Enhancing Brightness with Multi-Color Holography

Koray Kavaklı*, Liang Shi**, Hakan Urey*, Wojciech Matusik**, Kaan Akşit***

***Koç University, Istanbul Türkiye**
****Massachusetts Institute of Technology, Cambridge, MA, Unites States**
*****University College London, London, United Kingdom**

Abstract

Holographic displays traditionally project full-colored holograms time-sequentially to achieve colored images. Time-sequential image formation limits the achievable brightness levels. This work introduces a new method to achieve brighter images in holographic displays. Unlike the usual approach, our method allows three light sources to simultaneously illuminate the displayed holograms at different intensity levels. We optimize phase holograms along with the required intensity levels for each frame using our gradient-descent based optimization pipeline.

Author Keywords

Computer-generated holography; Holographic displays; Brightness; Multi-color holograms; phase-only holograms

1. Introduction

In recent years, there have been notable advancements in holographic displays, holding the potential to provide high-quality three-dimensional (3D) images [1] at interactive rates [2], all within compact, slim eyeglass-like form factors [3]. However, holographic displays have yet to prove themselves in achieving perceptual realism, and one of the roadblocks is their brightness levels. In a typical holographic display, Spatial Light Modulator (SLM) can form full-color images by time-sequentially displaying single-color holograms while illuminated with single wavelength light source. Increasing brightness levels in holographic can be achieved by hardware modifications such as adopting light sources with higher power ratings. However, this introduces risks such as eye safety concerns for users, unwanted heat generation, and increased hardware costs and complexity (e.g., requiring more powerful cooling units), particularly for mobile or wearable display applications. Holographic displays can attempt to render scenes with brightness levels surpassing the peak intensity of their respective color channels. it often results in darker images than intended, causing visual distortions and color mismatches. This case is illustrated in Figure 1 (Left) In such instances, the achievable brightness range is usually confined to the peak intensity of the light source. Therefore, new hologram computation methods are required in order to increase the brightness in holographic displays.

Our work achieves improved brightness levels over conventional methodology by introducing our multi-color optimization scheme for holographic displays. Our new Computer-Generated Holography (CGH) driving scheme allows optimized holograms to operate across multiple light wavelengths. We compute these multi-color holograms using a Gradient Descent (GD) based solver, guided by a blend of application-specific loss functions. Our pipeline co-optimizes the intensity levels that are required to illuminate each multi-color hologram. Using our multi-color hologram computation pipeline, we experimentally demonstrate artifact-free and color-accurate reconstructions with higher peak brightness levels.

2. Related Work

The development of High Dynamic Range (HDR) technology to improve brightness levels in traditional displays has been investigated in span of two decades [4]. Moreover, ongoing research is specifically delving into tailored HDR versions for VR displays [5]. Previous studies have explored methods to enhance color production in displays by either reducing [6] or expanding [7] the number of color primaries. While advancements have been made in improving brightness and color accuracy in Spatial Light Modulators (SLMs) [8, 9, 10], these efforts primarily function as beam-shaping tools and can generate images like an actual display. Recently, Chao et al. [11] proposed a light-efficiency loss function to enhance brightness levels in holographic projection systems. Our work also addresses the enhancement of brightness in holographic displays while improving on supported brightness levels with respective to previous work [11].

In the context of multi-color holograms for holographic displays, nearly all hologram types, such as rainbow holograms [12] or conventional Holographic Optical Elements (HOEs) [13], can be illuminated by a broadband light source. However, illuminating these holograms often results in distorted or spatially separated reconstructions. Notably, designing or optimizing such holograms to function simultaneously with multiple light wavelengths is rare, unless these holograms serve a specific function, such as beam-shaping or steering, within optical components [14] like relay lenses or mirrors.

Figure 1: Photographs demonstrating the contrast between conventional (left) and our approach (right) when aiming for ×1.8 brightness (Source image: Midjourney, Link: Github:complight/images).

3. Multi-color Hologram Synthesis

Our approach relies on a power-adjustable light source, often available in consumer level laser light engines. Our multicolor hologram technique involves optimizing three phase patterns, each illuminated by multiple color primaries at varying light intensities. This diverse set of illuminations help form a multi-color hologram [15]. Let T represent the total subframes needed to reproduce one color image,

$$\hat{u}_t, \hat{l}_{(p,t)} \leftarrow \underset{u_t,\, l_{(p,t)}}{\operatorname{argmin}} \sum_{p=1}^{3} \left\| \left(\sum_{t=1}^{T} \left| l_{(p,t)} e^{i \frac{\lambda_p}{\lambda_{p_{anchor}}} u_t} * h_p \right|^2 \right) - s I_p \right\|_2^2$$

where p denotes the index of a color primary, u_t is the SLM phase, $\hat{u}_t$ is the optimized SLM phase, h_p is the wavelength-dependent light transport kernel [16, 17], I_p is the target image

ISSN 0097-996X/24/5502-0809-$1.00 © 2024

intensity, s is an intensity scaling factor, set by default to 1, $*$ denotes the convolution operation, $l(t,p)$ represents the laser amplitude for the p-th primary at the t-th subframe, where λ_p denotes the wavelength of the active primary, and $\lambda_{p_{anchor}}$ signifies the wavelength of the anchor primary. The anchor primary's wavelength (e.g., λpanchor = 515 nm in our hardware prototype) serves as the reference for the nominal value of the SLM phase calibration. Our optimization pipeline supports both phase-only [1] and double phase encoding methods [2, 16]. Our optimization also allows higher refresh rates when T is set as 2 or 1. However, in our observation $T = 3$ provides the best color accuracy.

Our multi-color hologram generation pipeline utilizes a loss function with three components,

$$L_{total} = w_1 L_{image} + w_2 L_{laser} + w_3 L_{variation}$$

Where w_1, w_2, w_3 are wights for each loss component. L_{image} checks the quality of our reconstructed images, we largely adapted this component from Kavaklı et al [16]. L_{laser} encourages the sum of laser intensities across the subframes to match the scaled maximum intensity of the target image. Finally, $L_{variation}$ introduces a regularization term to ensure smooth phase profiles for the optimized phase holograms. Further detail on the implementation details of L_{laser} and $L_{variation}$ can be found in our full technical manuscript [15].

4. Evaluation

We evaluated the achieved brightness levels using our holographic display prototype. In Figure 3, the photographs from our holographic display show the results for both conventional and multi-color schemes. For a given scene in Figure 3, our scheme robustly sustains peak intensities up to ×1.8 without introducing significant image distortions or artifacts. In contrast, conventional holograms struggle to support peak intensities beyond ×1.0. This effect is also visible for other results that are presented in Figure 3. Beyond ×1.0 peak intensity, conventional images are often heavily affected by noise. On the other hand, our method allows higher peak brightness levels with some loss in color integrity.

Table 1. The ablation study for our multi-color holograms using the scene in Figure 2 and in house built holographic display. We systematically remove one component at a time from our pipeline and report image quality metrics.

Removed component	PSNR (dB)	SSIM	LPIPS
Double phase constrain	11.48	0.32	0.72
Variation loss	13.72	0.57	0.55
Laser loss	19.04	0.81	0.38
-	19.17	0.81	0.37

To further assess our optimization model, we also conducted an ablation study. Table 1 presents our study's results, employing PSNR, SSIM, and LPIPS image quality metrics. We perform an ablation study by systematically removing one component at a time: double phase constraint, variation loss, laser loss, and running the complete optimization pipeline without removal. For this we used the scene depicted in Figure 2 while targeting ×1.8 brightness levels. Our findings highlight the importance of total variation loss and phase constraint in preserving image quality. Moreover, practical observations indicate that laser loss contributes to maintaining accurate colors in reconstructed images.

5. Discussion

Our multi-color holograms can enable brighter images in holographic displays without modifying any hardware components. Furthermore, there might be potential other benefits of multi-color holograms. In our evaluations, we use three subframes as it provides the best color accuracy. However, as previously discussed in the previous section, our method could also use a lower number of frames as it is depicted in Figure 2. Fewer subframes can particularly be useful to increase the refresh rate when the targeted images are monochrome or don't contain high intensity values.

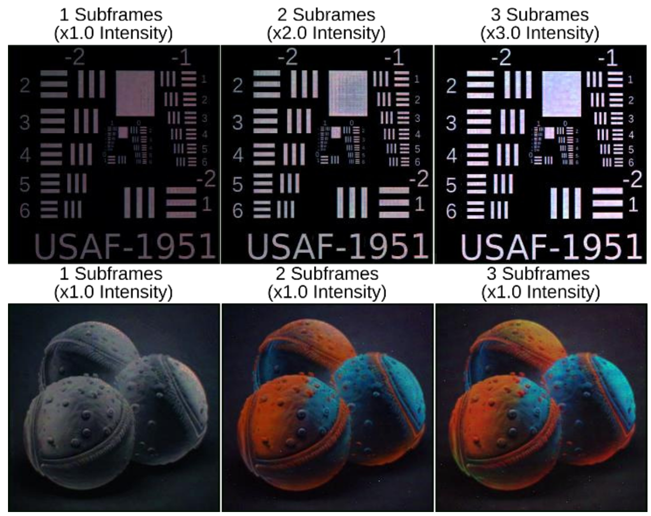

Figure 3: Employing fewer subframes using multi-color holograms. Photographs represented in the first row shows the peak brightness increase for a grayscale content. The second row demonstrates the color reproduction quality increase for a full-color scene with the increasing number of subframes (Source image: Midjourney, Link: Github:complight/images).

There are also some limitations for multi-color holograms. First, the maximum achievable brightness scale is significantly dictated by the spatial color distribution of the scene. In instances where color primaries are entirely separated within a scene, the optimization of multi-color holograms cannot provide a peak brightness greater than x1.0. In such scenarios, our multi-color hologram optimization routine returns the identity matrix as laser powers, like the behavior of conventional holograms. Secondly, despite the peak brightness enhancement, dynamic contrast may not be increased, in fact it could be marginally reduced. As multi-color holograms depend on multiple light sources operating simultaneously, they require more time. This may result in more unmodulated light due to the limited diffraction efficiency of the SLMs. Consequently, although peak brightness increases, black levels may not be preserved perfectly. Furthermore, unlike conventional models that aim for an optimal response in a single color, in multi-color holograms, each sub-frame requires balancing to approximate the desired scaled target image across all three color channels. This may also cause our method to find results that could cause minor deviations in color production. Further analysis of multi-color holograms may overcome these problems, particularly by employing perceptual color methods [18].

Figure 2: Photographs demonstrate our method achieving up to ×1.8 peak intensity without artifacts or distortions whereas conventional holograms struggle to exceed ×1.0 (Source image: Midjourney, Link: Github:complight/images).

Lastly, the optimization process of multi-color holograms is slow. In our results we utilized 1000 steps with 0.015 learning rate. The recent works in the field demonstrated that it possible to achieve faster convergence by introducing a learned method for estimating the optimal light source powers required for illuminating multi-color holograms [19].

6. Acknowledgements

We thank the knight of holography, Professor Byoungho Lee, for his services in the field [18]. The authors thank anonymous reviewers for their feedback. Kaan Akşit is supported by the Royal Society's RGS/R2/212229 and Meta Reality Labs' inclusive rendering initiative. Liang Shi is supported by Meta Research PhD Fellowship. Hakan Urey is supported by the European Innovation Council's HORIZON-EIC-2021-TRANSITION-CHALLENGES program (101057672) and Tübitak's 2247-A National Lead Researchers Program (120C145).

References

Note: As of the 2020 technical program and digest, authors should use the Vancouver reference style.

Last name of author followed by initial, et al. for more than six authors, etc. Example below:

[1] Suyeon Choi, Manu Gopakumar, Jonghyun Kim, Matthew O'Toole, Gordon Wetzstein. 2022. Time-multiplexed Neural Holography: A flexible framework for holographic near-eye displays with fast heavily-quantized spatial light modulators In ACM SIGGRAPH 2022 Conference Proceedings. 1–9.

[2] Liang Shi, Beichen Li, Changil Kim, Petr Kellnhofer, and Wojciech Matusik. 2021. Towards real-time photorealistic 3D holography with deep neural networks. Nature 591, 7849 (2021), 234–239.

[3] Jonghyun Kim, Manu Gopakumar, Suyeon Choi, Yifan Peng, Ward Lopes, and Gordon Wetzstein. 2022. Holographic glasses for virtual reality. In ACM SIGGRAPH 2022 Conference Proceedings. 1–9.

[4] Helge Seetzen, Wolfgang Heidrich, Wolfgang Stuerzlinger, Greg Ward, Lorne Whitehead, Matthew Trentacoste, Abhijeet Ghosh, and Andrejs Vorozcovs. 2004. High dynamic range display systems. In ACM SIGGRAPH 2004 Papers. 760–768.

[5] Nathan Matsuda, Alex Chapiro, Yang Zhao, Clinton Smith, Romain Bachy, and Douglas Lanman. 2022. Realistic Luminance in VR. In SIGGRAPH Asia 2022 Conference Papers. 1–8.

[6] Fu-Chung Huang, Dawid Pajak, Jonghyun Kim, Jan Kautz, and David Luebke. 2017. Mixed-primary factorization for dual-frame computational displays. ACM Trans. Graph. 36, 4 (2017), 149–1.

[7] Isaac Kauvar, Samuel J Yang, Liang Shi, Ian McDowall, and Gordon Wetzstein. 2015. Adaptive color display via perceptually-driven factored spectral projection. ACM Trans. Graph. 34, 6 (2015), 165–1.

[8] Jorge Albero, Pascuala García-Martínez, José Luis Martínez, and Ignacio Moreno. 2013. Second order diffractive optical elements in a spatial light modulator with large phase dynamic range. Optics and Lasers in Engineering 51, 2 (2013), 111–115.

[9] Jeffrey A Davis, Benjamin K Gutierrez, Ignacio Moreno, and Don M Cottrell. 2020. Spatial light modulators with large phase-modulation: application to encode lenses with very short focal lengths. In Advances in Display Technologies X, Vol. 11304. SPIE, 57–62

[10] Elisabet Pérez-Cabré and María S Millán. 2016. First-order and multi-order diffractive lens using a device with 8π phase modulation range. In 2016 15th Workshop on Information Optics (WIO). IEEE, 1–3.

[11] Brian Chao, Manu Gopakumar, Suyeon Choi, and Gordon Wetzstein. 2023. High brightness holographic projection. Opt. Lett. 48, 15 (Aug 2023), 4041–4044.

[12] Hyon-Gon Choo, Maksymilian Chlipała, and Tomasz Kozacki. 2018. Image blur and visual perception for rainbow holographic display. In Optics, Photonics, and Digital Technologies for Imaging Applications V, Vol. 10679. SPIE, 195–201.

[13] Ozan Cakmakci, Yi Qin, Peter Bosel, and Gordon Wetzstein. 2021. Holographic pancake optics for thin and lightweight optical see-through augmented reality. Optics Express 29, 22 (2021), 35206–35215

[14] Koray Kavaklı, Hakan Urey, and Kaan Akşit. 2022. Learned holographic light transport. Applied Optics 61, 5 (2022), B50–B55.

[15] K. Kavaklı, L. Shi, H. Ürey, W. Matusik and K. Akşit. Multi-color Holograms Improve Brightness in Holographic Displays. 2023. In SIGGRAPH Asia 2022 Conference Papers. 1–11.

[16] Koray Kavaklı, Yuta Itoh, Hakan Urey, and Kaan Akşit. 2023. Realistic Defocus Blur for Multiplane Computer-Generated Holography. IEEE VR 2023 (March 2023).

[17] Koray Kavakli and Kaan Akşit. 2022. Introduction to Odak: a Differentiable Toolkit for Optical Sciences, Vision Sciences and Computer Graphics, In Frontiers in Optics + Laser Science 2022 (FIO, LS). Frontiers in Optics + Laser Science 2022 (FIO, LS), FTu1A.1.

[18] Ahmet H Güzel, Jeanne Beyazian, Praneeth Chakravarthula, and Kaan Akşit. 2023. ChromaCorrect: prescription correction in virtual reality headsets through perceptual guidance. Biomedical Optics Express 14, 5 (2023), 2166–2180.

[19] Yicheng Zhan, Hakan Urey, Qi Sun, Kaan Akşit. 2024. AutoColor: learned light power control for multi-color holograms. Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR) V, Vol. 12449. SPIE

[20] YongKeun Park, Jae-Hyeung Park, Hwi Kim, Hong-Seok Lee, Yoshio Hayasaki, and Ting-Chung Poon. 2023. The knight of holographic displays. Nature Photonics (19 Jan 2023). https://doi.org/10.1038/s41566-022-01150-4.