RAPHO : A Rapid Occluding Photochromic Occlusion Capable See-Through Display

Chun-Wei Ooi* The University of Tokyo
Yuichi Hiroi† Cluster Metaverse Lab
Takefumi Hiraki‡ Cluster Metaverse Lab
Yuta Itoh§ The University of Tokyo

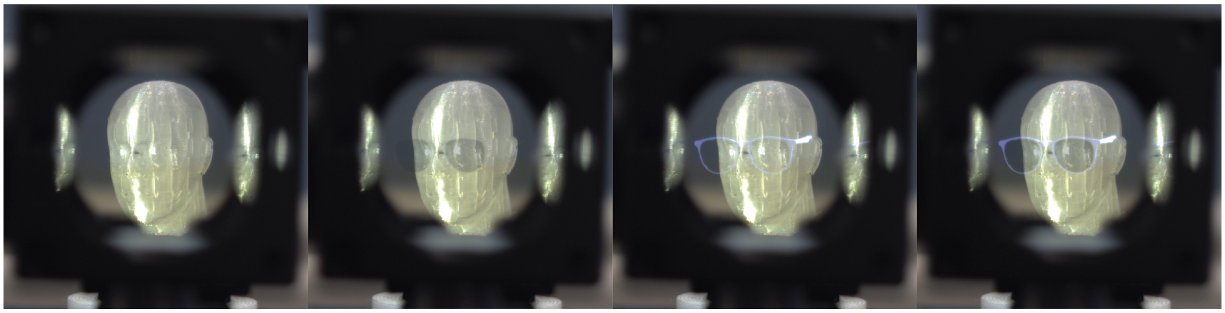

Figure 1: Rapid photochromic occlusion mask captured from the viewpoint. (a) shows a real 3d printed object. (b) shows the activated areas of the photochromic solution darken in response to UV exposure. (c) shows a CG spectacles frame overlay. (d) demonstrates the combined CG and occlusion mask for a possible AR visualization.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Communication hardware, interfaces and storage—Displays and imagers

1 Introduction

The OST-NEDs technology still faces major challenges—particularly, the ghosting effect, in which virtual objects appear semi-transparent against the background due to additive optics. This compromises depth perception, occlusion cues, and overall visual realism [2].

To address this issue, researchers have explored optical occlusion techniques, which spatially block real-world light corresponding to the projected virtual content, enabling mutual occlusion between real and virtual objects [4,5]. A widely adopted approach to achieving optical occlusion is to employ spatial light modulators (SLMs), which dynamically control the light transmission or reflection properties of a display.

However, transmissive SLMs such as liquid crystal displays (LCDs) suffer from a critical drawback of causing visual aberration in the see-through view. Due to the pixel grid structure and transparent electrodes, diffraction and scattering artifacts, known as the screen door effect (SDE), degrade the see-through image quality, making the real world appear as if viewed through a mesh screen [1, 3].

To eliminate see-through visual degradation while preserving occlusion functionality, researchers have proposed the use of photochromic materials, which reversibly change from transparent to darkened states under ultraviolet (UV) light exposure. As these materials are continuous and lack pixel structures, they can serve as optical occlusion masks without introducing diffraction artifacts. For example, Chae et al. and Ooi et al. proposed systems that project spatially modulated UV light onto a photochromic film, generating occlusion masks without SDE [1, 5]. However, the photochromic film they proposed suffers from the slow recovery time of conventional photochromic materials—typically 60 to 120 seconds—which prevents real-time occlusion control.

To address this limitation, we propose a real-time optical occlusion system using a fast-response photochromic material with millisecond-scale recovery time. This enables rapid updates to the occlusion mask, overcoming the latency barrier of previous photochromic approaches. As the available fast-response photochromic compounds must be used in liquid form, we implement a proof-of-concept system using a sealed glass cell filled with photochromic liquid. Spatially modulated UV light is used to generate high-resolution occlusion masks on demand.

We demonstrate a bench-top OST-HMD system using this approach and evaluate the optical occlusion performance both qualitatively and quantitatively. Our work shows the potential of fast photochromic occlusion masks as a viable solution for compact, real-time OST-AR systems free from SDE and optical bulk. Our main contributions include the following:

- Evaluating an occlusion layer made of a fast responsive photochromic material.
- Demonstrating a proof-of-concept display built as a bench-top system.

2 Implementation

Our prototype system implements an occlusion layer using a fast-response photochromic material, enabling millisecond-scale switching performance. Figure 1 illustrates the overall optical configuration of the system.

We use a liquid-state photochromic compound known as pseudogem-bisDPI[2.2]PC, which reversibly changes from transparent to colored under ultraviolet (UV) light exposure. Unlike conventional photochromic materials with slow fade-back times, this compound exhibits a thermal recovery time of approximately 33 milliseconds at room temperature, allowing real-time updates of occlusion masks. It also maintains consistent switching performance across a wide temperature range and under repeated cycling.

To implement this material in our optical system, we designed

*e-mail: ooic@g.ecc.u-tokyo.ac.jp
†e-mail: y.hiroi@cluster.mu
‡e-mail:t.hiraki@cluster.mu
§e-mail: yuta.itoh@iii.u-tokyo.ac.jp

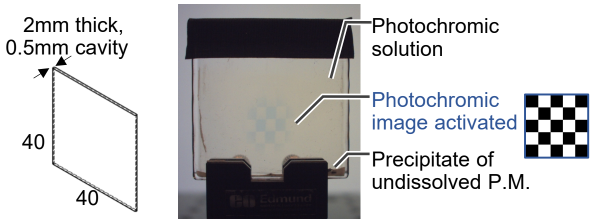

Figure 2: Custom-fabricated quartz glass cell filled with a photochromic solution. The left diagram illustrates the structure of the cell, which is 2 mm thick and includes a 0.5 mm sealed internal cavity. The center image shows the actual cell in use, with the photochromic solution, a visibly activated image pattern (checkerboard), and undissolved precipitate of the photochromic material (P.M.). The design enables a thin, uniform optical layer suitable for integration into imaging systems.

a custom-fabricated quartz glass cell filled and hermetically sealed with the photochromic solution as shown in Fig. 2. The glass cell has an overall thickness of 2mm, with a sealed internal cavity of 0.5mm containing the solution. This design provides a thin and uniform optical layer with high transmittance and stability.

UV illumination is provided by a Civillaser LSR405CP6-15W-FC fiber-coupled laser system, which emits at 405 nm. The laser beam is coupled into a 400 μm core fiber (NA:0.22) and collimated using the integrated lens system. The collimated UV beam is spatially modulated using a DMD, then directed through a beam splitter onto the photochromic plate. A long-pass optical filter (cutoff near 420 nm) is placed in the optical path after the photochromic layer to block residual blue and UV light from reaching the user-perspective camera.

As a remark, we did not conduct any experiments involving human participants in this study. All optical evaluation and occlusion visualization were conducted using a user-perspective camera placed at the eye box position in the optical system.

A separate display renders the visible AR content and is optically overlaid with the real-world view using a combiner optic. The visible and UV light paths are separated, allowing independent control of occlusion masks and virtual imagery. The spatial alignment between the UV and visible channels is calibrated geometrically.

Although the current implementation is a bench-top setup, it is designed to emulate key characteristics of the fast photochromic optical occlusion.

3 Evaluation

3.1 Response time and refresh rate

The main claim of this paper is the rapid response time of photochromic material. To evaluate the response time and also find out the refresh rate of RAPHO, we measure the time taken for the photochromic to change from transparent to its maximum opaqueness, and back to transparent. To do so, we display a white line pattern that sweep across the DMD every second, each line appears for approximately 16 ms before moving to the next row of pixels. In Figure 3, we captured a series of images using the Ximea MQ013CG-ON camera in 120 fps. In Frame 1, the lightness increases due to the UV illuminates the transparent photochromic. In Frame 2, the lightness decreases because the photochromic is activated to darken in response to the UV light. In Frame 3, the lightness decreases further because the UV light is now illuminating the next row of pixels. In Frame 4, the lightness increases again due to the photochromic is turning back to transparent until Frame 7 where the lightness returns to the previous level indicating the photochromic is completely deactivated. Each frame is 8.33 ms, so the activation of the photochromic material takes $\approx$ 8.33 ms while the deactivation to

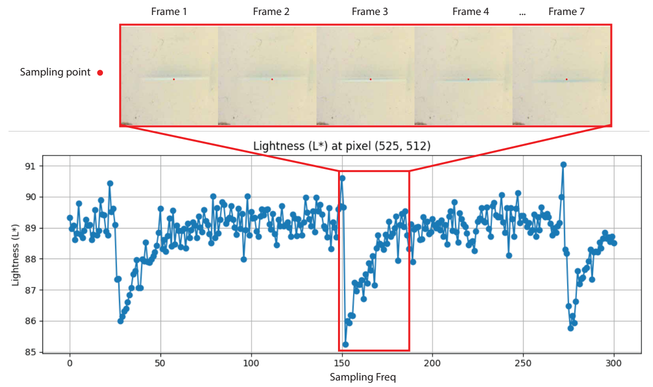

Figure 3: Top row shows the change in color of the photochromic solution when the white line(UV) passes through the sampling point frame-by-frame. The graph below shows the change in lightness corresponded to the sampling frequency.

complete transparent takes from Frame 3 to Frame 7, which is $\approx$ 41.5 ms. However, according to Steven's brightness law [6], where we do not perceive the change in lightness linearly, the transparency could be perceived as soon as at Frame 6, which equal to 33ms or 30Hz.

4 Conclusion

In this paper, we proposed an OCOST HMD using fast-responding photochromic materials. By using a photochromic solution with an exceptionally short recovery time of about 33 milliseconds, which is significantly faster than conventional photochromic materials, we achieved real-time updateable occlusion masks(30 fps). This enables reciprocal occlusion representation in AR applications, while eliminating the screen door effect that has plagued traditional LCD-based occlusion methods and maintaining high transparency without visual artifacts.

5 Acknowledgement

This research is supported by JST FOREST Grant Number JPMJFR206E, JST ASPIRE Grant Number JPMJAP2327 and JPNP23025 commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] M. Chae, K. Bang, Y. Jo, C. Yoo, and B. Lee. Occlusion-capable see-through display without the screen-door effect using a photochromic mask. *Optics Letters*, 46(18):4554–4557, 2021.

[2] J. L. Gabbard, J. E. Swan, and A. Zarger. Color blending in outdoor optical see-through ar: The effect of real-world backgrounds on user interface color. In *2013 IEEE virtual reality (VR)*, pp. 157–158. IEEE, 2013.

[3] Y. Itoh, T. Hamasaki, and M. Sugimoto. Occlusion leak compensation for optical see-through displays using a single-layer transmissive spatial light modulator. *IEEE TVCG*, 23(11):2463–2473, 2017.

[4] M. C. Macedo and A. L. Apolinario. Occlusion handling in augmented reality: Past, present and future. *IEEE Transactions on Visualization and Computer Graphics*, 29(2):1590–1609, 2021.

[5] C.-W. Ooi, Y. Hiroi, and Y. Itoh. A compact photochromic occlusion capable see-through display with holographic lenses. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 237–242. IEEE, 2023.

[6] M. E. Rudd and D. Popa. Stevens's brightness law, contrast gain control, and edge integration in achromatic color perception: a unified model. *J. Opt. Soc. Am. A*, 24(9):2766–2782, Sep 2007. doi: 10.1364/JOSAA.24.002766