Scoopirit: A Method of Scooping Mid-air Images on Water Surface

Yu Matsuura
The University of Electro-Communications
Chofu, Japan
matsuura@uec.ac.jp

Naoya Koizumi
The University of Electro-Communications
JST PREST
Chofu, Japan
koizumi.naoya@uec.ac.jp

ABSTRACT

We propose Scoopirit, a system that displays an image standing vertically at an arbitrary three-dimensional position under and on a water surface. Users can scoop the image from an arbitrary horizontal position on the water surface with their bare hands. So that it can be installed in public spaces containing water surfaces visited by an unspecified number of people, Scoopirit displays images under and on a water surface without adding anything to the water and enables users to interact with the image without wearing a device. Because of the configuration of the system, users can easily understand the relationship between the real space and the mid-air image.

This study makes three contributions. First, we propose a method to scoop the mid-air image at an arbitrary horizontal position. Second, we design the offset that is useful for measuring the water level of the water surface scooped by hand with an RGB-D camera. Third, we propose a method to design interaction areas.

CCS Concepts

• Human-centered computing~Displays and imagers

Author Keywords

mid-air images; mixed reality; water surface reflection; interaction.

INTRODUCTION

In this research, we propose a new interaction method for water surfaces in public space using mid-air images and water surface reflection and contribute to the field of interactive surfaces. A water surface is a primitive interactive surface. Everyone has soaked their hands in water and enjoyed its response. In addition, a water surface is an important component used for designing public spaces around the world.

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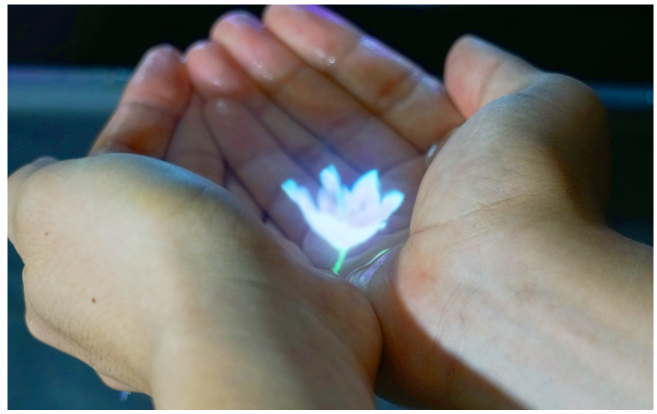

Figure 1. Scooped mid-air image using Scoopirit.

The purpose of this research is to introduce an interactive visual expression that users can touch and manipulate directly with water on a water surface in a public space. Although many interaction methods using water have been proposed, no interactive visual expression method has been developed that can be installed in public spaces and enable users to manipulate information by touching water directly. Manipulation of information using real objects is a means to seamlessly merge digital space and real space and eliminate the gap between them [1]. In particular, we need to adapt a simple and everyday interaction with water into an interaction with an interactive visual expression that an unspecified number of people in public spaces can manipulate.

A water surface reflecting light in the dark attracts people. The surface of water such as a sea or river reflecting the night view is an important tourism resource. Even in indoor public spaces, there are many spaces for rest and relaxation with a water surface. In this research, visual representation is assumed to occur, especially at night and on indoor water surfaces, in public spaces.

In this research, we use a mid-air imaging technique as a visual expression method to seamlessly connect digital space and real space. For a mid-air image, an optical system such as a lens or a mirror array reflects and refracts light rays emitted from the light source to form an image in the air. Therefore, the user does not need to wear a special device. Furthermore, real objects and computer graphics images can be shown together in real space. For these reasons, a mid-air imaging technique is suitable for applications that show real space and images together in public spaces where unspecified numbers of people gather.

We propose an interaction system that enables users to scoop up mid-air images with water. The reason for focusing on scooping rather than other direct touching water interactions is that scooping water is an easy everyday action most people perform, such as when they wash their faces in the morning.

We aim to meet three design requirements for a mid-air image interaction: 1. no water processing, 2. no device wearing, and 3. geometric consistency. The first requirement is that the introduction of the system does not change the characteristics of water in the public space. Because water in public spaces has wide surfaces like a sea or river or needs to be circulated for hygiene, its characteristics are difficult to always change by processing it. The second requirement is that multiple users can share experiences simultaneously without needing to wear a device like a head mounted display. The third requirement is that the system always maintains the three-dimensional positional relationship between the real space and the mid-air image. By satisfying this requirement, the user can easily understand the relationship between the real space and the image. The geometric consistency in this paper includes the property that the motion of the water surface in the physical space affects the image.

We propose Scoopirit as a mid-air image interaction system that enables the user to directly touch and interact with water in public spaces and satisfies the above three requirements. Scoopirit consists of two subsystems: optical and interaction. The optical subsystem uses a mid-air imaging technique to display an image vertically standing in an arbitrary three-dimensional space under and on a water surface [2]. The interaction subsystem tracks the water level of the scooped up water using an RGB-D camera and controls the position of the image. By this control, the system maintains the position relative to the water level of the image floating on a water surface and enables the user to scoop up the image with water.

The contributions of this research are as follows:

1. We propose a control method to scoop up mid-air images at an arbitrary horizontal position.
2. We determine the necessary offset value when tracking the water level of the water scooped by hand with an RGB-D camera.
3. We show the interaction area that users can scoop up.

RELATED WORKS

Water Interface

There are many digital visual expression methods for water environments that users can see with the naked eye. Koike et al. proposed a method to control the vertical position of an arbitrarily shaped object by manipulating water pressure [3, 4]. Nakagaki et al. proposed a method of manipulating the shape of a fountain by changing the shape of the target against that the water stream hits [5]. There are also a display system in which water drops are arranged in an array [6, 7] and a method of driving liquid itself [8, 9]. Our system produces a visual expression with a frame rate and color like a normal LCD (liquid crystal display) while satisfying the requirement of "no water processing."

Sensing methods using water without device wearing have been proposed. Since the water environment limits the technologies that can be used [10], methods have been proposed for noncontact sensing of user behavior by investigating the change in capacitance [11, 12, 13]. However, these methods cannot sense the exact distance from the water surface to the hand. Our system senses the level of water scooped up with bare hands from an arbitrary horizontal position.

O-Key and Aquatop Display realized an interaction in which a user scoops images projected on the bottom of the water and the water surface using projectors, cameras, and RGB-D cameras [14, 15]. In this research, we propose a system with higher 'geometric consistency' by enabling interaction in which a user scoops up an image that is vertically standing on the water.

Mid-air Interaction

By using a mid-air imaging technique, users can see the images located in mid air without wearing special eyeglasses or the like. There are several mid-air imaging techniques such as MMAPs (Micro-Mirror Array Plates: AIP (Aerial Imaging Plate) [16], DCRA (Dihedral Corner Reflector Array) [17], and AIRR (Aerial Imaging by Retro-Reflection) [18]. In this research, MMAPs are used to form mid-air images with high luminance.

Several mid-air image interaction systems using MMAPs exist. One of them, MARIO (Mid-air Augmented Reality Interaction with Objects) [19], enables users to interact with images on a table using real objects. The system detects changes in the environment on the table with the RGB-D camera and moves the image toward the highest detected point. In this research, we propose an interaction to enable a user to scoop up the image following the movement of the user's hand.

Yamamoto et al. proposed a method of displaying a mid-air image using reflection on a table surface [20]. In this method, the user sees the reflected MMAPs through a half mirror placed on the table surface, so the user can see the image while looking at the table surface. In this research, we extend this method, and in addition to the user seeing the image with the water surface as the background, our system enables superimposition of a real object under water and the image.

A method of displaying images under water using AIRR has been proposed [21]. However, the user cannot put hands between the image and the optical components with this method.

SYSTEM DESIGN

Figure 2 shows our proposed system, Scoopirit. It is roughly divided into two subsystems: optical and interaction. We will explain the optical subsystem, interaction area, and the interaction subsystem.

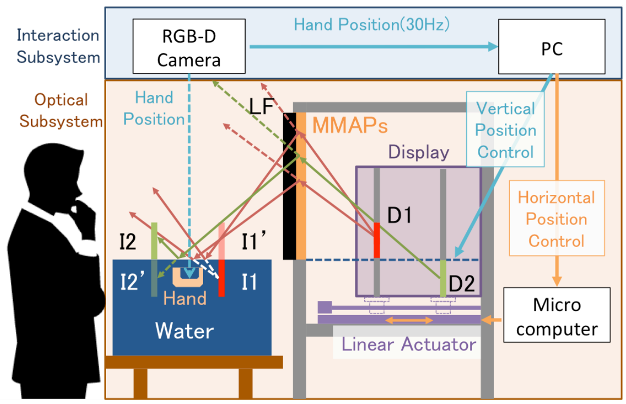

Figure 2. Proposed system: Scoopirit.

Optical Subsystem

The optical subsystem displays images in three-dimensional space under and on the water surface and enables interaction with water. We extend the previous system [19] that displays a mid-air image on a table surface. The optical subsystem consists of a display (D), MMAPs, linear actuator (LA), microcomputer, louver film (LF), water tank, and light shield (LS). The microcomputer is used to control the linear actuator.

To form a mid-air image under and on a water surface, the images require different optical paths. MMAPs form a mid-air image (I1') with light from a light source (D1) located above the water level. The virtual image (I1) of the mid-air image (I1') reflected on the water surface is the underwater image seen by the user. The water surface forms a mid-air image (I2) on the water surface with light reflected from the MMAPs from another light source (D2) located below the water level. When there is no water, the MMAPs form the mid-air image (I2').

To move the mid-air image in the depth direction, a linear actuator moves the light source display. As the light source display moves closer to the MMAPs, the image also appears close to the MMAPs, and as the light source display moves further from the MMAPs, the image approaches the user.

LF shields the light of the optical subsystem that passes through MMAPs and goes directly to the user's eyes. LF is an optical element that blocks light rays in a specific direction. To avoid the effect of external light, LS covers the equipment.

Interaction Area

When the maximum height of scooping water in the proposed system is h_{sMAX}, the range in which users can see the mid-air image is the shaded area in Figure 3. As the water level rises, the height and position of the reflected MMAPs (V-MMAPs) change, so the field of view also changes.

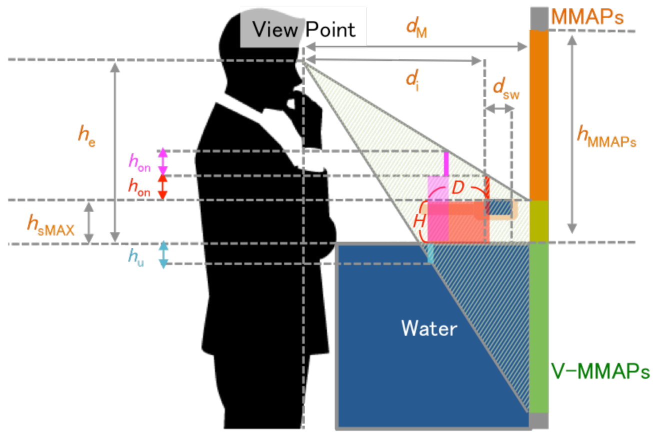

Figure 3. Optical parameters and interaction area.

However, to realize the interaction, it is necessary to consider the movable area of the hand where the user can always view the image on the scooped water surface. In this paper, we refer to this area as the interaction area. This area is smaller than the shaded visible area and satisfies the following three conditions.

1. There is a scooped water surface and V-MMAPs on the extended line of the line connecting the viewpoint and the top edge of the scooped water image.
2. A line segment connecting the viewpoint and the bottom edge of the scooped underwater image intersects the scooped water surface, and V-MMAPs exist on the extended line of the line segment.
3. All points from the start of scooping until the end satisfy 1 and 2.

Assuming that the depth distance of the floating image in which users can interact is D and the maximum height of the scooped water surface is H, the interaction area is a red rectangular area consisting of D and H (Figure 3). The following seven parameters are distance parameters.

- h_{on} : Maximum height of the image on water surface
- h_u : Maximum height of the image under water surface
- h_e : Height from the bottom edge of the MMAPs to the viewpoint
- h_{MMAPs} : Height of the MMAPs
- d_{sw} : Depth width of scooped water surface
- d_M : Depth distance from viewpoint to MMAPs
- d_i : Depth distance from viewpoint to the image

The following relational formula holds for D and H.

$$D = -\frac{d_{sw}}{h_{on}} H + d_{sw}\left(\frac{h_e}{h_{on}} - 1\right) - d_M \frac{h_e + h_u}{h_e + h_{MMAPs}} \quad (1)$$

As shown in the formula, there is a trade-off between D and H. The magenta rectangular area in Figure 3 is an example of an interaction area with different D and H parameters.

Viewable Angles

Figure 4 shows the viewable angle when the user scoops the mid-air image on water surface at the frontmost position of the palm. The shaded area from θ_{MIN} to θ_{MAX} is the viewable angle. Assuming that d_z is the horizontal distance from the MMAPs to the image, each angle can be obtained by the following formula.

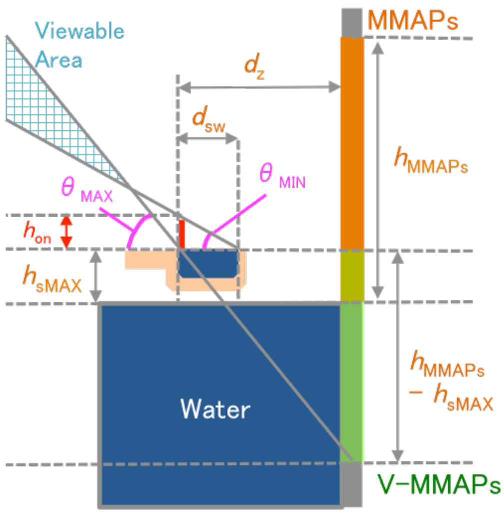

Figure 4 Viewable Angles

$$\theta_{MIN} = \tan^{-1}\left(\frac{h_{on}}{d_{sw}}\right) \quad (2)$$

$$\theta_{MAX} = \tan^{-1}\left(\frac{h_{MMAPs} - h_{sMAX}}{d_z}\right) \quad (3)$$

Interaction Subsystem

The interaction subsystem controls the display position of the light source display in accordance with the water level scooped by hand, enabling the user to scoop up the image. The subsystem consists of an RGB-D camera and a control PC. The system uses the RGB-D camera to measure the water level scooped up by the user and the control PC to control the display position of the light source.

The control to move the display position of the image of the light source by the same amount as the displacement of the water level makes it possible to scoop up the image. When the image is scooped without the control, the vertical position of the mid-air image relative to the water level also changes. For example, if the water level rises by 3 cm when an image is on it, the imaging position of the image rises twice because the vertical components of the optical path before and after reflection change as the water level increases.

In this study, we use an RGB-D camera to measure the level of water scooped at an arbitrary horizontal position. We investigated using an infrared distance sensor, ultrasonic sensor, and RGB-D camera as a method to measure the level of water scooped by hand without the user having to wear a device. Since the infrared sensor and the ultrasonic sensor have a strong directivity when measuring the plane object, to measure the water level at an arbitrary horizontal position, the sensors must be arranged in a two-dimensional array form. Then, since the system requires a ceiling the same size as the water surface, there are few places it can be installed. On the other hand, the RGB-D camera can obtain the depth for each pixel in the measurement area, so it is suitable for measuring an arbitrary horizontal position.

In this paper, we consider the water depth of the scooped water as constant and take an approach to approximate the water level by adding an offset to the distance to the palm measured by the RGB-D camera. Since light passes through the water surface, the RGB-D camera measures the distance to the palm of the bottom of the scooped water. On the other hand, since sound bounces off the water surface, we thought that we could measure the distance to the water surface by using ultrasonic sensors. However, when the water level scooped was actually measured with the ultrasonic sensor, a finger or wrist of the user positioned higher than the water level became noise, and a measurement error of 2 to 3 cm occurred. This error is comparable to the water depth of water scooped by a user with average sized hands. Therefore, the RGB-D camera is suitable for accurate measurement.

IMPLEMENTATION

System

Figure 5 shows the implemented device. D is LITEMAX SLD 2126 (LCD Display). MMAPs are ASUKANET Aerial Imaging Plate [16] with a height of 50 cm and a pitch of 0.05 cm. The water tank is a plastic case with depth × width × height of 37 cm × 25 cm × 11.5 cm. LF is LINTEC WINCOS Vision Control Film W - 0055. The microcomputer is Arduino Uno. The RGB-D camera is Intel Realsense D 435. The control PC is ASUS Transbook T303UA. The display area of the display is 47.6 cm high and has a maximum luminance of 1600 cd/m^2. W-0055 is a unidirectional opaque film with an opaque angle of 0° to 55°. The water tank was placed so that the water surface was the same height as the lower end of the MMAPs. Since the reflectance of vertically polarized light is higher than that of parallel polarized light in water surface reflection, the display was installed in such a direction that vertically polarized light is made incident on the water surface.

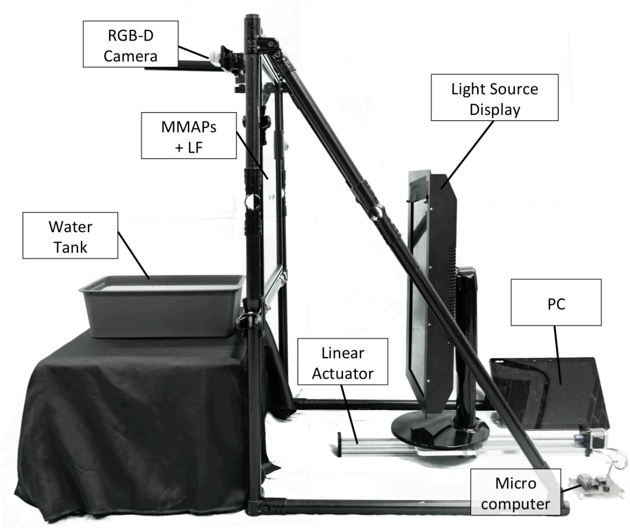

Figure 5. Implemented System without LS.

Control Algorithm

The system obtains the water level of the water scooped by hand by the following procedure. The algorithm operates on the premise that the hand is put in to scoop within the field angle of the camera. It does not recognize hand posture or gestures. The update rate is about 30 fps. Figure 6 shows the detection of a scooping palm.

1. A background subtraction method using depth information extracts what does not exist in the background and binarizes it
2. Noise is removed by an opening process
3. Linked regions are extracted by labeling
4. The largest connected area is treated as a hand scooping up water
5. The center of the widest position of the hand is treated as the bottom of the hand
6. An offset value is added to the distance to the bottom of the hand. The initial offset value is set to 1.5 cm.

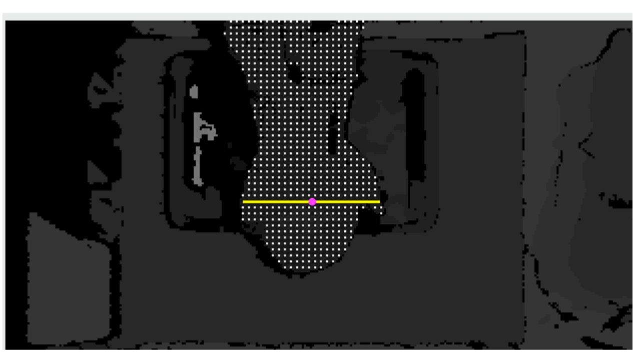

Figure 6. Detection of scooping palm. The area of the detected hand is displayed in white, and a black line is drawn in the y coordinate with the widest width of the hand

The system moves the display position of the light source by displacement of the water level. The displacement is the average value for the last five frames. The light source was limited so as not to move downward from the initial position so that the mid-air image did not float from the initial position.

EVALUATION

Offset

When a user scooped a floating mid-air image on the water surface of the water tank, we obtained the value of the offset at which the user recognized that the scooped image was floating on the water. We also examined the correlation between the offset value and hand length (Figure 7 Left). To scoop the water, the user needs to bend his/her fingers like a cup. The longer the user's hand, the deeper the scooped water is expected to be, so we hypothesized that the offset, which looks like a scooped image floating on the water, is proportional to the length of the hand.

There were 8 participants (22 to 24 years old, 6 males) in the experiment, and the procedure was as follows.

- The horizontal position of the participant was adjusted to d_M = 60 cm. An image was displayed at a position of d_i = 25 cm. However, participants were allowed to move their upper body.
- As a presentation stimulus, a white square image with a side of 2 cm on the water surface was displayed on the water, and an image of a white line was displayed at the water level. To give the participant a depth clue, the same square with about 60% of luminance of the image on the water was displayed under the water surface as a reflected image (Figure 7 Right). After the experimenter explained what each image was, the experiment continued after the participant was able to recognize it.
- Participants adjusted the vertical position of the image with the keyboard to the lowest height at which the image could be recognized as floating on the water.
- Participants scooped up the images with both hands and adjusted the offset to the lowest height at which they could recognize the position as floating on the water. The initial value of the offset was randomly set between 0 and 4 cm. After confirming whether the participant was able to recognize the image floating on the water, the experimenter recorded the adjusted offset value and the height of the scooping h_{sMAX}. At this time, the experimenter adjusted the offset with the keyboard in accordance with the verbal instructions of the participant. This procedure was carried out 10 times. Participants decided the height of scooping h_{sMAX}.
- After recording, the eye height (h_e) and the length of the scooping hand were measured.

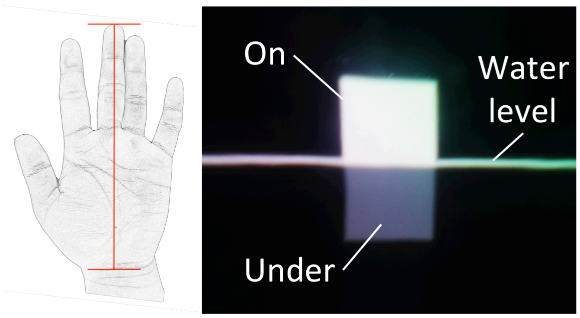

Figure 7. Left is measured hand length. Right is presentation stimulus image.

As a result, the average of the offset was 2.19 cm, and the standard deviation was 0.45 cm. A one-way ANOVA analysis of the offset value for each participant showed no significant difference, and there was no correlation between hand lengths and offset (correlation coefficient - 0.18). The average h_{sMAX} and h_e of the 8 participants were 9.77 and 35.7 cm, respectively. The standard deviations were 1.95 cm for h_{sMAX} and 6.7 cm for h_e.

We think that the reason the hand length and offset did not correlate is that it is difficult for participants to distinguish between an underwater image and a floating image. Participants with short hand lengths may possibly have adjusted the offset to a position higher than the actual water depth, making it easy to see the image. In this system, d_{sw} becomes smaller as hand length becomes shorter, and the maximum visible height (h_{on}) of the image on the water surface becomes smaller. Also, as the offset becomes higher, the position of the light source rises, so the vertical position of the image reflected on the water surface decreases. Then the image sinks to the scooped water surface. Participants misunderstood that this sunken image was also floating on the water. Therefore, we think that it is difficult to correctly recognize whether the image is floating on the water when scooping the image with water by hand.

On the basis of the above results, we used 3.09 cm, which is a value obtained by doubling the standard deviation of 0.45 cm and adding it to the average value of 2.19 cm, as the offset value of the proposed system so that many users can scoop up the image. The derivation process is as follows. First, we judged that the offset did not need to be dynamically set because the results did not significantly differ and the hand length and offset did not correlate. Next, the smaller the offset, the lower the visibility of the user with a short hand length. Therefore, we use the larger value of the 95% confidence interval as the offset.

Interaction

We confirmed that the proposed system enables users to scoop mid-air images at arbitrary horizontal positions. Figure 8 shows the result when scooping from the water surface at the four corners of the water tank.

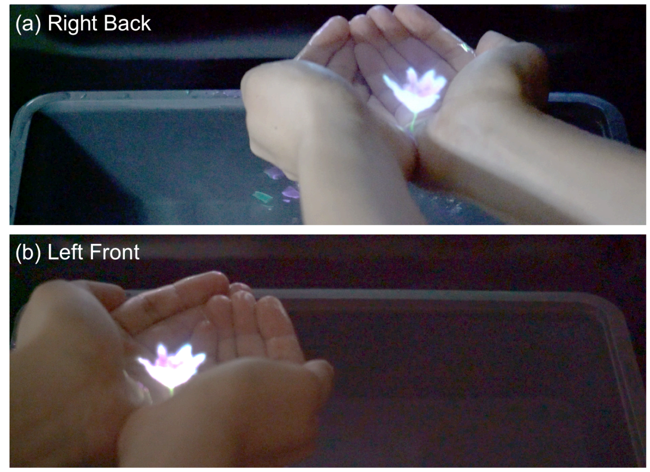

Figure 8. Scooped images on water surface at arbitary horizontal positions.

Brightness

To investigate the relationship between the water level and the brightness when displaying the mid-air image in the proposed system, we evaluated the brightness for each water level. We measured the brightness of the image above the water surface from the front by raising the vertical position of the water tank filled with water in steps of 5 cm up to 40 cm. The angle was measured from a depression angle of 15° to 30° in steps of 5°. 30° is the angle at which the image can be recognized even by raising the water level by more than half the height of the MMAPs. We measured the luminance of a white square image with a radius of 2 cm displayed at a horizontal distance of 30 cm from MMAPs using Konica Minolta CS-150 as a luminance meter. Figure 9 shows the experimental conditions.

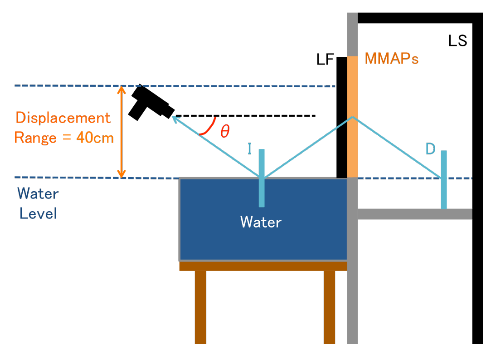

Figure 9. Experimental conditions. Depression angle is θ.

Figure 10 shows the results. At all angles, the brightness tends to increase as the water level reaches 15 and 20 cm. Especially at 15° and 20°, there was a nearly two-fold difference between the lowest value.

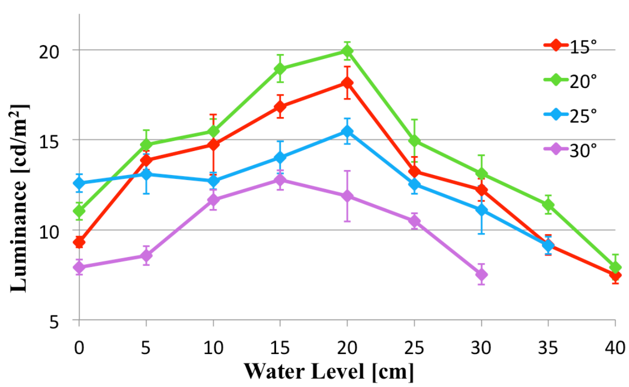

Figure 10. Relationship between water level and luminance.

The design shown below with the brightest brightness at the highest point where the image can be scooped is an example of an optical design using this result. The average h_s obtained by the offset experiment is about 10 cm, and when the depression angle is 20° or 25°, the brightness maximizes at a water level of 20 cm. Therefore, if the water surface of the water tank is arranged to be 10 cm from the lower end of the MMAPs and H of the interaction area is designed to be 10 cm, the brightness of the highest point at which the user can scoop the image becomes the brightest. Considering the parameters in Figure 3, h_e and h_{MMAPs} are reduced by 10 cm and the field of view is narrowed, so this design is suitable for applications where luminance should be prioritized over the field of view.

DISCUSSION

Limitation of Interaction Velocity

The relationship between the water surface rise speed and tracking update speed causes one limitation of this system. When the water level rises during one frame, the vertical position of the image with respect to the water level also rises. As a result, when the water surface no longer exists on the extension line of the line connecting the viewpoint and the top edge of the mid-air image to be displayed, the reflected light does not reach the user's eyes.

We obtain the maximum velocity V at which the image can be scooped while ensuring that the upper edge of the image is visible. Considering the parameters in Figure 3, the maximum height h_{on} of the scooped image becomes smaller as the water level rises. When the scooping height is h_{on}, the depth distance from the viewpoint to the image is d_i, and the distance to the scooped water surface from the viewpoint is d_{wf}, the following expression holds.

$$h_{on} = (h_e - h_s)(1 - \frac{d_i}{d_{wf} + d_{sw}}) \qquad (4)$$

When the height of the scooped image is h_n, h_{on} - h_n is the height of the margin that the image can display. When the water surface moves during one frame, if the vertical position of the image does not move more than this margin, the upper end of the image can be seen. Since the sensing rate is about 30 fps, the maximum speed V can be obtained by the following expression.

$$V = 30 \times (h_{on} - h_n)/2 \qquad (5)$$

V when the user with d_{sw} of 8 cm scoops a 3 cm image in the center of a hand is calculated using the distance parameter during the offset experiment to be 8.8 cm/s. The average speed at which the user scoops the image measured by the system demonstration was 4.2 cm/s, so V is sufficiently large for the user's scooping interaction.

Limitation of Brightness

The result of brightness seems to be derived from the fact that as the light source moves closer to the center of the MMAPs, the amount of light rays used for forming the mid-air image increases.

The maximum brightness of the installed system was 20.74 cd/m^2. Although the luminance largely decreases from the luminance of the light source due to the reflection of the water surface, two methods are considered for improving the luminance. One is to improve the light source using a display with higher luminance, and the other is to control the direction of light from the light source display with a prism sheet or the like. We will aim to further improve brightness in future research.

Limitation of Interaction Design

In the exhibition of the proposed method, when the user performs an operation exceeding the interaction area, there are two interactions that avoid the limit of the visible area using the RGB-D camera. One is to control the image to move horizontally and spill from the hand when trying to scoop the image higher than H. The other is to move the image to a position where the light beam is not shielded when the hand extends to a position where it blocks the light ray that forms the image. For example, the hand behind the image on the water blocks the ray that forms the image. This method avoids the limitation of optical occlusion.

The speed of the actuator used in this study is about 1 cm / sec. We have not yet been able to select an actuator with a speed fast enough for interaction. Although the current actuator speed is insufficient, since the RGB-D camera can also track the horizontal position of the hand, by using a linear actuator with a sufficient moving speed, information moving to an arbitrary three-dimensional position can be manipulated by scooping up the mid-air image.

The scooping action is not suitable as an interaction by which multiple people reach out to the mid-air image at the same time. For an interaction to be done simultaneously by multiple people, it is necessary to add a horizontal movement that pushes water by hand and moves the image.

The current system cannot detect whether hands contain water. Even if there is no water in the hand during interaction, the light source will rise with the height of the hand. At this time, the user sees the light diffused by the ray forming the mid-air image on his/her palms (Figure 11). If the system can detect if there is water in a user's hands, the system can make expressions more suitable to a situation. For example, when water spills from scooping hands, the system can return the position of the image to the water surface of the water tank.

Figure 11 (Left) Water in hands. (Right) No water in hands.

The underwater image displayed by the system does not have refraction characteristics generated when viewing an underwater object. Therefore, positional discrepancies occur in interactions combining an underwater image and an underwater real object.

Viewable angles and areas

We can derive two ways to widen the field of view from equations (2) and (3). One is to use larger MMAPs. Currently, 1 m × 1 m MMAPs can be used. The other is to make the mid-air image smaller.

It is difficult to show images to users of greatly different heights at the same time. In the prototype exhibition, we prepared a foot stand so that children could see the image.

Figure 12 shows a ghost image. As a limitation of the system, an unintended ghost image may be displayed near the aerial image. This is due to the structure of MMAPs.

Figure 12 Midair image (center) and ghost image (left)

CONCLUSION

The purpose of this research is to introduce an interactive visual expression that users can touch and manipulate directly with water on a water surface in a public space. To achieve this purpose, we added water reflection to a mid-air imaging technique and implemented an interaction in which the image is scooped up with water. The contributions of this research are as follows:

1. We proposed a control method to scoop up mid-air images at an arbitrary horizontal position.
2. We determined the necessary offset value when tracking the water level of the scooped water by hand with the RGB-D camera.
3. We showed the interaction area that users can scoop up.

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