Casting Virtual Shadows Based on Brightness Induction for Optical See-Through Displays

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Abstract

This paper proposes a novel method for casting virtual shadows on real surfaces on an optical see-through head-mounted display without any extra physical filter devices. Instead, the method presents shadows as results of brightness induction. To produce brightness induction, we place a texture of the real scene with a certain transparency around the shadow area to amplify the luminance of the surrounding area. To make this amplification unnoticeable, the transparency of the surrounding region is gradually increased as the distance from the shadow region. In the experiment with 23 participants, we confirmed that users tend to perceive the shadow region is darker than a non-shadow area under the conditions where a circular virtual shadow is placed on a flat surface.

Index Terms: Human-centered computing—Human-computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Human-computer interaction (HCI)—Interaction devices—Displays and imagers

1 Introduction

Optical see-through head-mounted displays (OST-HMDs) have several advantages such as wide field of view (FOV), and no latency, no insufficiency of resolution or contrast with respect to viewing the real scene including the peripheral FOV in mixed reality space. These advantages are based on the fact that a portion of the light rays from real scenes directly reaches the retina. This characteristic of OST-HMDs also becomes a disadvantage in situations where controlling the amount of incident light is required.

One example of such situations is the case where shadows are rendered on real surfaces. Shadows are an effect in which the illuminance to a surface is relatively lower than that of the surrounding area. Shadows play various important roles in virtual object perception with regard to position relative to the surrounding environment, movement of virtual objects themselves, and light sources [7]. Spatial light modulators (SLMs) allow one to control the intensity of each light ray [4]. In this approach, there is no method compatible with devices that are both small and highly transparent [3]. If projectors are available, shadows can be presented by raising the illuminance of the whole region excect the shadow area without using such SLMs [2] The adaptation functions of the human visual system, such as pupillary reflex and brightness constancy, work much as the auto gain control system in cameras does. As a result, observers feel that the shadow part becomes darker than the surrounding becoming brighter. Even if projectors are not available, it is possible to present shadows by overlaying the real texture [3] to amplify the luminance of the whole FOV except the shadow regions. However, this method is not available when the overlay FOV is narrower than the peripheral FOV, as it is in most OST-HMDs.

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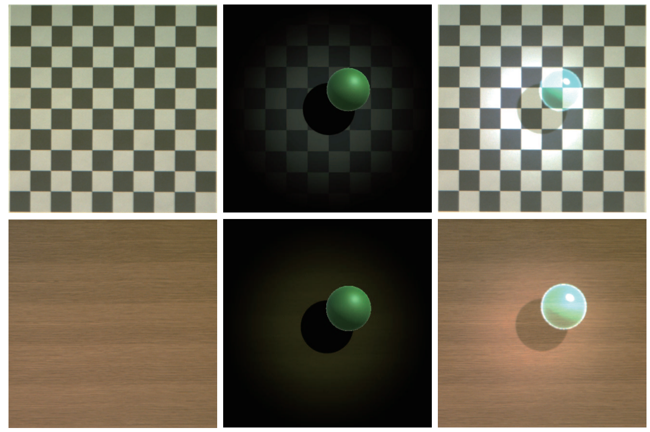

(a) Real scene. (b) Virtual objects. (c) Augmented view.

Figure 1: Virtual shadows used in the experiment. The real scene (a) and the augmented view (c) were captured through the HoloLens without and with the virtual object images displayed (b), respectively. The gradations in these images may or may not stand out depending on the color profiles of desktop displays or printers.

In this paper, we propose a method for casting virtual cast shadows real surfaces in an OST-HMD without any SLMs or projectors. The method presents shadows as results of the combination of the following two visual phenomena with regard to perception of brightness: i) overall brightness in a local area of the FOV is normalized so that an area surrounding a region with higher luminance is perceived to be darker than the real [6], ii) the human visual system is insensitive to gradual luminance changes [1]. Specifically, we place a virtual bright region (referred to as *shadow inducer*) around the area users might identify as a shadow (referred to as *shadow region*). In the shadow inducer, we set the contrast at the inner border of the shadow inducer high, and the outer border is a gradation. While a similar approach to ours has been patented [5], no experimental evidence was provided.

2 Experimental Method

We presented a circular shadow on a flat surface for simplification of the gradation. In particular, we amplified the luminance of the real scene by overlaying the real image with a transparency α as

$$O = (1+\alpha)I,$$

where I is the luminance of the light ray from the point on the real surface, and O is the luminance of the presented surface. The gradation we applied is represented by the following linear interpolation.

$$\alpha = \alpha_{\max}\frac{r_1 - r}{r_1 - r_0},$$

where $\alpha_{\max}$ is the maximum transparent coefficient, and r, r_0, and r_1 are distances from the center of the shadow, the boundary of the shadow, and the end of the gradation. In our experiment, $\alpha_{\max}$, r_0, and r_1 were set as 0.4, 40 mm, and 180 mm, respectively.

In the experiment, we investigated whether participants perceived the shadow as darker than the original area under the following three conditions using two displays (flat ordinary display and HoloLens as an HMD) and two scenes (checkerboard pattern and wooden texture).

Condition 1 For this condition, 23 unpaid participants (21 males, and 2 females; age 21 to 26) were recruited from a local university. All participants had normal or corrected to normal vision. We gave each participant a Google Form based questionnaire. We asked each participant to memorize the following three kinds of information:

- The positional relationship of the grid and the virtual object,
- A point in the shadow inducer as a reference,
- Two points X and Y in the shadow and non-shadow regions, respectively.

After that, the participants were asked to look at the camera-captured image, taken through the OST-HMD, that shows a green sphere and the surrounding region of the shadow over a real checkerboard-texture plane, as shown in Figure 1(c), and to rate the perceived brightness of X and Y assuming that the reference brightness is 100. Then, the participants were asked to input two magnitudes of their perceived brightness.

Condition 2 For this condition, 23 participants (21 males, and 2 females; age 21 to 26) with normal or corrected to normal vision were recruited in the same manner as for Condition 1. Of those, 20 had participated in the experiment of Condition 1. We showed each participant the same illustration and asked them to memorize the positions of X, Y, and the reference in the same manner as Condition 1. The participants observed the same virtual objects and background shown in Figure 1(a) not on the desktop display but through the OST-HMD so that the participants could slightly change the viewpoint from their standing point by moving their head. After that, we asked each participant to stand in front of the checkerboard and rate the perceived brightness of X and Y in the same manner as for Condition 1.

Condition 3 For this condition, 23 participants (22 males, and 1 female; age 21 to 26) with normal or corrected to normal vision were recruited similarly to the first two conditions. The same 20 participants from Conditions 1 and 2 were among the participants. Two of the others participated in Condition 2, and the third participated in Condition 1. We used a wooden surface as shown in Figure 1(a) as a background. In order to indicate where the participants should look, we displayed triangle indicators around the target area. The participants recognized the target points X, Y, and reference from the intersection of two straight lines connecting the paired triangles. Before presenting this visual stimuli, the participants asked to memorize the positions, as in Conditions 1 and 2. The method of evaluating the brightness and the target positions were completely the same as in Conditions 1 and 2.

Since there was almost no order effect in the preliminary experiments, the order of experiencing the three conditions was not counter-balanced. This experimental result also showed almost no order effects. For quantitative evaluations, we used an average of the magnitude values and a dimming rate of the shadow part X to the non-shadow one Y. For data analysis, we applied the paired t-test to compare X and Y and the Tukey-Kramer method to compare the conditions.

3 Results and Future Work

Figure 2 (a) shows the average magnitude values of the points X and Y in each condition. In every condition, the perceived brightness of the point X in the shadow area was significantly darker than that of the point Y in the non-shadow area. This result supports our hypothesis.

Figure 2 (b) shows the average dimming rate of the point X relative to the point Y in each condition. From this figure, the dimming

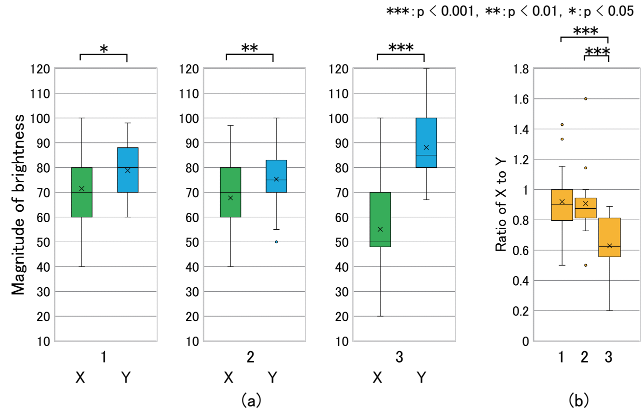

Figure 2: Results of the experiment. (a) Average magnitudes of perceived brightness of the points X and Y. (b) Average dimming rates of perceived brightness. The bottom and top of the whiskers indicate the 5th and 95th percentiles, respectively. The bottom, middle, and top of the boxes represent the 1st quartile, the median, and the 3rd quartile, respectively.

rate in Condition 3 was found to be significantly lower than that in both Condition 1 and 2 although we did not find a significant difference between Conditions 1 and 2. One natural explanation for this result may be that the dimming rate of a virtual shadow relative to the original depends on the background patterns. This is supported by previous work showing that the brightness contrast occurs more strongly when the surrounding inducer region has complex patterns [6] rather than homogeneous patterns.

Future work will include generating the shadow inducers automatically from any given scene. For this purpose, we will introduce a computational model of brightness induction in addition to conventional shadow rendering techniques such as 3D scene reconstruction, illumination environment estimation, and shadow mapping. By computing predicted perceived brightness images from camera images, the system must be able to estimate some sort of optimal shadow inducer that presents the target shadows on the predicted image. Such a computational model potentially realizes representation of situations in which a shadow exists on a non-planar surface or a plurality of shadows overlap each other. We will also confirm the usability of the proposed method in some applications.

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