# Simulation of Mid-air Image Interaction in Virtual Reality

Ryugo Hayashi
*Graduate School of Informatics and Engineering*
*The University of Electro-Communications*
Tokyo, Japan
hayashi@media.lab.uec.ac.jp

Naoya Koizumi
*Graduate School of Informatics and Engineering*
*The University of Electro-Communications*
Tokyo, Japan
koizumi.naoya@uec.ac.jp

***Abstract*—Mid-air images are CG visuals that float in real space and can be observed without using any devices. Owing to the unique display of mid-air images, a virtual reality (VR) simulation system is essential for designing and evaluating interactions with these images. However, no such simulation has been developed thus far. We hypothesized that simulating characteristics, such as view area and occlusion problems, would result in similar user behavior in VR and real space. In this study, we propose and implement a VR system to test this hypothesis by incorporating a method to simulate the occlusion problem without measuring object shapes or positions. By comparing interactions using our method, actual mid-air images, and typical VR objects, we found that simulating the viewing area led to similar observation behavior in both VR and real space. However, significant differences in the touch interaction penetration depth indicated that independently simulating the occlusion problem was insufficient.**

***Index Terms*—virtual reality, mid-air image, touch interactions**

## I. Introduction

Advancements in virtual reality (VR) technology have enabled the recreation of real-world phenomena and experiences within the cyberworld. In VR environments, it is easy to control the surrounding environment as well as the size and appearance of objects. Consequently, VR spaces are used in various applications, including research tools and designing new assistive tools.

We are engaged in developing a VR system to design and evaluate mid-air image interactions within VR spaces. A mid-air image is a CG image formed in mid-air, which can be used as a display. Mid-air images have two main characteristics: a limited view area and occlusion problems. Designing mid-air image interactions requires an understanding of these characteristics and the use of physical devices. By simulating mid-air images using these characteristics in the VR space, individuals without specialized knowledge or equipment can easily prototype mid-air image interactions. Moreover, placing mid-air image simulations in the metaverse enables support from distant experts and facilitates user feedback collection.

Thus far, no systems have been proposed that can simulate the characteristics of mid-air images in VR spaces, and the requirements have not been clarified. Traditional mid-air image simulations are limited to designing optical devices and cannot be used for interaction design. Therefore, it is necessary to clarify the requirements for VR mid-air image simulations, which are essential for designing and evaluating mid-air image interactions within VR spaces.

The main requirements for VR simulation of mid-air images can be considered from three aspects: the characteristics of mid-air images, the characteristics of optical elements, and the real-time performance. The characteristics of mid-air images include common features such as viewing area and occlusion problems. The characteristics of optical elements depend on the optical devices used to form the mid-air image. In addition, real-time performance is essential for interactions in VR. We hypothesized that by simulating the characteristics of mid-air images, user behavior in VR would mirror their behavior in the real world. Thus, we propose the following hypotheses:

- Hypothesis 1: By simulating the view area of a mid-air image in VR, users will observe the mid-air image from the same directions as they would in real space.
- Hypothesis 2: By simulating occlusion problems, the degree of penetration when users touch the mid-air image in VR will be similar to that in real space.

In this study, we aim to test these two hypotheses through a VR system that simulates the characteristics of mid-air images. This research aims to investigate whether users interact with mid-air images in VR in the same manner as they do in real space by simulating the view area and occlusion problems. To test our hypotheses, we designed and implemented a VR system of mid-air images that allows interaction and simulates the viewing area and occlusion problems. Furthermore, we tested our hypotheses by comparing the interaction results of actual mid-air images, typical VR objects, and the proposed VR system.

The contributions of this study are as follows.

- We propose and implement a new VR system for designing and evaluating mid-air image interactions, which has been difficult with conventional simulations.
- We design a method to simulate occlusion problems without measuring the shape and position of objects contacting the mid-air image.
- We reveal that simulating occlusion problems independently is insufficient to achieve the same degree of penetration in VR touch interactions as in real space.

## II. Related Work

### A. Use of VR Environments

Several previous studies have demonstrated the use of simulations in VR environments. Ville et al. [1] conducted a field study on public displays in a VR environment and compared the results with those obtained in a real-world setting. Similarly, Mathis et al. [2] investigated the suitability of VR environments for evaluating authentication systems. These studies indicated that VR environments can be used effectively to evaluate public displays and authentication systems. They also reported the potential influence of VR technology on user behavior and evaluation outcomes. Furthermore, Uwe et al. [3] developed a tool for prototyping c ross-reality systems within VR environments, demonstrating that implementation can be made more efficient.

Based on these findings, it can be inferred that VR environments can effectively be used to design and evaluate mid-air image interactions. VR environments can easily simulate even interactions with large-scale devices, such as ultra-walls [4], which are difficult to create in real-world settings. However, to understand the impact of VR technology on the simulation and evaluation of mid-air image interactions, it is necessary to clarify the differences in interactions between VR and real-world settings. This study clarified these differences by developing a VR system capable of interacting with mid-air images and comparing it with actual mid-air image interactions, marking a pioneering effort in this area.

### B. Mid-Air Image Optical Systems

Mid-air image optical systems are designed to project images that appear to float in mid-air by manipulating the light emitted from a source through reflection, refraction, and transmission via optical elements. The formation of mid-air images employs various optical elements such as a micro-mirror array plate (MMAP), dihedral corner reflector array (DCRA) [5], roof mirror array [6], and retroreflective mirror array [7]. Additionally, systems like aerial images by retro-reflective (AIRR) [8], which combine retroreflective materials with half mirrors, also create mid-air images.

In this study, we focused on mid-air images formed by MMAP. The MMAP is chosen because of its commercial availability and the simplicity of its optical system configuration. Moreover, mid-air images produced by MMAP are generally brighter and sharper than those produced by AIRR, making them more suitable for interactive applications.

### C. Mid-Air Image Interaction

There are three considerations when designing mid-air image interactions. This section describes these in the order of importance.

First, the design of mid-air image interactions requires careful consideration of the viewing area. For example, MRsionCase [9] forms mid-air images around an exhibit. Understanding the viewing area is crucial for designing devices that allow observations over an extended range and simultaneous viewing by multiple users.

Second, it is important to consider the inherent occlusion problem between mid-air images and physical objects. Applications such as MARIO [10], Scoopirit [11], and AIR-range [12] have been proposed, each placing mid-air images near physical objects, which necessitates careful design. MARIO allows mid-air image interactions by moving images over blocks constructed by the user. Scoopirit enables the scooping of mid-air images above water. The AIR-range displays stable brightness in mid-air images adjacent to tabletop objects, facilitating user interactions with mid-air images. These applications must address the occlusion problem in device design owing to the proximity of mid-air images to physical objects.

Third, the characteristics dependent on optical elements also impact mid-air image interactions. These factors include stray light, image brightness, and sharpness. Stray light, an unwanted light that accompanies mid-air images, can hinder image observation, leading to the removal of multiple proposed methods [13] [14]. Brightness and sharpness must be designed to ensure clear imaging.

This study focuses on viewing areas and occlusion problems among these considerations. These are the general characteristics of mid-air images, independent of optical elements, and are crucial for designing mid-air image interactions. However, the characteristics dependent on optical elements were excluded from this study. Stray light can be eliminated using various methods. The brightness of the mid-air image can be controlled by varying the brightness of the light source. Furthermore, it is unclear how the sharpness of the mid-air image decreases compared to that of the light source, and there are insufficient data to simulate this. Therefore, these elements were excluded from this study.

### D. Mid-Air Image Simulation

A simulation method using computer graphics was proposed for mid-air image simulations. Kiuchi et al. [15] introduced a simulation technique for MMAP using ray tracing, which is a rendering method that traces the paths of light rays. This method accurately modeled the MMAP, simulated the paths of light rays according to physical phenomena, and successfully simulated the appearance of mid-air images and stray light. Hoshi et al. [16] proposed a method for understanding the viewing area of mid-air images through simulations using ray tracing. However, ray tracing often demands extensive rendering time, making it unsuitable for the real-time updates required for HMDs, thereby complicating its use in designing and evaluating mid-air image interactions.

This study aims to develop a VR system capable of supporting the design and evaluation of mid-air image interactions that conventional simulations do not provide. Because mid-air images are a unique display technology, there is a lack of research on how users interact with them. Conventional mid-air image simulations cannot simulate the mid-air image interactions. Therefore, a VR system that can simulate and observe user behavior is necessary to design and evaluate mid-air image interactions.

Fig. 1. Overview of Mid-Air Image Simulation: (a) Capturing the light source for appearance simulation; (b) System appearance: Placing a captured image of the light source at the position of the MMAP to simulate the occlusion problem; (c) Perceived appearance: Creating parallax by capturing the light source from appropriate positions based on the viewpoint, making the image appear to form in mid-air

Fig. 2. (a)Principle of mid-air imaging; (b)When the azimuth angle relative to the mid-air image is large, part of the image is cut off

## III. Method

In this section, we propose a VR system for mid-air images that simulates the viewing area and occlusion problems, allowing us to test the aforementioned hypotheses. This section describes our VR system for simulating mid-air images.

### *A. Simulation of Mid-Air Images*

Our VR system aims to simulate the appearance, viewing area, occlusion problems, and imaging position of mid-air images. Using a game engine capable of real-time rendering, our method is compatible with HMD operations. However, the characteristics of MMAP such as stray light, brightness, and sharpness, should be considered in future studies.

To simulate the appearance of the mid-air images, we used a captured image of the light source (Fig. 1(a)). As shown in Fig. 2(a), mid-air images are formed by light emitted from a source and passing through MMAP, thus they appear identical to the light source. Therefore, we can simulate mid-air images using the captured images of the light source.

The viewing area was simulated by rendering only within the region overlapping the MMAP as seen from the viewpoint. This is because as shown in Fig. 2(b), the mid-air image cannot be observed outside MMAP.

Fig. 3. A part of the mid-air image is occluded by the finger behind the checkerboard: (a) Actual mid-air image; (b) Our mid-air image simulation; (c) Typical VR object; (d) Positional relationship between the finger and the mid-air image.

The occlusion problem was simulated by placing the light source image at the MMAP (Fig. 1(b)). This ensured that the mid-air image was occluded by other objects located near the imaging position of the mid-air image.

The imaging position of the mid-air image was simulated by capturing the light source image from an appropriate position to create a parallax (Fig. 1(c)). Specifically, we change the capture position of the light source image according to the user's viewpoint movement to create a motion parallax. Additionally, we captured separate light source images of the right and left eyes and placed them on MMAP to achieve stereoscopic vision. This parallax caused the mid-air image to float.

A crucial aspect of our method is that by placing the light source image at the position of MMAP, the occlusion problem can be simulated based on the position of the user. If the light source image is placed at the imaging position of the mid-air image, the mid-air image appears to be occluded, as shown in Fig. 3(c). To create an occlusion problem similar to that in an actual mid-air image (Fig. 3(a)), it would be necessary to carve out the mid-air image to match the shape of the fingertip, requiring complex calculations that consider the spatial relationship and shape of objects and viewpoint. However, our method, which places the light source image at the same position as MMAP, does not require this processing.

### *B. Implementation*

To test our hypothesis, we implemented the aforementioned VR system to simulate mid-air images using a game engine. We used Unity version 2020.3.28f, developed by Unity Technologies, and employed the default rendering pipeline.

The proposed method operates in real-time in Unity. The frame rate was verified on a development machine equipped with an Intel Core i7-10700 CPU and an NVIDIA RTX A6000 GPU. When the simulation was the only element placed in the scene, the frame rate exceeded 500 fps when outputted to a

Fig. 4. Overview of the Experimental System

2D display. When the VR HMD (VIVE Pro 2) was used as the output, the VR system operated at 90 fps. Considering that the VIVE Pro 2 has a refresh rate of 90Hz, this is a sufficiently high frame rate.

## IV. Experiment

Two experiments were conducted to test our hypotheses. To test Hypothesis 1, Experiment 1 investigated the direction in which users observed mid-air images. Experiment 2 examined the penetration depth during touch interaction with mid-air images to test Hypothesis 2.

Both the experiments were conducted under three conditions: actual mid-air images (Fig. 3(a)), our mid-air image simulation (Fig. 3(b)), and typical VR objects (Fig. 3(c)). Thus, there were only one real-world and two VR conditions. In the mid-air image simulation condition, we used our VR system to simulate the characteristics of mid-air images, such as viewing area and occlusion problems. A typical VR object condition was set up without simulating the viewing area or occlusion problem.

The experiments involved 12 adult participants (11 males and one female) aged 21–24 years, all of whom had prior experience with HMD. All participants participated in both experiments consecutively and experienced all conditions. We counterbalanced the order of the experiments and conditions for each participant to offset order effects.

### A. Experimental System

An overview of the mid-air imaging apparatus used in the experiment is shown in Fig. 4. For the two VR conditions, we implemented the same apparatus design in Unity to present mid-air images. An external display connected to a PC was used as the light source for the mid-air images, as shown in Fig. 5. Button sizes were designed based on the experimental setup of Bermejo et al. [17]. The pop-out distance of the mid-air image was determined to be 48 cm after ensuring that stray light was not visible from the front by applying a louver film to the surface of the display.

Fig. 5. Mid-Air Image Buttons Used in the Experiment

The positions of the participants' viewpoints and hands were measured using an OptiTrack (PrimeX 13) optical motion tracking system. In addition, the position of the MMAP was tracked to determine the position of the mid-air image under the real-world condition. Tracking results from OptiTrack were used as positional information in Unity.

We used the VIVE Pro 2 as the HMD. The position of the HMD was tracked using SteamVR. The origin of the world space in Unity aligned with the origin of the coordinate space in the OptiTrack tracking system. The HMD had an interpupillary distance (IPD) adjustment feature and the participants adjusted the IPD when they first wore the HMD. This IPD setting is reflected in the position of the camera, representing the viewpoint of Unity.

### B. Experiment 1: Investigation of Observation Direction

This experiment aimed to determine whether users observed mid-air images from the same direction as they would with actual mid-air images by simulating the viewing area. The viewing area of mid-air images is limited, and the images may not be visible from certain positions. By simulating this characteristic, we investigated whether users in a VR environment would observe mid-air images in the view-area direction.

Participants were allowed to move freely around the mid-air image and observe it. There were no restrictions on posture during the experiment, and the participants were informed beforehand that they could move freely. The experiment consisted of one trial per condition, for a total of three trials. The procedure for each trial was as follows.

1) The participant moves to a position where they can see the mid-air image well and inform the experimenter when they are ready.
2) The participant observes the mid-air image freely for one minute.

In this experiment, we measured the direction in which the participants observed mid-air images. In the real mid-air image condition, we recorded the position of the eye mask with markers worn by the participants. In the two VR conditions, we recorded the position of the HMD. These positions were recorded in Unity for every frame during Step 2 and used to determine the azimuth angle of the participants relative to the mid-air image.

The measured observation positions of the participants were converted into azimuthal angles relative to the mid-air image for analysis. This conversion was chosen because although there is no distance restriction for observing the mid-air image, there is a limitation in the angle. Although there was also a height restriction for observing the mid-air image, height differences among the participants led to the decision to exclude height from the analysis.

The azimuthal angle of the mid-air image was defined as the front of the image at 0 ° . The movement to the right of the mid-air image was assigned a positive angle, and movement to the left was assigned a negative angle (Fig. 2(b)). This angle was calculated from the participant ' s viewpoint and mid-air image positions. In the real mid-air image condition, the position of the mid-air image was determined from the position of the MMAP and pop-out distance of the mid-air image. Under the two VR conditions, the position of the mid-air image is obtained from its position in Unity.

### C. Experiment 2: Investigation of Penetration Depth

This experiment aims to determine whether the penetration depth of a user's finger when interacting with mid-air images in VR is comparable to that in the real world by simulating the occlusion problem. Users tend to move their fingers deeper than the actual imaging position when touching mid-air images [17]. We hypothesized that this behavior was due to the occlusion problem and aimed to investigate whether this penetration depth occurs similarly in the VR environment by simulating this characteristic.

The participants touched the red button on nine mid-air image buttons using their fingertips. The experiment consisted of 36 trials per condition, totaling 108 trials. After all the conditions were met, the experimenter measured the length of the participants' fingers, and the participants were invited to freely comment on the experiment. The procedure for each trial was as follows:

1) Participants sit in a position they consider easy to touch the mid-air image button and receive instructions about the experiment.
2) One button turns red, and the participant touches that button.
3) When the participant feels they have touched the button, they say "beep" and remove their finger from the button.
4) The experimenter changes the button that turns red in response to the participant's "beep."
5) Steps 2 to 4 are repeated 36 times.

The order in which the buttons turned red was randomly generated with adjustments to ensure that the same button did not become the target consecutively. Participants were instructed to say "beep" to indicate the exact moment they felt they touched the mid-air image. This was because the preliminary experiment showed that some participants had their fingers placed deeper than in the mid-air image at the start, making collision detection at the actual imaging position difficult. Detection was based on the participant's "beep" sound.

The positions of the participants' hands and the time required to touch them were measured. The participants wore gloves with markers, and the glove positions were tracked as hand positions. The time taken to touch the button was measured from the moment the button turned red in Step 2 until the participant vocalized in Step 3. The hand positions were recorded in Unity for every frame during the measurement, and the touch time was calculated based on the elapsed time in Unity.

All the participants used their right index finger to touch the mid-air image buttons. In the real mid-air image condition, the participants used their actual hand, whereas in the two VR conditions, they used a virtual hand model that moved in accordance with their real hand. The participants were instructed to maintain their hand in a posture with the index finger extended, and the virtual hand model in the VR condition was fixed in the same posture.

The participants were seated during the experiment. The chair had casters and an adjustable height that allowed the participants to adjust freely. At the beginning of each condition, the participants moved the chair to a position they found suitable for touching the mid-air image buttons. Once the chair position was adjusted, the researcher initiated the trial.

For each condition, the first 10 of the 36 trials were considered a warm-up period for the participants to become accustomed to the task and were excluded from the analysis. The fingertip positions were calculated from the measured finger lengths and hand positions, and the penetration depth of the fingertips relative to the mid-air image was determined. For each trial, the penetration depth was calculated from the data of all measured frames, and the maximum value was used for the analysis. The time taken to touch was analyzed using only the remaining 26 trials per condition, excluding the first 10.

The Wilcoxon signed-rank test was used to perform multiple comparisons for both the maximum penetration depth and touch time to determine if there were significant differences between all combinations of conditions. Bonferroni correction was applied to adjust the p-values.

## V. Results

### A. Experiment 1: Investigation of Observation Direction

Fig. 6 shows a violin plot of the directions from which participants observed the mid-air image during Experiment 1. This plot combines the data from all participants categorized by condition. The vertical axis represents the azimuthal angle relative to the mid-air image. The view areas for the actual mid-air image and simulation conditions are shown in green. By contrast, for the typical VR object condition, the viewing area was unrestricted, allowing observations from any direction. Height differences among the participants were not considered, and height was excluded from the analysis.

Under the actual mid-air image and simulation conditions, participants observed a mid-air image within the viewing area. For the actual mid-air image condition, 99.4% of the data were within the viewing area, whereas for the simulation

Fig. 6. Distribution of Observation Angles for Mid-Air Image

Fig. 7. Maximum Penetration Depth Relative to the Mid-Air Image

condition, 85.5% of the data were within the viewing area. In contrast, for the VR floating object condition, only 64.8% of the data were within the viewing area. Additionally, in this condition, observations from the rear side ($\pm$ 180 degrees) were prominent.

### *B. Experiment 2: Investigation of Penetration Depth*

Fig. 7 shows the box plot of the maximum penetration depth measured in Experiment 2. In the conditions with the actual mid-air image and simulation, the errors were larger compared to the typical VR object condition. The errors were 6.31 cm for the actual mid-air image condition, 15.24 cm for the simulation, and 0.97 cm for a typical VR object. Furthermore, the Wilcoxon signed-rank test for multiple comparisons showed significant differences for all combinations ($\mathrm{p} < 0.01$).

However, as shown in Fig. 8 shows that there are no significant differences in the time taken to touch among the conditions ($\mathrm{p} > 0.05$). The median times were 1.08 s for the actual mid-air image condition, 1.18 s for the simulation, and 1.54 s for the typical VR object.

Observations during the experiment revealed that several participants noticed that their fingertips were occluded when penetrating the mid-air image under the typical VR object condition. One participant noted that occlusion of their fingertips in the typical VR object condition led to more errors than in other conditions. Another participant commented that it was difficult to focus simultaneously on both the mid-air image and their fingertips when placing them at the perceived position of the mid-air image.

Fig. 8. Time Taken to Touch

## VI. Discussion

### *A. Experiment 1: Investigation of Observation Direction*

Hypothesis 1, which predicted that simulating the viewing area of mid-air images would lead users to observe the mid-air image in the same direction as they would in the real world, is supported. The simulation condition, which simulated the view area, yielded results closer to those of the actual mid-air image than the typical VR object condition, which did not simulate the view area. Specifically, the proportion of data within the view area increased from 64.8% to 85.5% owing to the simulation of the view area. In other words, the discrepancy to the actual mid-air image results (99.4%) decreased from 34.6% to 13.9%. Therefore, the results support Hypothesis 1, indicating that the simulation of the viewing area is effective to cause behavior in VR space similar to actual mid-air image.

However, in the simulation, the percentage of viewpoints tracked within the viewing area was 99.4%, which was higher than 85.5% in the actual mid-air image. This discrepancy may be attributed to differences in participant behavior between the real and VR environments. Ville et al. [1] compared user behavior in real and VR environments and reported that participants generally moved more actively in VR. Similarly, in our simulation, users were likely to move more actively than when observing an actual mid-air image. This is one of the limitations of simulating interactions in VR environments. Further investigation is needed to find out if this discrepancy is acceptable in the design and verification of mid-air image interactions, and how to make it even smaller.

### B. Experiment 2: Investigation of Penetration Depth

The difference in the penetration depth during touch interactions between the actual mid-air image condition and simulation condition led to the rejection of Hypothesis 2. The difference between the simulation and typical VR object conditions indicated that simulating the occlusion problem caused the fingertip to penetrate the mid-air image. However, the penetration depth under simulation conditions was significantly greater than that under the actual mid-air image conditions. Therefore, merely simulating the occlusion problem is insufficient for achieving the same penetration depth as that in a real-world scenario.

The variance in the fingertip penetration depth when touching the mid-air image was greater in the actual mid-air image condition than in the two VR conditions. This may be due to a decrease in the sharpness of the mid-air image. The actual mid-air image appears to be less sharp relative to the light source. However, as our study did not focus on the sharpness of mid-air images, the VR conditions did not include this effect. In the actual mid-air image condition, the reduced sharpness may have made it relatively difficult to focus on the image, thereby affecting depth perception. Implementing the sharpness effect and investigating its impact on interactions is a potential area for future research.

In addition, the penetration depth was greater under the simulation conditions than under the actual mid-air image conditions. This can be attributed to the accommodation function of the human eye. The human eye has a limited focusing range, and as the penetration depth increases, it becomes more challenging to focus on both fingertip and mid-air images simultaneously. In the actual mid-air image condition, this phenomenon might have helped limit the penetration depth. By contrast, when using an HMD, the focus remains constant regardless of the object's depth, allowing participants to focus on both the fingertip and mid-air image simultaneously. This makes it more difficult to notice penetration under the simulation conditions, leading to a higher median maximum penetration depth. This highlights a limitation in simulating with HMDs that use a fixed-focus display.

## VII. Conclusion

In this study, we propose a VR system for mid-air images that allows interaction, simulates the viewing area and occlusion problem, and tests two hypotheses. Our VR system enables interactions with mid-air images that are difficult to achieve using conventional simulation methods. We designed a method to simulate the occlusion problem without requiring the shape or position of objects near the mid-air image and used it in our VR system. Furthermore, we compare the results of mid-air image interactions using our VR system with those obtained from actual mid-air images and typical VR objects.

The results indicated that simulating the viewing area allowed users to observe mid-air images within the viewing area. However, regarding the penetration depth during touch interactions, we found that simulating the occlusion problem independently was insufficient for achieving the same penetration depth as in the real world. This suggests the necessity of simulating a decrease in the sharpness of mid-air images. In addition, challenges have been identified when simulating mid-air image interactions using VR and fixed-focus HMDs.

## Acknowledgment

This work was supported by JST FOREST Program, Grant Number JPMJFR216L.

## References

[1] V. Mäkelä, R. Radiah, S. Alsherif, M. Khamis, C. Xiao, L. Borchert, A. Schmidt, and F. Alt, "Virtual field studies: Conducting studies on public displays in virtual reality," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, ser. CHI '20. New York, NY, USA: Association for Computing Machinery, 2020, p. 1–15. [Online]. Available: https://doi.org/10.1145/3313831.3376796

[2] F. Mathis, K. Vaniea, and M. Khamis, "Replicueauth: Validating the use of a lab-based virtual reality setup for evaluating authentication systems," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, ser. CHI '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411764.3445478

[3] U. Gruenefeld, J. Auda, F. Mathis, S. Schneegass, M. Khamis, J. Gugenheimer, and S. Mayer, "Vrception: Rapid prototyping of cross-reality systems in virtual reality," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, ser. CHI '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3491102.3501821

[4] O. Chapuis, R. James, M. Rafiei, and A. Bezerianos, "Comparing physical and vr-emulated ultra-walls in a classification task: Comparaison entre ultra-murs physiques et ultra-murs émulés en rv dans une tâche de classification," in *Proceedings of the 35th Conference on l'Interaction Humain-Machine*, ser. IHM '24. New York, NY, USA: Association for Computing Machinery, 2024. [Online]. Available: https://doi.org/10.1145/3649792.3649797

[5] S. Maekawa, K. Nitta, and O. Matoba, "Transmissive optical imaging device with micromirror array," in *Three-Dimensional TV, Video, and Display V*, B. Javidi, F. Okano, and J.-Y. Son, Eds., vol. 6392, International Society for Optics and Photonics. SPIE, 2006, pp. 130–137. [Online]. Available: https://doi.org/10.1117/12.690574

[6] Y. Maeda, D. Miyazaki, and S. Maekawa, "Aerial imaging display based on a heterogeneous imaging system consisting of roof mirror arrays," in *2014 IEEE 3rd Global Conference on Consumer Electronics (GCCE)*, 2014, pp. 211–215.

[7] T. Koike and Y. Onishi, "Aerial 3d imaging by retroreflective mirror array," in *Proceedings of the 2018 ACM Companion International Conference on Interactive Surfaces and Spaces*, ser. ISS '18 Companion. New York, NY, USA: Association for Computing Machinery, 2018, p. 25–29. [Online]. Available: https://doi.org/10.1145/3280295.3281365

[8] H. Yamamoto, Y. Tomiyama, and S. Suyama, "Floating aerial led signage based on aerial imaging by retro-reflection (airr)," *Opt. Express*, vol. 22, no. 22, pp. 26 919–26 924, 2014. [Online]. Available: http://www.opticsexpress.org/abstract.cfm?URI=oe-22-22-26919

[9] H. Kim, S. Nagao, S. Maekawa, and T. Naemura, "[paper] mrsioncase: A glasses-free mixed reality showcase for surrounding multiple viewers," *ITE Transactions on Media Technology and Applications*, vol. 2, no. 3, pp. 200–208, 2014.

[10] H. Kim, I. Takahashi, H. Yamamoto, S. Maekawa, and T. Naemura, "Mario: Mid-air augmented reality interaction with objects," *Entertainment Computing*, vol. 5, no. 4, pp. 233–241, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1875952114000433

[11] Y. Matsuura and N. Koizumi, “Scoopirit: A method of scooping mid-air images on water surface,” in *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces*, ser. ISS ’18. New York, NY, USA: Association for Computing Machinery, 2018, pp. 227–235. [Online]. Available: https://doi.org/10.1145/3279778.3279796

[12] T. Kikuchi, Y. Yahagi, S. Fukushima, S. Sakaguchi, and T. Naemura, “[paper] air-range: Designing optical systems to present a tall mid-air image with continuous luminance on and above a tabletop,” *ITE Transactions on Media Technology and Applications*, vol. 11, no. 2, pp. 75–87, 2023.

[13] K. Hiratani, D. Iwai, Y. Kageyama, P. Punpongsanon, T. Hiraki, and K. Sato, “Shadowless projection mapping using retrotransmissive optics,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 29, no. 5, pp. 2280–2290, 2023.

[14] H.-L. Zhang, H. Deng, H. Ren, X. Yang, Y. Xing, D.-H. Li, and Q.-H. Wang, “Method to eliminate pseudoscopic issue in an integral imaging 3d display by using a transmissive mirror device and light filter,” *Opt. Lett.*, vol. 45, no. 2, pp. 351–354, Jan 2020. [Online]. Available: https://opg.optica.org/ol/abstract.cfm?URI=ol-45-2-351

[15] S. Kiuchi and N. Koizumi, “Simulating the appearance of mid-air imaging with micro-mirror array plates,” *Computers & Graphics*, vol. 96, pp. 14–23, 2021.

[16] A. Hoshi, S. Kiuchi, and N. Koizumi, “Simulation of mid-air images using combination of physically based rendering and image processing,” *Optical Review*, vol. 29, no. 2, pp. 106–117, Apr 2022. [Online]. Available: https://doi.org/10.1007/s10043-022-00729-0

[17] C. Bermejo, L. H. Lee, P. Chojecki, D. Przewozny, and P. Hui, “Exploring button designs for mid-air interaction in virtual reality: A hexa-metric evaluation of key representations and multi-modal cues,” *Proceedings of the ACM on Human-Computer Interaction*, vol. 5, no. EICS, pp. 1–26, 2021.