Empowering Head-up AR: Leveraging Holographic Display Engine, Geometry Optical Combiner, and Learned Calibration

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Figure 1: Conceptual illustration of a holographic HUD that applies to windshield AR navigation scenarios and supports multi-plane display experience, leveraging an off-the-shelf free-form geometry optical combiner, which can be compensated by a learning-empowered, calibrated hologram generation algorithm to deliver virtual 3D scenes without distortion.

ABSTRACT

Holography, enabling next-generation Augmented Reality Head-Up Displays (AR-HUDs) through precise wavefront control of light, offers compelling advantages including natural depth perception, enhanced visual comfort, aberration correction, and reduced power consumption. However, widespread adoption of holographic displays, particularly in AR scenarios that incorporate optical combiners, has been hindered by persistent challenges in image quality. This work demonstrates how the state-of-the-art learned, camera-calibrated Computer-generated Holography (CGH) algorithms can mitigate this limitation, delivering compelling holographic imagery on a prototype AR-HUD. Crucially, the system employs an off-the-shelf freeform optical combiner, providing adaptability to diverse windshield shapes that could facilitate future practical automotive integration.

KEYWORDS

Holography, Head-up Display, Augmented Reality, Calibration

ACM Reference Format:

Wenbin Zhou, Xiangyu Meng, Li Liao, Yifan Peng. 2018. Empowering Head-up AR: Leveraging Holographic Display Engine, Geometry Optical Combiner, and Learned Calibration. In *Proceedings of XXX (Conference acronym 'XX)*. ACM, New York, NY, USA, 3 pages. https://doi.org/XXXXXXX.XXXXXXX

Conference acronym 'XX, 2025, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/2025/12
https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Head-up displays with augmented reality (AR-HUDs) exhibit great potential for various applications including entertainment, education/training, medical visualization, and automotive/robotic assistance. Although existing research [1, 5] has made encouraging progress in developing see-through HUDs for 2D content, the lack of 3D cues hinders the immersive depth perception and spatial intuition critical for applications demanding realistic interaction or precise spatial judgment. In contrast to multi-view, light field, and volumetric displays, holographic displays provide depth control of 3D content along with inherent benefits in aberration correction, compact form factor, and high dynamic range [8].

Embedding holographic light engines into AR-HUDs typically requires an optical combiner to blend virtual image with real-world scene (Figure 1). Recent work utilizing diffractive waveguide combiners has achieved state-of-the-art imagery quality and compelling 3D depth cues [2]. Notably, these solutions can encounter challenges including high cost, complex manufacturing, and reduced energy efficiency. Holographic displays with geometric combiners can offer both compact form factor and low cost [7]. However, distortion calibration still requires tedious algorithms or hardware [3, 4]. In light of these, we seek to leverage a learned, camera-calibrated wave propagation model to compensate for optical aberrations induced by the curved windshield-type optical combiner to deliver 3D content in reasonably high fidelity. Our main contributions include:

- We present an AR-HUDs with the geometry optical combiner for lightweight and cost-effective 3D holographic displays.
- We explore a set of CGH algorithms to calibrate the wave propagation and geometric distortion for AR-HUDs.
- We validate the proposed method in experiments with a windshield-type optical combiner, allowing seamless integration of holography across various optical see-through AR platforms.

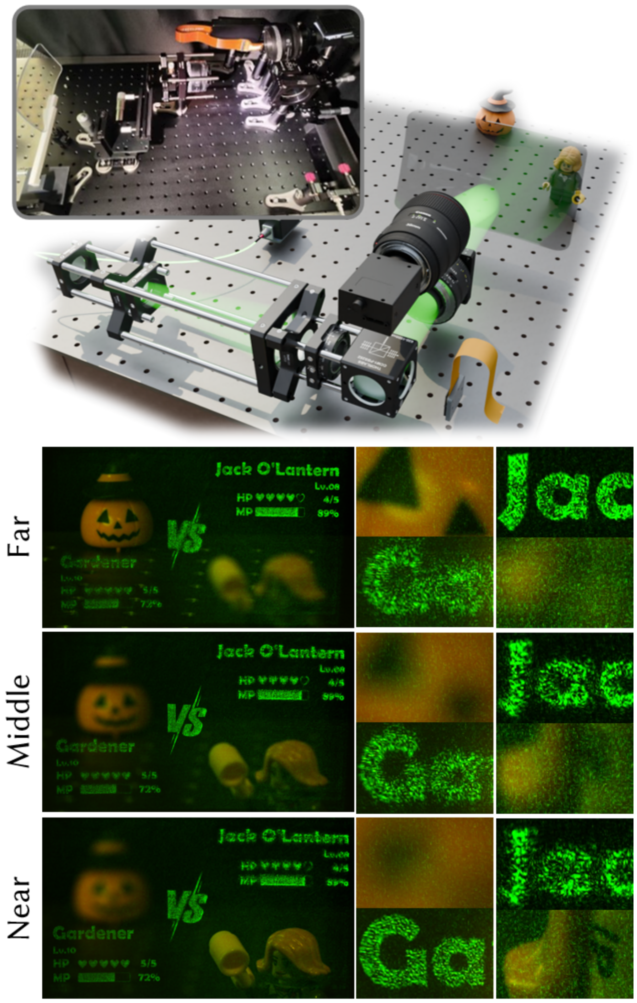

Figure 2: Our holographic AR-HUDs prototype and experimental results. Top: photograph and illustration of the prototype. Bottom: captured holographic display results on three depth planes. Zoomed-in patches reveal in-focus/defocus effects for real and virtual scenes across depths.

2 METHOD AND RESULTS

2.1 HUD Configuration

Figure 2 illustrates our holographic AR-HUD prototype and experimental results. The prototype leverages a phase-only SLM (HDSLM80R-Plus) operated at 60 Hz with the 8μm pixel pitch. The SLM has a resolution of 1,920×1,080 with a bit depth of 10 bits. We utilize a single-color (Green) laser operated at a wavelength of 524.9 nm. All results were captured with a FLIR Grasshopper3 color USB3 vision sensor through a Canon EF 50 mm lens, which can refocus at different depths. We utilize a Nikon 50 mm DSLR lens as the eyepiece, which yields an eye box of 3.28 mm in both directions, following established settings [6]. Additional optical components are utilized, including a polarized beam splitter, collimating lens, polarizer, iris, and neutral density filter.

To verify depth cues of holography, we optimize a 3-depth phase-only hologram, which can focus on the near, middle and the far plane. The 2 real objects (character and pumpkin) are placed at near and far depths, same as the virtual planes. Captured images at 3 these depth planes demonstrate that our holographic AR-HUD prototype provides nearly aligned defocus effects that are consistent with the real scene.

2.2 Calibrated Hologram Generation

Compared to VR holographic displays, the geometry optical combiner adopted in AR-HUDs can introduce extra aberrations and distortions. To calibrate these optical aberrations and other SLM imperfections, we apply the CITL framework [6] with the established stochastic gradient descent (SGD) algorithm to optimize phase-only holograms, minimizing losses between captured and target RGB-D images. The CITL framework can effectively reduce aberrations introduced by curved combiners, especially distortion around edges.

To further model the diffraction induced by the combiner in addition to the geometric distortion, we model the windshield's phase delays using Zernike polynomials with learnable parameters. Additionally, we use two CNNs to construct this learned forward model: the first to model the imperfections of the light source and SLM, such as laser uniformity, SLM crosstalk, and phase-voltage response; while another to model the lens aberrations of the eyepiece and the camera lens. A mask function at the Fourier plane is applied to simulate the iris.

We train the forward model on a dataset consisting of holograms and their captured images at the proposed prototype. The holograms contain natural images and common optical phase functions that are generated by various CGH methods to prevent overfitting. The SGD method is then adopted with the trained forward model to reduce geometric distortion while improving image contrast. To accelerate hologram generation, we can adopt a neural network-based inverse model [9] trained on a dataset consisting of phase-only holograms and target images to infer 3D holograms for 3 channels in real-time.

2.3 Summary

In this work, we demonstrate a set of learned, camera-calibrated CGH algorithms for holographic AR-HUDs, built upon off-the-shelf geometric optical combiners. Beyond displaying the captured scenes on a monitor, we will set up an additional beam splitter for users to directly view the output of this AR-HUDs prototype. In such a way, users can perceive 3D content through the windshield combiner projected at designated depths, experiencing holographic displays with nearly true depth perception using their own eyes.

We envision this AR-HUDs design has great potential in applications such as in-vehicle HUDs, exhibitions, and education. To further improve our holographic HUD, an RGB laser can be integrated and synchronized with the SLM to enable a color holographic AR-HUD. Several optical elements in existing prototype can be further optimized, and the propagation distance can be shortened to facilitate a more compact AR display.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (62322217) and the Research Grants Council of Hong Kong (ECS 27212822, GRF 17208023).

REFERENCES

[1] Shimpali Deshpande, Geeta Uplenchwar, and DN Chaudhari. 2013. Google glass. *International Journal of Scientific & Engineering Research* 4, 12 (2013), 1–4.

[2] Manu Gopakumar, Gun-Yeal Lee, Suyeon Choi, Brian Chao, Yifan Peng, Jonghyun Kim, and Gordon Wetzstein. 2024. Full-colour 3D holographic augmented-reality displays with metasurface waveguides. *Nature* 629, 8013 (2024), 791–797.

[3] Yuichi Hiroi, Kiyosato Someya, and Yuta Itoh. 2022. Neural distortion fields for spatial calibration of wide field-of-view near-eye displays. *Optics Express* 30, 22 (2022), 40628–40644.

[4] Hosung Jeon, Youngmin Kim, and Joonku Hahn. 2023. Aberration-free warp projection on a horopter screen using freeform holographic optical elements. *Optics Express* 31, 5 (2023), 7466–7479.

[5] Joshua Olexa, Kevin T Kim, Jordan R Saadon, Maureen Rakovec, Madison Evans, Jonathan Cohen, Jacob Cherian, and Maureen Rokovec. 2024. Apple Vision Pro augmented reality-assisted minimally invasive surgical treatment of spinal dural arteriovenous fistula. *Cureus* 16, 7 (2024).

[6] Yifan Peng, Suyeon Choi, Nitish Padmanaban, and Gordon Wetzstein. 2020. Neural holography with camera-in-the-loop training. *ACM Transactions on Graphics (TOG)* 39, 6 (2020), 1–14.

[7] Koki Wakunami, Po-Yuan Hsieh, Ryutaro Oi, Takanori Senoh, Hisayuki Sasaki, Yasuyuki Ichihashi, Makoto Okui, Yi-Pai Huang, and Kenji Yamamoto. 2016. Projection-type see-through holographic three-dimensional display. *Nature communications* 7, 1 (2016), 12954.

[8] Xinxing Xia, Daqiang Ma, Xiangyu Meng, Feifan Qu, Huadong Zheng, Yingjie Yu, and Yifan Peng. 2025. Off-axis holographic augmented reality displays with HOE-empowered and camera-calibrated propagation. *Photonics Research* 13, 3 (2025), 687–697.

[9] Wenbin Zhou, Feifan Qu, Xiangyu Meng, Zhenyang Li, and Yifan Peng. 2025. 3D-HoloNet: fast, unfiltered, 3D hologram generation with camera-calibrated network learning. *Optics Letters* 50, 4 (2025), 1188–1191.

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009