SkyAnchor: Optical Design for Anchoring Mid-air Images onto Physical Objects

Hajime Kajita[1] **Naoya Koizumi[2]** **Takeshi Naemura[1]**
The University of Tokyo[1]
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
{kajita, naemura}@nae-lab.org
The University of Electro-Communications[2]
1-5-1 Chofugaoka, Chofu-shi, Tokyo, Japan
koizumi.naoya@uec.ac.jp

ABSTRACT
For glass-free mixed reality (MR), mid-air imaging is a promising way of superimposing a virtual image onto a real object. We focus on attaching virtual images to non-static real life objects. In previous work, moving the real object causes latency in the superimposing system, and the virtual image seems to follow the object with a delay. This is caused by delays due to sensors, displays and computational devices for position sensing, and occasionally actuators for moving the image generation source. In order to avoid this problem, this paper proposes to separate the object-anchored imaging effect from the position sensing. Our proposal is a retro-reflective system called "SkyAnchor,'' which consists of only optical devices: two mirrors and an aerial-imaging plate. The system reflects light from a light source anchored under the physical object itself, and forms an image anchored around the object. This optical solution does not cause any latency in principle and is effective for high-quality mixed reality applications. We consider two types of light sources to be attached to physical objects: reflecting content from a touch table on which the object rests, or attaching the source directly on the object. As for position sensing, we utilize a capacitive marker on the bottom of the object, tracked on a touch table. We have implemented a prototype, where mid-air images move with the object, and whose content may change based on its position.

Author Keywords
Mid-air Images; Display; Optics; Visible Range; Mixed Reality.

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

INTRODUCTION
Mixed Reality (MR) has been proposed to extend everyday objects with visual images [1]. Mid-air imaging is a promising way for glass-free MR interactions, and several optical designs have recently been proposed to show mid-air images in 3D space. Nevertheless, if the mid-air image needs to be moved around the space, these designs [2,3] require actuators to move the light source physically. Delays due to this actuation and real-object sensing, can make it challenging to produce real-time and high quality mid-air images, in particular when these need to be attached to physical objects that can move around the space. The result is that users can see the latency of the MR system.

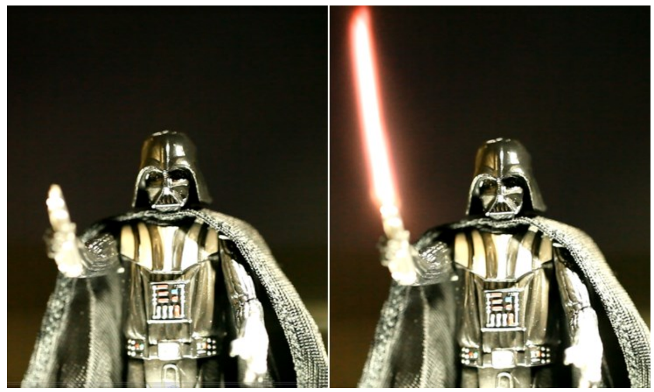

Figure 1 Superimposition of a virtual object in the real world with SkyAnchor.

This paper solves the latency problems by elaborating the composition of optical devices instead of using a very high-speed position sensor and actuation. We propose a retro-reflective system called "SkyAnchor," which consists of two mirrors and an aerial-imaging plate (AIP). The system reflects light from a light source anchored directly under the object, and forms an image anchored around the object. This optical solution can in principle have zero latency as there are no actuators involved, allowing for realistic mixed reality applications. Users can manipulate the object, and its anchored image, on a table. Two light sources are considered for creating the anchored image: reflecting content from a touch table on which the object rests, and attaching the source directly on the object. As for position sensing, we utilize a capacitive marker on the back of the bottom of the physical object that is tracked on the touch table. We have implemented a prototype, where mid-air images move with the object and may change content based on its position.

The rest of the paper describes the design of the SkyAnchor approach, and its contributions are as follows:

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1. A retro-reflective system for attaching mid-air images to physical objects, where the light-source is anchored to the physical objects, allowing the user to manipulate the mid-air image by simply moving the object directly.
2. Two ways of combining the physical object and its light source: reflecting the content of the touch table under the object by sensing its position, and zero-latency mid-air imaging by attaching a light-source to the object.

RELATED WORK

Superimposed image onto physical object

Typical Augmented Reality(AR) consists of a camera, a computer, and a display. Text, graphics, video, and audio can be superimposed onto a target object in real-time. These superimposed graphics enrich the information of the real world, and are used in many application areas, such as education [4], museums [5], and entertainment [6]. However, the problem with the display monitor is the weight [7]. Adopting a see-through Head-Mounted Display (HMD) seems to have benefits, but still the user has to wear something. Karnik et al. [8] and Plasencia et al. [9] designed AR systems using glass cases that merge the space in front and behind them. But in their systems users cannot directly touch the physical objects. On the other hand, mid-air imaging systems enable users to manipulate physical objects with superimposed images anchored to them. So we focus on mid-air imaging systems next.

Mid-air imaging

We already know a lot of proposed mid-air imaging display methods, such as fog, laser-plasma, and optical imaging. For example, Yagi et al. [10] has developed a novel fog display system that enables users to observe a virtual object from multiple viewpoints. It consists of one cylindrical fog screen and multiple surrounding projectors. Fog screens are effective for forming mid-air images for interactive systems, however, fog diffuses light, thus reducing the visibility of real objects.

Laser plasma is a method to form a mid-air display without any deterioration of visibility. Saito et al. [11] presents a mid-air display that can show 3D contents in free space using laser-plasma scanning in the air. The laser-plasma technology can generate a point illumination at an arbitrary position in free space. Also, Ochiai et al. [12] presented a method of rendering aerial and volumetric graphics using femtosecond lasers. A high-intensity laser excites physical matter to emit light at an arbitrary three-dimensional position. However, this laser-plasma method is highly expensive and complex and it requires safety precautions.

Optical imaging is also an effective method to form mid-air images. Roof mirror array (RMA) [13], dihedral corner reflector array (DCRA) [14] and aerial-imaging plate (AIP) [15] are micro mirror array structures, that form mid-air images in a symmetrical position around a mirror plate. Aerial imaging by retro-reflection (AIRR) [16] and RePro3D [17] are similar methods that combine retro-reflective material and a beam splitter. Smoot [18] demonstrates a volumetric display which consists of a large-aperture, a rim-driven, an adjustable-resonance, and a varifocal beamsplitter. FuwaVision [19] and HaptoMirage [20] use a frenel lens and a transparent LCD to form 3D mid-air images. fVisiOn uses multiple projectors and special screen to from a 360 degree multi-view 3D image on the table, but it requires the use of 280 projectors [21]. In this research, we adopted the optical imaging method because it is safe, simple and provides high quality imaging. In particular, aerial-imaging plate (AIP) is easy to use and commercially available, so we choose it for our optical design. Existing approaches that use AIP often rely on creating moving mid-air images using mechanical actuation of the light source [2,3,22]. Other work using AIP creates mid-air images at a static location without any registration onto the object. For example, HaptoClone [23] can optically copy part of an environment in real-time at a different, but static, location. And HoVerTable [24] can generate a (static) image over a specific location on a digital tabletop. Our approach goes further, as it generates moving mid-air images attached to physical objects, without the need for mechanical actuation. Nevertheless, by only using the AIP, we get a viewing area for mid-air images that is too small (see Figure 3), so we designed a new retro-reflective system described in the following section.

Mid-air interaction

Interaction in a MR system is very important. It is essential to design a system where real and virtual worlds are well integrated and users can interact with them in real time. There are three aspects that need to be consistent across real and virtual world: illumination, geometry and time [25]. About consistency of illumination, Li-wei et al. investigated the problem of interactively controlling mid-air images [26] and proposed shadow projection of the user's hand. Mario [2] and EnchanTable [3] also enabled mid-air virtual character interaction and proposed a shadow projection of virtual characters to enhance depth perception of image position. To achieve consistency of geometry and time, a system has to track the position of the physical object and display the image to the correct position. To obtain this, Kim et al. [2] adapted an actuator-united display to present mid-air images on physical objects tracked by a kinect. In that system [3], the light source of the mid-air image is behind the optical system. Thus, if you attach the image to a physical object, you need a display that can physically move, or a complex display system such as an integral photography display. It is a challenging problem to attach the image to a physical object strictly, so that it moves with the object. Previous approaches require high-speed tacking and actuation. In this paper we propose another method to guarantee consistency of geometry and time between physical and virtual, an approach for real-time mid-air images attached on moving physical objects.

APPROACH

We propose an optical design for anchoring mid-air images onto real objects. This system consists of three elements:

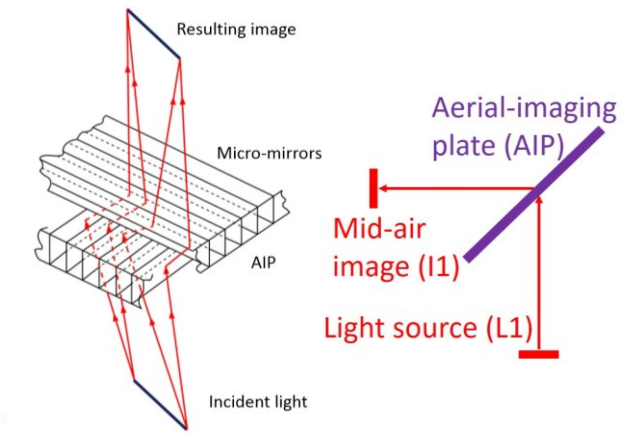

Figure 2 Aerial-imaging plate that forms mid-air images at the plane-symmetric position.

retro-reflective optical transfer system, position sensing of objects on the table, and object-anchored imaging.

Retro-reflective optical transfer system

Our optical design uses an AIP and two mirrors. This design changes the optical path to achieve a horizontal visible range.

As shown in Figure 2, AIP is a real imaging device which forms an image at the plane-symmetric position. Typically, a light source *L1* is placed behind AIP. Thus, when a user wants to change the depth of the mid-air image *I1*, the light source *L1* should be moved by a mechanical actuator.

In our approach, the light source is attached to an object, and thus no actuation is needed. As shown in Figure 3 (Top), even if the user moves the light source *L1* horizontally, the relative position of the mid-air image *I1* does not change. However, the mid-air image *I1* is only visible in front of the AIP, i.e. into the visible range of the AIP. The visible range is a pyramid formed by the viewpoint and the endpoints of the virtual AIP. As such, in this simple setup, depending on the position of the viewer, there are possible positions of the light source *L1* where mid-air images are not visible. Figure 3 (Bottom) describes the visible range of *I1* when a user moves the object, and thus *L1* back and forth. The visible range is the pyramid linking the user's viewpoint and the endpoints of the AIP. As shown in Figure 4, when the object and its light source is furthest from the viewer, the entire mid-air image is visible, but when it is closer to the viewer, part of it falls outside the visible range, and is thus not shown.

We propose an optical design using an AIP and two mirrors that keeps the same forming position as the AIP, but that changes the optical path to achieve a larger visible range. In this design, the user can see *I1* easily from a fixed viewpoint. Figure 5 (Top) shows this optical design. The goal of the design is for *I1* to be formed right above *L1*.

The proposed design consists of a light source *L1*, two mirrors (*M*), and the AIP. Light from *L1* is reflected by *M* and forms *L1'*. *L1'* goes through the AIP and forms *I1'*, *I1'* is reflected by *M* and finally forms *I1*. In the first step, we

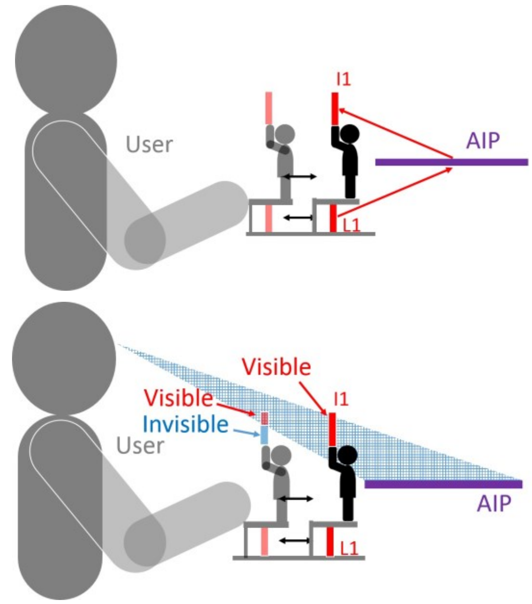

Figure 3 (Top) Imaging position using only AIP, (Bottom) Visible range in this design.

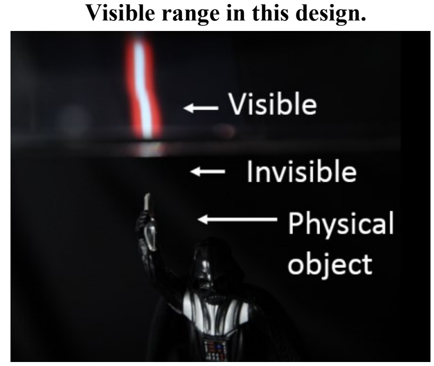

Figure 4 Example with a partially invisible mid-air image.

placed the AIP at 45 degrees to *L1'* and formed *I1'* at the symmetric position. By placing it at such a position, if *L1'* moves, *I1* moves symmetrically. For anchoring a mid-air image onto an object, *L1'* is formed from *L1*, and *I1* is formed from *I1'* by *M*. Therefore, *I1* is formed right above *L1*, and *I1* is anchored onto *L1*.

We introduce the concept of a virtual AIP, that essentially expresses how the visible range of the actual AIP is extended using the two mirrors to bend the optical path. The virtual AIP is an AIP formed in a mirror that was used to bend the optical path. The resulting mid-air image seems to come from the virtual AIP. As is shown in Figure 5 (Bottom), the visible range of this system is decided by the viewpoint, the point within the virtual AIP, and the virtual walls. Virtual walls are the formed image of obstacles, for example the end of the touch table and table surface. As an obstacle blocks the light rays from the light source, virtual walls also block the light ray. These virtual walls are transferred the same way as image I1.

We have placed the mirrors and AIP in such a way, that the light incident angle (incoming to AIP from lower mirror and

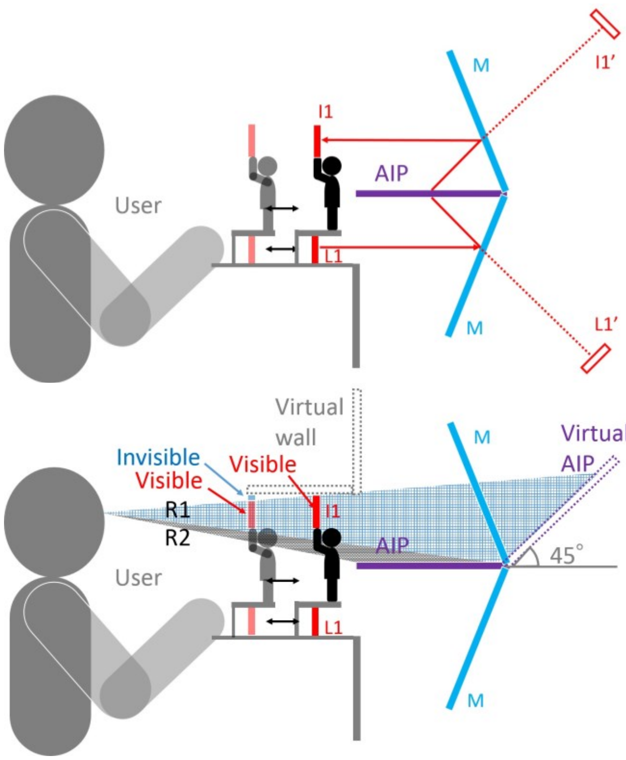

Figure 5 (Top) Change in the optical path using two mirrors, (Bottom) Visible range (R1 and R2) in this design.

outgoing for upper one) is 45 degrees. This is because light transmissivity in mirror holes decreases for light paths beyond angles of 45 degrees [14]. As such, the range R2 (shown in Figure 5 Bottom) is an inadvisable range to use for forming mid-air images, as they tend to be too dark.

Imaging with position sensing of object on the table

In our prototype, the light source can come from the touch table on which physical objects are placed, using a mirror system that is attached at the base of the object to reflect the table light coming from underneath. To control what image is displayed under an object, we need to track its' position on the table. The touch display can sense the position of a physical object, if it is instrumented by capacitive markers. We place such marker at the bottom of a rest on which the physical object sits. The object is a daily-life physical object, and the system can thus detect its position and rotation through the markers placed on the bottom of the rest.

As shown in Figure 6, we propose a rest for the physical object, that includes 4 mirrors positioned in an inverted pyramid formation. The physical implementation can be seen in Figure 10. We call the combination of the physical object and its rest an "object-united pyramid mirror". These mirrors reflect light from the touch table on which the object (and rest) are placed. Thus, by tracking the object on the table using markers, and using the table itself as a light source, input and output are unified by the touch table.

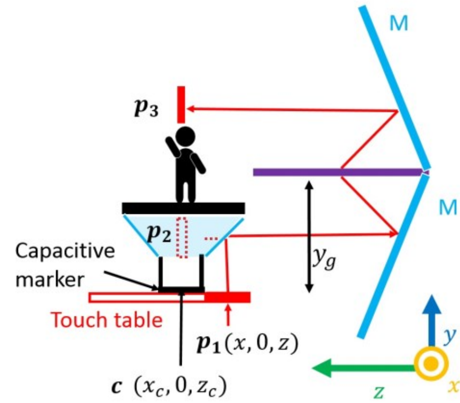

Figure 6 Image formation using pyramid-shaped mirror.

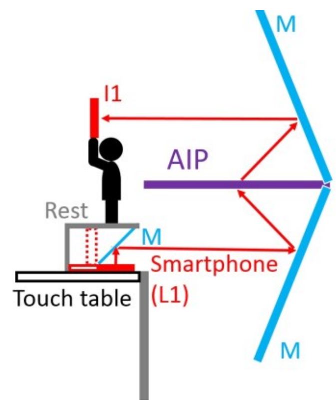

Figure 7 No latency anchoring with object-united display.

When the center of the capacitive maker ($\boldsymbol{c}$) is placed on the table, the touch table ($\boldsymbol{p_1}$) is reflected by the pyramid-shaped mirror ($\boldsymbol{p_2}$), and formed by the main optical system ($\boldsymbol{p_3}$). $\boldsymbol{c}$, $\boldsymbol{p_1}$, $\boldsymbol{p_2}$, and $\boldsymbol{p_3}$ are defined as (1) when the object does not rotate.

$$\boldsymbol{c} = \begin{bmatrix} x_c \\ 0 \\ z_c \end{bmatrix}, \boldsymbol{p_1} = \begin{bmatrix} x \\ 0 \\ z \end{bmatrix}, \boldsymbol{p_2} = \begin{bmatrix} x \\ z - z_c \\ z_c \end{bmatrix}, \boldsymbol{p_3} = \begin{bmatrix} x \\ 2y_g - (z - z_c) \\ z_c \end{bmatrix} \quad (1)$$

The resulting image is formed right above the center of the capacitive marker.

Object-anchored imaging without latency

Alternatively, to achieve zero latency superimposing, we propose a rest that incorporates a light source, that we call an "object-united display". The rest consists of the base of the rest, a mirror, and a smartphone.

It is challenging to produce real time registration of mid-air images. In previous research, to enable moving images, systems detect the position of objects and move the light source appropriately using mechanical actuators [2]. In the previous section, we describe how we achieved mid-air imaging using a touch enabled display. However, there is still some latency in mid-air imaging due to the registration in the display. Thus we propose a new imaging method called anchored imaging. The anchored imaging provides zero latency and achieves real-time registration.

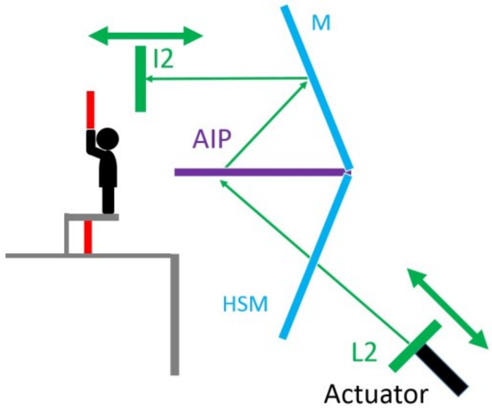

Figure 8 Additive optical system for non-anchored images.

As shown in Figure 7, the rest consists of the base of the rest, a mirror, and a smartphone (L1). Light from L1 is reflected by M in the rest and goes through the main optical system and finally forms I1. The relative position of L1and I1 is always the same as long as the object is not lifted off the touch table.

Moreover, more than one object-united display can be placed on the table. The depths of resulting images are the same as the depths of the objects they are attached to.

Non-anchored imaging

In addition, we placed a light source *L2* that moves automatically using an actuator. This *L2* acts as a light source for forming mid-air image *I2*. *I2* is not anchored to specific physical objects. As shown in Figure 8, *M* is changed into a half-silvered mirror (*HSM*), and *I2* is added. By moving *I2* with an actuator, the depth of *I2* can be changed. A combination of the anchored and non-anchored setup, enables showing mid-air images whose position is controlled both by the user and by the system. As expected, the non-anchored part of the system suffers from delays due to the actuation.

The visible range of this system is decided by the viewpoint, the point within the virtual AIP. In additive non-anchored images, the visible range is not influenced from the virtual wall unlike anchored images.

IMPLEMENTATION

Figure 9 shows the details of the SkyAnchor implementation. This system consists of two acrylic mirrors, an AIP made in Asukanet Co., Ltd., ProLite T2336MSC-2 (23 inch, 1920× 1080) as the touch table made by iiyama corporation, and a 3D printed stand made of an acrylic pyramid-shaped mirror.

The size of the mirror used in SkyAnchor is 230 (*W*) × 230 mm (*H*). The AIP, placed horizontally, has a size of 360 mm (*W*) × 360 mm (*H*). Touch table (510 (*W*) × 287 (*H*) mm) are used as a light source of mid-air images.

In an additive system, a non-anchored mid-air image can move in a 3D space measuring 350 (*W*) × 300 (*D*) × 250 (*H*) mm. *W* and *H* are defined by the AIP's size, and *D* is defined by the actuator's length. *L2* is SLD1968 V2 (1600cd⁄m^2). The transmittance of the half-silvered mirror is 10%.

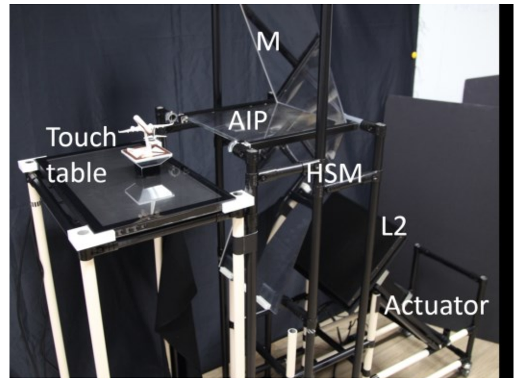

Figure 9 Implemented system.

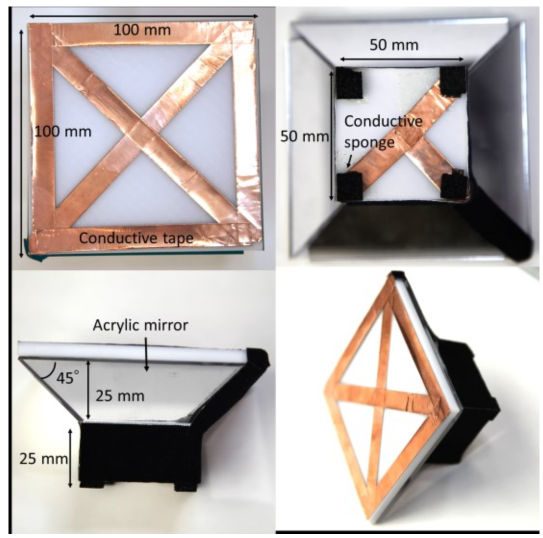

Figure 10 Pyramid-shaped mirror with capacitive marker.

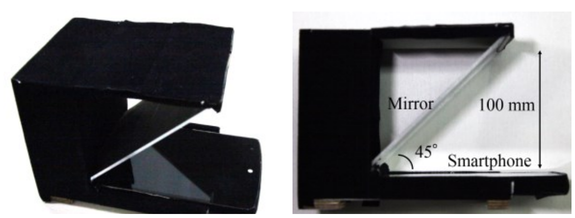

Figure 11 Implemented object-united display.

Figure 10 shows the details of the pyramid-shaped mirror stand that consists of a 3D printed base, an acrylic mirror, conductive tape, and a conductive sponge. This system can detect the position and rotation by the sponge's pattern. The pyramid-shaped mirror provides the rotation-dependent information. The top of it measures 100 (*W*) × 100 (*D*) mm. the bottom measures 50 (*W*) × 50 (*D*) mm. The mirror is set to 45 degrees. The imaging zone in the mirror is a rectangle measuring 50 (*W*) × 25 (*H*) mm.

Figure 11 shows the details of the object-united display. This consists of a 3D printed base, an acrylic mirror, conductive

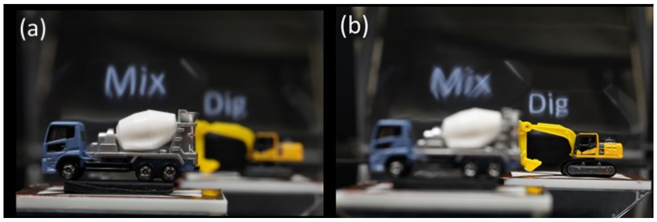

Figure 12 Mid-air images at multiple depths. (a) front image is focused, (b) rear image is focused.

tape, conductive sponge, and smartphone (Nexus 5). The imaging zone is a rectangle measuring 100 (W) × 100 (H) mm.

Figure 12 shows the anchored mid-air images at multiple depths. Regardless of the viewing point, the image anchors onto real objects.

EVALUATION

Visible range

As shown in Figure 13, on the touch table the pyramid that linked these points is the visible range that can display the mid-air image.

Although our calculations predicted a given visible range, we wanted to verify this experimentally. We also wanted to evaluate the quality of the mid-air images, given that (i) we use an inclined AIP that could reflect undesirable light, and (ii) our light sources move with regard to the AIP plane, and as such the luminance of the generated mid-air image may be affected.

In this section, we describe how we tested that the superimposed image can indeed be seen in the theoretical computed range that Figure 13 shows. We note that a mid-air image is not formed in the deepest area of the touch table, because a pyramid-shaped mirror cannot reflect the display zone in this area.

Procedure

We placed a luminance meter as shown in Figure 14. The standard position of the luminance meter was decided to be the same as the center of the anchored image. We changed the height of the luminance meter to three points in order to take the motion of the viewer's head into consideration: the standard position and the standard position $\pm$ 50 mm.

The touch table was divided into sixteen vertical and nine horizontal lines, totaling 144 segments and we placed the pyramid-shaped mirror at all the points and measured the luminance of the anchored image for them.

We measured the luminance at the center of the anchored image. When the center cannot be seen, we regarded the luminance to be 0 cd/m^2.

Results

Figure 15 shows the luminance of the superimposed mid-air image. The visible range was a trapezoid form, as was thought theoretically. We found that the luminance is higher

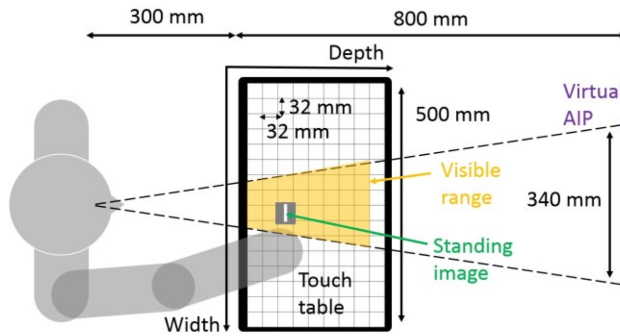

Figure 13 Theoretical visible range on the table.

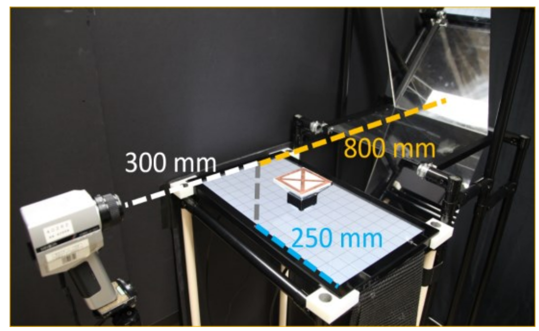

Figure 14 Environment of the visible range measurement.

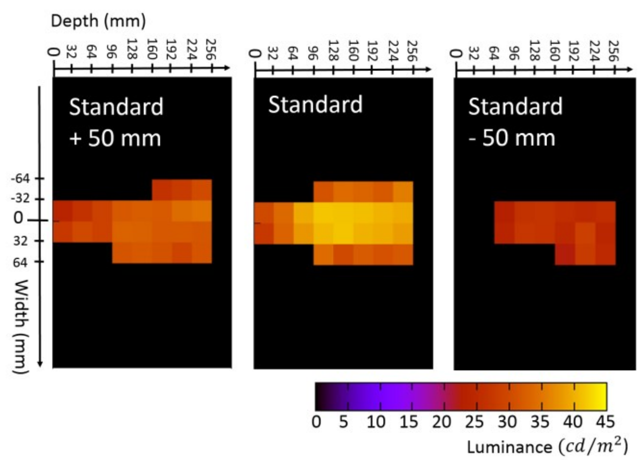

Figure 15 Resulting visible range.

at the center area of the display. This is because the luminance distribution of the display has such a feature.

In the evaluation we did not measure any undesirable image, suggesting our positioning of the AIP plane was a good one. We also verified that the mid-air images was always exactly above the physical object irrespective of their position on the table.

APPLICATIONS

Superimposing rotation-dependent information

As is shown in Figure 16, with SkyAnchor, we superimposed virtual information to the plastic model of an airplane. This system can display four types of different information depending on the rotation of the model. Because the

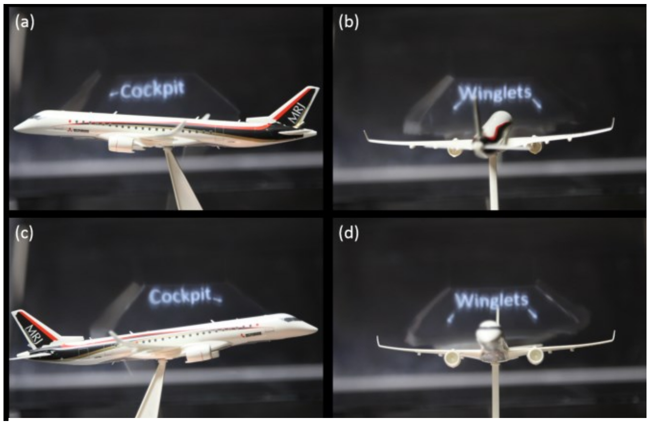

Figure 16 Different anchored information when the object rotates in each direction. (a) "Cockpit", (b) "Winglets", (c) "Cockpit", (d) "Winglets".

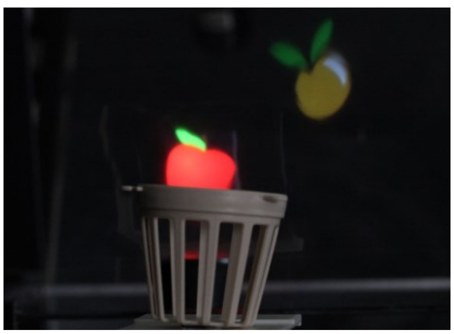

Figure 17 AR falling block puzzle game.

information is displayed close to the model, it is easy to understand which part of the airplane it relates to. In addition, because the mid-air image is anchored even if the model moves and rotates, users can manipulate the physical object intuitively.

Superimposing no-latency information

As shown in Figure 17, we implemented an AR falling block puzzle game. Players can manipulate small fruit baskets as real objects. The player can move the basket back, forward, left and right. A lot of fruits fall in sequence, and the player must put them in the basket. The fruit is a non-anchored image while it drops, but after it is put in the basket, it changes to an anchored image. We use a marker under the rest of the physical baskets to track their position on the touch table, and use it to decide when to switch a non-anchored fruit image into an anchored one.

DISCUSSION

Manipulation range

In the visible range section, we explained that the visible range is a pyramid formed by the viewpoint and the endpoints of the virtual AIP. In this paper, we used an AIP measuring 360 mm (W) × 360 mm (H), so the visible range looks narrow. On the other hand, the manipulation range of human hand is wider than this visible range. In this section, we confirm the relation between the size of AIP, the object-

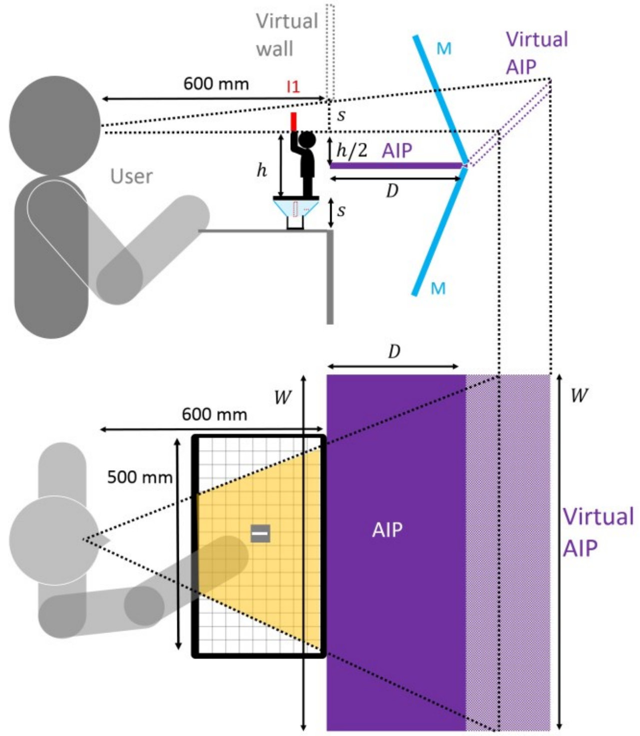

Figure 18 The setup parameters that help define the relationship of the size of the AIP, the manipulation range and table size.

united display and the possible manipulation range. This is to show how to calculate the AIP size needed for a desired manipulation range and different touch table sizes.

We now consider how to calculate the needed AIP size given a desired setup. As is shown in Figure 18, let h be the height of the object, and let s be the height of the object stand, let W be the width of the AIP, and let D be the depth of the AIP. The viewpoint is horizontal to the bottom of the anchored image. The distance from the user to the furthest edge of the touch display is calculated to approximately 600mm in our setup, and the width of the touch display is 500mm. The virtual AIP is tilted by 45 degrees. We calculate the D and W as follows:

$$D = \frac{s + \frac{h}{2}}{\frac{1}{\sqrt{2}} - \left(1 + \frac{1}{\sqrt{2}}\right)\frac{s}{600}} \qquad (2)$$

$$W = \frac{500}{600}\left(D + \frac{h}{2} + 600\right) \qquad (3)$$

The more the AIP's width increases, the larger the provided visible range becomes. Using these calculations, we can decide on a sufficient size of the AIP to manipulate objects. Figure 18 shows a sufficient AIP width when the user wants to manipulate 500 mm aside. For example, if we want a setup where, s is 50, and h is also 50, we substitute these parameters into eq. (2) and eq. (3), which gives us the desired size of the AIP with D being 132 and W being 630.

Limitations

The current design of SkyAnchor has several limitations. First, due to the principle of real imaging, real images can be viewed only behind physical objects. Although sufficient for nearby imaging onto physical objects, front imaging is preferred for perfect superimposing. This occlusion is a challenging problem.

In addition, since 2D displays (Nexus 5) are used as a light source of imaging systems, the resulting mid-air images are also only 2D images, which include only one depth layer. Changing to a 3D light source such as integral photography (IP) displays would enhance the depth perception of mid-air images.

SkyAnchor has a limited interactive zone. When the user lifts the object from the table, the anchored image disappears. As mentioned in the evaluation section, users can move the object only in the visible range. In addition, when the object is far from the main optical system, the anchored image has low resolution.

The size of the image is another issue. The size of the anchored image is dependent on the size of the rest of the object-united tool. The image of the pyramid mirror measures $50\text{ mm }(W) \times 25\text{ mm }(H)$. The image of the object-united display measures 100 mm (W) × 100 mm (H). The size of the image can be enlarged by using a larger rest for the object-united display. However, a larger rest is more difficult to move.

Initial user feedback

We exhibited our implementation to around 100 people at our open lab. In the demo, we utilized a character figure and the object-united display as shown in Figure 1. The feedback we got indicated that people could not perceive any anchoring latency. We observed that users tended to not lift the object from the table. We guess this is because of the weight of object-united display. Additionally, this interaction is familiar as it is similar to moving a mouse.

Increase in the added value of the object

SkyAnchor can display rotation-dependent information using an object-united pyramid-shaped mirror. This feature might motivate users to approach SkyAnchor and view the object. We believe that the anchored image is effective as a trigger to view the object from a number of perspectives. This is why it can be used for education and museums.

We have focused on users who can manipulate an object, but SkyAnchor can be viewed by people far away. We believe that SkyAnchor can pull in customers from afar. This is because the customers can view an everyday object on which additional information is anchored.

CONCLUSION

In this paper, we proposed SkyAnchor, an optical design for anchoring mid-air images onto real objects. The proposed design has two contributions: The first is a retro-reflective system for attaching mid-air images to physical objects allowing the user to manipulate the mid-air image by simply moving the object directly. The second is two variations for combining the physical object with a light source. We evaluated the true visible range of this system. In the results, the system provides the same visible range as the theoretical range and doesn't suffer from undesirable images. We created two applications for superimposing rotation-dependent information and an AR falling block puzzle game. Finally, we discuss how to compute the size of the needed AIP that can allow mid-air images for physical objects within a desired manipulation range.

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REFERENCES

1. Milgram, P., & Kishino, F.: A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems,* Volume 77, No. 12, pp. 1321-1329, (1994).
2. Kim, H., Takahashi, I., Yamamoto, H., Maekawa, S., & Naemura, T.: Mario: Mid-air augmented reality interaction with objects. *Entertainment Computing*, Volume 5, Issue 4, pp. 233-241, (2014).
3. Yamamoto, H., Kajita, H., Koizumi, N., & Naemura, T.: EnchanTable: Displaying a Vertically Standing Mid-air Image on a Table Surface using Reflection. *In Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces,* ACM, pp. 397-400, (2015).
4. Yilmaz, R. M.: Educational magic toys developed with augmented reality technology for early childhood education. *Computers in Human Behavior*, Volume 54, 240-248. (2016).
5. Okada, N., Imura, J., Narumi, T., Tanikawa, T., & Hirose, M.: Manseibashi Reminiscent Window: On-Site AR Exhibition System Using Mobile Devices. *In International Conference on Distributed, Ambient, and Pervasive Interactions,* Springer International Publishing pp. 349-361, (2015).
6. Ishiguro, Y., & Rekimoto, J.: Peripheral vision annotation: noninterference information presentation method for mobile augmented reality. *In Proceedings of the 2nd Augmented Human International Conference,* ACM, p. 8, (2011).
7. Julian Seifert, Sebastian Boring, Christian Winkler, Florian Schaub, Fabian Schwab, Steffen Herrdum, Fabian Maier, Daniel Mayer, and Enrico Rukzio.: Hover Pad: interacting with autonomous and self-actuated displays in space. *In Proceedings of the 27th annual ACM symposium on User interface software and technology (UIST '14)*. ACM, 139-147, (2014).
8. Karnik, A., Mayol-Cuevas, W., & Subramanian, S.: MUSTARD: a multi user see through AR display. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* ACM, pp. 2541-2550, (2012).

9. Martinez Plasencia, D., Berthaut, F., Karnik, A., & Subramanian, S.: Through the combining glass. *In Proceedings of the 27th annual ACM symposium on User interface software and technology,* ACM, pp. 341-350, (2014).

10. Yagi, A., Imura, M., Kuroda, Y., & Oshiro, O.: 360-degree fog projection interactive display. *In SIGGRAPH Asia 2011 Emerging Technologies,* ACM, p. 19, (2011).

11. Saito, H., Kimura, H., Shimada, S., Naemura, T., Kayahara, J., Jarusirisawad, S., ... & Asano, A.: Laser-plasma scanning 3D display for putting digital contents in free space. *In Electronic Imaging 2008,* International Society for Optics and Photonics, pp. 680309-680309, (2008).

12. Ochiai, Y., Kumagai, K., Hoshi, T., Rekimoto, J., Hasegawa, S., & Hayasaki, Y.: Fairy Lights in Femtoseconds: Aerial and Volumetric Graphics Rendered by Focused Femtosecond Laser Combined with Computational Holographic Fields. *ACM Transactions on Graphics (TOG),* Volume 35, Issue 2, Article 17, 14 pages. (2016).

13. Maeda, Y., 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)*, IEEE, pp. 211-215, (2014).

14. Maekawa, S., Nitta, K., & Matoba, O.: Transmissive optical imaging device with micromirror array. *In Optics East 2006,* International Society for Optics and Photonics, pp. 63920E-63920E, (2006).

15. Otsubo, M. U.S. Patent No. 8,702,252. Washington, DC: U.S. Patent and Trademark Office, (2014).

16. Yamamoto, H., Tomiyama, Y., & Suyama, S.: Floating aerial LED signage based on aerial imaging by retro-reflection (AIRR). *Optics express*, Volume 22, Issue 22, pp. 26919-26924, (2014). .

17. Yoshida, T., Kamuro, S., Minamizawa, K., Nii, H., & Tachi, S.: RePro3D: full-parallax 3D display using retro-reflective projection technology. *In ACM SIGGRAPH 2010 Emerging Technologies,* ACM, No. 20, (2010).

18. Smoot, L., Smithwick, Q., & Reetz, D.: A volumetric display based on a rim-driven varifocal beamsplitter and led backlit LCD. *In ACM SIGGRAPH 2011 Emerging Technologies,* ACM, No. 22, (2011).

19. Nii, H., Zhu, K., Yoshikawa, H., Htat, N. L., Aigner, R., & Nakatsu, R.: Fuwa-Vision: an auto-stereoscopic floating-image display. *In SIGGRAPH Asia 2012 Emerging Technologies,* ACM, No. 13, (2012).

20. Ueda, Y., Iwazaki, K., Shibasaki, M., Mizushina, Y., Furukawa, M., Nii, H., ... & Tachi, S.: HaptoMIRAGE: mid-air autostereoscopic display for seamless interaction with mixed reality environments. *In ACM SIGGRAPH 2014 Posters,* ACM, No. 30, (2014).

21. Yoshida, S.: fVisiOn: Glasses-free tabletop 3D display that provides virtual 3D images on a flat tabletop surface. *In Information Optics (WIO), 2015 14th Workshop on,* IEEE, pp. 1-3, (2015).

22. Inoue, S., Kobayashi-Kirschvink, K. J., Monnai, Y., Hasegawa, K., Makino, Y., & Shinoda, H.: Horn: The hapt-optic reconstruction. *In ACM SIGGRAPH 2014 Emerging Technologies,* ACM, No. 11, (2014).

23. Makino, Y., Furuyama, Y., Inoue, S., & Shinoda, H.: HaptoClone (Haptic-Optical Clone) for Mutual Tele-Environment by Real-time 3D Image Transfer with Midair Force Feedback. *In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems,* ACM, pp. 1980-1990, (2016).

24. Kim, H., Yamamoto, H., Koizumi, N., Maekawa, S., & Naemura, T.: HoVerTable: Combining Dual-sided Vertical Mid-air Images with a Horizontal Tabletop Display. *Information and Media Technologies,* Volume 10, No. 4, pp. 509-520, (2015).

25. Sato, I., Sato, Y., & Ikeuchi, K.: Acquiring a radiance distribution to superimpose virtual objects onto a real scene. *IEEE transactions on visualization and computer graphics*, Volume 5, No. 1, pp. 1-12, (1999).

26. Chan, L. W., Kao, H. S., Chen, M. Y., Lee, M. S., Hsu, J., & Hung, Y. P.: Touching the void: direct-touch interaction for intangible displays. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems,* ACM, pp. 2625-2634, (2010).