Mid-air Imaging Based on Truncated Cylindrical Array Plate

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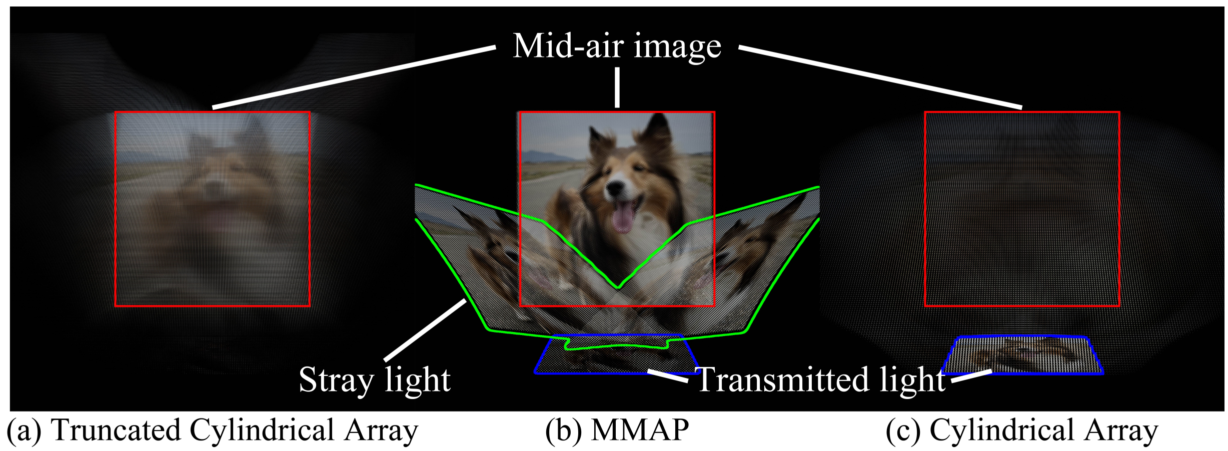

Figure 1: Mid-air images are formed by (a) our proposed design based on truncated cylinders, (b) micro mirror array plate (MMAP), or (c) cylinders. The red frame indicates the mid-air image and the green and blue frames indicate the stray and transmitted light, respectively. Images of (a) are less clear than (b), but there is no stray light.

Abstract

This paper presents a mid-air imaging optical system consisting of two dimensionally arranged truncated cylindrical optical elements. The proposed system aims to reduce the impact of stray light and improve the limited viewing range of mid-air images in micromirror array plates, an existing mid-air imaging optical system. In this study, we used ray tracing to assess mid-air images formed by our proposed optical system. The results show that our method is practical in terms of the invisibility of stray light and brightness of the image when viewed from an angle.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Displays and imagers;

1 Introduction

Mid-air imaging is a visual-information-presenting technology of AR/MR that can form real images in the physical space using optical systems, such as micromirror array plates (MMAP). This study demonstrates a mid-air image-forming optical system consisting of two-dimensionally arranged cylindrical optical elements with truncated ends, as shown in Fig. 2. The aim is to expand the horizontal viewing angle and reduce the impact of stray light.

Ray tracing was used to evaluate the optical design against three types of mid-air imaging optical systems: the proposed truncated cylindrical array (TCA), MMAP, and conventional cylindrical array [5].

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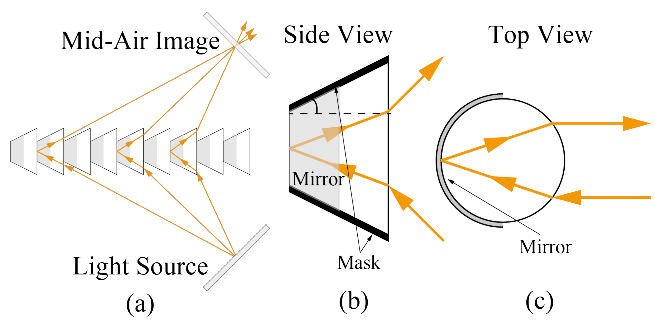

Figure 2: Principle of mid-air image formation using truncated cylinders. (a) Side view of a whole optical system consisting of truncated cylinders. (b) Side view of each truncated cylinder. (c) Top view of each truncated cylinder.

2 Related Work

Mid-air imaging can be achieved by modifying the structure of the retroreflective material. We define a 3D Cartesian coordinate system (XYZ), where the z-axis is perpendicular to the retroreflective material. Retroreflective materials reflect all XYZ components of the light rays. Mid-air imaging can be realized by modifying the structure of this retroreflective material to one in which one component of the light rays travels straight.

Mid-air imaging that changes one of the XYZ axes of the corner cube retroreflector to go straight has been proposed. Examples include a retroreflective mirror array [3], MMAP, and a dihedral corner reflector array [4].

Mid-air imaging that modifies one of the XYZ axes of the retroreflective beads to go straight has also been proposed. Takenaka proposed a structure in which transparent cylinders were

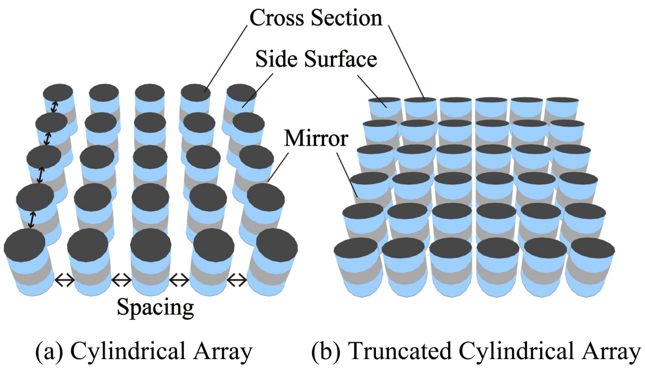

Figure 3: Comparison of (a)cylindrical array and (b)TCA in mid-air imaging optical system. The blue part indicates the side surface of the cylinder, which is the light path for mid-air imaging. The black part indicates the cross-section that does not contribute to forming a mid-air image. Using truncated cylinders makes it possible to increase the intensity of light for forming the mid-air image.

two-dimensionally arranged [5]. The optical system consists of a cylinder with transmission and reflection surfaces. The mirror reflected light from the lateral surface of the cylinder on the opposite side and re-emitted it onto the incident side. However, it has yet to be implemented, and its theoretical limits have yet to be tested.

Several methods have been proposed to simulate mid-air imaging optical systems. Kiuchi *et al.* employed ray tracing to simulate the appearance of mid-air images [2]. Ray tracing is also used in designing optical systems. Jang *et al.* used ray tracing to design and optimize a holographic optical element system [1]. Similar to these studies, we designed the proposed optical system using ray tracing, which reproduces the image formation and stray light.

3 Principle

In this paper, we propose a structure in which both ends of a cylinder are cut diagonally, as shown in Fig. 2. In a plane parallel to the TCA, the optical element returns light rays to the light source, similar to a retroreflective glass bead. In contrast, the component of the ray perpendicular to the TCA travels straight. Light emitted from the cross-section of the cylinder is blocked because it causes stray light.

This shape enables high-resolution mid-air imaging in a specific direction, while leveraging the wide horizontal viewing angle of an optical system with cylindrical arrays because the cylinders are arranged without spacing in TCA (Fig. 3).

4 Evaluation

Instead of using an actual optical system, we used ray tracing to evaluate the mid-air image formation.

We modeled mid-air imaging optical systems in Blender and used Cycles as the rendering engine. Modeling and simulation assumed that distance 1 in Blender was 1 cm in real space. The mirror reflectance in the optical system was determined as 0.87. A Glass BSDF was used for the transmission surface of the cylinder with an index of refraction (IOR) of 1.70. The diameter of the cylinder and the spacing of the MMAP mirror array were set to 1 mm. In addition, the length of the mirror portion at the center of the cylinder was set to 0.46 mm, and the angle of the cross section at both ends of the truncated cylinder was set to 35°. The optical system occupied an area of 500 mm square, and the distance between the light source and the optical element was set to 100 mm.

The mid-air imaging optical systems were rotated with an azimuth of 0° – 40° to evaluate the relationship between the incident angle of light and the appearance of mid-air images. Mid-air images

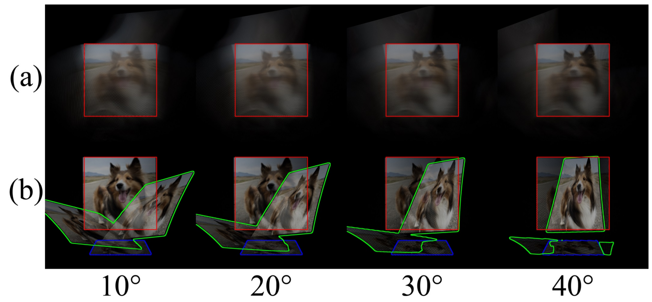

Figure 4: The angle of optical systems and simulated mid-air images formed by (a) our proposed design or (b) MMAP.

were rendered for each optical system with and without cutting the cylinder ends at an angle to investigate the effects of truncated ends and compared using the MMAP model proposed by Kiuchi *et al.*. In a conventional optical system where the ends of the cylinders are not cut, both the lengths of the upper and lower transmitting surfaces of the cylinder and the spacing of the cylinders were set to 0.46 mm. This is equal to the mirror surface length at the center of the cylinder. The spacing of the MMAP mirror array was set to 1 mm, which is the same as the cylinder diameter.

The experimental rendering results are showed in Fig. 1 (0°) and Fig. 4 (10° to 40°). The results demonstrate that the range in which the mid-air image with observable brightness can be formed is approximately 40 degrees on the side from the front. In addition, while stray light was visible in the MMAP, the proposed system produced almost no stray light that interfered with the observation. This confirmed that the visibility of the mid-air image observed from the front was improved when both cylinders' ends were cut.

5 Conclusion

We demonstrated a mid-air imaging optical system consisting of a two-dimensionally arranged truncated cylinders to obtain a mid-air image with a wide viewing angle. Our method is practical in terms of the horizontal viewing area and invisibility of stray light while observing a mid-air image from a certain angle with respect to the optical system.

Acknowledgments

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