Passive Mid-air Display

Naoya Koizumi
The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo, Japan
koizumi.naoya@uec.ac.jp

Takeshi Naemura
The University of Tokyo.
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
naemura@nae-lab.org

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Abstract
We propose a passive mid-air display in which an image is made visible by illuminating an empty space with a flashlight. In this study, we design an optical configuration that reacts to the light source of the user. This design has an inconsistency of illumination that surprises the user. We confirm the basic operational principle and measure the brightness. We also observe user behavior to consider the possibility of this technique for entertainment. With this work, we make three research contributions. First, we design a passive mid-air display that can be used for entertainment displays. Second, we confirm its operational principle and measure the brightness. Third, we observe user behavior. We also summarize the advantages of our display as well as the issues that remain.

Author Keywords
Mixed reality, mid-air imaging, passive reflective display

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g., HCI): User Interfaces.

Introduction
Many of us love adventure stories such as *The Adventures of Tom Sawyer*, *Two Years' Vacation*, and

Figure 1: Passive mid-air display. The green monster floating near the physical tree object is a mid-air image formed by our proposed method.

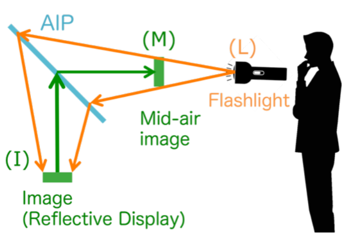

Figure 2: Optical design.

The Wonderful Wizard of Oz. Recent advances in CG technology have enabled us to visually express magical things in a more realistic way, so there are now many fantasy movies. The best part of an adventure is finding out something that nobody else knows. For example, haunted houses are extremely popular areas to explore as entertainment in the real world. In this research, we focus on the interaction design of experience discovery in the real world. What if a game player could search for an invisible ghost by lighting up a dark space with just a normal flashlight and no specialized devices? If such features could be realized, the physical world could be mixed with computational space, thus enabling people to enjoy interactions with CG characters in more intuitive ways [1].

The purpose of this research is to design an experience that enables users to see and react naturally to CG characters in an empty space using illumination. An image presenting the concept of our research is shown in Figure 1. Specifically, we have created a new optical design for an entertainment computing system that delivers inconsistency of illumination to provide users with an enticing and fantasy-like experience without any special wearable devices.

Our goal is essentially to realize a special interaction for the purposes of entertainment. We are inspired by the television series named *Yokai Watch*. In this story, a boy obtains a magical item called a Yokai watch. A Yokai is a kind of ghost that has a special optical feature. It is normally invisible, but becomes visible when a light is turned on. This interaction is also a kind of discovery story. To merge the real and computational worlds seamlessly, we have developed an interaction technique that passively reacts to the illumination conditions without any illumination sensors. We built a prototype and tested it with a flashlight to determine the validity of the proposed technique.

We make three main contributions in this work:

- We propose an illumination inconsistency design to enable exploring interaction for an entertainment computing system.
- We build a prototype of passive reaction midair imaging and confirm its validity.
- We ensured the interaction of our optical design using a physical object to prompt the user into action.

Related Work

Mid-air imaging

For displaying computer graphics images in the real world without any special wearable devices, mid-air imaging is very suitable. There are many mid-air imaging display methods in use today, such as those that use fog, laser-plasma, and optical imaging. Yagi et al. [3] and Plasencia et al. [4] proposed mid-air interaction using a fog screen. A fog screen is effective in terms of forming mid-air images and building an interactive system easily, but fog diffuses the light, thereby reducing the visibility of real objects. The use of lasers is another method for mid-air imaging [5,6], but it requires a strong and expensive light emitting device. In contrast to the above, optical imaging is suitable for our purpose because these systems only utilize mirrors or lenses that reflect or refract light rays. There are many optical designs for midair imaging. In this study, we use a plate-shaped imaging optics device called the aerial imaging plate (AIP) [7] to design a passive mid-air display. It forms a mid-air image at the

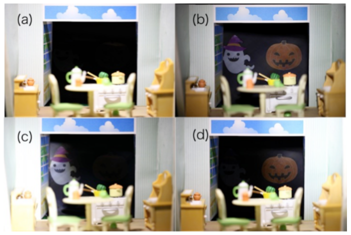

Figure 3: Mid-air image formed by optical system B. Each photo shows (a) no illumination, (b) center illumination, (c) left illumination, and (d) right illumination.

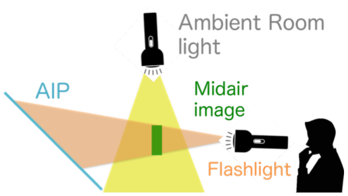

Figure 4: Requirement for light direction (side view).

plane-symmetric position of a light source using two reflections. It is convenient and easy to prototype mid-air interactions such as HaptoClone [4] or Mario [1]. The function of AIP is light transfer. In the Mario system, LCD light is transferred to form a mid-air image. In the HaptoClone system, two AIPs are used to copy the light field of each other. In other words, the consistency of illumination between two connected spaces is realized. Our purpose is slightly different in that we want to design optical inconsistency to provide a fanciful and otherworldly experience. We therefore design not only the optical device arrangements but also the illuminating direction of the environment and the user's flashlight.

Passive display

There are several passive displays in use today. For clarity, we define the two meanings of "passive:" one is to react in response to the action of a user and the other is to generate different light fields depending on the incident illumination. As examples of the former, the BiDi screen has the ability to both capture images and display them [8], and Glasner et al. introduced a programmable, spatially varying, dynamic reflectance display based on the wave optics approach [9]. As an example of the latter, Fuchs et al. presented a multi-dimensional display that passively reacts to the light of the environment behind without any sensors [10], and Yue et al. presented a technique for computing the shape of a transparent object that can generate user-defined caustic patterns [11]. In this study, we design a passive mid-air display that not only reacts to the action of the user but also integrates light from outside the system.

Proposal

Optical design

For the interaction, we adopt a flashlight as the light source. Figure 2 shows the optical design. The light ray from the flashlight goes to the AIP and is reflected to image (I). Image (I) diffuse-reflects the incident light. This image then acts as the light source of the AIP and forms a mid-air image.

We confirmed the principle for this optical design. This optical setup was able to form a mid-air image selectively using light direction. The results of the optical design are shown in Figure 3. These images demonstrate that our proposed design works well.

Consistency

For mixed reality applications, consistency is crucial when designing reality guidelines.

Our system is only composed of passive optical devices and does not require any sensors to control the luminance of the mid-air image. Therefore, there is no latency caused by user action, that is, mid-air images are formed by the light from a user-operated flashlight, and the illumination is changed without any latency.

In this design, we achieve a system that works naturally in response to user actions while also functioning in a fantasy-like way for the flashlight used as entertainment. It creates an inconsistency of illumination and can surprise players.

One of the inconsistencies relates to reflection: namely, an invisible virtual character does not reflect the environment's light but instead reflects only the user's flashlight light. To realize this experience, we designed

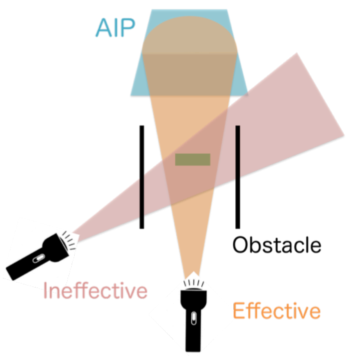

Figure 5: Obstacles to prevent ineffective light projection.

Figure 6: Walls to lead the interaction.

the direction of light as shown in Figure 4. The ambient room light is attached from above to simulate a normal situation so that users can see the physical object normally while ensuring that these light rays do not enter the AIP. This means users cannot see a mid-air image without a flashlight.

Another optical inconsistency involves shadow. Specifically, physical objects block the light and make shadows and shade, but the mid-air image does not block any light. The content designer can use this mismatch to express an otherworldly, magical feeling.

In this study, there is a limitation on the position and orientation of the user's light. It is necessary to shine the light from the user to the AIP, and the mid-air image must be placed on a straight line connecting the AIP and the flashlight.

This problem is shown in Figure 5. If the user illuminates a virtual character from the side, the light ray does not enter the AIP. In this case, the virtual character does not glow. Therefore, we designed various obstacles (described in the next section) to limit inappropriate behaviors of the user and ensure a more natural enjoyment.

Interaction Design

In order to illuminate things the user cannot see, this system needs an interaction design that prompts the user to move the flashlight naturally. At the same time, it is necessary to prevent any geometric mismatch caused by the positional relationship between the lighting and the AIP. To address these issues, we place various wall-like objects around the mid-air image to prevent the user from performing an undesired lighting operation. This results in the user projecting the light from the front of the system.

We demonstrate our proposed technique with an implementation called the "haunted dollhouse." We placed a dollhouse (Figure 6) that does not contain any dolls in front of our optical system, and when a player illuminates the dollhouse, a ghost suddenly appears. The idea here is to provide the experience of seeing an invisible character in a haunted attraction.

Evaluation

Consistency

With this optical configuration, we can control the depth position of a mid-air image by moving the position of image (I) up and down (Figure 2). Figure 7 shows a mid-air image formed by the system and the change in depth of the image. The image moves from the back to the front, and the camera keeps the image in focus at each depth.

Brightness

Because this optical system utilizes the retro-reflective feature of the AIP, the brightness of a mid-air image is changed by the viewpoint or by the illumination position. Therefore, we measured the relationship between the light of the orientation and the brightness to determine the robustness of the brightness of the mid-air image.

The experimental setup is shown in Figure 8. We used a small projector (M150, 3M) as a flashlight and measure the brightness with a CS100 luminance meter. We used the entire white screen. We fixed the CS100 in front of the AIP and a Mirasol display by Qualcomm was used as the image source. This display is a reflective-type

Figure 7: Image taken by camera focused at different depths. The rabbit in left image is 12 cm closer than the rabbit in right image. In the top image, the texture of the right card and the rabbit are in focus. In the bottom image, the texture of the left card and the rabbit image are in focus.

display. We also measured the reflectance of the Mirasol itself by placing the Mirasol in front of the AIP to calculate the attenuation of light by the AIP.

The results of the measurement are shown in Figure 9. The Mirasol display is around four times brighter than the midair image. Thus, the attenuation of our proposed optical design is about 1/4.

User Study

We exhibited our proposed system three times to about 150 participants at our open laboratory. On these occasions, we observed the user actions and obtained the following findings.

The orientation of the light is very important in this technique. To ensure suitable illumination, it is necessary to prompt the user to act, so we consider the creation of various walls to be useful in our proposed optical design. After our observation of user behavior, we were able to confirm that our proposed obstacle placement was effective. Nobody was confused about how or where to illuminate the scene. Some of the participants swung the light around and realized there was no latency. Moreover, when they rotated the flashlight by twisting their wrist, they did not report any light artifacts, as shown in Figure 5.

Brightness design

The brightness of the mid-air image is approximately 1/4 that of the direct illumination for the display when it is placed at the same position as the mid-air image, so it is possible that the user might feel a heterogeneous sense of brightness. However, nobody pointed out this problem in the demonstration. We assume this is because the environment around the mid-air image was sufficiently illuminated by the light source from the ceiling, so the flashlight did not cause too much brightness. This demonstrates that we can solve the problem of non-uniform brightness by ensuring sufficient illumination from the ceiling.

Differences in adults and children

We found a difference in the reaction of adults and children. Normally, adult audiences were surprised by our system because they understood the inconsistency of illumination. In contrast, children were not as surprised. This is because children do not really understand optical phenomena. Therefore, additional design is needed to surprise children.

Limitation of proposal optical design

There are certain limitations to our proposed design in terms of photometric consistency. One pertains to shadow representation. To achieve this expression, we need to add a method for sensing the direction of the light. This causes latency in the interaction. In other words, there is a trade-off between photometric consistency and temporal consistency. In our demonstration, some users were surprised because there was no latency.

Another issue is the glare caused by the specular reflection on the AIP itself or on the reflective display surface. Although most of the participants did not notice this, we received feedback from an optical expert who observed our system carefully. Although this is not really an issue for a system of this size, we have to consider reflection light if the system is large enough to reflect more light.

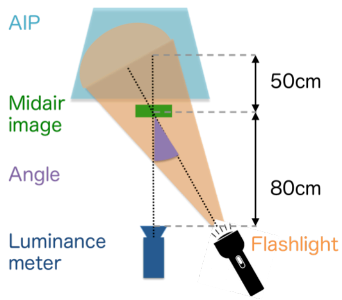

Figure 8: Experimental setup (top view).

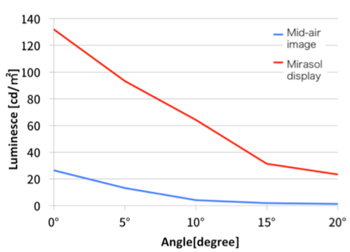

Figure 9: Brightness of the mid-air image (blue line) and of the Mirasol display (red line).

In addition, the reflective display is currently limited to two-dimensional representations. We also demonstrated the system with three-dimensional computer graphics, and some participants said it looked three-dimensional. We therefore need to determine the limits of possible pseudo three-dimensional representation using this method.

Conclusion

We have presented a new technique for passive mid-air imaging that passively reacts to illumination in real time without any illumination recording sensors. We prototyped some optical configurations and confirmed the operating principle. We chose an optical arrangement with a reflective LCD and designed an additional interaction technique that features the placement of a physical object to influence user action. We observed user actions in a real-life setting and discussed the potential of this system for entertainment use.

Acknowledgements

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