays directly. Instead, in typical phase-only SLM-based holographic displays, we must determine the phase values required to generate the desired visuals through interference and diffraction. Computing these phase values per frame at interactive rates remains a challenge as the relationship between desired visuals and phase values is complex. The generation of high-quality visuals without artefacts is a significant challenge for CGH. Thus, whilst CGH is a promising technique, it is not yet convenient.

In conventional display literature, gaze-contingent approaches[6–9] are known to reduce demands in terms of hardware and computational load. For this purpose, we ask ourselves whether exploiting gaze-contingency for CGH can help meet the Human-Visual System (HVS) demands in practice.

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2. METAMERIC VARIFOCAL HOLOGRAPHY

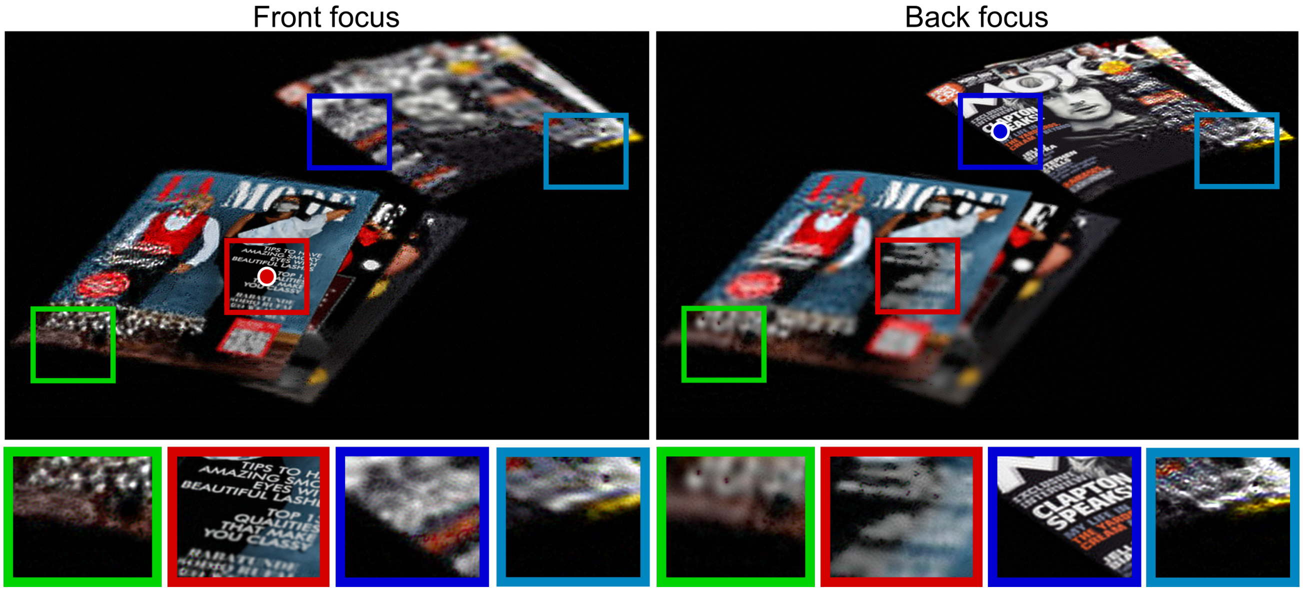

Figure 1. Simulated reconstutions of metameric varifocal holograms. Our holograms reconstruct single-plane images at the correct focus levels. These holograms reconstruct high-resolution visuals at a user's fovea while displaying statistically correct content across their peripheral vision indistinguishable from the target images (metamers). Top row: simulated image reconstructions at two different focus levels (gaze location marked with a dot). Bottom row: contains zoomed-in insets from these two reconstructions. Best viewed at a 60 cm wide display from a viewing distance of 80 cm. We intentionally choose sparse content as a target image to depict our approach's suitability for the emerging trend of augmented reality displays. (Three-dimensional assets from Vilém Duha ©2021)

Knowing the user's gaze gives us two critical pieces of information we exploit in this work (see Fig. 1).

First, it tells us which parts of the image fall in the user's periphery rather than their fovea. To exploit this, we draw inspiration from state of the art in foveated graphics literature.[10] This work focuses on generating visuals that are not pixel-accurate to a target image in the periphery of the user's vision but are still perceived as identical to the target. We exploit their work to dedicate more of the expressive power of the SLM to generating high-quality visuals at the fovea as described in work by Chakravarthula et al.[11] In contrast, visuals at the periphery need only be statistically correct and will still be perceived as accurate. As highly accurate simulation models become available in the future, such a method can pave the way towards distributing the speckle-noise at a holographic display[12] in a statistically correct way, enabling indistinguishable images at the periphery in the future.

Second, given the depths of each pixel in the displayed image, it allows us to infer the user's current focal depth. We can use this information only to enforce our reconstruction to be correct at the user's current focus. Whilst CGH is undoubtedly capable of displaying multi-plane images, this often leads to image quality issues as the hologram pixels are used to deliver images at multiple planes at once. For that purpose, we draw inspiration from existing literature on varifocal near-eye displays[7] and varifocal holograms.[13] We argue that generating images at a single plane instead of multiple planes will help assure quality in visuals generated by CGH. We envision combining these described arguments to enable CGH computation pipelines that are perceptually accurate and offer high visual quality.

Having all these benefits in mind, we derive a perceptually guided CGH pipeline, and we introduce technical details of our CGH pipeline in our main publication.[14] We call this new pipeline a metameric varifocal CGH and built it using our holography simulation library[15] and learned light transport method.[16] There are three primary parts of our pipeline these are as follows:

(1) Metameric loss function. We introduce a fast metameric loss that can help us quantify image quality within the peripheral field of view by comparing the statistics of images. We believe this loss couples well with a gaze-contingent display and graphics application, specifically holographic displays, as they are often proposed as the next-generation display technology.

(2) Metameric varifocal holograms. We introduce a complete optimisation pipeline for metameric varifocal holograms using our metameric loss function. Note that our holograms change focus in a gaze-contingent manner, avoiding the complexity of representing light fields or multiplane images using CGH;

(3) Proof-of-concept prototype. We build a single colour holographic display to experiment with our metameric varifocal holograms. We assess the results of our CGH method using this proof-of-concept display.

3. CONCLUSION

We argue that gaze-contingent CGH can be the key to achieving a practical holographic display with perceptually accurate three-dimensional visuals. For this purpose, we build upon state-of-the-art perceptual graphics. We formulate a new differentiable hologram optimisation pipeline that relies on our perceptually guided loss function. Rather than reconstructing imperfect three-dimensional scenes, our CGH method can reconstruct visuals right at the user's focus. It offers improved image quality at the fovea, while displaying true metamers of target images in the periphery. Using gaze-contingency, we formulate our phase optimisation as a two-dimensional image reconstruction problem, removing the need to match a light field or multiplane image. In this way, our CGH method paves the way towards a practical holographic display that provides perceptually accurate three-dimensional visuals with a less demanding data overhead.

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